Position Paper

Hydrogen Europe
Research

Advancing Hydrogen Technologies

Key Research and Innovation Priorities

Extended Edition – Including 10 Technical Papers Expanding Research Priorities

A roadmap for pioneering research projects

November 2025

Position Paper

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Key Research and Innovation Priorities

A roadmap
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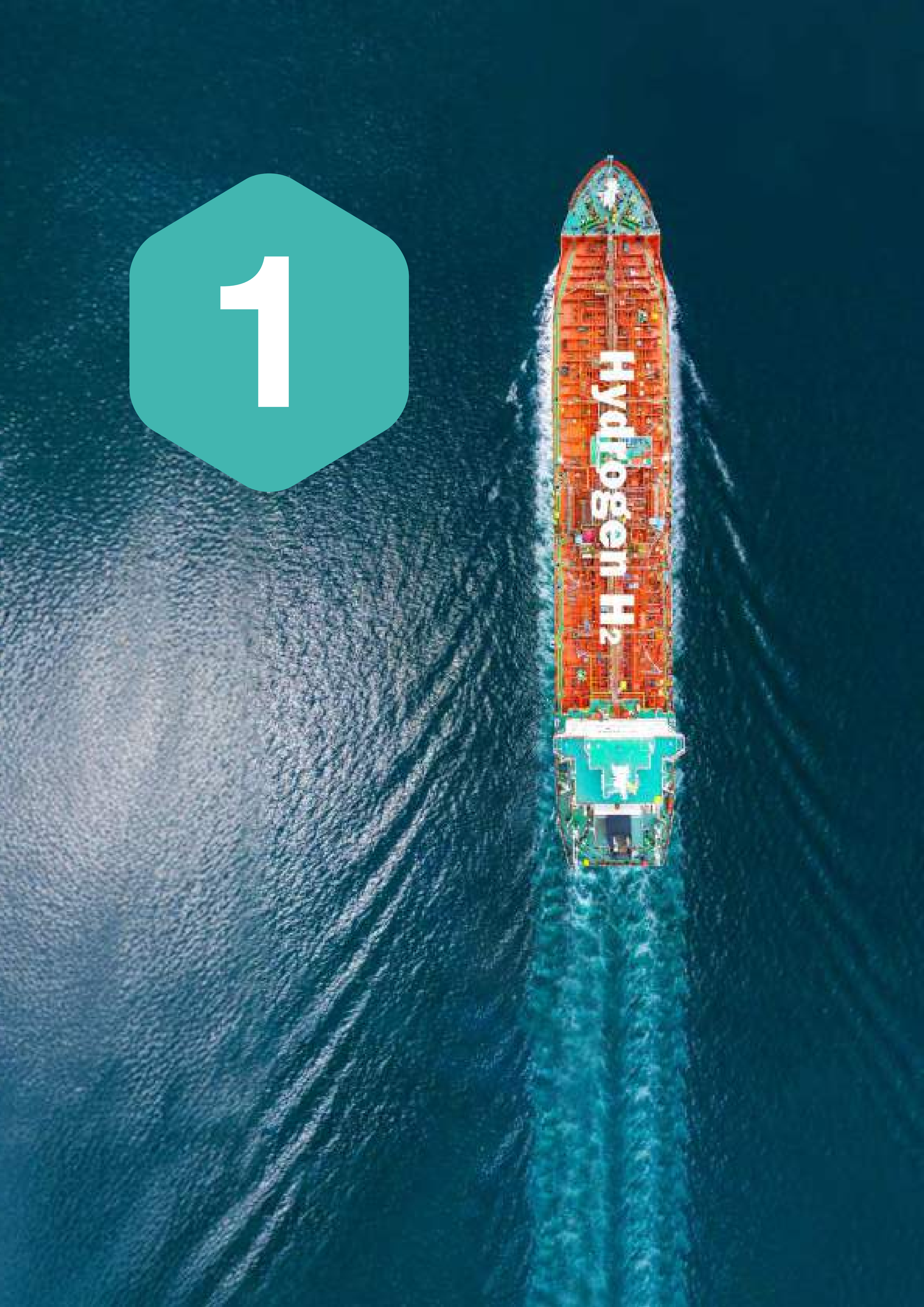

Foreword

In emerging sectors like hydrogen, research is crucial for developing and refining technologies. Exploring multiple pathways at early technology readiness level (TRL), is essential to identify the most efficient solutions and bring them to market. Hydrogen Europe Research represents the European hydrogen research community, continuously working to break barriers in this vital field.

Two years ago, we published a position paper on research needs in the hydrogen sector. Since then, significant developments have taken place, and many topics are now actively being researched thanks to funding from the Clean Hydrogen Partnership. Given the dynamic nature of the sector, there is an urgent need for a new position paper that reflects these changes and provides an updated perspective on the current research landscape. Drawing on the expertise of Hydrogen Europe Research's Low TRL Working Group and its broader membership, this paper outlines the most pressing research priorities for the coming years.

The position paper also emphasizes the need for sustained, adequate funding. Europe is beginning to fall behind other global players, particularly in the realm of innovation, as highlighted by the recent Draghi report. Investment in research is essential to drive innovation, keep European technologies in the lead and develop new solutions that can be commercialized. Two variables are relevant to master this challenge: time and money. Without sufficient investment, industries may relocate to regions offering more favourable conditions and financial incentives. It is therefore essential to establish a comprehensive development pipeline, encompassing various roles from early-stage research and technology readiness level innovation to the validation of technologies at the relevant industrial scale, culminating in the co-design and co-development of solutions in close collaboration with the private industrial sector. Hydrogen Europe Research envisions a collaborative dynamic where traditional researchers work closely with innovators—specialists who combine scientific excellence with industrial methodology and timing. It is increasingly important for Europe to have a well-integrated network of research and technology infrastructures that provides these ideal conditions in one place. Through our Working Group on Technology and Research Infrastructures, we are mapping these facilities, identifying gaps and needs, and highlighting the strengths of the European network.

Now is the time to act decisively to ensure Europe maintains its leadership in hydrogen technologies by investing in cutting-edge research, including the critical and promising topics discussed in this paper. Research should follow a circular approach, comparable to a Formula 1 championship, where our team meticulously prepares its car to stay ahead of the competition in every round.

Luigi Crema

Luigi Crema
President, Hydrogen Europe Research

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Executive Summary

Hydrogen is one of the key solutions to reach climate neutrality. Its production, transportation, storage and application are, however, in need of research and development. As representatives of the research community, Hydrogen Europe Research has prepared this position paper giving an overview of the most urgently needed research topics to ensure that hydrogen can play its envisaged role.

Electrolytic hydrogen production remains a key area of focus. Innovative designs for cells and stacks are needed to reduce costs and increase efficiency. Another area of focus is enhancing the Balance of Plant (BoP) components, but also research into alternative water resources, such as seawater and wastewater, for use in electrolysis is important to enable a more sustainable hydrogen production. Additionally, reversible electrolysis technologies, which allow for bidirectional energy conversion, could play a key role in optimizing energy use in response to fluctuating demand. Further advancements are also needed in the integration of co-electrolysis processes, which can generate synthetic fuels by capturing and converting CO_2. It is equally important to explore alternative production methods, such as photo-induced hydrogen production. Thermal production routes, including gasification and thermolysis, present opportunities for renewable hydrogen generation from diverse resources such as municipal waste and biomass. In parallel, exploring geological hydrogen production and leveraging biological processes could broaden the range of hydrogen resources available. Finally, the adoption of sustainable manufacturing technologies, such as additive manufacturing, will be critical to reduce waste and lower production costs.

As the shift toward a hydrogen economy accelerates globally, the need for comprehensive research in hydrogen storage, transport, and distribution has become increasingly important. Developing cost-effective storage solutions, particularly for liquid and compressed hydrogen, is critical. A deeper understanding of material behaviour in the presence of hydrogen, as well as hydrogen's interaction with non-metal materials, is needed to enhance the safety and efficiency of storage systems. Research into alternative and advanced materials for storage and distribution will further help enable large-scale hydrogen use, including for onshore and shipping applications. Another storage option, metal hydrides, offer potential due to their compact, energy-efficient storage capabilities. Underground hydrogen storage, including in salt caverns and depleted gas fields, is another promising area. Research must focus on understanding hydrogen behaviour in different conditions, pressure requirements, and environmental considerations to ensure efficient and safe large-scale storage. Researching retrofitting existing gas pipelines for hydrogen transport is also critical. This involves researching the effects of hydrogen on pipeline materials, including corrosion, permeation, and embrittlement. Inhibitors, coatings, and advanced sensors must be developed to prevent leakage and ensure safe transportation. Research into safety and flow dynamics through pipelines is vital for integrating hydrogen into existing gas networks. Cost-competitive hydrogen carrier solutions and related conversion technologies are equally important. Developing efficient hydrogenation and dehydrogenation processes, along with exploring synthetic fuels and green ammonia synthesis, will enable massive hydrogen transportation. Further research into advanced technologies, such as hybrid redox flow batteries and hydrogen purification methods, can enhance the reliability and scalability of hydrogen storage and distribution systems. Additionally, assessing hydrogen carriers and refuelling demand is critical to building an efficient distribution infrastructure.

The rapid growth of the fuel cell and hydrogen sector presents opportunities for innovation across various industrial sectors. Research is pivotal in overcoming technological barriers, optimizing processes, and integrating hydrogen into existing and novel applications. This includes exploring new fuel cell designs beyond classical architecture, such as membrane-less, air-breathing, lightweight, and static-passive feeding designs. Developing new electrolytes such as boron-based compounds, multicomponent liquid electrolytes, and composite electrolytes, can enhance fuel cell performance and pave the way for PFAS-free polymers. While hydrogen has maritime applications, hydrogen and hydrogen carrier storage beneath the deck poses safety concerns. Research into storage, leak detection, containment systems, and emergency response protocols is essential. Hydrogen is also a promising energy carrier for aviation, but challenges arise in integrating liquid hydrogen storage, maintaining low temperatures, and minimizing boil-off. Compact, energy-dense fuel cells with optimized cooling are critical. Hydrogen combustion in gas turbines also holds potential for reducing NOx emissions, requiring advanced combustor designs. Hydrogen as a heating agent in glass production can reduce carbon emissions but may cause issues such as metal depletion, acidification, and discolouration. While hydrogen is also a key decarbonisation option for European steel-makers, impurities in ores and the decarbonisation of alloying elements like ferro alloys need further research. Hydrogen plasma could be a promising route for full decarbonisation. Optimizing hydrogen combustion burners for industrial applications is crucial for enhancing efficiency and reducing emissions. Research on flame stabilization, fuel-air mixing, turbulence, and burner design will improve operational stability. Developing advanced combustion systems capable of using hydrogen and ammonia fuels safely and efficiently will facilitate wider industrial adoption. Research into ammonia cracking technologies and direct combustion can enable decarbonisation in sectors such as metallurgy.

Research challenges in the hydrogen sector also include transversal challenges. Key areas of focus include sustainability, safety, pre-normative research, infrastructure, education, and societal acceptance. Research into the recycling of hydrogen technologies at their end of life (EoL) is crucial for promoting circularity and resource efficiency. For substances that are hard to recycle and harmful to the environment, such as PFAS, alternatives such as non-fluorinated membranes must be developed and tested. AI applications in hydrogen research hold significant potential for accelerating advancements. Data-driven approaches using machine learning and artificial intelligence (AI) can enhance our understanding of complex systems, optimize processes, and identify novel materials. Understanding materials behaviour when processed into pipeline coatings, electrodes, membranes, and cells is critical for improving hydrogen technologies. By combining electro-chemistry, nano-scale analysis, and automated prognostics with validated multi-scale modelling, researchers can better predict performance and longevity. Developing more comprehensive models and scenario analysis tools is essential to understand the full impact of hydrogen technologies on the energy transition. Expanding techno-economic models and integrating them with short-term dispatch models will provide more detailed insights into how hydrogen fits into energy systems, particularly with the rise of renewable energy sources. Pre-normative research is essential for developing regulations, codes, and standards to support the safe deployment of hydrogen technologies. As the hydrogen sector grows, clear regulations must be established across the hydrogen value chain to facilitate widespread adoption. Accelerated Stress Test (AST) protocols are needed to validate new materials and solutions for hydrogen technologies, particularly given the long lifetimes expected of these materials. The lack of training standards in the hydrogen sector presents a challenge for education and workforce mobility. Defining these standards and developing modular training programs accessible to learners and training providers will promote workforce up-skilling and reskilling, especially as the industry evolves rapidly. Research and technology infrastructures are vital for fostering innovation and scaling up manufacturing capacity in hydrogen-related industries. Co-developing solutions in common labs and testing facilities can accelerate the industrialization of the hydrogen sector.

3

Introduction

3.1 Present state of affairs

Europe is steadfast in its commitment to reducing greenhouse gas (GHG) emissions by 55% by 2030 and ultimately achieving climate neutrality by 2050. Recognising the formidable challenges posed by sectors such as heavy industry and mobility, where emissions reduction is particularly complex, hydrogen has emerged as a cornerstone solution. However, harnessing the full potential of hydrogen hinges on robust Research and Innovation (R&I) efforts.

The development of hydrogen technologies necessitates not only advancements in performance, combined with sufficient durability, but also significant cost reductions. While R&I efforts have been instrumental in driving progress, additional funding and a supportive regulatory framework are imperative to accelerate the transition. Collaboration between research institutions and industry is paramount in this regard, as it enables the refinement of existing technologies and the exploration of innovative solutions.

Europe's leadership in hydrogen technology is contingent upon sustained collaboration and cooperation across sectors. By fostering synergies between various European initiatives and partnerships, the use ofresources can be optimised, and development efforts streamlined. At the same time, alignment with strategies at the national and regional levels are essential to facilitate the widespread adoption of hydrogen technologies, taking into account local contexts, regulatory frameworks and energy landscapes.

Despite significant progress, challenges remain in effectively allocating resources and addressing key research priorities. Further funding is needed to propel advancements in hydrogen technologies, particularly in areas with low Technological Readiness Levels (TRL) thereby enabling the breakthroughs required to fully uncover the potential of hydrogen technologies. Hydrogen Europe Research advocates for European cooperation to drive innovation and foster the global hydrogen economy, ensuring a sustainable future for generations to come.

3.2 Purpose and benefits of low technology readiness research

Low Technology Readiness Level (TRL) research plays a pivotal role in the advancement of hydrogen technologies. Such research can be broadly defined as an ideas-based research, where concepts (components and/or technologies) are not yet fully validated. Low TRL research can be seen as a process paving the way for concepts to be tested and then validated as prototypes in laboratories, subsequently enabling the process of demonstration and validation of technologies in relevant environments. While high TRL research focuses on refining existing technologies (mature and under development), low TRL research explores novel concepts and solutions that have the potential to revolutionise the sector. By investing in low TRL research, the hydrogen ecosystem can unlock innovative pathways to address pressing challenges and achieve breakthroughs that propel the industry forward.

The purpose of low TRL research is twofold: exploration and innovation. It provides a platform for scientists and engineers to explore uncharted territory at the frontiers of knowledge between disciplines, pushing the boundaries of what is possible. By combining multi-disciplinary and cross-sectorial work force and advanced infrastructure available in Europe, it allows iterative and agile research necessary to uncover new materials, processes, methodologies and technologies that have the potential to reshape the energy landscape. Low TRL research is also contributing to increase sustainability and European leadership of existing and next-generation technologies, by addressing fundamental research on materials and components to replace existing solutions relying on critical and strategic raw materials (CSRM).

3.3 Purpose and benefits of high technology readiness research

High Technology Readiness Level (TRL) research is instrumental in bridging the gap between innovation and practical application, driving the widespread adoption of hydrogen technologies. Unlike low TRL research, which focuses on exploration and testing, high TRL research is geared towards refining and commercialising existing technologies to make them ready for market deployment. By advancing technologies from the laboratory to real-world applications, high TRL research accelerates the transition to a sustainable energy future.

The purpose of high TRL research is to validate and optimise technologies to ensure their reliability, scalability, and cost-effectiveness. This involves rigorous testing, validation, verification and demonstration activities to prove the performance and viability of hydrogen technologies under real-world conditions. In this view, technology infrastructures are essential platforms to pursue such testing and validation activities. By addressing technical challenges and refining engineering processes, high TRL research enhances the readiness of technologies for commercialisation and mass adoption.

The benefits of high TRL research are manifold. It de-risks investments by providing stakeholders with confidence in the performance and reliability of hydrogen technologies. Through comprehensive testing and validation, high TRL research identifies and mitigates potential technical, standards, certification and regulatory barriers, paving the way for successful market deployment.

4

Research requirements & recommendations

The European Union is tackling research challenges in the hydrogen ecosystem with four key objectives:

Scientific Excellence: Ensuring Europe maintains its global scientific leadership by covering the entire hydrogen value chain and investing in breakthrough technologies at low TRL. Moreover, collaboration in international networks and securing relevant intellectual property are key strategies.

Industrial Leadership: Supporting the industrial sector through European and national programs, with funding allocated to both next-generation technologies and the upscaling of already developed technologies. This approach aims to foster a dynamic industrial environment conducive to the emergence of newcomers and start-ups.

Market Development: Research contributes to accelerating the development and deployment of hydrogen technologies while also fostering the development of new markets. Pre-normative research and the validation of criteria for new reference standards are crucial for overcoming technological, economic, legal, and social barriers to adoption.

Territorial Impact: Research plays a vital role in defining, developing, and implementing pilot projects with "First of a Kind" technologies. This involves supporting techno-economic analyses, developing business cases, and monitoring and validating districts and "Hydrogen Valleys." By identifying the best technologies and integration schemes, research supports the industry in improving or developing new systems for territorial implementation.

> Clean hydrogen production is crucial to developing a hydrogen economy. Electrolysis, the leading method for renewable and low-carbon hydrogen production , requires further research to enhance performance, durability, reliability, and cost. Emerging technologies, with potential for higher efficiency and noble catalyst-free processes, also need extensive research due to their lower TRL. This includes developing advanced materials, cell designs, and BoP components. Alternative methods, like photo-induced and thermal processes, also hold promise, though they require deeper understanding and development to prove viability.
> Together, these efforts will expand the range of clean hydrogen production technologies for the energy transition.

Julie Mougin,
Technical Committee Leader Hydrogen Production

4.1 Hydrogen production

To ensure cost-competitive and efficient low-carbon hydrogen production with minimal reliance on critical and strategic raw materials (CRSMs) as well as forever chemicals such as PFAS, low TRL research efforts must prioritise the development of next-generation technologies as regulatory bans threaten to come into place in the future. By focusing on breakthrough innovations and novel solutions, the European research community can consolidate its global leadership in the hydrogen production sector. These efforts should encompass both incremental improvements to existing technologies and the exploration of new materials and processes to radically enhance performance and durability while reducing costs.

Central to these research endeavours is the advancement of electrolytic hydrogen production. Nevertheless, while electrolysis remains a primary focus, it is essential to also explore alternative production methods to meet the diverse needs of low-carbon hydrogen from various renewable and recoverable sources. Diversification of hydrogen resources and production technologies will enhance the resilience of the clean hydrogen supply chain, ensuring reliability and sustainability.

Moreover, research should address the critical issue of minimising, or even eliminating, the use of CRSM, as well as the eco-design of components, in hydrogen production processes. By developing more efficient technologies, with longer lifetime and higher integration of recycled & alternative materials, dependencies and supply chain risks can be mitigated.

On the following pages, HER has grouped research topics that deserve particular attention within the topic of hydrogen production in the coming years.

1

Innovative Cell and Stack Designs for Electrolysis

Further research into innovative cell and stack designs is imperative for advancing all types of electrolysis technologies. Optimising designs for low temperature electrolysis could include research on stack designs without membranes or redox mediators decoupling the reaction at the anode and cathode, while for high-temperature electrolysis this could include finding solutions reducing polarisation losses or exploring specific operating modes such as co-electrolysis of steam and CO_2, thus reducing cost in hydrogen production and utilisation in down stream processes.

2

Advanced Materials and Novel Material Concepts for Electrolysis

Research aimed at improving current materials, or developing advanced materials, used in electrocatalysts, membranes, electrolytes, bipolar plates, coatings, seals, current collectors, and other functional layers (interlayers, porous transport layer, etc.) at cell and stack levels, as well as developing durable low loading catalyst layers and new materials is essential. One pathway to achieve this is through the development of material acceleration platforms and use of digital solutions for high throughput screening and fundamental understanding of the degradation processes in the proposed advanced and novel materials through multi-scale and multi-physics modelling. These advancements, jointly with the process of integrating them into the cell or stack, can enhance the performance, durability, efficiency and flexibility of electrolysis systems, making them more competitive and sustainable while reducing the use of CRSMs. Specifically, emerging technologies such as Anion Exchange Membrane (AEM) and Proton Conducting Ceramic (PCC) electrolysis stand to benefit from such research, driving forward their commercial viability.

3

Optimisation of Balance of Plant (BoP)

Research focused on optimising the Balance of Plant (BoP) aspects of all types of electrolysis systems is of high importance. Safety, high-water purity requirements and the need for flexible operation at low and high temperatures, as well as potentially high pressures, present significant challenges that must be addressed through innovative solutions. Furthermore, research focusing on power electronics and converter technologies to optimise their use in hydrogen applications coupled with renewable energy sources is needed to reduce the currently high costs. By optimising BoP components and thermal management system performance, hydrogen purity, reliability, water consumption and overall efficiency can be improved.

4

Alternative Water Resources for Hydrogen Production by Electrolysis

Exploration of the feasibility of utilising alternative water sources, namely seawater and wastewater, as feedstock for hydrogen production via electrolysis is currently being investigated in laboratories. Further support is needed to build upon recent research projects with the aim to reap the benefits using alternative water sources can bring, notably removing the need for high-purity water and harnessing the production of hydrogen in remote locations (such as offshore electrolysis for example).

5

Investigation of Reversible Electrolysis

Reversible electrolysis technologies enable bidirectional operation, allowing to produce hydrogen and generate electricity as needed to meet fluctuating demand and optimise energy utilisation. While theoretically feasible for any fuel cell, current devices are typically optimised for unidirectional operation. To harness the full potential of reversible electrolysis, research is essential to develop fuel cells capable of maintaining high efficiency levels in both directions of operation.

6

Integration of Co-Electrolysis Processes

Investigating co-electrolysis processes offers significant possibilities for expanding the scope of hydrogen production. By incorporating co-electrolysis of CO_2 (both at low and high temperatures), processes can also be adapted for the generation of synthetic fuels. This approach not only utilises hydrogen but should also capture and convert biogenic CO_2 into valuable hydrocarbons. The integration of co-electrolysis can lead to more efficient and sustainable methods of synthetic fuel production, leveraging the dual benefits of mitigating carbon emissions and producing energy-dense fuels. This synergy can enhance the overall efficiency of the technology and broaden its application in various industrial sectors, potentially transforming energy systems to be more environmentally friendly and resource efficient.

7

Novel processes to produce hydrogen via photo-induced processes

Novel processes for hydrogen production via photo-induced methods, such as artificial photosynthesis, photo-(electro-)catalytic and solar thermochemical techniques offer multiple pathways for sustainable hydrogen production. Increased solar to hydrogen efficiency and lower cost are crucial for these technologies to move to higher TRL research. These approaches involve developing innovative CSRM-free photo-electrodes and reactor designs enabling increased photon management, exploring efficient redox coupling reactions to reduce overpotential & enhance reaction rates and ensure proper separation of hydrogen & oxygen. Such advancements can significantly lower device costs and enable decentralised hydrogen production that can be integrated with other processes, making it more accessible and sustainable. Moreover, hydrogen production from water can be synergistically enhanced using hybrid processes that combine photocatalysis with sonolysis (ultrasonic irradiation). This research area focuses on understanding the complementary mechanisms of sonolysis and photocatalysis and optimising their integration to achieve better hydrogen generation efficiency and selectivity.

8

Technological Development of Alternative Production Routes (gasification, thermolysis, thermochemical processes):

Research into alternative routes for renewable hydrogen production is critical. These processes are typically thermally driven by heat from renewable sources but can also incorporate hybrid routes (for example, integrating solar or wind electrical energy and concentrated solar heat), in which one or several steps can be driven by electrical energy or electrochemical reactions (electrochemical steps in thermochemical cycles, electrically assisted thermolysis or extraction of high purity hydrogen from diluted gas streams via membrane processes). These thermal and hybrid alternative routes offer opportunities to diversify hydrogen production methods based on heat, which can be stored in a straightforward way enabling continuous operation, enhancing overall sustainability of hydrogen production.

9

Exploration of Geological Hydrogen Production

Further exploration of geological hydrogen sources is necessary for diversifying hydrogen production pathways and enhancing overall sustainability. The focus should lie on establishing safety protocols to ensure the risk of hydrogen production/extraction remains low, develop purification technologies for purifying the extracted hydrogen stream, and develop further understanding on the regenerative processes involved (i.e. chemical and physical conditions, presence of precursor). By tapping into natural hydrogen reservoirs and leveraging biological processes, the range of available hydrogen resources can therefore be expanded.

10

Non-Conventional and more Sustainable Manufacturing Technologies

Exploring non-conventional and less subtractive manufacturing technologies, such as additive manufacturing, is crucial for unlocking creativity in cell and stack designs, while also contributing to reducing manufacturing waste and increasing efficiency in hydrogen production processes. Techniques such as microfabrication, 3D printing, fast sintering processes and plasma-based deposition techniques offer promising avenues for improving manufacturing processes. Automation and/or combination of more traditional techniques to increase yields and recycled materials use, as well as replacing harmful solvents/organics, are also crucial to lower the environmental footprint and reduce cost. Methodologies for process and quality control including in-line ones are crucial to optimise production yield.

> To establish a global hydrogen economy, hydrogen production and end-uses need to be efficiently connected through cost-competitive and safe storage, transport and distribution technologies.
> In this sense, we need to continue developing and scaling-up novel storage materials and solutions (both aboveground and underground), grids and hydrogen carriers for massive transport and distribution, and key technologies such as purifiers and compressors for bringing hydrogen to end-users with the required quality.
>
> **Ekain Fernandez,**
> **Technical Committee Leader Hydrogen Distribution**

4.2 Hydrogen storage, transport, and distribution

As the global transition towards a hydrogen economy gains momentum, the need for robust research in hydrogen storage, transport, and distribution becomes increasingly apparent. Developing cost-competitive solutions for massive hydrogen transportation, retrofitting existing gas grids, and understanding material interactions are among the critical research areas. The following pages explore the current research needs and highlights emerging topics to address the challenges and opportunities in realising a hydrogen-based energy landscape.

1

Developing Cost-Competitive Storage Solutions

Research is crucial for developing cost-competitive storage solutions for liquid and compressed hydrogen. Understanding material behaviour and compatibility with hydrogen is essential for ensuring the safety and efficiency of storage systems and for the prevention of corrosion and material embrittlement. Additionally, research into alternative and/or advanced materials can offer innovative approaches to hydrogen storage for different applications in storage and distribution. Such advancements can facilitate large-scale onshore and shipping storage, enabling the widespread adoption of hydrogen as an energy carrier.

2

Investigating Material Interactions

Research is required to understand the effects of high-pressure hydrogen on polymer and composite materials. While much is known about hydrogen's damaging effects on metals, less is understood about its interactions with non-metallic materials crucial for preventing leakage. Investigating phenomena such as uptake, swelling, and phase separation under a wide range of operation conditions will guide the development of materials resistant to hydrogen-induced damages, ensuring the integrity of hydrogen storage and transportation systems.

3

Investigating Metal Hydrides for Reversible Hydrogen Storage

Metal hydrides offer an energy-efficient, compact, reversible and low-cost storage of hydrogen at ambient pressure and temperature through a thermal process. Even though there are some commercial applications of metal hydrides, more research is needed to explore the potential of new tank designs and their coupling with other components of the hydrogen chain, such as electrolysers and fuel cells. The design of the metal hydride reservoirs should be optimised by analysing and simulating different geometries, also considering manufacturability. The design of materials to store hydrogen as a hydride compound should focus on utilising recyclable and non-critical raw components and high porosity compounds whilst improving the effective thermal conductivity for proper heat management, aiming for economic efficiency.

4

Hydrogen Underground Storage

Understanding hydrogen behaviour and best sealing practices in different underground settings is important to avoid considerable losses to the amount of gas injected. Understanding pressure requirements for different settings is important to ensure safe operating environments and ensure both containment and optimal recovery of the stored gas. In addition, the cyclability (charging and discharging) of large quantities of hydrogen for industry demand should be further explored. Moreover, considering different cushion gas options in view of optimising the cushion gas to working gas ratio will be another step towards more efficient storing of hydrogen. Finally, environmental aspects of large-scale underground storage infrastructure (salt caverns, depleted gas fields or artificial underground cavities) should be given emphasis.

5

Adapting Existing Gas Pipelines

There is a critical need for research to adapt and retrofit existing gas pipelines for hydrogen transportation and distribution and investigate effects of hydrogen on materials (corrosion, permeation, embrittlement…). This also includes developing mitigation technologies such as inhibitors and coatings, as well as identifying cost-competitive materials suitable for hydrogen pipelines. As hydrogen is more prone to leakage than natural gas, due to its smaller molecular size, components such as compressors, pressure regulators, valves and seals need to be replaced to adapt gas networks to hydrogen. Advanced sensors and measurement & monitoring tools are also necessary for detecting leaks and ensuring gas quality. Pre-normative research is vital for understanding and addressing the challenges of integrating hydrogen into gas grids, including modelling flow dynamics through pipelines. Furthermore, research on safety aspects and leakages is needed to ensure safe operation.

6

Developing Cost-Competitive Carrier Solutions and related conversion technologies

Research is essential to develop cost-competitive solutions for massive hydrogen transportation. Innovative hydrogenation and dehydrogenation technologies need exploration to ensure efficiency, flexibility, safety and affordability. Synthetic fuels, as well as green ammonia synthesis, integrating electrolytic hydrogen and/or co-electrolysis, should be further explored to improve the flexibility of the Fischer-Tropsch and the Haber-Bosch processes, coupled with renewable energy sources. A challenge is to define the optimal plant size and operation to maintain the same level of process efficiency as conventional larger ones. At smaller scales, heat and mass transfer, reactor design, and process control become more critical and may require innovative solutions for optimisation. In order to improve conversion efficiency, reaction kinetics, and cycle stability, novel catalysts, reactor designs, and process conditions must be explored.

7

Exploring Advanced Purification Technologies

Further research is necessary to explore advanced hydrogen purification solutions such as membrane or electrochemical technologies. They have the potential to purify hydrogen stored underground as well as geological hydrogen and hydrogen found in industrial waste streams to high purity hydrogen. These innovative technologies should be tested at lab-scale and then scaled up to market level. The purification technologies might also be integrated in advanced reactors (e.g. membrane reactors, electrochemical reactors, plasma reactors) to enhance the performance of chemical reactions, such as reforming and cracking of hydrogen derivatives as well as the synthesis of these hydrogen derivatives.

8

Assessing Hydrogen Carriers and Refuelling Demand

Research is essential to assess the state of various hydrogen carriers and identify research gaps to improve processes for the imminent importation of hydrogen to Europe. Additionally, understanding refuelling and energy demand patterns is crucial for designing efficient hydrogen distribution networks and infrastructure. Data-driven computational modelling can serve as a powerful tool to identify and validate optimal candidates for hydrogen storage, transport, and separation among a wide range of materials, accelerating the development and deployment of hydrogen technologies.

> Unlocking hydrogen’s potential requires targeted research that prioritizes process optimization, technology refinement, and scalable integration to meet industry needs sustainably. It is crucial to prioritize advancements in fuel cell technologies, developing more compact, efficient, and versatile fuel cell systems suitable for an even wider range of stationary applications. Advances in fuel cell and combustion technologies are essential to overcoming technical challenges, expanding hydrogen’s applications, and establishing it as a viable, clean energy solution across a range of industrial sectors.

Viviana Cigolotti,
Technical Committee Leader Heat & Power Industry

> While fuel cells for transport historically were developed for passenger cars, the main focus is now on heavy duty (HD) transport applications including heavy duty trucks, maritime, rail and aviation. These applications require significantly higher power and much longer lifetimes, which cannot be met with incremental improvements of existing fuel cell technologies. Thus, new fuel cell concepts and designs, beyond the classical architecture, as well as new, more stable, recyclable and sustainable materials must be developed to succeed in full commercial market deployment of fuel cells in HD transport applications.

Steffen Møller-Holst,
Technical Committee Leader Hydrogen Transport

4.3 Hydrogen end-uses

As the fuel cell and hydrogen sector continues to experience rapid growth and development, it is imperative to identify and address the research needs critical for advancing hydrogen applications across various transport and industrial sectors. In this context, research plays a pivotal role in overcoming technological barriers, optimising processes, and ensuring the seamless integration of hydrogen technologies into existing processes while exploring novel applications where it could be utilised. This overview explores the diverse research needs within transport and industry applications for hydrogen.

1

New fuel cell concepts and designs, beyond the classical architecture

Exploring new fuel cell concepts and designs beyond the classical architecture represents an opportunity for breakthroughs, innovation and optimisation. Currently, the fuel cell stack itself has reached a relative mature level, providing reliable power for reasonable long lifetimes. However, the classical fuel cell architectures are limiting their use to certain market segments, while others are still out of reach. This is typically either caused by stack related issues or linked to the heavy, voluminous and costly Balance of Plant Components. Focus on reducing the complexity of fuel cell systems, through simplification and/or elimination of some BoP components, can lead to new fuel cell concepts and designs. By investing in research on membrane-less configurations, air-breathing, lightweight designs, efficiency can be enhanced and the scope of applications expanded. New cooling strategies along with static and passive fuel cell feeding systems, also offer the potential to address current technological limitations and new possibilities for fuel cell technology can be unlocked. This research can lead to the development of more compact, efficient, and versatile fuel cell systems suitable for an even wider range of applications, from transportation to stationary power generation. Exploring new fuel cell concepts and designs beyond the classical architecture presents an opportunity for innovation and optimisation. By investing in research on membrane-less, air-breathing, lightweight designs, new cooling concepts and static-passive feeding fuel cell designs, existing limitations can be overcome and new possibilities for fuel cell technology can be unlocked. This research can lead to the development of compact, efficient, and versatile fuel cell systems suitable for a wide range of applications, from transportation to stationary power generation.

2

New types of electrolytes

The development of new types of electrolytes for fuel cells focuses on the fundamental research and initial testing stages of innovative materials that could significantly enhance fuel cell performance and/or make use of PFAS free polymers. This developmental phase includes exploration and formulation of novel electrolytes such as boron-based compounds, multicomponent liquid electrolytes, and composite electrolytes. Boron-based compounds are investigated for their unique chemical properties and potential to facilitate higher conductivity and electrochemical stability in fuel cells. These compounds are in the early stages of synthesis and characterisation to determine their feasibility in operating environments. Multicomponent liquid electrolytes involve the combination of several chemical components to create a fluid medium with optimised ionic conductivity and reduced degradation rates under fuel cell operating conditions. At low TRL, the focus is on identifying the right chemical blends that can operate efficiently at varying humidities, temperatures and pressures. Composite electrolytes represent a hybrid approach, integrating different materials such as polymers, ceramics, and conductive fillers to create multifunctional electrolytes. These are designed to leverage the strengths of each component material, such as improved mechanical strength from ceramics and enhanced ionic conductivity from polymers. Initial development involves material screening and selection, prototype manufacturing, and basic performance testing under controlled conditions.

3

Maritime

Research into hydrogen and hydrogen carrier (ammonia, methanol) conversion and storage beneath deck in maritime transport is critical for addressing safety concerns and advancing the adoption of these as a clean fuels in the maritime sector. Hydrogen storage beneath the deck presents unique safety challenges due to the potential risks associated with hydrogen, such as flammability, toxicity (in the case of hydrogen carriers) and the formation of explosive mixtures. Therefore, it is essential to conduct comprehensive research to understand and mitigate these risks effectively. Investing in pre-normative research can lay the foundation for developing standardised safety protocols and regulatory frameworks, ensuring the safe and efficient integration of hydrogen and hydrogen carrier storage systems on ships. By investigating factors such as hydrogen and hydrogen carrier leak detection, containment systems, and emergency response protocols, researchers can develop robust safety measures to protect crew members, passengers, and the environment. Furthermore, pre-normative research plays a crucial role in establishing industry standards and regulations for hydrogen storage in maritime transport. By collaborating with regulatory bodies, industry stakeholders, and research institutions, researchers can identify best practices, define safety requirements, and develop testing procedures to ensure compliance with international safety standards.

4

Aviation

The aviation sector faces particular challenges due to the range of flight missions and the high energy consumption on medium and long-haul flights. Hydrogen as an energy carrier represents a promising solution as it can be converted into electricity in fuel cells or via gas turbines. In both cases, storing the hydrogen in liquid form and integrating the tank into the fuselage remains an important and complex task due to the significant challenges of maintaining extremely low temperatures, minimising hydrogen boil-off and preventing leakages. These challenges are particularly prominent during landing when most of the hydrogen has been used, and the remaining hydrogen could quickly evaporate if warmed. In addition, fuel cell drives must also include very compact and energy-dense fuel cells, with extremely high mass and volume-specific performance. Moreover, their cooling is extremely critical and currently require larger system sizes increasing the weight of propulsion systems. Thus, low TRL development of new materials based on membranes and particularly catalysts and electrodes are required to increase fuel cell operating temperatures above 100 °C and efficiently reduce the cooling system requirements. Moreover, the newly identified materials need to be optimised towards higher volumetric power densities and long-term stability. Hydrogen gas turbines could also play a significant role by cutting CO_2 emissions. However, reducing NOx emissions from combustion of hydrogen is crucial. Thus, it's essential to design, test, and implement combustors that improve hydrogen and air mixing, enhance flame stability, and exhibit good thermo-acoustic properties. By collaborating with regulatory bodies, industry stakeholders, and research institutions, researchers can identify best practices, define safety requirements, and develop testing procedures to ensure compliance with international safety standards.

5

Hydrogen in glass and ceramics production

Despite promising results, using hydrogen in ceramic tile production poses technical challenges. Its lower calorific value than methane requires a higher gas volume, potentially necessitating kiln and burner adjustments to maintain efficiency. Hydrogen combustion can also affect tile color consistency, particularly with color-sensitive glazes, which may alter shades due to combustion variations. Further research is needed to ensure color quality without losing efficiency. In glass production, hydrogen use shows potential but presents unique issues, such as metal depletion, acidification, and foam formation in the melt, which limits heat transfer and accelerates furnace wear. High water vapor levels exacerbate these effects, potentially discoloring glass and reducing quality. Research aims to refine heating methods and process parameters, focusing on minimizing metal loss, acidification, and discoloration to ensure hydrogen's viability in environmentally and economically sustainable glass production.

6

Hydrogen in metal production

Hydrogen is one of the favoured decarbonisation options for European steel-makers, but several research questions remain before this solution is viable economically. The influence of impurities in ores will be important as also low-quality ores and industrial by-products must be used as feedstock. Furthermore, steel requires not only iron, but alloying elements such as ferro alloys, whose decarbonisation options are even more limited than for iron. Hydrogen can be used in the pre-reduction of some of the ores such as chromite and manganese ores, giving potential for substantial carbon reductions. One of few options for complete decarbonisation which should be further investigated could be hydrogen plasma. In addition, significant challenges for these processes and applications arise from the fuel switch from natural gas to hydrogen. The significant change in water vapour content (+89% for air combustion) in the off-gas can affect the gas-solid or gas-liquid interaction between the furnace atmosphere and the product in direct heating applications leading to potential increase of surface oxidation effects. The impact on refractory and other auxiliary products and materials is also relevant.

7

Hydrogen and ammonia combustion burners

Research into hydrogen combustion burners and combustion behaviour is needed for optimising the use of hydrogen as a clean energy source in various industrial applications. By investigating the combustion characteristics of hydrogen and developing efficient burners, researchers can improve combustion efficiency, reduce emissions, and enhance the overall performance of industrial processes. Notably, research into flame stabilisation mechanisms is necessary for ensuring stable and reliable combustion of hydrogen and ammonia fuels. By understanding the factors influencing flame stability, such as fuel-air mixing, turbulence, and burner design, researchers can develop innovative flame stabilisation techniques to enhance combustion performance and operational stability in industrial settings. This research can lead to the development of advanced combustion systems capable of operating efficiently and safely with hydrogen and ammonia fuels, paving the way for widespread adoption in industry.

8

Direct use of ammonia

Research on using ammonia directly in industry holds promise for leveraging ammonia as a versatile and clean energy carrier. By investigating cracking technologies based on combustion or electrochemical processes and developing ammonia-based cracking technologies, researchers can explore new pathways for decarbonising industrial processes. Ammonia combustion offers the potential to reduce greenhouse gas emissions and air pollutants while providing a scalable and cost-effective energy solution for various industrial applications. Research on the impact of ammonia on materials is crucial to ensure feasibility of these technologies. Where hydrogen is needed as a reducing agent in high temperature environments, such as in metallurgical applications, the process temperatures are sufficient for ammonia decomposition. This could bypass the need for expensive cracking units. Further research on direct use of ammonia in production of iron and other metals holds potential to reduce the overall costs across the hydrogen-ammonia-metal value chain.

> Hydrogen is called to play a pivotal role in achieving a European carbon-neutral society. Therefore, research is crucial to ensure that it will be safe and sustainable from environmental, economic and social perspectives, educating the next generations and getting society involved in its deployment.
>
> **Javier Dufour,**
> **Technical Committee Leader Cross-Cutting Activities**

> Even though hydrogen valleys are not part of this position paper, the research outlined here plays a crucial role in advancing hydrogen ecosystems, fostering local industrial clusters, and supporting regional decarbonization efforts. At a regional level, it enables multi-scale, multi-purpose initiatives, and guides policy-makers in strategic planning. Through rigorous techno-economic monitoring, research provides data-driven insights that build confidence among investors and identify areas for improvement. By generating technical, economic, and workforce requirements, research also supports training programs tailored to hydrogen industry needs
>
> **Guillermo Figueruelo,**
> **Technical Committee Leader Hydrogen Valleys**

4.4 Transversal activities

As the fuel cell and hydrogen sector continues to evolve rapidly, it faces a myriad of challenges that span across various research domains. These challenges demand transversal research efforts to address critical issues and drive innovation in hydrogen technology. The following pages explore the research needs in key transversal research topics within hydrogen research, focusing on sustainability, pre-normative research, safety, research and technology infrastructures, education and training needs, and social aspects. By delving into these areas, opportunities to advance the development and deployment of hydrogen technologies can be uncovered while ensuring their sustainability, safety, and societal acceptance.

1

Recycling of Hydrogen Technologies

Research into the recycling of hydrogen technologies at their End of Life (EoL) is crucial for promoting circularity and resource efficiency in the hydrogen industry. By recovering and reusing Critical Raw Strategic Materials (CRSMs) from decommissioned hydrogen technologies, reliance on virgin materials can be reduced and waste generation minimised. In complementarity with the aforementioned, eco-design and sustainability by design are research pathways that will enable the development of sustainable next generation of technologies.

2

Replacement of PFAS in Hydrogen Technologies

As regulatory pressures increase and bans on PFAS usage loom, the need to investigate alternative substances for hydrogen production, logistics, and end-use technologies becomes imperative. However, the availability of non-fluorinated components remains limited, highlighting the necessity for continued research efforts. Understanding the emissions and environmental behaviour of a subclass of PFAS used in hydrogen applications, fluoropolymers, is therefore also essential, as they will likely continue to be in use until alternatives are widely available. Additionally, while alternatives such as non-fluorinated membranes show promise, they require rigorous stress and durability testing to ensure suitability for widespread adoption. Funding for research in this field is crucial, particularly as Europe is lagging behind in the development of alternatives to PFAS. Further research is needed not only to understand the requirements for replacement substances but also to ensure their durability and environmental harmlessness. By investing in research, we can accelerate the discovery and implementation of viable alternatives, ensuring continued progress and compliance with evolving environmental standards.

3

Development of life cycle inventories of hydrogen technologies for life cycle sustainability, material criticality and circularity assessment

The few sustainability assessments that can be found in literature have emphasised the need for building a transparent and reliable database of life cycle inventories of FCH systems. Along with the application of currently available guidelines for life cycle (sustainability) assessment of FCH systems, the availability of such a database would enable robust life cycle studies for analytical, benchmarking and sustainable-by-design purposes, also including material criticality and circularity aspects. This initiative should take into account public life cycle inventories developed so far within the framework of CHP-funded projects, as well as relevant inventory data available in specialised reports and the scientific literature. Life cycle inventories should be prepared in line with the requirements of the Life Cycle Data Network (LCDN). Furthermore, considering the future market, the development of product environmental footprint category rules (PEFCRs) of FCH products, which also increases the number of LCDN-ready inventories of FCH systems while promoting an environmentally responsible market of FCH products, should be consolidated by the preparation of new PEFCRs.

4

AI Applications in Hydrogen Research

Data-driven approaches exploiting machine learning and artificial intelligence (AI) techniques for computational modelling and screening methods hold great promise for accelerating advancements in hydrogen technologies. By harnessing the power of AI/data-driven approaches, we can enhance our understanding of complex systems at every level, optimise conversion, separation and transport processes, and identify novel and tailored materials for innovation and efficiency gains. With this we can develop routes for their accelerated implementation to reduce time from discovery to application and up to system level with diagnostic, prognostic and control tools. These developments could have broader impacts and could be used in testing platforms, for the definition of Accelerated Stress Test (AST) protocols, as well as in pre-normative research and safety assessment.

5

Modelling and characterisation of materials behaviour when processed into pipeline coatings, adsorbing (host) substrates, electrodes, electrolytes, membranes, and cells

By integrating diverse disciplines such as electro-chemistry, nano-scale micro-structural analysis, and automated learned prognostics, there is a significant opportunity to advance the understanding of materials behaviour in pipeline coatings, adsorbing (host) substrates, electrodes, membranes, and cells. Through a collaborative effort, employing validated multi-scale and multi-physics modelling alongside experimental characterisation at various levels, from the nano to macro-scale, we can develop a comprehensive "toolbox." This toolbox enables the identification of critical parameters influencing performance and lifetime, paving the way for enhancements in next-generation materials and components. By comprehensively assessing materials behaviour under various operating conditions, we can improve predictions and optimise performance, driving progress in the development of more efficient pipeline coatings, adsorbing (host) substrates, electrode, membrane, and cell technologies.

6

Developing more comprehensive models and scenario analysis tools

This is essential for understanding the full impact of deploying hydrogen technologies in the energy transition. Current techno-economic optimisation models have limitations regarding the spatio-temporal resolution needed for short-term operational characteristics, especially with the increasing penetration of variable renewable energy sources. Expanding the scope of scenario analysis tools is crucial to assess the broader implications of alternative low-carbon pathways on health, environmental and social impacts, and resource depletion, as well as the coupling between energy production and energy demand. Additionally, enhancing the integration between energy system models, unit commitment, economic dispatch models, and energy network models can better quantify the contribution of hydrogen technologies to integrating non-dispatchable renewable energy sources like power to gas technologies. Developing alternative optimisation paradigms in models, beyond minimising the cost of the energy system, is necessary. These paradigms should incorporate health outcomes related to changes in air pollutant emissions and integrate short-term dispatch models with long-term reference energy and technology systems. Additionally, modelling tools that not only cover systems but also subsystems such as electrolysers, storage tanks, or compressors will be required in order to model individual technologies and a combination of different technologies. These models should then be combined with IoT to create digital twins that can operate, monitor and optimize hydrogen plants in the future. This cross-sectoral and integrated approach would provide more informative scenarios for informed decision-making in energy systems policy.

7

Defining Regulations, Codes and Standards through further pre-normative research

The hydrogen sector has experienced significant growth in recent years, but the transition from technological advancements to widespread deployment faces non-technological hurdles. To sustain momentum and expand the use of hydrogen technologies across various applications, a robust policy and regulatory framework, coupled with stringent safety criteria, are essential. Clear codes, technical regulations, and standards are needed throughout the hydrogen value chain to facilitate deployment. Hydrogen Europe Research emphasises the importance of Pre-Normative Research (PNR) in informing and shaping regulations to prevent delays in technology deployment due to regulatory gaps. Harmonising regulations across the European Union jurisdictions is crucial to avoid fragmentation hindering technology development. Furthermore, the definition of certification schemes for the hydrogen technologies and their components is be needed to ensure a guarantee on the quality of the commercial and novel technologies and components.

8

Development of Accelerated Stress Test (AST) Protocols

The validation of new materials and solutions for long-term durability, expected to last over a decade, poses challenges due to the time required for development. Thus, there is a pressing need to develop accelerated testing protocols that accurately simulate long lifetimes without altering material behaviour and without changing the mechanisms responsible for the evolution of performances over time. AST protocols representative of usage conditions, in which acceleration factors for the degradation (e.g. temperature, current) need to be embedded, must be defined. They should then be compared to long-term tests performed in real or simulated environments. A combination of these simulations together with AI-driven developments and the advanced micro-structural characterisation techniques is needed to define and validate the best possible AST protocols.

9

Defining training standards, developing modular training and improving access to continuous education for working

The lack of training standards in the field of hydrogen poses a challenge for training providers who lack common recognised guidelines to define the expected proficiency level for specific tasks and professions (particularly in the area of safety). Having these standards in place would facilitate workers mobility between companies and across projects. They should outline the specific learning outcomes, core competencies, and performance indicators that individuals should acquire and demonstrate to meet the requirements of a particular profession or industry. To facilitate this, building a modular training corpus accessible to learners and training providers, as done in European projects, would support the development of education across Europe. Modular learning units could be selected and combined to create personalised learning paths tailored to individual needs and aspirations. Such a design simplifies the replication of training programmes and/or modules across different national educational systems. Training providers could pick the most relevant items and integrate them in their training rather than having to adopt a full programme proposed as a block. Additionally, a modular approach would leave room to introduce modules addressing local requirements and specificities. In addition, given the rapid pace of technological advancements, the European workforce must be continually up-skilled or re-skilled to meet the evolving market demands. Moreover, the acceleration of the transition towards clean energy is reducing the demand for certain professions while increasing it for others. Speed is of the essence to offer workers and industries with up-skilling and re-skilling opportunities, as well as to facilitate knowledge transfer from research to industry.

> Research and innovation in the field of hydrogen technologies quite often requires sophisticated and large infrastructures for testing or studying manufacturing aspects. A significant number of such research infrastructures is available to support industry and in particular SMEs to increase Technology Readiness level (TRL) and Manufacturing readiness level (MRL) of their products. New challenges in hydrogen production, distribution, safety, heavy duty transport and stationary application areas will benefit from use and expansion of such infrastructures, up to the relevant industrial scale.
>
> **Ludwig Jörissen,**
> **Technical Committee Leader Hydrogen Supply Chain**

4.5 Research and Technology Infrastructures

Funding research and technology infrastructures is crucial for fostering innovation and enabling breakthrough technologies, especially in scaling up manufacturing capacity for hydrogen-related industries. Co-designing and co-developing solutions in common labs can facilitate the industrialisation of the European hydrogen sector by testing and validating technologies in the right operating environments.

Hydrogen Europe Research has conducted a mapping of relevant infrastructures along the hydrogen value chain to identify gaps and direct European investments effectively. Bridging these gaps and fostering collaboration across research entities and companies can create a conducive environment for technological innovation. Adequate funding and monitoring are essential to support the development of these infrastructures, particularly for SMEs facing financial constraints. Including both Technology Readiness Level (TRL) and Manufacturing Readiness Level (MRL) measures in infrastructure assessments will provide a more comprehensive understanding of their role in developing, testing, and validating hydrogen technologies. As an example of welcomed recent developments, recently funded Open Innovation Platforms (e.g. Open Innovation Test Beds) are a way of creating a collaborative network of infrastructures.

Research and Technology Infrastructures

Research Infrastructure

Technology Infrastructure

Hybrid Infrastructure

Pilot

Medium

Small

Large

Full value chain

Hydrogen transport

Heat & power end-users

Materials

Hydrogen production

Mobility distribution

Mobility and heat & power end-users

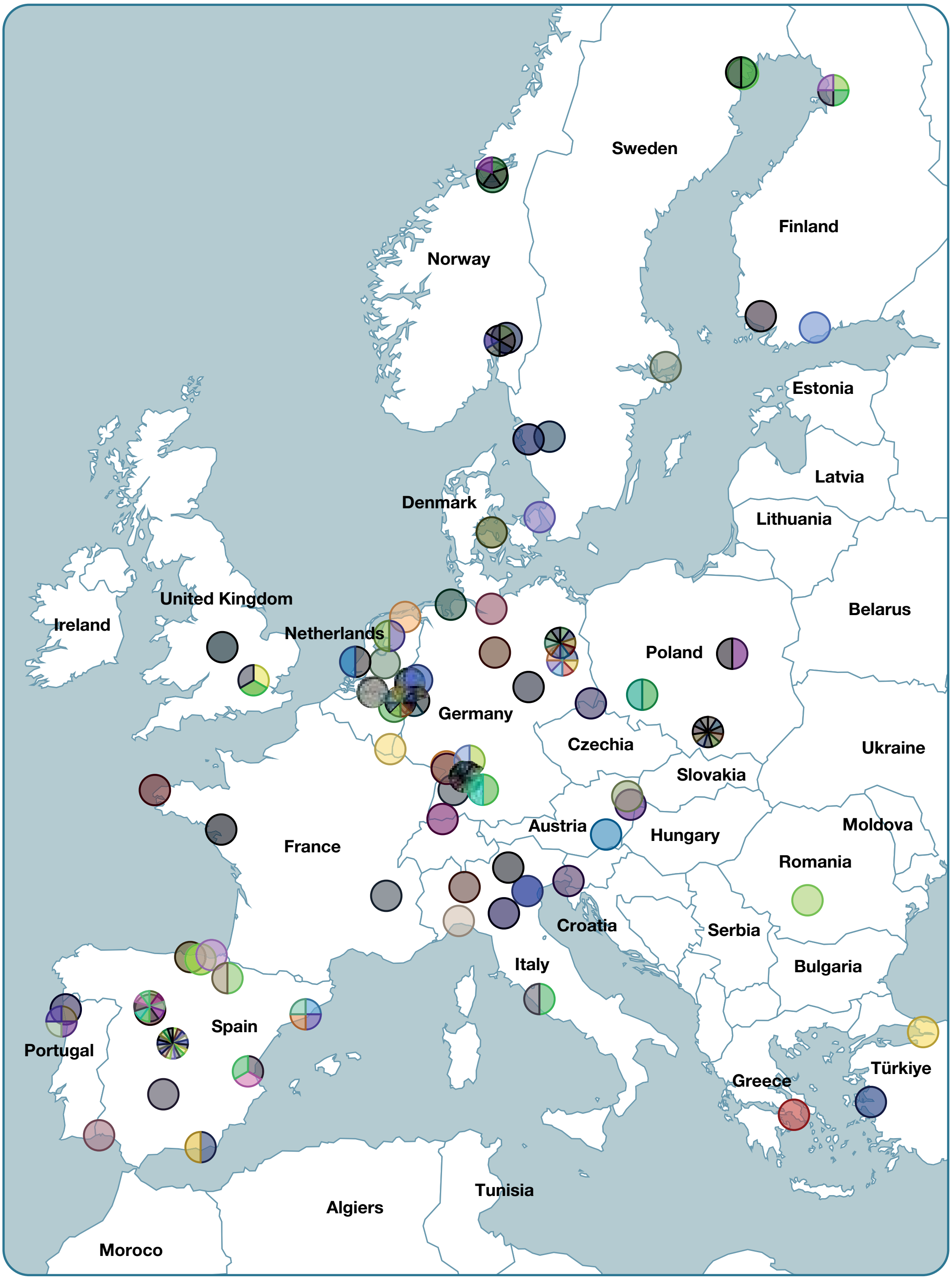
Modelling

Hydrogen storage

Mobility end-users

Industrial end-users

Built environment end-users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Romania
Croatia
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Italy
Bulgaria
Spain
Portugal
Greece
Türkiye
Tunisia
Algiers
Moroco

5

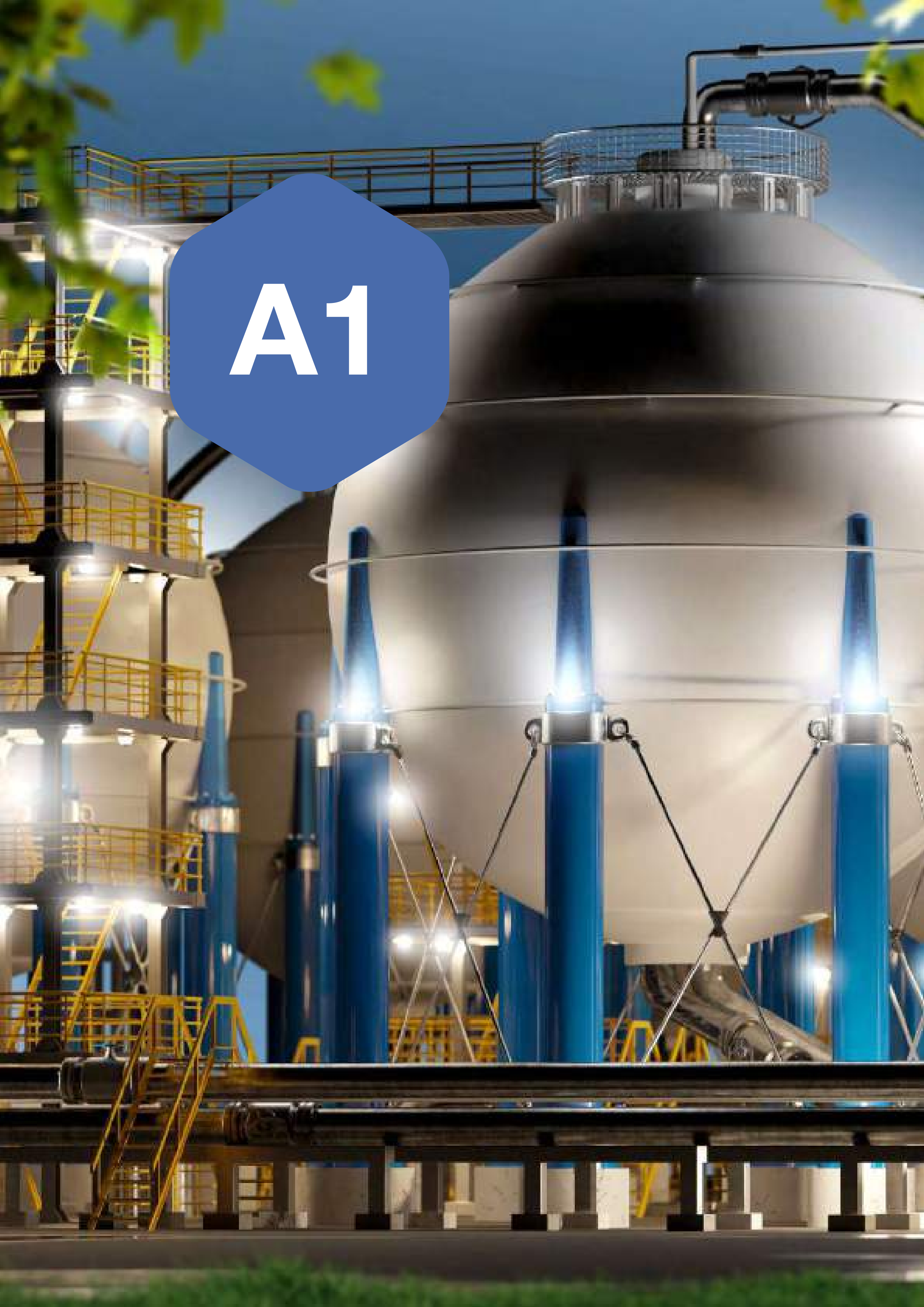
Closing Remarks

Hydrogen technology stands at the forefront of the clean energy transition, offering vast potential to decarbonize multiple sectors, from transport to heavy industry. The research landscape outlined here highlights key areas of focus that will shape the future of hydrogen. These include innovations in fuel cell designs, electrolytes, and combustion systems, advancements in AI and modelling for materials and processes, as well as the critical role of safety and standardization in accelerating deployment. Key industrial applications, such as maritime, aviation, glass, and steel production, underscore the diverse possibilities for hydrogen. However, there is also a pressing need for continued research in safety, efficiency, and the optimal integration of hydrogen in industrial processes. Issues such as hydrogen storage, the replacement of harmful substances like PFAS, and the optimization of materials are central challenges that must be addressed through targeted efforts. Simultaneously, transversal activities such as recycling, sustainability assessments, the development of regulations, codes and standards, and education and training programs are essential for fostering a robust hydrogen ecosystem. By advancing these fields and ensuring societal acceptance, Europe and other regions can achieve a sustainable and resilient hydrogen economy.

This position paper not only outlines the most important research areas but also offers a vision for the long-term impact of hydrogen in reducing global carbon emissions and transforming key industries. To achieve this vision, it should be considered that hydrogen technologies are not entering into an existing market, but that an entire value chain must be developed and put in place. This is difficult, and it requires an overall and integrated strategy. Funding for research is essential, but competitiveness can be built only coupling research and innovation with other actions such as scaling up, first industrial deployment, development of the demand side and activation of early markets.

A private-public partnership such as the Clean Hydrogen Joint Undertaking is crucial in supporting the development of the value chain, of new technologies and bringing existing ones to the market. Thus, providing funding mechanisms is paramount to ensure the research gaps highlighted in this paper are addressed. Through collaboration, continued investment, and innovative thinking, the full potential of hydrogen as a clean, versatile energy source can be realized.

Annex



A1

Alternative hydrogen production processes

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Abstract

The transition to a sustainable hydrogen economy remains constrained by the limited share of low-emission hydrogen production, with conventional carbon-based processes dominating current supply. Conventional water electrolysis, on the other hand, is not the most viable alternative in all use cases. This review provides a comprehensive overview of alternative hydrogen production pathways, focusing on electrochemical, photolytic, and biomass-based processes. Depolarized electrolysis, including SO_2 and nitrogen-compound-assisted methods, offers lower energy requirements and the potential for co-production of value-added chemicals. Biomass-based approaches, such as two-stage anaerobic digestion, pressurized pyrolysis, and thermochemical cycles, enable decentralized, renewable hydrogen production while valorising waste streams. Photolytic methods, including photoelectrochemical and photocatalytic systems, mimic natural photosynthesis to directly convert solar energy into hydrogen, offering long-term sustainable solutions. Despite promising advances, these technologies face challenges including catalyst development, system scalability, feedstock variability, process integration, and techno-economic feasibility. By mapping current research, pilot-scale demonstrations, and knowledge gaps, this review highlights the potential of alternative hydrogen production processes to complement conventional electrolysis, diversify supply chains, and support a resilient, flexible, and decarbonized hydrogen economy.

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1

Introduction

Despite significant efforts by authorities, funding agencies, and researchers to advance a clean hydrogen economy, less than 1% of the produced hydrogen is obtained through low-emission processes, according to the latest IEA report[1]. Many of the most economically viable "clean" alternatives currently involve carbon capture technologies applied to traditional methods, rather than fully sustainable processes.

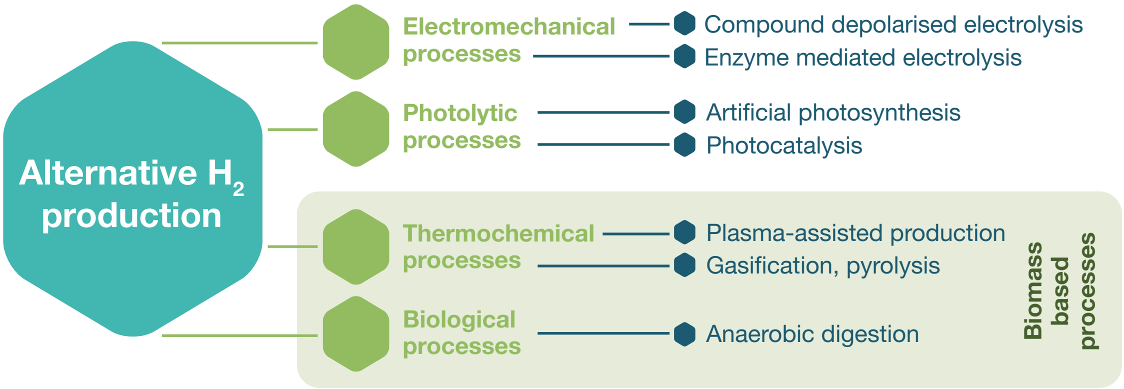
A more effective way to address this challenge is to recognize that, particularly in the energy and mobility sectors, there is rarely a one-size-fits-all solution. Instead, a spectrum of coexisting technologies is required to collectively achieve a shared goal—in this case, a versatile, reliable and scalable supply of clean hydrogen.

This report presents the current state of the art, challenges, and future development needs for selected alternative hydrogen production methods. It is organized into three main categories (Figure 1):

- **Electrochemical Processes:** Involving feeding compounds - other than water - into electrochemical cells. While the fundamental hydrogen production remains unchanged in comparison to water electrolysis, the altered reaction pathways lower energy requirements and potentially produce additional value-added products.
- **Photoactivated Processes:** Aiming to replicate naturally occurring phenomena such as photosynthesis, utilizing solar energy directly for hydrogen generation.
- **Biomass-Based Processes:** In these methods, hydrogen stored within organic compounds is extracted through gasification or pyrolysis or via biological pathways such as bacterial digestion and hydro-genesis.

Each of these alternatives offers unique opportunities for expanding hydrogen production into sectors where traditional water electrolysis may be impractical or economically not viable.

Figure 1: Classification of alternative clean routes for hydrogen production



2

Current state of research

2.1 Electrochemical processes

2.1.1 Compound-based depolarized electrolysis

Compound-based depolarized electrolysis, has the potential to reduce both the energetic costs and mitigating the overall product costs by obtaining valuable by-products. This approach to water electrolysis relies on the introduction of a compound – other than water – into the anode, therefore altering the anodic reaction, without modifying the cathodic reaction (HER). Theoretically, any oxidation reaction that releases protons could be used to “depolarize” the anode on a water electrolysis cell, without altering the cathodic HER, though the main alternative currently studied is the SO_2 depolarized electrolysis (SDE). In SDE, the oxygen evolution reaction (OER) is replaced by the SO_2 oxidation reaction (SOR), reducing the theoretical voltage from 1.23 V to 0.158 V vs RHE, replacing the O_2 by H_2SO_4 in the anode. In spite of being the most researched alternative, SDE still is currently in early stages of development. Current state of the art studies[2–4] are all carried out on either fuel cell or electrolysis components, slightly adapted to operate under SDE conditions. Consequently, the concept of a SDE stack arrangement has not been designed or proposed, the optimization of the specific components for SDE is a necessary step to achieve the established targets from the DoE of 500 mA/cm^2 at 1.0 V with a concentration of H_2SO_4 of $\geq$ 50%, which would position the SDE-sourced H_2 as economically competitive with natural gas derived H_2[4].

Another promising approach for OER replacement in electrolysis involves the oxidation of aqueous solutions containing N-based compounds, where a N-compound reacts instead of O_2. This approach offers significantly lower theoretical energy requirements compared to conventional water splitting: 0.057 V *vs* RHE for ammonia, – 0.334 V *vs* RHE for hydrazine, and 0.072 V *vs* RHE for urea. These nitrogen-containing compounds are attractive due to their high hydrogen content and good solubility in water[6–8]. Ammonia, a carbon-free compound, is produced on a large scale and can be readily liquefied and transported over long distances, making it a practical hydrogen carrier. Urea is a cost-effective and widely available compound with a well-established production infrastructure. The electrochemical oxidation of hydrazine is particularly attractive because it generates nitrogen gas without forming any carbon-containing by-products - unlike urea - although hydrazine is toxic and highly reactive, its hydrate form is non-flammable, making it comparatively safer to store and manage under controlled conditions[9].

The concept of methane/natural gas-assisted electrolysis has also been proposed as a method to enhance the efficiency of solid oxide electrolysers (SOECs) and molten carbonate electrolysers (MCEC) thereby enabling more competitive syngas production compared to SMR. Principle of this strategy is a reforming reaction performed in an electrochemical way. From thermodynamic perspective, the introduction of a fuel such as methane lowers the open-circuit voltage, and thus the electricity consumption. Additionally, the reductive nature of methane diminishes the chemical potential difference between the anodic and cathodic compartments, further contributing to improved system performance. Compared with steam reforming reactors, the modular design of the electrolyser and the absence of extensive heat exchangers, allows this approach to be used to build small-scale hydrogen production units.

2.1.2 Biomass-based depolarised electrolysis

Biomass electrolysis presents a sustainable and energy-efficient alternative to conventional water electrolysis. Unlike water electrolysis, which requires high cell voltages (>1.8 V) and energy input (~4.8 kWh/Nm^3 H_2) [10], biomass electrolysis utilizes organic feedstock to generate hydrogen at significantly lower voltages (~0.6 V), reducing energy consumption by up to three times[11]. The energy balance of ethanol production—expressed as the energy return on energy invested (EROI)—varies significantly depending on the feedstock and production process. The most energy-efficient biofuel sources are the 1st generation ethanol, in particular that produced from sugarcane has a EROI ranging from 8:1 to 10:1.[12] The 2nd generation ethanol, derived from lignocellulosic biomass has an EROI ranging from 2:1 to 4:1[13] as it's a more complex and energy demanding process, but benefits from the utilisation of non-food biomass (e.g., agricultural residues, wood chips) and still offers a good carbon balance. Different biomass-derived feedstock offers distinct advantages in hydrogen production. Ethanol electrolysis requires relatively low input energy (1.6–2.3 kWh/Nm^3 H_2) and benefits from an established supply chain[14]. However, a big challenge is to find highly active catalysts for breaking the C–C bond to accomplish ethanol complete oxidation to CO_2 releasing 12 e^-. Moreover, in addition to CO_2, carbon-containing by-products (e.g. aldehydes) can be also produced. Glycerol, a by-product of biodiesel production, provides high hydrogen selectivity and valuable oxidation coproducts[15]. This process can be designed to co-produce value-added chemicals, significantly improving economic viability[16]. The most interesting feedstock is lignocellulosic biomass. It is an abundant and renewable hydrogen source. However, its complex polymeric structure, made of cellulose, hemicellulose, and lignin, requires pre-treatment to release fermentable sugars for electrolysis. This process is scalable for distributed hydrogen production, with an estimated H_2 cost of \$2.50–\$3.50/kg, making it competitive with clean hydrogen from electrolysis[17].

2.1.3 Enzyme mediated electrochemical processes

Enzyme-mediated electrochemical systems represent a biologically inspired and increasingly promising route for sustainable hydrogen production. These systems exploit hydrogenases - highly efficient metalloenzymes - as natural catalysts for the hydrogen evolution reaction.[18] Particularly, [FeFe]- and [NiFe]-hydrogenases have been integrated into electrochemical platforms to enable hydrogen generation under ambient conditions, providing an attractive alternative to platinum-based catalysis. Compared to platinum, enzyme-based systems demonstrate excellent catalytic behaviour, especially given their operation at low overpotentials and mild reaction environments.[17] Although platinum remains unmatched in universal catalytic performance, its scarcity and cost limit scalability. By contrast, enzymatic systems leverage earth-abundant materials and offer site-specific catalysis, making them attractive for clean hydrogen technologies.

In enzyme-electrode assemblies, hydrogenases are immobilized onto conductive supports such as carbon nanotubes, redox polymer matrices, or nanostructured metal oxides, enabling direct electron transfer.[18] Strategies to overcome oxygen sensitivity include protective encapsulation and protein engineering approaches to preserve catalytic activity under aerobic or semi-aerobic conditions.[19] Oxygen-tolerant [FeFe]-hydrogenases, such as CbA5H from *Clostridium beijerinckii*, can switch reversibly between an active oxidized state (Hox) and an oxygen-stable inactive state (Hinact).[20]

Structural studies used cryo-electron-microscopy for insights in the protein structure, further revealing a “safety cap” mechanism that protects the active site from oxygen damage.[21] Integration with nanostructured semiconductors has also advanced significantly. For instance, electrodes modified with TiO_2 nanostructures and immobilized [FeFe]-hydrogenase from *Clostridium perfringens* (CpHydA) achieved hydrogen production rates around 29 μmol $H_2 \cdot h^{-1}$, with a Faradaic efficiency exceeding 90%.[22]

In microbial electrolysis cells (MECs), hydrogenase-based bio-cathodes have achieved notable hydrogen production efficiencies. Albuquerque et al.[23] reviewed the progress in this field, reporting hydrogen yields up to 3.36 mol H_2/mol acetate under alkaline conditions (pH 11.2), operating at current densities up to 83.7 A/m^3.[24] In recent years, Webb and Milton[25] reviewed scalable electroenzymatic hydrogen production using engineered [FeFe]-hydrogenases on conductive electrodes, maintaining high Faradaic efficiencies. Additionally, Zhuang and Wang[26] updated the state-of the-art on enzyme-mimetic electrocatalysts based on hydrogenase active site architectures, with many examples achieving increased catalytic stability and rates.

2.1.4 Sea- and wastewater electrolysis

Utilization of non-pure sources of water such as seawater or brackish water, theoretically represent a financial and geographical solution for hydrogen production, as often the places where renewable energies are abundant, fresh water is scarce (e.g. north Africa and southern Europe). Though the financial feasibility of this is constantly discussed[27], as the economic cost of seawater desalination and purification, represents - over the overall H_2 production cost - less than 1% in most cases and less than 5% in the most extreme of cases.

The contaminants present in these water sources can result fatal for the current available technologies, with chlorine and sodium being both the prime example and the most abundant contaminant, causing, for example, the chlorine evolution reaction in PEMEL[28] and sodium poisoning the sulfonic groups of the membrane[29]. Nevertheless, continuous efforts are carried out for the development of materials that could adapt PEMEL and AEMEL to cope with non-pure water electrolysis[30] (e.g. complex and noble metal catalysts, electrolyte additives, electroactive substrates) as well as alternative routes to electrolyse seawater that avoid the issues that impede PEMEL or AEMEL utilization for example; Solid oxide seawater electrolysis[31], Molten Carbonate Electrolysis, Sulfion oxidation electrolysis [32] or self-damping electrode [33].

2.2 Photolytic hydrogen processes

2.2.1 Artificial photosynthesis, photocatalysis and photoelectrochemical cells

Photoelectrochemical (PEC) and photocatalytic (PC) solar technologies are recognized as long-term alternatives to coupled photovoltaic-electrolysis units. While the hydrogen production rate is lower than in high intensity electrolysis, PEC and PC systems are simple, bringing about additional options for abundant materials and sustainability. So far, low production rates have not been compensated by solar concentration technologies, as a fall in the solar to hydrogen (STH) efficiency typically occurs [34]. Active materials in PEC and PC systems combine light capture and catalytic abilities in a single component. The PEC cell allows separate compartments, one of them ideally generating pure H_2. On the contrary in a PC reactor, being the simplest configuration, H_2 evolves mixed together with the other reaction products. Therefore, implementation of PEC and PC concepts require specific research efforts, which have received attention from European programmes since FP7 and H2020 to the present.

As a result of SOLHYDROMICS project, a PEC prototype, achieved around 1% STH efficiency for 1-day operation [35]. A first scaling PEC design was accomplished during the ARTIPHYCTION project, consisting of 20 modules of 5 PEC-PV units with a 2% STH efficiency, 1000 h of operation and a total H_2 production of > 1 g/h [36]. Another relevant PEC scaling project was PECDEMO, with STH efficiency of 10%, stability of 1000 h and electrode areas of 50 cm^2.[37] After that, FotoH2 focused on abundant materials and the economic viability of the PEC prototype [38]. Other currently active projects consider the use of metal-free materials [39] or the simultaneous waste treatment with the synthesis of high added-value chemicals [40]. On the purely PC mechanism, a large-scale array of panel reactors was demonstrated by Domen et al.[41]. Current trends focus on novel materials [42] and waste treatment [43].

2.3 Biomass-based and thermochemical processes

2.3.1 Two-stage anaerobic digestion

Two-stage anaerobic digestion (TSAD) systems represent a promising route for decentralized biological hydrogen production using biomass feedstock. These systems, followed by a methanogenic stage, also enable energy-rich bio-hythane generation. Notable performance has been observed in a thermophilic two-stage continuous stirred tank reactor (CSTR) system, which co-digested livestock effluents with starchy wastes. The system achieved volumetric production rate of hydrogen of 2.1 Nm^3H_2/m^3d with a corresponding yield of 99 Nm^3H_2/kg_{vs} indicating strong energy recovery potential. In Bulgaria, a lab-scale pilot using corn steep liquor demonstrated hydrogen production rates of up to 1.0 L/L/day with H_2 concentrations near 35% [44]. Italian studies involving municipal organic waste and waste sludge under thermophilic conditions yielded 24 L H_2 and 570 L CH_4 per kg of volatile solids, underscoring the potential for urban-scale integration and fuel-grade bio-hythane recovery [45]. Náthia-Neves et al.[46] conducted a pilot-scale co-digestion study using restaurant food waste and vinasse, reporting hydrogen yields of up to 76.5% H_2 by volume after 8 days. These findings validate the operational efficiency of TSAD systems in managing diverse organic residues.

A techno-economic analysis by Mahmod et al.[47] on palm oil mill effluent estimated 225,225 m^3 of $BioH_2$ and 51.19 million m^3 of $BioCH_4$ per annum, with production profitability feasible at payback time of 8 years and internal rate of return of 21.48%. A more recent review outlines payback times between 2 and 6 years, also citing examples at TRL greater than or equal to 5, highlighting that TSAD favoured an energy recovery higher than 30% compared to the monostage AD [48]. This suggests that TSAD can be cost-effective, particularly when integrated into existing waste treatment infrastructures and utilizing readily available organic residues.

2.3.2 Thermochemical cycles and biomass-based processes

Thermochemical cycles produce hydrogen through a series of chemical reactions involving high-temperature heat, often sourced from concentrating solar energy. These cycles split water into hydrogen and oxygen without direct electrolysis, offering the potential for high-efficiency operation at scale. Ongoing research is focused on improving the durability and redox performance of active materials—typically metal oxides—while reducing the overall thermal input required. The ability to decouple reduction and oxidation steps also allows for integration with intermittent renewable sources and thermal energy storage, supporting continuous hydrogen production even in variable conditions. Thermo-electrochemical cycles working in solid-state are emerging as alternative processes to reduce operational temperatures up to 850 °C.

Plasma-assisted hydrogen production involves the generation of reactive environments using electric discharges to activate gas-phase reactions at lower bulk temperatures.

These systems are particularly relevant for the conversion of methane, ammonia, or other hydrogen carriers, and can operate with or without catalysts. Plasma reactors offer rapid response times, tuneable reaction pathways, and compact designs, making them suitable for modular or distributed applications. While still at relatively low technology readiness levels, advances in reactor engineering and process control are steadily improving their efficiency and scalability.

In the frame of hydrogen production from biomass through thermochemical processes, gasification and pyrolysis of lignocellulosic feedstock are the most common processes. However, their wide implementation is held back by several technical and economic challenges that should be addressed at both research and process integration levels. In fact, process integration can help reduce the cost of biomass thermochemical conversion by leveraging economies of scale, similar to those seen with more centralized feedstock such as petrol or natural gas. In particular, the integration of biomass-based thermochemical routes with other processes or streams of the clean hydrogen value chain or renewable energy and chemicals value chain can enhance overall efficiency and sustainability [49,50].

Regarding the type of biomass employed, the use of lignocellulosic biomasses is well established. However, in the view of circular economy other biomasses with high humidity degree coming from different processes may be used. On the other hand, a key limitation in current thermochemical processes is the utilization of air and nitrogen (in gasification and pyrolysis, respectively), which leads to diluted hydrogen streams. The production of higher quality hydrogen can be addressed operating on the process by reducing the nitrogen input using for instance enriched air or oxygen [51] coming from other processes or utilizing efficient separation systems, such as pressure swing adsorption (PSA) or membrane systems, suitable for the small scales typical of decentralized biomass facilities.

Biomass pressurized pyrolysis is an advanced thermochemical conversion technique for producing hydrogen, which aligns with current sustainability and decarbonisation strategies [52,53]. This process entails the thermal degradation of biomass feedstock under elevated pressures (typically 5–50 bar) and high temperatures (450–650 °C) in an oxygen-free environment, yielding syngas composed predominantly of hydrogen (H_2), carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4), and minor hydrocarbons.

Operating under pressurized conditions has demonstrated increased efficiency in hydrogen production and improved syngas quality compared to atmospheric pyrolysis processes. High pressures enhance hydrogen yields by promoting reforming reactions and suppressing tar formation, thus generating a cleaner syngas stream suitable for subsequent hydrogen extraction and purification stages [54]. Additionally, the integration of catalytic systems within the pyrolysis reactor can significantly enhance hydrogen selectivity, reduce undesirable by-product formation, and lower energy requirements [55]. The adoption of biomass pressurized pyrolysis for hydrogen production provides several technical advantages, such as increased energy density, higher purity of the syngas produced, and improved compatibility with existing hydrogen infrastructures, facilitating downstream applications like fuel cells and industrial processes [56]. Moreover, the utilization of biomass as a renewable feedstock contributes to waste valorisation, supports circular economy principles, and enhances regional energy security through local resource exploitation [53].

Nevertheless, significant technical challenges persist, notably the optimization of reactor configurations, selection and stability of catalysts under harsh operational conditions, and process cost reductions to ensure economic viability. Overcoming these challenges demands ongoing research, innovation, and supportive policy frameworks to encourage industrial-scale deployment.

3

Research challenges

3.1 Electrochemical processes challenges

As previously mentioned in the section 2, compound-based depolarized electrolysis introduces compounds to alter the oxidation (anodic) reaction on an electrochemical cell. By replacing the OER for a less energy demanding reaction, the overall cell voltage is lowered and an extra anodic product is obtained, ideally more valuable than the O_2 produced by the OER. This approach helps mitigate the overall costs of the process, reducing the production cost of the obtained H_2. One of the advantages of the SDE is the cross-compatibility of its components with water electrolysis as well as fuel cells, nevertheless it also represents an opportunity to further develop these technologies. To the date, no specific component has been designed or manufactured, therefore the whole electrochemical cell and its components (gas diffusion layer (GDL), catalyst coated membranes (CCMs), Flow field and Gaskets) have potential to be improved. To achieve long term durability and stability, considering the challenges regarding the feedstock and products – with e.g. SO_2 and H_2SO_4 being highly corrosive and reactive – research and studies must be carried out to determine the effect of each component over and its relation to SDE performance (viscosity, flow velocity, porosity, membrane lifetime, F- emissions, water retention, etc.). Current SoA does not surpass 100 hours of operation and still, variable operation, contaminants in the SO_2 feed as well as the reaction mechanisms, are yet to be studied.

To optimize efficiency of biomass based electrochemical processes, various electrocatalysts have been investigated, including Ni-based catalysts, which improve biomass oxidation at the anode. Recently, polyoxometalates (POMs) have emerged as promising electrocatalysts due to their high redox activity, tuneable electronic structure, and ability to facilitate multi-electron transfer reactions. POMs have shown potential in improving catalytic efficiency for both HER and OER, thereby enhancing overall hydrogen production efficiency from biomass-derived feedstock. Specifically, POMs, such as phosphomolybdates and phosphotungstates, function as electron shuttles, facilitating oxidation reactions and improving catalyst stability under acidic and alkaline conditions [57]. These materials also enable selective oxidation of biomass-derived molecules, increasing the yield of value-added products like FDCA and glyceric acid. Another promising approach involves the use of $FeCl_3$ as a redox mediator in biomass electrolysis. $FeCl_3$ can effectively facilitate electron transfer in oxidation reactions, improving the efficiency of lignocellulosic biomass breakdown. Studies have shown that $FeCl_3$-assisted electrolysis can lower the overpotential required for oxidation, reducing energy consumption and increasing hydrogen selectivity [58]. This approach is particularly useful in combination with Ni- or POM-based catalysts, creating synergistic effects that boost overall process efficiency.

3.2 Photolytic hydrogen processes challenges

The process that is typically considered as an inspiration, natural photosynthesis, is not particularly efficient or fast in terms of solar energy conversion. Artificial photoactivated processes apparently require a high solar-to-hydrogen (STH) efficiency to balance fabrication and operation costs. Research on low cost, abundant non-critical materials for all cell/reactor components is still timely, also including polymeric, organic, hybrid and biological materials, as well as their chemical stability for long life under prolonged solar irradiation.

Recently, ideas for the use of non-pure water, simultaneous wastewater treatment and oxidative photo-reforming towards high added-value products have been considered in various EU projects. However, they will probably require further efforts for their intrinsic complexity and multiplicity of possible target chemicals. Finally, combining photolytic methods with other physical/chemical aids has been proposed, but still remains a powerful source of new approaches.

Photoactivated hydrogen production systems that utilize hydrogenases continue to advance as promising routes for sustainable hydrogen fuel generation. A major development in semiconductor-enzyme integration is the use of TiO_2 nanoparticles as photoanodes. In a study by Polliotto et al.[59], highly active [FeFe]-hydrogenase enzymes from *C. perfringens* were anchored onto modified TiO_2 surfaces (N-TiO_2, more efficient than bare TiO_2 in harvesting visible light, bypassing the limitation of expensive dye-sensitizing with Ru-based systems). Tested for hydrogen production under direct solar light with triethanolamine (TEOA) as a sacrificial donor, these systems showed turnover frequency numbers (TOF) of $4.1 \pm 0.1\ s^{-1}$.

Engineering photosynthetic organisms for integrated hydrogen production is another active area of research. For example, fusion of Hydrogenases with Photosystem I – a specific type of protein-pigment complex – in genetically engineered cyanobacteria and algae, facilitate direct electron transfer from light-harvesting complexes to hydrogenase enzymes [60].

As for artificial photosynthesis, Reisner group reported in 2018 a semi-artificial system for the unassisted, light-driven water splitting with PSII and [FeFe] hydrogenase, able to generate H_2 and O_2 from water with high Faradaic efficiencies in a 2:1 ratio and proposing an effective strategy to stabilize biotic–abiotic hybrid systems [61].

PH2OTOGEN [43] project focuses on optimizing transparent, porous, conductive photocatalyst supports that electronically couple hydrogen-evolving and oxidizing particles. The goal is to achieve a solar-to-hydrogen efficiency exceeding 5% over 500 hours of operation in a 500 cm^2 demonstrator.

The PHOTOSINT [62] project aims to develop sustainable processes for producing hydrogen and methanol using only sunlight, wastewater, and CO_2 as inputs. This involves the creation of new catalytic materials and the integration of perovskite solar photovoltaic cells with photoelectrochemical systems to enhance efficiency. The project seeks to maximize solar-to-fuel conversion rates and assess the feasibility of scaling up these renewable energy technologies for industrial applications.

3.3 Thermochemical cycles and biomass-based processes challenges

Regarding biomass-based processes, enhanced process control was a central theme in recent TSAD research. Furthermore, the impact of reactor temperature and hydraulic retention time (HRT) on microbial activity was reiterated across multiple case studies. In parallel, microbial community studying and engineering has emerged as a critical component for process stability [63-65].

Several pilot studies emphasized the potential of underutilized and co-digested biomass streams. Using cacao pod husk (CPH) as a feedstock, Kriswantoro et al.[66] reported successful biohydrogen production. This demonstrated the feasibility of agricultural waste valorisation in a TSAD system. TSAD is also increasingly being positioned within integrated municipal and industrial waste management strategies. Dell'Orto and Trois [67] evaluated the integration of TSAD into South African municipal solid waste frameworks, demonstrating its potential to reduce methane emissions and divert organics from landfills. Masoud et al.[68] reported high hydrogen production on bio-char derived from sugarcane bagasse and then employed as a conductive material in two-phase AD of food waste.

The integration of biomass thermochemical conversion with other processes of the hydrogen value chain can make these processes more suitable for the industrial application of hydrogen production. In this framework the utilization of biomasses from different sources and the reduction of the inert gas content can be ways to increase the competitiveness of gasification. However, these solutions need the development of innovative materials while pursuing process integration. In fact, the utilization of biomasses with high degrees of humidity or of impurities may change the gas composition at the thermochemical process outlet not only in terms of water but also in terms of poisonous impurities. This has an important effect on the downstream catalytic upgrade, needed to reduce the amount of hydrocarbons, tars and impurities, increasing the hydrogen content while preserving the catalyst stability. In this framework the development of stable and critical raw material (CRM)-Free catalysts, including biocatalysts, still need to be addressed at low-TRL to get insights into the mechanism and reaction conditions that can lead to deactivation and to catalytic formulations with high stability and activity.

Regarding the reduction of inert gas in the outlet gas (e.g. using enriched air in gasification) by increasing the amount of oxidant may lead to temperature changes in the gasifier and in the upgrading process. In this framework innovative materials able to resist and disperse heat in a more efficient way, while retaining performances and catalytic stability are necessary. The use of membranes has shown promising results, though the presence of impurities in the gas produced from biomasses may alter their stability and performances. For this reason, innovative systems also based on disruptive concepts for hydrogen separation on small-medium scale should be developed.

Importantly, microwave-assisted thermochemical water splitting has demonstrated the ability to lower the reduction temperature of redox-active materials such as lanthanum-doped ceria to below 500 °C. This reduction in temperature requirements decreases the thermal burden of the process and enhances compatibility with lower-grade heat or renewable electricity sources. Overall, these alternative production routes are contributing to a broader technological landscape in which hydrogen can be generated through multiple energy vectors—thermal, electrical, or hybrid—depending on local resources and infrastructure. As these systems advance toward higher technology readiness levels, emphasis will be placed on system integration, process modelling, and techno-economic validation. Their development supports the goal of creating a flexible, resilient, and decarbonized hydrogen supply chain that complements large-scale electrolysis and other established technologies.

4

Research Priorities for the Future

Despite the growing interest in a hydrogen economy, virtually all alternatives for achieving depolarized electrolysis remain under- (or non-) explored. The overwhelming focus of research and funding has been directed toward the most popular technologies (PEMEL, AEL and AEMEL). However, there are several cases where alternative electrolysis pathways, like depolarized electrolysis, could serve as complementary solutions especially in contexts where PEMEL or AEMEL systems are not feasible or cost-effective. For these alternatives to become competitive, a thorough understanding of the electrochemical reaction mechanisms is essential. This knowledge would enable the development of specialized components tailored to optimize system performance. Currently, no commercial components are specifically designed for any type of depolarized electrolysis. As a result, research and development in this area have relied on modified components originally intended for PEMEL, AEMEL, or fuel cells. It would not be far-fetched to estimate that, with targeted component development and a deeper understanding of the respective system's reaction dynamics, these alternative technologies could emerge as a competitive solution for industrial-scale hydrogen and clean chemical production in the near future.

Techno-economic analyses suggest that ethanol and glycerol electrolysis are currently the most cost-competitive, while lignocellulosic biomass and waste electrolysis offer long-term scalability for net-zero carbon hydrogen production. Life cycle assessments indicate that biomass electrolysis can reduce CO_2 emissions by up to 86% compared to steam methane reforming (SMR) [10]. Biomass waste electrolysis provides an alternative for reducing emissions from bio refinery processing. Despite its potential, biomass electrolysis faces challenges, and further research is required to improve feedstock processing and scale up this technology for industrial deployment. Future research should focus on improving reaction selectivity, enhancing electrolysis cell efficiency, and developing scalable bio refinery-integrated hydrogen production systems. By addressing these challenges, biomass electrolysis could play a crucial role in the future hydrogen economy while contributing to environmental sustainability.

Photocatalytic (PC) and photoelectrochemical (PEC) systems for H_2 production need design concepts demonstrating economic viability. A way towards efficient and economic artificial photosynthesis preferably lays on supported photocatalysts, facilitating reutilization, and bias-free PEC systems, producing separate pure H_2 and totally avoiding electricity consumption. New resources for solar light management, including light concentration, are yet to be investigated, trying to keep the maximum STH efficiency. Widening the wavelength range of captured and transformed solar photons, keeping a high quantum efficiency, will also improve the STH conversion. Scaling cell/reactor configurations require suitable combinations of optical characteristics of absorption, transmittance, etc. in active composite materials and stacked layers. In addition, connection to H_2 collection and compression systems, as well as direct local uses of the produced H_2 are yet to be researched as well.

Results on pilot systems underline the feasibility, scalability and adaptability of two-stage fermentation platforms for sustainable hydrogen production, particularly when integrated with circular bio-economy frameworks and waste management strategies. Detailed studies on optimised microbial consortia are required in order to obtain inoculum which is resilient to inhibitory compounds and effective in processing possible recalcitrant biomasses such as lignocellulosic (from corn stover, wheat straw and rice husk) or chitin, feathers and keratin-rich waste (e.g., poultry processing residues) or food processing waste (for example from orange and olive) with high content of inhibitory compounds like phenolics, tannins and terpenes. While specific cost assessments of hydrogen produced via two-stage anaerobic digestion are still emerging, available studies suggest promising economic feasibility under certain conditions.

Alternative hydrogen production processes
Position Paper

5

Concluding remarks

There are multiple approaches to produce hydrogen through alternative pathways that are noteworthy and may provide solutions to more specific applications and use case scenarios. However, these approaches at the moment lack support, as they still require substantial efforts to both develop the technologies as well as to understand some of the underlying fundamental mechanisms, sensitivities and limitations. Further development of these alternative hydrogen production technologies is essential to address a critical, yet often overlooked, gap in the transition toward truly sustainable production systems, meaning the possibility to provide a clean, sustainable and economical solution for all the scenarios where energy, fuel, or storage is needed, status that currently can't be fully covered by just PEMEL and AEL technologies. Achieving true sustainability requires solutions that can operate across the full spectrum of energy, manufacturing, and industrial scenarios, many of which cannot be addressed by existing mainstream technologies due to technical, economic, or logistical constraints. The technologies presented in this report offer a diverse set of complementary solutions, each contributing in its own way to the establishment of a robust hydrogen ecosystem;

- **Depolarized Electrolysis** capitalizes industrial chemical waste—such as SO_2, and NO_x—as a feedstock, enabling the co-production of clean hydrogen and value-added chemicals, while promoting circularity in heavy industries.
- **Biomass-Based Processes** offer cost-effective pathways for converting municipal and biological waste into hydrogen, creating opportunities for integrated value chains that support the transition to a zero-waste society.
- **Photolytic Processes** enable passive energy storage in the form of hydrogen by mimicking natural processes such as photosynthesis, representing a novel approach to solar-to-fuel conversion.
- **Thermal Processes** can capitalize on otherwise unused waste heat, improving overall energy efficiency and resource utilization.

Overall, these alternative production routes collectively contribute to a broader technological landscape in which hydrogen can be generated through multiple energy vectors—thermal, electrical, or hybrid—depending on local resources and infrastructure, allowing the technology to adapt to diverse contexts and supporting the development of a flexible, inclusive, and sustainable hydrogen economy. Under the right conditions, covered throughout this report, these technologies present the potential to produce economically competitive H_2 in the future. As these systems advance toward higher technology readiness levels, emphasis should be placed on further understanding and development of these technologies, system integration, process modelling, and techno-economic validation. Their development supports the goal of creating a flexible, resilient, and decarbonized hydrogen economy that complements and coexists with large-scale electrolysis and other established technologies.

References

1 IEA (2024), Global Hydrogen Review 2024, IEA, Paris https://www.iea.org/reports/global-hydrogen-review-2024, Licence: CC BY 4.0

2 Colón-Mercado, H. R.; Mauger, S. A.; Gorensek, M. B.; Fujimoto, C. H.; Lando, A. A.; Ganesan, P.; Meekins, B. H.; Meeks, N. D. Electrode Optimization for Efficient Hydrogen Production Using an SO2-Depolarized Electrolysis Cell. *Int. J. Hydrog. Energy* 2022, *47* (31), 14180–14185. https://doi.org/10.1016/j.ijhydene.2022.02.166.

3 Roessler Escudero, L.; Hacker, V.; Bodner, M. Adjusting the Operating Boundaries for the Mitigation of SO2 Crossover in Sulphur Depolarized Electrolysers. *J. Power Sources* 2024, *622*, 235329. https://doi.org/10.1016/j.jpowsour.2024.235329.

4 Xue, L.; Zhang, P.; Chen, S.; Wang, L.; Wang, J. Sensitivity Study of Process Parameters in Membrane Electrode Assembly Preparation and SO2 Depolarized Electrolysis. *Int. J. Hydrog. Energy* 2013, *38* (25), 11017–11022. https://doi.org/10.1016/j.ijhydene.2012.12.120.

5 Gorensek, M. B.; Summers, W. A. Hybrid Sulfur Flowsheets Using PEM Electrolysis and a Bayonet Decomposition Reactor. *Int. J. Hydrog. Energy* 2009, *34* (9), 4097–4114. https://doi.org/10.1016/j.ijhydene.2008.06.049.

6 Chen, L.; Shi, J. Chemical-Assisted Hydrogen Electrocatalytic Evolution Reaction (CAHER). *J. Mater. Chem. A* 2018, *6* (28), 13538–13548. https://doi.org/10.1039/C8TA03741H.

7 Burshtein, T. Y.; Yasman, Y.; Muñoz-Moene, L.; Zagal, J. H.; Eisenberg, D. Hydrazine Oxidation Electrocatalysis. *ACS Catal.* 2024, *14* (4), 2264–2283. https://doi.org/10.1021/acscatal.3c05657.

8 Sun, X.; Ding, R. Recent Progress with Electrocatalysts for Urea Electrolysis in Alkaline Media for Energy-Saving Hydrogen Production. *Catal. Sci. Technol.* 2020, *10* (6), 1567–1581. https://doi.org/10.1039/C9CY02618E.

9 Asazawa, K.; Yamada, K.; Tanaka, H.; Taniguchi, M.; Oguro, K. Electrochemical Oxidation of Hydrazine and Its Derivatives on the Surface of Metal Electrodes in Alkaline Media. *J. Power Sources* 2009, *191* (2), 362–365. https://doi.org/10.1016/j.jpowsour.2009.02.009.

10 Luo, H.; Barrio, J.; Sunny, N.; Li, A.; Steier, L.; Shah, N.; Stephens, I. E. L.; Titirici, M.-M. Progress and Perspectives in Photo- and Electrochemical-Oxidation of Biomass for Sustainable Chemicals and Hydrogen Production. *Adv. Energy Mater.* 2021, *11* (43), 2101180. https://doi.org/10.1002/aenm.202101180.

11 Boddula, R.; Lee, Y.-Y.; Masimukku, S.; Chang-Chien, G.-P.; Pothu, R.; Srivastava, R. K.; Sarangi, P. K.; Selvaraj, M.; Basumatary, S.; Al-Qahtani, N. Sustainable Hydrogen Production: Solar-Powered Biomass Conversion Explored through (Photo) Electrochemical Advancements. *Process Saf. Environ. Prot.* 2024, *186*, 1149–1168. https://doi.org/10.1016/j.psep.2024.04.068.

12 Hong, W.; Huang, W. Application of Sugarcane in Ethanol Fuel Production: Theoretical Basis and Commercial Potential. J. Energy Biosci. 2024, 15 (0).

13 Wyman, C. E. Ethanol from Lignocellulosic Biomass: Technology, Economics, and Opportunities. Bioresour. Technol. 1994, 50 (1), 3–15. https://doi.org/10.1016/0960-8524(94)90214-3.

14 Caravaca, A.; Sapountzi, F. M.; de Lucas-Consuegra, A.; Molina-Mora, C.; Dorado, F.; Valverde, J. L. Electrochemical Reforming of Ethanol–Water Solutions for Pure H2 Production in a PEM Electrolysis Cell. *Int. J. Hydrog. Energy* 2012, *37* (12), 9504–9513. https://doi.org/10.1016/j.ijhydene.2012.03.062.

15 *Coproducing Value-Added Chemicals and Hydrogen with Electrocatalytic Glycerol Oxidation Technology: Experimental and Techno-Economic Investigations | ACS Sustainable Chemistry & Engineering*. https://pubs.acs.org/doi/10.1021/acssuschemeng.7b00868 (accessed 2025-05-06).

16 Zhang, G.-R.; Sun, Z.; Liu, X.; Wang, J.; Li, H.; Qu, X.; Yu, H.; Shen, L.-L.; Mei, D. Toward Selective Electrooxidation of HMF to FDCA: Suppressing Non-Faradaic Transformations via Low Temperature Electrolysis. *J. Catal.* 2025, *444*, 116002. https://doi.org/10.1016/j.jcat.2025.116002.

17 Lubitz, W.; Ogata, H.; Rüdiger, O.; Reijerse, E. Hydrogenases. *Chem. Rev.* 2014, *114* (8), 4081–4148. https://doi.org/10.1021/cr4005814.

18 Vincent, K. A.; Cracknell, J. A.; Parkin, A.; Armstrong, F. A. Hydrogen Cycling by Enzymes: Electrocatalysis and Implications for Future Energy Technology. *Dalton Trans.* 2005, No. 21, 3397–3403. https://doi.org/10.1039/B508520A.

19 Winkler, M.; Esselborn, J.; Happe, T. Molecular Basis of [FeFe]-Hydrogenase Function: An Insight into the Complex Interplay between Protein and Catalytic Cofactor. *Biochim. Biophys. Acta BBA - Bioenerg.* 2013, *1827* (8), 974–985. https://doi.org/10.1016/j.bbabio.2013.03.004.

20 Morra, S.; Arizzi, M.; Valetti, F.; Gilardi, G. Oxygen Stability in the New [FeFe]-Hydrogenase from Clostridium Beijerinckii SM10 (CbA5H). *Biochemistry* 2016, *55* (42), 5897–5900. https://doi.org/10.1021/acs.biochem.6b00780.

21 Winkler, M.; Duan, J.; Rutz, A.; Felbek, C.; Scholtysek, L.; Lampret, O.; Jaenecke, J.; Apfel, U.-P.; Gilardi, G.; Valetti, F.; Fourmond, V.; Hofmann, E.; Léger, C.; Happe, T. A Safety Cap Protects Hydrogenase from Oxygen Attack. *Nat. Commun.* 2021, *12* (1), 756. https://doi.org/10.1038/s41467-020-20861-2.

21 Morra, S.; Valetti, F.; Sarasso, V.; Castrignanò, S.; Sadeghi, S. J.; Gilardi, G. Hydrogen Production at High Faradaic Efficiency by a Bio-Electrode Based on TiO2 Adsorption of a New [FeFe]-Hydrogenase from *Clostridium Perfringens*. *Bioelectrochemistry* 2015, *106*, 258–262. https://doi.org/10.1016/j.bioelechem.2015.08.001.

22 Albuquerque, M. M.; Martinez-Burgos, W. J.; de Bona Sartor, G.; Medeiros, A. B. P.; de Carvalho, J. C.; Soccol, C. R. Microbial Electrolysis Cells in Biohydrogen Production. In *Biohydrogen - Advances and Processes*; Soccol, C. R., Brar, S. K., Permaul, K., Pakshirajan, K., de Carvalho, J. C., Eds.; Springer Nature Switzerland: Cham, 2024; pp 429–453. https://doi.org/10.1007/978-3-031-49818-3_17.

23 Cui, W.; Liu, G.; Zeng, C.; Lu, Y.; Luo, H.; Zhang, R. Improved Hydrogen Production in the Single-Chamber Microbial Electrolysis Cell with Inhibition of Methanogenesis under Alkaline Conditions. *RSC Adv.* 2019, *9* (52), 30207–30215. https://doi.org/10.1039/C9RA05483A.

24 Webb, S.; Milton, R. D. Towards Scalable Electroenzymatic Hydrogen Production with [FeFe]-Hydrogenase. *ChemElectroChem n/a* (n/a), e202400700. https://doi.org/10.1002/celc.202400700.

25 Zhuang, Z.; Wang, D. Advancing Hydrogen Energy through Enzyme-Mimetic Electrocatalysis. *Front. Energy* 2025. https://doi.org/10.1007/s11708-025-0975-7.

26 Khan, M. A.; Al-Attas, T.; Roy, S.; Rahman, M. M.; Ghaffour, N.; Thangadurai, V.; Larter, S.; Hu, J.; Ajayan, P. M.; Kibria, M. G. Seawater Electrolysis for Hydrogen Production: A Solution Looking for a Problem? *Energy Environ. Sci.* 2021, *14* (9), 4831–4839. https://doi.org/10.1039/D1EE00870F.

27 Kuhnert, E.; Kiziltan, O.; Hacker, V.; Bodner, M. Investigation of the Impact of Chloride Contamination on Degradation in PEM Water Electrolyzer Cells. *ECS Trans.* 2023, *112* (4), 485. https://doi.org/10.1149/11204.0485ecst.

28 Zhang, L.; Jie, X.; Shao, Z.-G.; Wang, X.; Yi, B. The Dynamic-State Effects of Sodium Ion Contamination on the Solid Polymer Electrolyte Water Electrolysis. *J. Power Sources* 2013, *241*, 341–348. https://doi.org/10.1016/j.jpowsour.2013.04.049.

29 Mishra, A.; Park, H.; El-Mellouhi, F.; Suk Han, D. Seawater Electrolysis for Hydrogen Production: Technological Advancements and Future Perspectives. *Fuel* 2024, *361*, 130636. https://doi.org/10.1016/j.fuel.2023.130636.

30 Liu, Z.; Han, B.; Lu, Z.; Guan, W.; Li, Y.; Song, C.; Chen, L.; Singhal, S. C. Efficiency and Stability of Hydrogen Production from Seawater Using Solid Oxide Electrolysis Cells. *Appl. Energy* 2021, *300*, 117439. https://doi.org/10.1016/j.apenergy.2021.117439.

31 Zhang, L.; Wang, Z.; Qiu, J. Energy-Saving Hydrogen Production by Seawater Electrolysis Coupling Sulfion Degradation. *Adv. Mater.* 2022, *34* (16), 2109321. https://doi.org/10.1002/adma.202109321.

32 Xie, H.; Zhao, Z.; Liu, T.; Wu, Y.; Lan, C.; Jiang, W.; Zhu, L.; Wang, Y.; Yang, D.; Shao, Z. A Membrane-Based Seawater Electrolyser for Hydrogen Generation. *Nature* 2022, *612* (7941), 673–678. https://doi.org/10.1038/s41586-022-05379-5.

33 Vilanova, A.; Dias, P.; Azevedo, J.; Wullenkord, M.; Spenke, C.; Lopes, T.; Mendes, A. Solar Water Splitting under Natural Concentrated Sunlight Using a 200 Cm2 Photoelectrochemical-Photovoltaic Device. *J. Power Sources* 2020, *454*, 227890. https://doi.org/10.1016/j.jpowsour.2020.227890.

34 *Nanodesigned electrochemical converter of solar energy into hydrogen hosting natural enzymes or their mimics | FP7*. CORDIS | European Commission. https://cordis.europa.eu/project/id/227192/reporting (accessed 2025-05-06).

35 *ARTIPHYCTION*. https://www.artiphyction.org/ (accessed 2025-05-06).

36 *Photoelectrochemical Demonstrator Device for Solar Hydrogen Generation | FP7*. CORDIS | European Commission. https://cordis.europa.eu/project/id/621252/reporting (accessed 2025-05-06).

37 *Innovative Photoelectrochemical Cells for Solar Hydrogen Production | H2020*. CORDIS | European Commission. https://cordis.europa.eu/project/id/760930/reporting (accessed 2025-05-06).

38 *Controlled Growth of Lightweight Metal-Free Materials for Photoelectrochemical Cells | MFreePEC | Projekt | Fact Sheet | H2020*. CORDIS | European Commission. https://cordis.europa.eu/project/id/849068 (accessed 2025-05-06).

39 *Optimised Halide Perovskite nanocrystalline based Electrolyser for clean, robust, efficient and decentralised pRoduction of H2 | OHPERA | Projekt | Fact Sheet | HORIZON*. CORDIS | European Commission. https://cordis.europa.eu/project/id/101071010 (accessed 2025-05-06).

40 Nishiyama, H.; Yamada, T.; Nakabayashi, M.; Maehara, Y.; Yamaguchi, M.; Kuromiya, Y.; Nagatsuma, Y.; Tokudome, H.; Akiyama, S.; Watanabe, T.; Narushima, R.; Okunaka, S.; Shibata, N.; Takata, T.; Hisatomi, T.; Domen, K. Photocatalytic Solar Hydrogen Production from Water on a 100-M2 Scale. *Nature* 2021, *598* (7880), 304–307. https://doi.org/10.1038/s41586-021-03907-3.

41 *Metal Organic Frameworks for Hydrogen production by photocatalytic overall water splitting | MOF2H2 | Projekt | Fact Sheet | HORIZON*. CORDIS | European Commission. https://cordis.europa.eu/project/id/101084131 (accessed 2025-05-06).

42 https://lgi.earth, L. S. I.-. *PH2OTOGEN*. PH2OTOGEN. https://ph2otogen.eu/PERMALINK (accessed 2025-05-06).

43 Chorukova, E.; Hubenov, V.; Gocheva, Y.; Simeonov, I. Two-Phase Anaerobic Digestion of Corn Steep Liquor in Pilot Scale Biogas Plant with Automatic Control System with Simultaneous Hydrogen and Methane Production. *Appl. Sci.* 2022, *12* (12), 6274. https://doi.org/10.3390/app12126274.

44 Bolzonella, D.; Mıcoluccı, F.; Battısta, F.; Cavınato, C.; Gottardo, M.; Pıovesan, S.; Pavan, P. Producing Biohythane from Urban Organic Wastes. *Waste Biomass Valorization* 2020, *11* (6), 2367–2374. https://doi.org/10.1007/s12649-018-00569-7.

45 Náthia-Neves, G.; De Alencar Neves, T.; Berni, M.; Dragone, G.; Mussatto, S. I.; Forster-Carneiro, T. Start-up Phase of a Two-Stage Anaerobic Co-Digestion Process: Hydrogen and Methane Production from Food Waste and Vinasse from Ethanol Industry. *Biofuel Res. J.* 2018, *5* (2), 813–820. https://doi.org/10.18331/BRJ2018.5.2.5.

46 Mahmod, S. S.; Jahim, J. M.; Abdul, P. M.; Luthfi, A. A. I.; Takriff, M. S. Techno-Economic Analysis of Two-Stage Anaerobic System for Biohydrogen and Biomethane Production from Palm Oil Mill Effluent. J. Environ. Chem. Eng. 2021, 9 (4), 105679. https://doi.org/10.1016/j.jece.2021.105679.

47 Bertasini, D.; Battista, F.; Mancini, R.; Frison, N.; Bolzonella, D. Hydrogen and Methane Production through Two Stage Anaerobic Digestion of Straw Residues. Environ. Res. 2024, 247, 118101. https://doi.org/10.1016/j.envres.2024.118101.

48 Doddapaneni, T. R. K. C.; Ahmad, F.; Valgepea, K.; Kikas, T. Chapter 3 - Integrated Thermochemical and Biochemical Processes for the Production of Biofuels and Biochemicals. In *Biomass, Biofuels, Biochemicals*; Varjani, S., Pandey, A., Bhaskar, T., Mohan, S. V., Tsang, D. C. W., Eds.; Elsevier, 2022; pp 67–105. https://doi.org/10.1016/B978-0-323-89855-3.00025-X.

49 Okolie, J. A.; Epelle, E. I.; Tabat, M. E.; Orivri, U.; Amenaghawon, A. N.; Okoye, P. U.; Gunes, B. Waste Biomass Valorization for the Production of Biofuels and Value-Added Products: A Comprehensive Review of Thermochemical, Biological and Integrated Processes. *Process Saf. Environ. Prot.* 2022, *159*, 323–344. https://doi.org/10.1016/j.psep.2021.12.049.

50 Liu, W.; Tian, Y.; Yan, H.; Zhou, X.; Tan, Y.; Yang, Y.; Li, Z.; Yuan, L. Gasification of Biomass Using Oxygen-Enriched Air as Gasification Agent: A Simulation Study. *Biomass Convers. Biorefinery* 2023, *13* (17), 15993–16000. https://doi.org/10.1007/s13399-021-02035-2.

51 Biohydrogen. In *Biohydrogen: For Future Engine Fuel Demands*; Demirbas, A., Ed.; Springer: London, 2009; pp 163–219. https://doi.org/10.1007/978-1-84882-511-6_6.

52 Bridgwater, A. V. Review of Fast Pyrolysis of Biomass and Product Upgrading. *Biomass Bioenergy* 2012, *38*, 68–94. https://doi.org/10.1016/j.biombioe.2011.01.048.

53 Mettanant, V.; Basu, P.; Butler, J. Agglomeration of Biomass Fired Fluidized Bed Gasifier and Combustor. *Can. J. Chem. Eng.* 2009, *87* (5), 656–684. https://doi.org/10.1002/cjce.20211.

54 Kan, T.; Strezov, V.; Evans, T.; He, J.; Kumar, R.; Lu, Q. Catalytic Pyrolysis of Lignocellulosic Biomass: A Review of Variations in Process Factors and System Structure. *Renew. Sustain. Energy Rev.* 2020, *134*, 110305. https://doi.org/10.1016/j.rser.2020.110305.

55 Anca-Couce, A. Reaction Mechanisms and Multi-Scale Modelling of Lignocellulosic Biomass Pyrolysis. *Prog. Energy Combust. Sci.* 2016, *53*, 41–79. https://doi.org/10.1016/j.pecs.2015.10.002.

56 Li, M.; Wang, T.; Chen, X.; Ma, X. Conversion Study from Lignocellulosic Biomass and Electric Energy to H2 and Chemicals. *Int. J. Hydrog. Energy* 2023, *48* (55), 21004–21017. https://doi.org/10.1016/j.ijhydene.2022.09.191.

57 Du, X.; Liu, W.; Zhang, Z.; Mulyadi, A.; Brittain, A.; Gong, J.; Deng, Y. Low-Energy Catalytic Electrolysis for Simultaneous Hydrogen Evolution and Lignin Depolymerization. *ChemSusChem* 2017, *10* (5), 847–854. https://doi.org/10.1002/cssc.201601685.

58 Polliotto, V.; Morra, S.; Livraghi, S.; Valetti, F.; Gilardi, G.; Giamello, E. Electron Transfer and H2 Evolution in Hybrid Systems Based on [FeFe]-Hydrogenase Anchored on Modified TiO2. *Int. J. Hydrog. Energy* 2016, *41* (25), 10547–10556. https://doi.org/10.1016/j.ijhydene.2016.05.002.

59 Appel, J.; Hueren, V.; Boehm, M.; Gutekunst, K. Cyanobacterial in Vivo Solar Hydrogen Production Using a Photosystem I–Hydrogenase (PsaD-HoxYH) Fusion Complex. *Nat. Energy* 2020, *5* (6), 458–467. https://doi.org/10.1038/s41560-020-0609-6.

60 Sokol, K. P.; Robinson, W. E.; Warnan, J.; Kornienko, N.; Nowaczyk, M. M.; Ruff, A.; Zhang, J. Z.; Reisner, E. Bias-Free Photoelectrochemical Water Splitting with Photosystem II on a Dye-Sensitized Photoanode Wired to Hydrogenase. *Nat. Energy* 2018, 3 (11), 944–951. https://doi.org/10.1038/s41560-018-0232-y.

61 *PHOTOelectrocatalytic systems for Solar fuels energy INTegration into the industry with local resources* | *PHOTOSINT* | *Projekt* | *Fact Sheet* | *HORIZON*. CORDIS | European Commission. https://cordis.europa.eu/project/id/101118129 (accessed 2025-05-06).

62 Morra, S.; Arizzi, M.; Allegra, P.; La Licata, B.; Sagnelli, F.; Zitella, P.; Gilardi, G.; Valetti, F. Expression of Different Types of [FeFe]-Hydrogenase Genes in Bacteria Isolated from a Population of a Bio-Hydrogen Pilot-Scale Plant. *Int. J. Hydrog. Energy* 2014, *39* (17), 9018–9027. https://doi.org/10.1016/j.ijhydene.2014.04.009.

63 Arizzi, M.; Morra, S.; Gilardi, G.; Pugliese, M.; Gullino, M. L.; Valetti, F. Improving Sustainable Hydrogen Production from Green Waste: [FeFe]-Hydrogenases Quantitative Gene Expression RT-qPCR Analysis in Presence of Autochthonous Consortia. *Biotechnol. Biofuels* 2021, *14* (1), 182. https://doi.org/10.1186/s13068-021-02028-3.

64 Harirchi, S.; Wainaina ,Steven; Sar ,Taner; Nojoumi ,Seyed Ali; Parchami ,Milad; Parchami ,Mohsen; Varjani ,Sunita; Khanal ,Samir Kumar; Wong ,Jonathan; Awasthi ,Mukesh Kumar; and Taherzadeh, M. J. Microbiological Insights into Anaerobic Digestion for Biogas, Hydrogen or Volatile Fatty Acids (VFAs): A Review. *Bioengineered* 2022, *13* (3), 6521–6557. https://doi.org/10.1080/21655979.2022.2035986.

65 Kriswantoro, J. A.; Tseng, C.-H.; Fois, F.; Chu, C.-Y.; Manzo, E.; Petracchini, F. Synergetic Hydrogen and Methane Productions from Anaerobic Digestion of Selected Rural-Farming Plant and Animal-Based Biomass Wastes. *Korean J. Chem. Eng.* 2025, *42* (4), 775–790. https://doi.org/10.1007/s11814-024-00294-z.

66 *Double-Stage Anaerobic Digestion for Biohydrogen Production: A Strategy for Organic Waste Diversion and Emission Reduction in a South African Municipality.* https://www.mdpi.com/2071-1050/16/16/7200 (accessed 2025-05-06).

67 Masoud, A.; Samy, M.; Allam, N. E.; Dhar, B. R.; Meshref, M. N. A.; Elagroudy, S. Improving the Biogas Production in Two-Phase Anaerobic Digester of Food Waste Using Sugarcane Bagasse-Derived Biochar. *Biomass Convers. Biorefinery* 2025. https://doi.org/10.1007/s13399-025-06724-0.

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Compatibility of polymer-based materials for the hydrogen transport Infrastructure

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Abstract

Hydrogen is central to Europe's decarbonization strategy, yet the safe and cost-effective transport remains a critical challenge. Polymer-based materials are increasingly considered for pipelines, storage vessels, seals, gaskets, and flexible connectors due to their corrosion resistance, lightweight properties, and cost advantages. However, their long-term performance under hydrogen exposure—especially under high pressures, fluctuating temperatures, and cyclic loading—remains insufficiently understood. Unlike metals, polymers do not chemically react with hydrogen, but they are subject to permeation, swelling, and rapid gas decompression damage, which can compromise integrity and safety. Existing qualification standards, often inherited from the oil and gas sector, are not fully suited to hydrogen applications. This position paper outlines the state of knowledge on hydrogen–polymer interactions, identifies research gaps, and proposes priorities for advancing material qualification. Key needs include standardized accelerated testing protocols, reliable lifetime prediction models, and the development of PFAS-free sealing solutions. Establishing shared databases and coupling experimental benchmarks with modelling approaches will be essential to accelerate innovation. Addressing these challenges will enable safer and more efficient hydrogen transport, reduce costs, and strengthen public confidence in hydrogen technologies, thereby supporting Europe's clean energy transition.

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1

Introduction

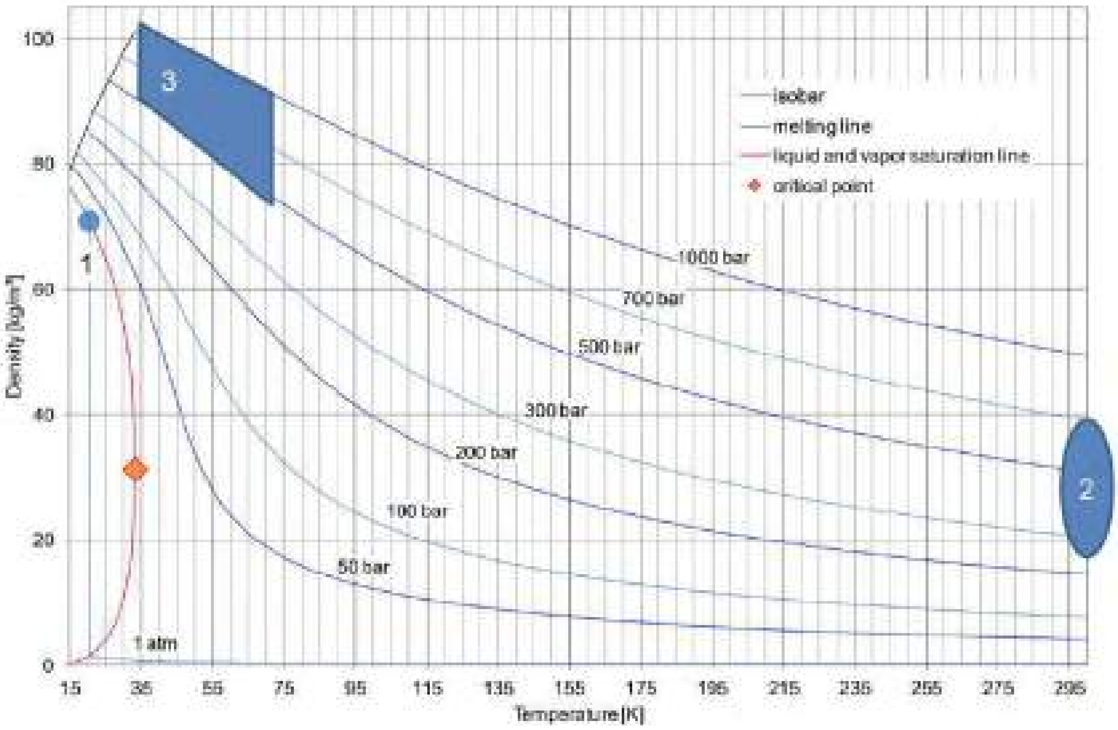
As the global energy landscape shifts toward decarbonization, H_2 is emerging as a key enabler of a low-carbon economy. Its versatility as an energy carrier and feedstock offers compelling solutions for sectors such as transportation, power generation, and industrial manufacturing. However, the widespread deployment of hydrogen infrastructure poses significant materials challenges, particularly in the safe and efficient transport of hydrogen gas under varying pressure and temperature conditions. The transition towards H_2 as an energy carrier is already gradually progressing, with low-medium concentrations of H_2 blended with natural gas (NG) being trialled on small scales to decarbonise gas supplies in Germany, France, UK and Denmark[1]. Further implementation will be dictated by the confidence in technology, as well as economic and regulatory drivers. In the *Clean Hydrogen to Europe* project, which is part of the Zero Carbon Energy Hub, blending hydrogen into NG for pipeline distribution from 2030 is considered for a transition period to reduce upfront investment costs. Nevertheless, to ensure safe and reliable H_2 transport and storage, the performance of the materials used in the infrastructure must be well understood.

Table 1. Main polymers used in H_2 transport[2,3,19].

Typical Thermoplastics	Applications
Polyethylene (HDPE/UHMWPE)	High/low pressure pipes, valve seats, coatings, composites
Polyamides (PA6, PA66, PA12)	
Polyphenylene sulfide (PPS)	
Polyaryletherketones (PAEK)	
Fluoropolymers (PTFE, PVDF)	
Polyvinyl chlorides (PVC/CPVC)	
Typical Elastomers	**Applications**
Ethylene propylene diene monomer (EPDM)	Overmoulded or loose O-rings, gaskets, energized seals
Fluoroelastomers (FKM, FFKM)	
Nitrile butadiene rubbers (NBR)	
Chloro-rubbers (CR, ECO)	
Typical Thermosets	**Applications**
Epoxy resins (e.g. FBE)	Flow coatings
Phenolic resins (VER)	
Polyurethanes (TSU)	

Polymer-based materials have received increasing attention for their vital roles in hydrogen transport systems, especially in pipelines, storage vessels, seals, gaskets, and flexible hoses (Table 1). High-density polyethylene (HDPE) and polyamides (PA) are commonly used in H_2 storage tanks and as liner material in H_2 pipelines (> 100 bar). Polypropylene (PP) or polyvinyl chlorides (PVC/CPVC) are typically used in low-pressure H_2 pipelines.

Figure 1: **H_2 storage conditions: (1) liquid H_2 around 20 K at low pressure, (2) pressurised H_2 at pressure range between 250 and 700 bar at room temperature, and (3) cryogenic compressed H2 around 500 – 1000 bar. Reproduced from [5].**



Fluoropolymers (PTFE/PVDF), polyether-etherketones (PEEK/PEKK) and fluoroelastomer (FKM) are common sealing materials in valves, while PTFE is also used as a material for low temperature seals. More generally, elastomeric materials are widely used in sealing components and for example, control valves, flexible hoses, and connectors, which are also directly exposed to high-pressure H_2 conditions. Here, materials such as ethylene propylene copolymer (EPM), silicones and neoprene (CR) are applied.

Compared to metals, polymers offer advantages such as corrosion resistance, ease of fabrication, reduced weight, and cost-effectiveness. However, while the damaging embrittlement effects of H_2 on metals has been the subject of many research projects[4], much less is known about the effects of H_2 on polymer and composite materials. Nonetheless, their interaction with hydrogen involves complex phenomena, including permeation, physical or chemical aging, and potential degradation under high-pressure cyclic loading, all of which could compromise long-term performance and safety.

Especially challenging for the application of polymer-based materials along the H_2 value chain is the wide range of temperature and pressure that the materials can potentially experience as indicated in Figure 1[5]. For example, conditions can range from cryogenic storage at medium pressure though at very low temperatures (<35 K and 5-15 bar) to pressurised H_2 storage at 250 to 1000 bar. A typical temperature range for gaseous pressurised H_2 systems is 233 K (-40 °C) to 358 K (85 °C), but temperatures as high as

473 K (200 °C) can be reached in some compressors, while in the cryo-compressed range polymers can potentially be exposed to 35-75 K at pressures between 700-1000 bar.

The scope of this position paper on the “Compatibility of polymer-based materials for the hydrogen transport Infrastructure” is to guide research efforts and align priorities for future advancements in the use of polymer-based materials along the hydrogen value chain. The position paper highlights the current state of research and introduces research challenges.

2

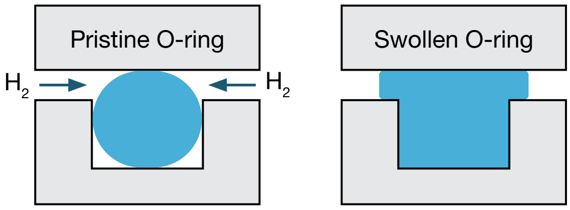
Current State of Research

In contrast to metals that can react with hydrogen and form brittle metal hydrides, polymers are basically chemically inert to hydrogen, with the exception of few peculiar cases (e.g., acrylonitrile butadiene rubber[6] (NBR) and HDPE[7]). Nevertheless, the most significant effects are due to dissolved hydrogen that can interact physically with polymers[8] and any damage to the polymer is believed to primarily result from mechanical failure related to the absorption of hydrogen[9]. It is widely accepted that most damage to polymers in hydrogen applications occurs during sudden decompression of high-pressure hydrogen, commonly referred to as explosive decompression failure (XDF) or rapid gas decompression (RGD) damage. In addition to decompression damage effects, other hydrogen effects are related to physical stability (dimensional and property changes), dynamic frictional wear, rapid temperature cycling effects and issues related to material contamination. Furthermore, permeation (hydrogen fugitive emission) needs to be specifically assessed, especially under high pressure and temperature, and to be guaranteed over time. Polymers are indeed inherently permeable to small molecules and gases and these represent a drawback which must be addressed. In particular, semicrystalline polymers such as polyamides (and PA6 in particular) or HDPE have been mainly considered in order to meet the leak rates suggested for the different applications[10],[11]. For this reason, in the open literature many studies are available which focus on the characterization of hydrogen permeability in these polymers.

For PAs, Humpenoder[12] measured hydrogen permeability and diffusivity in an undefined polyamide between -10 and 30 °C while, Kanesugi *et al*.[13] considered the same quantities in PA6, PA12 and PA11 at 30 °C. Tests for PA 11 were then extended to high pressures up to 900 bar. Similar pressure range was also considered by Dong et al.[14] who measured the variation of H_2 permeability in PA6 at pressure ranging from 150 and 900 bar for different temperatures (35–85 °C). The increase of barrier properties related to the addition of different fillers such as carbon fibers or nanoclays was also considered and estimated by different authors[15],[16]. In the case of HDPE, Humpenöder[11] measured hydrogen permeability and diffusivity at temperatures ranging between -10 and 30 °C. Smith and Anovitz[17] pointed out that the permeability of hydrogen in HDPE is affected by the forming process and pressure, while more recently Fujiwara *et al.*[18],[19] measured hydrogen transport properties in HDPE and other polyethylenes at 30 °C and pressures up to 900 bar. General results shows that PA, and PA6 in particular, has lower permeability with respect to HDPE despite the lower crystallinity. It is therefore preferred as barrier for hydrogen storage applications. In particular, liner thicknesses in the order of 1-3 mm allow to fulfil the EU regulation for hydrogen storage on vehicles[20],[21].

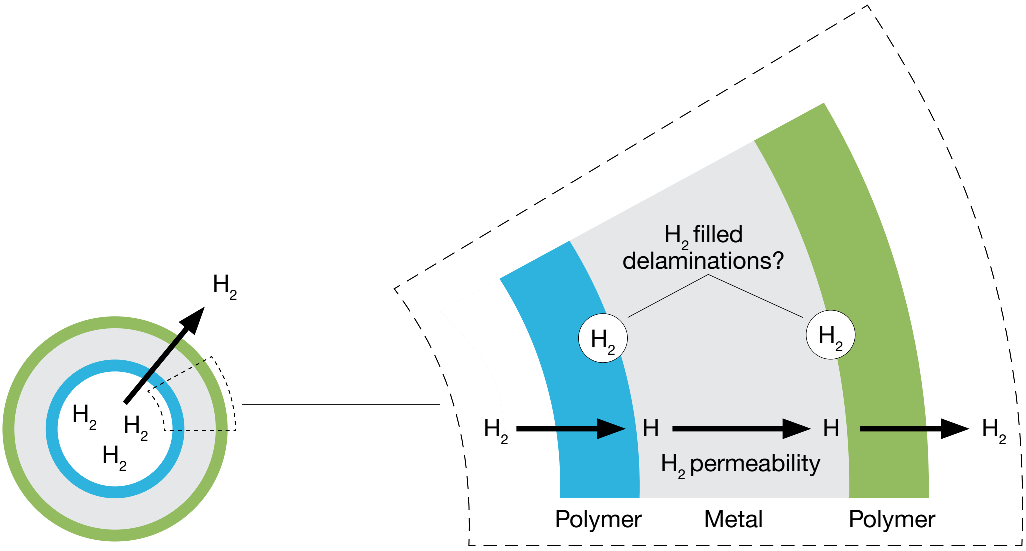
Polymer based materials used today in oil and gas distribution are often based on those qualified use in that industry (e.g. NORSOK M710 or ISO 23936-2), but not designed for transport of pure or blended H_2 or H_2 carriers, like MeOH or NH_3. Even though the solubility of H_2 in polymers is low in view of its very low condensability, swelling of 70-80 % has been reported in elastomer compounds exposed to high pressure H_2[22], which clearly risks seal extrusion (Figure 2) and tearing[23]. Even though massive swelling is often seen, it should not be forgotten that such changes are often less relevant for H_2 compared to other gases, and observed to be reversible (in case no explosive decompression or tearing damages have occurred).

Figure 2: O-ring extrusion due to H_2 swelling. Adapted from Balasooriya, 2022.



On depressurisation, this absorbed H_2 can then cause rapid gas decompression (RGD) damage, in which gas absorbed under pressure (in polymer free volume or in pre-existing pores) expands to tear the elastomer. For example, it has been reported that elastomeric seals can contain 3 % voids, often <40 µm, which may act as inflation points[5]. Pre-existing defects may act as nucleation sites for decompression damage, also known as blister fracture, which were measured in EPDM by Yamabe and Nishimura using atomic force microscopy[24]. Alternatively, gas under pressure can create new pores under depressurization by nucleating at defect sites such as at polymer-filler interfaces. The degree of inflation of bubbles within the polymer has been reported in literature, allowing a prediction of damage based on polymer properties and depressurisation parameters[25]. The toughness of the polymer will influence the effect of this damage; less tough polymers (for example, polymers below their glass transition temperature, or elastomers with high shear modulus, high crosslink densities or which have become more brittle due to aging effects[26] or embrittlement by plasticizer extraction/blooming[7]) are more likely to tear or fracture. In addition, the volumetric swelling caused by H_2 absorption has been shown to enable phase separation of unbound additives (*e.g.* plasticizers). This phase separation can cause local changes in mechanical properties, further reducing tear resistance. This has for example been shown to occur for EPDM under high pressure hydrogen cycling[27]. Regarding thermoplastic materials, such RGD damages have also been evidenced experimentally, the severity of the phenomenon depending on material properties (strength and transport properties) as well as environmental conditions (pressure delta, decompression speed, number of cycles, simultaneous mechanical loading)[28,29]. Experiments have supported the establishment of models able to predict the probability of the occurrence of RGD damages[30]. Since thermoplastics are often used when structural properties are needed, the major damage risk is at the interface between materials, due to cyclic (de-)pressurizations, and rapid expansion mismatches with the non-polymer counterparts. In the case of fibre reinforced thermoplastics, fibre-matrix and ply interface damage reduces load transfer

Figure 3: Diffusion of H_2 through a polymer-metal multimaterial structure (pipe wall).



efficiency, lowering the mechanical properties and enhance leak path creation[31]. Graphite has long been studied for fuel-cell applications[32], but the influence of hydrogen exposition on graphite-based fibre-reinforced polymers has hardly been investigated up to now. In the case of multi-material structures comprising metals and thermoplastics (e.g. polymer-metal laminates in combined power/hydrogen transport umbilicals, or coated metal structures) interfacial delamination may lead to shortcuts through the polymer, increasing overall leakage. Since the diffusion of gases through metals is slower than through most polymers or polymer-based composites, high pressure gas accumulation at defects at the polymer-metal interface (e.g. due to manufacturing defects or progressive damage) are a particularly complex scenario to understand, but are a key part of failure modes of these structures (Figure 3). In the long term, the effects of H_2 on polymers and multi-material structures with polymers have not been comprehensively determined; further research is needed to investigate progressive failure modes.

With the development of H_2 as an energy vector, its delivery and transport from the production site to the end user remains an issue. Hydrogen blending in natural gas networks is gaining momentum as a strategy to decarbonize energy systems. This approach involves mixing hydrogen, typically up to 20% by volume, into existing natural gas pipelines, leveraging current infrastructure to reduce carbon emissions. In other cases the blending with up to 60 vol.% H_2 (H2NG) is investigated. For example, the EU-funded THyGA project[33] "Testing Hydrogen for Gas Applications" investigated the impact of blends of natural gas and hydrogen on end use applications, specifically in the domestic and industrial sectors. The key challenge to overcome for the existing pipeline network is the higher H_2 permeation through existing polymer infrastructures used for natural gas distribution. As the amount of hydrogen injected into the natural gas grid increases, the elastomeric materials used in fittings and gaskets may be challenged to withstand H_2 permeation. As a result, sealing difficulties may occur at fittings that are effective with natural gas but not in the presence of hydrogen. Also, due to its higher solubility, the co-existence of high pressure (>150 bar) CH_4 could cause significant swelling, affecting the polymer free volume and so reducing the barrier properties. Klopffer *et. al.* investigated the permeation of pure hydrogen and mixtures with natural gas (20% of CH_4 and 80% of H_2) in pipeline materials[34]. In this work the permeability of both hydrogen and methane has been found independent of gas composition, which makes direct comparison possible in spite of the various experimental conditions. Also, within the FP6 project NATURALHY[35] (*Preparing for the hydrogen economy by using the existing natural gas system as a catalyst*), key issues of blending hydrogen into the natural gas pipeline networks were investigated. With respect to H_2 permeation through PE, an increase in gas loss with hydrogen content was seen, partially as expected because of the higher H_2 permeation rate compared to CH_4. No clear change in either the hydrogen or methane permeability was observed as function of gas composition. The EU-funded HIGGS project[36] also aimed to identify and bridge knowledge gaps on the impact of high amounts of H_2 on the high-pressure gas infrastructure and its components. To reach its aim, it has mapped technical, legal and regulatory barriers, helped determining the economic viability of hydrogen injection into the gas grid, and tested various technical solutions. The tightness and compatibility of different components and equipment of the existing high-pressure gas grid up to 100% H_2 was evaluated. All valves remained tight for the duration of the test, with just minor hydrogen losses due to hydrogen leakage through the main body of the valves. Finally, no apparent damage was found on the different parts of the valves, pressure regulator, cartridge filter and turbine gas meter components after their exposure to hydrogen. According to the results, the high-pressure natural gas grid would be ready for its repurpose, aiming for the large-scale transport of 100% hydrogen.

3

Research Challenges

As exemplified in section 1 and 2, the use of polymeric materials in the H_2 value chain has knowledge gaps, complicating material selection. An increased understanding of properties and failure modes will greatly advance material qualification and standardization, which are both of great industrial importance. One focus is thus to relate short-term accelerated testing of H_2-induced polymer aging to the long-term effects of H_2 on the polymers and multi-material structures, setting the basis for the future material qualification. Ongoing research focuses on multilayer structures and polymer composites to improve barrier properties and mechanical strength. Long-term durability data is limited, especially for cyclic loading, wear and aging effects in hydrogen-rich environments. Moreover, the influence of environmental impurities on their behaviour has to be considered to assess the reliability of their use. The effect of some parameters such as temperature, material crystallinity or internal stresses is however little to not documented in the literature. As such parameters can have competitive positive-detrimental influence on the initiation of RGD-induced damages, such understanding would benefit the establishment of clear guidelines for the test parameters to adopt in a procedure to assess the compatibility of polymers for hydrogen applications. Accurate benchmarks need to be developed to study the behaviour of novel components and seals in operating conditions to strengthen their reliability. As part of these studies, particular attention must be paid to assembly techniques and as a consequence to heterogeneous interfaces, focusing on the risks of leakage and maintaining their integrity in a hydrogen environment subject to external stresses. Using exhaustive databases and instrumented benchmarks, these experimental works must also be coupled with numerical and mechanistic modelling studies in order to offer a better understanding of their behaviour in service, to support new developments and lifetime prediction.

While PFAS (per- and polyfluoroalkyl substances) restriction is under discussion, their use is critical for the hydrogen sector because of the strict performance requirements that demand a high level of tightness and limitation of fugitive emissions from sealing devices and processing equipment. R&D works have to be launched on new PFAS-free material solutions and sealing design in order to evaluate the gap to be bridged to fulfil the expected in-service specifications using dedicated characterization equipment and benchmarks.

There is also a need for standardized testing protocols and lifetime prediction models under realistic hydrogen conditions. Recent international standards and guidelines, such as those from ISO and ASTM, are beginning to address hydrogen-specific performance criteria for polymeric components. However, a unified framework for long-term testing and certification under hydrogen exposure is still under development. Furthermore, the identification of a clear and reliable accelerated ageing protocols, for instance, will be of great relevance.

4

Timeline and Resources

The short-term focus of research activities is proposed to lay on the establishment of standardized test-protocols for accelerated material qualification to facilitate rapid deployment of a variety of polymeric or composite materials in the hydrogen economy. Special focus in the short-term should be on the development of a test linking short-term test results to long-term properties under hydrogen atmosphere. Studies should include the investigation of the effect of gas impurities, cyclic loading, wear and tear and initial material properties such as material crystallinity and micro-structure, or internal stresses to enable establishment of comprehensive guidelines.

In the medium-term, focus should be on the qualification of novel sealant materials to replace existing PFAS-based structures to facilitate the envisioned phase-out of PFAS materials in industrial production. Concurrently, establishment of accurate benchmarks for novel components and materials should be developed with particular attention to the assembly techniques.

Complementary to the efforts in the short- and medium-term, establishment of a shared database for the effects of hydrogen on polymers facilitates the long-term utilization of gathered data in numerical and mechanistic studies of new components and their behaviour in service.

5

Rationale for Advancing Research in This Area & Potential Applications

One of the key enablers of societal acceptance of novel technologies such as hydrogen and related infrastructure is the trust of stakeholders in the research processes as well as the institutions involved[37]. A large-scale rollout of hydrogen infrastructure thus requires the active involvement and communication to local communities regarding safety and health risks of planned hydrogen projects. Extensive investigation, assessment and qualification of long-term stability and safety of employed materials prior to deployment is one of the factors for strengthening public trust in hydrogen technologies. As polymer products such as sealings, gaskets, pipes or fibre reinforced tanks are being applied along the whole hydrogen value chain, research clarifying the effects of hydrogen on polymer products paves the way for further implementation and societal integration of the European hydrogen economy. Enabling a rapid qualification of novel materials for hydrogen applications by development of a methodology permitting transfer of short-term experimental results to long-term property predictions shortens the development cycles of new products, thereby improving competitiveness of industry actors. Furthermore, enabling utilization of polymer pipes and tanks for the hydrogen economy facilitates a reduction in transport and installation costs and a subsequent reduction in carbon footprint of the infrastructure needed for deployment. The transition to a hydrogen-based energy system is a cornerstone of Europe’s decarbonization strategy. However, the safe, efficient, and cost-effective transport of hydrogen remains a critical bottleneck. Polymer-based materials, due to their corrosion resistance, lightweight nature, and cost advantages, are increasingly considered for use in hydrogen infrastructure. Yet, their long-term behaviour under hydrogen exposure—especially under high pressure, temperature fluctuations, and cyclic loading—remains insufficiently understood. Offering a cost-effective alternative to metals, polymers may contribute to a massification of new hydrogen usages supporting the reduction of the overall cost of the value chain. Moreover, these developments may support the optimization of hydrogen infrastructure facilitating the compatibility with existing gas networks, reducing capital expenditure and accelerating deployment timelines. The development of advanced materials and testing infrastructure foster innovation, supporting SMEs and industrial competitiveness in the hydrogen economy, while enhancing reduction of the risk of leaks and failures, thus ensuring safer energy systems for communities with an alignment with environmental regulations and reduction of long-term ecological risks associated with persistent chemicals.

References

1 Topolski et al., Hydrogen Blending into Natural Gas Pipeline Infrastructure: Review of the State of Technology 2022, National Renewable Energy Laboratory, USA.

2 Barth, R.R., Simmons, K.L., San Marchi, C., Polymers for Hydrogen Infrastructure and Vehicle Fuel Systems: Applications, Properties, and Gap Analysis, Report SAND2013-8904; 477341, Sandia National Laboratories, CA, USA, 2013.

3 Sun, Y, Lv, H., Zhou, W., Zhang, C., Research on hydrogen permeability of polyamide 6 as the liner material for type IV hydrogen storage tank. *Int. J. Hydrogen Energy*, 2020, 45, 24980.

4 E.g. HyLINE, Safe Pipelines for Hydrogen Transport, 2019-2023, Norwegian Research Council of Norway Project, contract 294739.

5 Klier, J., M. Rattey, and G. Kaiser. A new cryogenic high-pressure H2 test area: first results. 2012.

6 Fujiwara, H., Yamabe, J., Nishimura, S., Evaluation of the change in chemical structure of acrylonitrile butadiene rubber after high-pressure hydrogen exposure, *Int. J. Hydrogen Energy*, 2012, 37(10) 8729.

7 Kim, M., Lee, C.H., Hydrogenation of High-Density Polyethylene during Decompression of Pressurized Hydrogen at 90 MPa: A Molecular Perspective, *Polymers*, 2023, 15(13), 2880.

8 Hertz, D., *The hidden cause of seal failure*. Machine Design, 1981.

9 Kulkarni, S.S., Choi, K.S., Kuang, W., Menon, N., Mills, B., Soulami, A., Simmons, K., *Damage evolution in polymer due to exposure to high-pressure hydrogen gas, Int. J. Hydrogen Energy*, 2021. 46(36) 19001.

10 Adams, P., Bengaouer, A., Cariteau, B., Molkov, V., Venetsanos, A.G., Allowable hydrogen permeation rate from road vehicles, *Int. J. Hydrogen Energy*, 2011. 36(3) 2742.

11 Dagdag, O., Kim, H., Recent Advances in the Hydrogen Gas Barrier Performance of Polymer Liners and Composites for Type IV Hydrogen Storage Tanks: Fabrication, Properties, and Molecular Modeling, *Polymers*, 2025, 17(9), 1231.

12 Humpenöder, J., Gas permeation of fibre reinforced plastics, *Cryogenics*, 38(1) 143.

13 Kanesugi, H., Keiko, O., Fujiwara, H., Nishimura, S., High-pressure hydrogen permeability model for crystalline polymers, *Int. J. Hydrogen Energy*, 2023. 48(2) 723.

14 Dong C., Liu Y., Li, J., Bin, G., Zhou, C., Han, W., Li, X., Hydrogen permeability of polyamide 6 used as liner material for type IV on-board hydrogen storage cylinders. *Polymers* 2023, 15, 3715.

15 Cond´e-Wolter, J., Ruf, M.G., Liebsch, A., Lebelt, T., Koch, I., Drechsler, K., Gude, M., Hydrogen permeability of thermoplastic composites and liner systems for future mobility applications. *Composites Part A*, 2023, 167, 107446.

16 Picard, E., Vermogen, A., Gerard, J.F., Espuche, E., Barrier properties of nylon 6-montmorilloniten nanocomposite membranes prepared by melt blending: influence of the clay and dispersion state Consequences on modelling, *J Membr Sci*., 2007, 292, 133.

17 Anovitz, L., Smith, B., Lifecycle Verification of Tank Liner Polymers, Oak Ridge National Laboratory, ORNL/TM-2014/48, Mar. 2014.

18 Fujiwara, H., Ono, H., Onoue, K., Nishimura, S., High-pressure gaseous hydrogen permeation test method -property of polymeric materials for high-pressure hydrogen devices (1), *Int. J. Hydrog. Energy*, 2020, 45(53) 29082–29094.

19 Fujiwara, H., Ono, H., Ohyama, K., Kasai, M., Kaneko, F., Nishimura, S., H2 permeation under high pressure conditions and the destruction of exposed polyethylene-property of polymeric materials for high-pressure hydrogen devices (2), *Int. J. Hydrog. Energy*, 2021, 46, 11832.

20 Commission Regulation (EU) No 406/2010 of 26 April 2010 implementing Regulation (EC) No 79/2009 of the European Parliament and of the Council on type-approval of hydrogen-powered motor vehicles. Off J Eur Union L 18.5.2010; 122. p.1.

21 Merlonghi, I., Atiq, O., Rea, R., Mangano, E., Stroeks, A., Giacinti Baschetti, M., De Angelis, M.G., An experimental study of hydrogen sorption and permeation in high-performance polyamides, *Int J Hydrogen Energy*, 2024, 88, 1463.

22 Simmons, K.L., et al., H-Mat H2 compatibility of polymers and elastomers. Int. J. Hydrogen Energy, 46, 2021, 12300.

23 Balasooriya (2022) Polymer Reviews 62:1.

24 Yamabe, J. and S. Nishimura, Nanoscale fracture analysis by atomic force microscopy of EPDM rubber due to high-pressure hydrogen decompression. *Journal of Materials Science*, 46, 2011. 2300-2307.

25 Gent, A.N. and D.A. Tompkins, Surface energy effects for small holes or particles in elastomers. *J. Polym. Sci., Part A-2: Polymer Physics*, 1969, 7(9) 1483-1487.

26 Alcock, B. and J.K. Jørgensen, The mechanical properties of a model hydrogenated nitrile butadiene rubber (HNBR) following simulated sweet oil exposure at elevated temperature and pressure. *Polymer Testing*, 46, 2015. 50-58.

27 Simmons, K.L. and C. San Marchi, H-Mat Overview: Polymers. 2021 Annual Merit Review & Peer Evaluation Meeting, 2021.

28 Ono H, F. H., et al, Influence of Repetitions of the High-Pressure Hydrogen Gas Exposure on the Internal Damage Quantity of High-Density Polyethylene Evaluated by Transmitted Light Digital Image. *Int. J. Hydrogen Energy*, 44, 2019, 23303–23319.

29 Boyer SAE, et al. Gas environment effect on cavitation damage in stretched polyvinylidene fluoride. *Polym. Eng*. Sci., 54, 2014, 2139.

30 Yersak, T. A. et al, Predictive Model for Depressurization-Induced Blistering of Type IV Tank Liners for Hydrogen Storage. *Int. J. Hydrogen Energy*, 42, 2017, 28910–28917.

31 Pravin Peddiraju, P. P. Characterization of effective permeability in cryogenic composite laminates. 2003 ASME International Mechanical Engineering Congress & Exposition, 03, pp. 16-21.

32 Lorenzo Vergari and Raluca O. Scarlat, Kinetics and transport of hydrogen in graphite at high temperature and the effects of oxidation, irradiation and isotopics, Journal of Nuclear Materials 558, 2022, 153142

33 THyGA Project, Testing Hydrogen admixture for Gas Applications. GA 874983, H2020-JTI-FCH-2019-1.

34 Klopffer, M.H., Éliane Espuche, P.B., Development of Innovating Materials for Distributing Mixtures of Hydrogen and Natural Gas. Study of the Barrier Properties and Durability of Polymer Pipes. Oil & Gas Science and Technology, 2015, 305-315.

35 Preparing for the H2 economy by using the existing natural gas system as a catalyst (NATURALHY), FP6, GA 502661, 2004-2009.

36 HIGGS Project, Hydrogen blending into gas networks to decarbonise the gas sector. GA 875091, H2020-EU.3.3.8. - FCH2.

37 Hildebrand, J., Sadat-Razavi, P., Rau, I., Different Risks—Different Views: How Hydrogen Infrastructure Is Linked to Societal Risk Perception, 13, *Energy Technolog*y, 2025, 2300998.

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Innovative materials for low-pressure hydrogen storage

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Abstract

The transition to a hydrogen-based energy system requires safe, efficient, and cost-effective storage technologies. While gaseous and cryogenic hydrogen storage are technologically mature, solid-state storage materials are emerging as a promising alternative for low-pressure applications. This paper reviews the current state and future prospects of innovative materials for hydrogen storage, with a focus on metal hydrides, high-entropy alloys (HEAs), and metal-organic frameworks (MOFs). Metal hydrides offer high volumetric densities and improved safety, but their widespread deployment remains limited by high costs, kinetics, and thermal management challenges. HEAs show potential for exceeding conventional hydrogen-to-metal ratios, yet scale-up and phase stability remain barriers. MOFs provide tunable pore structures and high surface areas, enabling rapid physisorption, though their reliance on cryogenic conditions and complex synthesis limits applicability. The paper highlights life cycle assessment considerations, recycling opportunities, and the role of circular economy approaches in reducing environmental and economic burdens. A research timeline is proposed, outlining pathways from material optimisation and pilot demonstrations to potential niche commercialisation over the next decade. Finally, we discuss the strategic rationale for advancing solid-state hydrogen storage, underlining its contributions to sustainability, energy security, and industrial innovation.

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1

Introduction

Decarbonising the energy sector is a major challenge in the climate crisis. A hydrogen-based economy is seen as a key solution, with significant socio-economic impacts. To support adoption, research not only addresses technical challenges in production, storage, and transport, but also social acceptance. While gaseous and liquid hydrogen storage are well studied, solid-state storage is gaining attention as a promising alternative.

Solid-phase hydrogen storage relies on the ability of certain materials to absorb or bind hydrogen through chemical or physical processes. Materials that can be used for this purpose generally include simple Metal Hydrides [1], High Entropy metal Alloys (HEA) [2], as well as porous materials like Metal-organic frameworks (MOFs) [3] and carbon-based materials, considering the latest studies carried out on carbonaceous matrix materials with insertion of metal catalysts [4]. Among the main advantages of solid-phase hydrogen storage is that they can achieve significantly higher volumetric energy densities (up to 150 kg/m^3) [5] than the gaseous (40 kg/m^3 at 15 °C) or liquid form (70 kg/m^3 at – 253 °C and 1 bar) [6], reducing the need for large reservoirs; they show increased safety as they are less susceptible to accidental leakage and the possibility of explosion compared to the gaseous form, making them safer for use in transport applications; hydrogen can be stored under less extreme conditions (e.g., lower pressure), simplifying the necessary infrastructure; solid-state storage systems can be cycled several times, improving system efficiency; lower environmental impact compared to energy-demanding gas compression at high pressure (i.e. 700 bar) or liquid phase at low temperature (i.e. -256 °C) [7]. Despite its potential, solid-phase hydrogen storage still presents some technological challenges: many hydride materials require high T to absorb or release hydrogen, increasing energy costs limiting their applicability; life cycles and stability: since some materials may degrade during repeated hydrogen loading and unloading cycles, it is necessary to improve the durability and strength of the materials; the speed at which hydrogen can be absorbed or released is another limiting factor, especially in applications that require a rapid response, such as fuel cell vehicles; some of the most promising materials, such as metal hydrides, are still too expensive.

This paper aims to discuss the current state, advances, and limitations in solid-phase hydrogen storage. We highlighted the most remarkable achievements and constraints for different types of materials (i.e., metal hydrides, MOFs, and metal alloys) and the key aspects that still need to be improved, suggesting a timeline for developing and deploying solid-state hydrogen storage technology.

2

Metal Hydrides - Current State of Research

Some metals and alloys can reversibly absorb significant amounts of hydrogen, typically by charging with atomic hydrogen supplied from an electrolyser. Their thermodynamic behaviour is described by Pressure–Composition Isotherm (PCI) curves. At a given temperature, hydrogen first dissolves at low concentrations to form a solid solution with the metal or alloy. When hydrogen saturates the first solid solution, the metal hydride formation starts. Such metal hydride formation occurs at a determined equilibrium pressure at the given temperature T. In the so-called pressure plateau region, there is an equilibrium between the hydrogen gas phase, the first solid solution phase, and the hydride phase, and the pressure stays almost constant. At the time of reaching the saturation state of the hydride phase, the pressure starts to increase, notably getting the system out of the plateau region where more hydrogen is supplied to the system and a second solid solution, hydride-hydrogen, is formed. The length of the plateau determines the amount of hydrogen that can be stored reversibly with small pressure changes. The equilibrium pressure strongly depends on T. From the equilibrium pressure and through the van't Hoff equation, it is possible to calculate the enthalpy ΔH and entropy ΔS changes. The enthalpy ΔH provides information on metal and hydrogen bond strength and the entropy ΔS about the change from gas molecular to dissolved solid hydrogen (the standard entropy of hydrogen is approximately 130 J/mo K).

High entropy alloys (HEA), in which five or more elements are mixed in near-equiatomic ratios, offer promising properties as hydrogen storage materials due to their ability to crystallise into simple bcc cubic structures in the presence of large lattice deformations resulting from the different sizes of atoms. Metal hydrides (MHx) represent a promising solution for storing large quantities of hydrogen in a future hydrogen-based energy system. Solid-phase hydrogen storage requires the design of alloys that allow a very high H/M ratio. Transition metal hydrides generally have a maximum H/M ratio of 2, and higher ratios can only be achieved in alloys based on rare earth elements. In this study, Witman et al. demonstrate, for the first time to the best of our knowledge, that a high entropy alloy of TiVZrNbHf [8] can absorb much higher amounts of hydrogen than its constituents and achieve an H/M ratio of 2.5.

The high cost of producing, distributing, and storing green hydrogen remains a major barrier to its large-scale replacement of fossil energy sources. Expenses stem from raw materials, specialised equipment, and energy-intensive production processes. In addition, some high-performance metal hydrides with desirable properties are inherently complex and costly to manufacture, further limiting their use in cost-sensitive energy storage and transport applications. Reducing these costs will require both technological innovation and economies of scale to unlock the full potential of the metal hydride market. Deposition is an example of an advanced synthesis technique that allows precise control over the morphology and properties of materials. Thanks to worldwide government incentives and an increased emphasis on hydrogen storage research, metal hydride research has surged in the past decade. This is because certain metals, such as zirconium, vanadium, niobium, and hafnium, have a high export value. Different metals are combined to create alloys with properties specifically designed for their intended uses. Compared to pure metal hydrides, alloyed metal hydrides have greater stability, better kinetics, and higher hydrogen storage capacity [9].

Recycling metal hydrides presents several environmental, economic, and strategic advantages. Minimising environmental impact is certainly one of the key factors since metal hydrides may contain heavy metals or reactive substances that, if not disposed of properly, can pollute soil and groundwater. Furthermore, reducing mining decreases the need to extract new metals (such as nickel, cobalt, and rare earth elements), activities that have significant ecological impacts. Recovering valuable materials would also lead to lower reservoir production costs, enabling metal hydrides to compete more effectively with other storage technologies in terms of price and to achieve the technology's goal of less than EUR 10 per kg of stored hydrogen. Additionally, while recycling is energy-intensive, it is often less energy-demanding than producing metals from virgin raw materials. Recycling spent metal hydrides also offers considerable strategic advantages by reducing dependence on foreign suppliers from geopolitically unstable regions. In this way, materials are transformed from waste into reuse resources, promoting a more sustainable production and consumption model. Moreover, recent research activities are oriented toward the production of metal hydrides starting from scraps instead of pure metals, enabling a reduction of the costs of the alloys and the environmental burdens and introducing a positive circular economy strategy [9-11].

The use of metal hydrides for hydrogen storage for transport applications is recognised as having significant yet unexplored potential. Indeed, the advantages of advanced metal hydride-based storage systems may outweigh their current disadvantages, especially for selected applications where weight is not a critical factor (e.g., heavy vehicles, tractors of various types, and end-use). A reduction in onboard operating pressure can drastically reduce the complexity and economic cost of the infrastructure, with clear benefits that could boost the hydrogen economy. Adopting (or procuring) advanced materials may also lead to a higher density of onboard storage energy, thus enabling hydrogen-powered vehicles to achieve a better driving range.

Life Cycle Assessment (LCA) is a key tool for evaluating the environmental impact of materials and technologies throughout their entire life cycle, from extraction to disposal. Low-pressure hydrogen storage systems rely on metal hydrides, porous materials, and advanced composites, each with varying environmental impacts and resource availability. LCA is crucial in evaluating these impacts, considering factors like raw material extraction, energy consumption, emissions, and end-of-life disposal. In Europe, the availability of key materials, including magnesium, titanium, and rare earth elements, influences the sustainability and feasibility of storage technologies. While some critical materials are imported mainly, increasing recycling rates and developing alternative materials could enhance resource security and reduce environmental burdens, supporting the EU's transition to a sustainable hydrogen economy. From a LCA and environmental protection perspective, using metal hydrides for hydrogen storage in transport applications offers several potential benefits. By reducing onboard operating pressures, infrastructure complexity, and energy requirements could be minimised, leading to lower environmental impacts on energy consumption and emissions. Furthermore, the increased energy density of hydrogen storage could enable longer driving ranges for hydrogen-powered vehicles, reducing the reliance on fossil fuels and contributing to decarbonization. However, the environmental impact of producing, recycling, and disposing of metal hydrides must be considered in the LCA to assess the full lifecycle sustainability of these technologies. Additionally, the widespread adoption of hydrogen could significantly reduce emissions from the transport sector, helping mitigate climate change [9], [12].

Despite the advantages in terms of gravimetric storage density and operational safety of solid-state hydrogen storage solutions and the fact that the current state of the technology allows for their implementation in certain specific sectors, e.g., use in certain industries, prototypes of hydrogen vehicles or the military sector, their widespread implementation as a mass hydrogen storage solution is not yet technically or economically feasible. Some of these challenges are common for different materials, like the adequate heat management during hydrogen sorption/desorption steps that kinetically limit the hydrogen charge/release operations; the correct balance between gravimetric and volumetric storage densities, although it is dependent on the use of the storage system in a mobile or stationary application; and the development of environmentally and economically sustainable industrial approaches for their large-scale production. The most relevant factors are reducing the carbon footprint and environmental impact during manufacturing and minimizing the critical consumption of raw materials. Also important are the challenges associated with their recycling and after-life treatment. Finally, despite the extensive efforts in measuring the thermodynamic and kinetic properties of the materials used as hydrogen sorbents, the relatively small reproducibility of many scientific measurements of storage capacity and behaviour of sorbent materials hampers the availability of high-quality data to compare and select the best materials for their application. This limitation avoids the escalation of scientific knowledge into standardised technology for solid-state hydrogen storage, except for specific materials used for some projects or prototypes. Developing and establishing harmonised measuring techniques, protocols, and reference materials would help increase the comparability of results from different sources and push up the development of sorbent-based technology [13].

3

Metal-Organic Frameworks (MOFs) - Current State of Research

Metal-organic frameworks, highly porous organic-inorganic hybrid materials formed by coordination bonding between organic ligands and metal ions/clusters, are extensively investigated for gas storage, including hydrogen. Hydrogen is stored in MOFs using physical adsorption of the diatomic molecule, which is different from metal-hydride systems where hydrogen atoms are chemically bonded to metals or occupy interstitial spaces in the metallic matrix. The physical mechanism is faster and fully reversible by pressure and temperature changes due to the lower interaction energy between the physically adsorbed hydrogen and the solids, also involving a smaller amount of heat during operation. However, this smaller energy interaction involves a low operating temperature for adsorption, usually needing cooling agents like liquid nitrogen or similar. Advantages of using MOF materials compared to other porous materials like carbons of covalent organic frameworks (COFs) are the presence of controlled and appropriate pore sizes in the range of micropores (< 2 nm), controllable and defined structure-related properties due to their crystallinity, large surface area per unit of mass and volume for specific MOF structures (gravimetric and volumetric surface areas), and chemical hybridization (organic and metallic) that increases the interaction energy compared to pure organic or carbonaceous materials, with additional advantages due to the easily modifiable surface chemistry.

Various strategies have been employed to improve the H_2 storage capacity of MOFs like ligand functionalization (e.g. modification with -F, $-CF_3$, -OH, -COOH, $-NH_2$), adjustment length of the ligand, replacing the original linker with another one, introduction of unsaturated metal sites e.g. Mn(II), Mg(II) and Ni(ii), interpenetration of framework with another MOF structure, or preparation of hybrid materials (combination of MOFs with carbon materials or metal nanoparticles).

One of the highest H_2 uptakes was determined for MOF-210 (17.6 wt.% at 77K, 80 bar), MOF-177 (7.5 wt.% at 77K, 80 bar), NU-100 (9.95 wt.% at 77K, 70 bar) [14].

4

Research Challenges in MOFs, hydrides and HEAs

Some specific limitations affect each type of material used for solid-state hydrogen storage. In the case of MOF materials, the most significant limitation is the high cooling energy consumption due to the weak interaction between hydrogen and the porous structures involved during the physisorption step. This limitation makes using considerable cooling agents like liquid nitrogen necessary to maintain the cryogenic operation. Research efforts have focused on developing structures for increasing the interaction strength, like reducing the pore size of materials still showing a high surface area and pore volume, modifying the chemistry of both metallic and organic secondary-building units, or including metallic nanoparticles to generate preferential sorption sites or promote hybrid physical-/chemical-sorption mechanisms like hydrogen spillover or hydrides nanoconfinement. Besides, since MOFs can be constituted by all the metals in the periodic table and hundreds of organic linkers, their huge chemical and structural variety make selecting the best-performing structures a big challenge. This task includes screening around 100,000 deposited MOF structures and designing and synthesizing new or hypothetical structures by rational approaches, high-throughput experimental or computational screening, and machine learning [15-16]. Finally, improvements in the sustainability and scalability of the synthesis of MOFs are necessary due to non-renewable and diverse metallic and organic precursors and organic solvents used in the specific chemical routes for their synthetic approaches. In this sense, alternative production methods like precipitation in water, electrodeposition, or solvent-free mechanochemical syntheses are under study and in industrial development [17].

For metal-hydride systems, the main challenges are related to the gravimetric storage density due to the high densities of the metallic bulk materials used, the production of alloys without critical raw materials (CRM), and using scraps to move toward a circular economy; the heat management of the storage tanks necessary for hydrogen sorption/desorption that is strictly related to the enhancement of sorption kinetics and thermal conductivity of the metallic powders or pellets used for H_2 storage. It is important to note that the production methods can mainly affect the number of oxides or secondary phases in the metal hydrides, with a possible significant change in sorption properties. This aspect can be critical when alloy production moves from a laboratory scale to an industrial scale with less clean conditions [18]. Finally, challenges are related to the stability and durability of the metal alloys that are measured by cycling the powders, usually for a limited number of cycles. At the same time, the material is expected to be charged/discharged daily for many years in real application storage systems. As pellets are considered, i.e., metallic powders dispersed into binders to avoid tank deformation during cycling, the durability of the polymers used as binders is even more important to consider, as the polymer's degradation can lead to pellet cracks [19].

Similar difficulties also limit the use of high-entropy alloys over traditional metal hydrides. However, they are also limited by the challenges in controlling the hydrogen storage properties due to their complex composition, the stability of their complex metallic phases, which could even change during the hydrogenation/dehydrogenation phases and produce segregation of phases, the lack of a precise understanding of the relationship between composition and the hydrogen storage properties, due to the known as "cocktail effect" basically related to the non-linearity of some properties resulting from mixing different metals, and the difficulties to scale the production of this kind of material further than the gram-scale generally produced in laboratories [20].

5

Timeline and Resources

Metal Hydrides – Short-Term Research Priorities

The short-term scenario in 1-3 years will focus on material optimisation, cost reduction, and pilot-scale testing. For Metal Hydrides, it is expected that:

Material Optimisation:

Continued exploration of lightweight hydrides (e.g., Mg-based alloys) and destabilized systems (e.g., MgH_2 + Si) is expected. Computational materials science and AI-driven screening will accelerate discovery, with 5–10 promising new alloy systems likely entering lab-scale validation. The focus will shift toward tuning thermodynamics and kinetics (e.g., through nanostructuring catalysts or composite design). Some systems will reach high TRL (Technology Readiness Level), with reversible storage capacities approaching 6–7 wt% and absorption/desorption temperatures closer to 150–200°C.

Cost Reduction:

Cost remains a barrier due to rare or expensive alloying elements (e.g., Ti, V). Research will aim to replace these with earth-abundant alternatives and simplify synthesis (e.g., mechanochemical processing). Pilot projects will benefit from economies of scale and improved manufacturing methods. Target costs for viable systems could drop to <9.3 €/kWh (hydrogen energy equivalent), nearing competitiveness with compressed or liquefied H_2 storage in select use cases (e.g., stationary, off-grid).

Pilot-Scale Testing:

Early-stage pilot demonstrations will begin in controlled environments (e.g., labs or university-led industrial partnerships), particularly in stationary storage, backup systems, or niche mobility (e.g., drones, submarines). At least 2–3 industrial-scale pilots are expected globally, potentially supported by government hydrogen roadmaps. Emphasis will be on safety, system integration, and cyclic durability (>1000 cycles), with feedback guiding design for full-scale commercialisation.

Metal-Organic Frameworks – Short-Term Research Priorities

Below is a forecast for the next three years for material optimisation, cost reduction, and pilot-scale testing of Metal-Organic Frameworks (MOFs) for hydrogen storage based on current trends and emerging research:

Material Optimisation:

Computational Design & AI Integration: Accelerated discovery using machine learning and high-throughput simulations will significantly reduce trial-and-error synthesis, identifying MOFs with optimal surface area, pore size, and binding enthalpies for hydrogen adsorption.

Enhanced Stability & Recyclability: Efforts will focus on MOFs with improved chemical and thermal stability under practical operating conditions (e.g., temperature, pressure cycling).

Hybrid Materials: Developing MOF composites (e.g., MOF-graphene, MOF-MOF hybrids) will improve performance metrics such as volumetric hydrogen density and mechanical robustness.

Cost Reduction:

Synthesis Scalability: Advances in greener, lower-cost synthesis routes (e.g., mechanochemical synthesis, solvent-free methods) will reduce MOF production costs by 30–50%.

Raw Material Optimization: Using earth-abundant metals (e.g., iron, aluminum) and simpler organic linkers will replace expensive rare metals (e.g., zirconium), cutting material input costs.

Recycling & Reusability: Recyclable MOF production processes and regeneration cycles will become central to cost-effective storage systems.

Pilot-Scale Testing:

From Lab to System Prototypes: More MOFs will move from academic research to TRLs 5–6, undergoing real-world pilot tests in hydrogen-powered vehicles and stationary storage units.

Integration with Storage Tanks: Demonstrations of MOF-based hydrogen storage integrated with Type IV composite tanks will test operational feasibility under SAE standards.

Industry Collaboration: Partnerships among research institutions, startups, and automakers (e.g., Hyundai, Toyota) will yield early-stage demonstration units, targeting 2027–2028 for pre-commercial evaluations.

Metal Hydrides – Medium-Term Research Priorities

Below is a concise 3-5-year forecast (2025-2030) focusing on prototype integration, scalability, and real-world testing of metal hydrides for hydrogen storage:

Prototype Integration:

Metal hydride systems will be integrated into niche prototypes, such as backup power units, portable hydrogen generators, and unmanned vehicles. These prototypes will emphasise compactness, thermal management, and system-level optimisation with fuel cells. Expect broader integration into hybrid energy systems, including renewable-based hydrogen microgrids and small-scale mobile platforms. Designs will move toward modular, plug-and-play formats, simplifying deployment.

Scalability:

Progress will focus on scaling synthesis processes (e.g., ball milling, reactive sintering) for stable, cost-effective materials. Pilot lines for tank fabrication will emerge, targeting batch production for controlled applications. Commercial pre-production may begin for selected markets (e.g., telecom backup, remote energy). Challenges such as heat exchange efficiency, cycle life consistency, and cost per kWh will continue to be refined as production scales.

Real-World Testing:

Testing in controlled operational environments will expand — off-grid sites, research campuses, and defence applications. Performance metrics like hydrogen retention, recharge time, and degradation under cycling will be closely monitored. Field trials in harsh and variable conditions (e.g., desert, arctic, maritime) will gain traction. Regulatory support and funding (e.g., EU Green Deal, US DoE H2@Scale) will boost public-private trials. The first long-term performance datasets will inform certification standards.

Metal Organic Frameworks – Medium-Term Research Priorities

Here’s a concise 3–5 years forecast (2025–2030) on Prototype Integration, Scalability, and Real-World Testing of Metal-Organic Frameworks (MOFs) for hydrogen storage:

Prototype Integration:

MOFs with high surface area and volumetric density (e.g., HKUST-1, MOF-5, NU-1501) will be integrated into prototype storage tanks, often in hybrid systems (e.g., MOF + compressed hydrogen). Challenges such as poor thermal conductivity and mechanical stability will be addressed through binder composites or pelletization techniques. Early prototypes move from lab-scale tanks to full-stack systems (e.g., integrated with fuel cells for mobility or backup power). Thermal management and cycling stability will be core focus areas, with system-level integration being tested in controlled demo environments.

Scalability:

Efforts will intensify to scale up MOF synthesis via green, low-cost routes (e.g., water-based synthesis, mechanochemistry). Supply chain maturity remains low, with production mostly limited to kilograms per batch.

Commercial-scale synthesis of at least 2–3 industrially relevant MOFs will be demonstrated, reaching ton-scale output with cost targets <46 €/kg. Adopting continuous flow synthesis and modular production systems will support scalability and reproducibility.

Real-World Testing:

MOF-based systems will be tested in academic-industry collaborations, primarily in stationary and small-scale mobile applications (e.g., drones, UAVs). Testing will focus on durability under humidity, temperature cycling, and mechanical stress. Real-world pilots in cold-chain logistics, off-grid power, and possibly range extenders for electric vehicles. At least one full deployment in a commercial setting (e.g., backup hydrogen storage for telecom towers or data centres) is expected by 2030, depending on policy support and performance data.

Metal Hydrides – Long-Term Research Priorities

The following is a forecast for the next 5-10 years on the full commercialisation, industry adoption, and large-scale storage of metal hydrides for hydrogen storage:

Full Commercialisation:

Metal hydride hydrogen storage is commercialised in niche markets for stationary backup systems and expected to see more and strategic commercialisation by 2030, primarily in applications such as:

Stationary backup power systems (e.g., telecom, remote infrastructure); military and aerospace applications where energy density and safety matter more than cost; Low- to medium-scale hydrogen refuelling stations, especially in regions prioritising solid-state hydrogen safety. Barriers: High cost of hydride materials (e.g., rare-earth alloys), thermal management challenges, and relatively slow kinetics compared to compressed gas systems.

Industry Adoption:

Wider industry adoption will remain application-specific, with automotive and heavy transport sectors likely favouring other storage technologies (like high-pressure tanks or liquid hydrogen) due to weight constraints. Industrial hydrogen users (e.g., semiconductor manufacturing, metal processing) may adopt metal hydrides for on-site storage where space and safety are premium; Hydrogen microgrids or renewable-energy-linked storage (e.g., solar-to-hydrogen) could leverage hydrides for long-duration, seasonal storage. Outlook: Moderate adoption driven by safety and reliability rather than cost-efficiency.

Large-Scale Storage:

Proper large-scale hydrogen storage using metal hydrides (e.g., hundreds of kg to tons of H_2) faces significant hurdles: Mass and cost scale poorly compared to underground or pressurized systems; Thermal management and charging/discharging rates remain a bottleneck. However, modular storage at the community or facility scale (10–100 kg H_2) could be a viable alternative to high-pressure systems where space and safety outweigh throughput needs. Within 10 years: Pilots of metal hydride storage modules for hydrogen hubs and standardised cartridges for off-grid hydrogen storage in specialised sectors.

Metal-Organic Frameworks – Long-Term Research Priorities

The following is a brief forecast of Metal-Organic Frameworks (MOFs) in hydrogen storage over the next 5-10 years, with a focus on full commercialisation, industry adoption, and large-scale storage:

Full Commercialisation:

MOF-based hydrogen storage will remain in the pilot and prototype phase, focusing on materials optimisation, cost reduction, and system integration. Commercial products using MOFs will be limited to high-value, niche markets (e.g., aerospace, defense, portable fuel cells). Commercialisation will expand as synthesis costs drop, stability improves, and performance targets (e.g., US DOE targets for gravimetric and volumetric storage) are approached or met. Early adoption in mobility sectors (e.g., drones, heavy-duty vehicles) and backup power systems are likely.

Industry Adoption:

In the energy and mobility sector, growing interest from hydrogen vehicle manufacturers and energy companies by 2028–2030 and strategic partnerships with MOF developers for on-board storage systems will drive adoption; industrial Gas Supply Chain where MOFs could be adopted for efficient transportation and buffering of hydrogen at ambient or near-ambient pressures and applications in hydrogen refuelling infrastructure may emerge around 2030.

Large-Scale Storage:

In the near term (5 years), grid-level or massive storage is not yet practical due to current scalability and cost issues. The focus will remain on modular, intermediate-scale storage (kg-scale rather than tons). In the long term (10 years), advances in MOF synthesis scalability, cost-efficiency, and thermal management could enable larger-scale storage, and the use in stationary energy storage systems, especially in off-grid or remote areas, may emerge late in this period.

6

Rationale for Advancing Research in This Area’s Potential Applications

Solid-state hydrogen storage is a promising alternative to conventional compressed gas and cryogenic liquid storage, offering sustainability advantages, societal benefits, economic potential, and alignment with global energy strategies.

Sustainability

Solid-state hydrogen storage materials, such as metal hydrides, complex hydrides, and metal-organic frameworks (MOFs), provide a safer and more energy-efficient storage solution. Unlike high-pressure or cryogenic storage, these materials operate at lower pressures and moderate temperatures, reducing the energy needed for compression and liquefaction. Additionally, certain materials, such as magnesium hydrides, utilise abundant and recyclable elements, further improving their environmental footprint. The adoption of solid-state storage supports the hydrogen economy by facilitating green hydrogen storage from renewable sources.

Societal Benefits

Deploying solid-state hydrogen storage enhances public safety due to its reduced risk of leaks and explosions compared to high-pressure hydrogen tanks. It also supports clean energy transitions by enabling reliable hydrogen storage for fuel cell vehicles, residential energy storage, and backup power systems. Solid-state solutions contribute to energy security and resilience in urban and rural communities by decentralising hydrogen storage and reducing infrastructure risks.

Economic Impact

Solid-state hydrogen storage has the potential to lower costs over time by reducing the need for high-pressure containment and specialised infrastructure. While initial material costs can be high, long-term durability and lower maintenance requirements contribute to overall cost reductions. Additionally, material science and manufacturing advancements are expected to drive down production costs, making solid-state storage more economically viable for automotive, aerospace, and industrial applications. The sector's growth could create jobs in material research, manufacturing, and hydrogen infrastructure development.

Alignment with Strategic Goals

Governments and international organisations increasingly prioritise hydrogen as a key component of their energy transition strategies. Solid-state hydrogen storage aligns with the UN Sustainable Development Goals (SDGs), particularly Goal 7 (Affordable and Clean Energy) and Goal 13 (Climate Action) [21]. European hydrogen strategies emphasise the importance of safe, efficient, and scalable hydrogen storage solutions. As global hydrogen demand rises, solid-state storage can be crucial in achieving decarbonization targets and energy security goals.

Applications

Solid-state hydrogen storage is applicable in various sectors, including transportation (fuel cell vehicles, drones, and aircraft), stationary energy storage (grid balancing, residential power), and portable energy systems (hydrogen-powered devices). Its ability to safely store and release hydrogen on demand makes it a key enabler of the hydrogen economy.

Solid-state hydrogen storage presents a sustainable, safe, and economically promising solution for hydrogen storage. Its alignment with global energy strategies and potential for widespread applications make it vital to achieving a cleaner and more resilient energy future.

References

1 Drawer, C. et al. (2024). “Metal hydrides for hydrogen storage – Identification and evaluation of stationary and transportation applications”, Journal of Energy Storage (Vol. 77). https://doi.org/10.1016/j.est.2023.109988

2 Shahi, R. et al. (2023). “Perspectives of high entropy alloys as hydrogen storage materials”. International Journal of Hydrogen Energy, 48(56). https://doi.org/10.1016/j.ijhydene.2022.02.113

3 Yuvaraj, A. R. et al. (2024). “Role of metal-organic framework in hydrogen gas storage: A critical review”. In International Journal of Hydrogen Energy (Vol. 59). https://doi.org/10.1016/j.ijhydene.2024.02.060

4 Carraro, P.M. et al. (2019). “Nanostructured carbons modified with nickel as potential novel reversible hydrogen storage materials: Effects of nickel particle size”. Microporous and Mesoporous Materials (273). https://doi.org/10.1016/j.micromeso.2018.06.057

5 Puszkiel, J.A. et al. (2018). “Emerging Materials for Energy Conversion and Storage”. Ed. Elsevier, USA, DOI: 10.1016/B978-0-12-813794-9.00012-0

6 Bellosta von Colbe, J. et al. (2019). “Application of hydrides in hydrogen storage and compression: Achievements, outlook and perspectives”. Int J Hydrogen Energy 44:7780–808. https://doi.org/10.1016/j.ijhydene.2019.01.104

7 Agostini, A. et al. (2018). “Role of hydrogen tanks in the Life Cycle Assessment of fuel cell-based Auxiliary Power Units”. Applied Energy 215, 1-12; https://doi.org/10.1016/j.apenergy.2018.01.095

8 Witman, M. et al. (2021). Data-Driven Discovery and Synthesis of High Entropy Alloy Hydrides with Targeted Thermodynamic Stability. Chemistry of Materials, 33(11). https://doi.org/10.1021/acs.chemmater.1c00647

9 Puszkiel, J.A. et al. (2025). “On the hydrogen storage properties and life cycle evaluation of a room temperature hydride for scale-up applications: The case of an AB2-alloy”, International Journal of Hydrogen Energy, 118, 482, https://doi.org/10.1016/j.ijhydene.2025.03.161

10 Garelli, F. et al. (2025). “Enhancing TiFe Alloy Activation for Hydrogen Storage Through Al, Cr, Co, and Cu Substitutions as a Step Towards Future Recycling, Condensed Matter, Materials Science, https://doi.org/10.48550/arXiv.2504.06990

11 Yuanyuan, S. et al. (2022). “Developing sustainable FeTi alloys for hydrogen storage by recycling, Communications Materials, 3, 101. 10.1038/s43246-022-00324-5

12 Alves, E.S. et al. (2025). “Life cycle assessment for the determination of the environmental impacts of an advanced large-scale hydrogen storage system from HyCARE EU project”, Journal of Cleaner Production, 515, 145836, https://doi.org/10.1016/j.jclepro.2025.145836.

13 Hirscher, M. et al. (2020). “Materials for hydrogen-based energy storage past, recent progress and future outlook”. Journal of Alloys and Compounds 827, 153548, https://doi.org/10.1016/j.jallcom.2019.153548

14 IEA (2023), Global Hydrogen Review 2023, IEA, Paris https://www.iea.org/reports/global-hydrogen-review-2023, Licence: CC BY 4.0

15 Furukawa, H. (2010). “Ultrahigh Porosity in Metal-Organic Frameworks, Science, 329 (5990), 424-428

16 Farha, O.K. et al (2010). “De novo synthesis of a metal-organic framework material featuring ultrahigh surface area and gas storage capacities”. Nature Chemistry 2 (11), 944-948, https://doi.org/10.1126/science.1192160

17 Dian Zhao, D. et al (2024). “Porous metal–organic frameworks for hydrogen storage”. ChenPhys. Chem. Chem. Phys., 2024, 26, 6490 https://doi.org/10.1039/D3CP05540J

18 Julien, P.A. et al. (2017). “Metal–organic frameworks meet scalable and sustainable synthesis”. GreenChem.19,2729, https://doi.org/10.1039/c7gc01078h

19 Warfsmann, J. et al. (2023). “Applying wash coating techniques for swelling-induced stress reduction and thermal improvement in metal hydrides”. Journal of Alloys and Compounds 950 (2023) 169814. https://doi.org/10.1016/j.jallcom.2023.169814.

20 Barale, J. et al. (2022). “TiFe0.85Mn0.05 alloy produced at industrial level for a hydrogen storage plant”. International Journal of Hydrogen Energy 47, 29866 – 29880, https://doi.org/10.1016/j.ijhydene.2022.06.295

21 Marques, F. et al. (2021). “Review and outlook on high-entropy alloys for hydrogen storage”. Energy Environ. Sci., 14, 5191, https://doi.org/10.1039/D1EE01543E

A4

Explosion free in any fire self-venting (TPRD-less) composite tanks: fundamentals and manufacturing guidance

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Abstract

The rupture of high-pressure hydrogen storage tanks in fires is a critical safety concern that undermines public confidence and restricts wider deployment of hydrogen technologies. Current safety strategies depend on thermally activated pressure relief devices (TPRDs), which have their disadvantages that can lead to critical consequences, for example failing to react in localised or low-intensity fires and creating additional hazards through high-pressure hydrogen release. This position paper introduces a breakthrough safety concept: explosion-free, self-venting composite tanks that remain safe under any fire scenario. Based on the microleaks-no-burst (μLNB) principle, these tanks eliminate the need for TPRDs by releasing hydrogen through distributed microchannels when exposed to fire. Prototype testing under both realistic and extreme conditions, including impinging hydrogen jet fires with heat release rates well beyond standard protocols, has validated the concept. Results confirm that self-venting tanks prevent rupture, blast waves, fireballs, and pressure peaking, thereby ensuring inherently safer performance across transport and stationary applications. Key challenges remain in advancing this technology, including composite-liner compatibility, thermal degradation, hydrogen permeability, sealing reliability and scaling to larger tanks. Existing test methods lack standardisation and often fail to represent real-world conditions, so underscoring the need for advanced fire testing protocols. Promising results were achieved with different fibre-resin composites and liners, however Type V tanks remain at low TRLs. Further opportunities include the use of thermoplastic materials for circular manufacturing and recycling. Addressing these gaps through coordinated research will accelerate industrial adoption, positioning self-venting tanks as a transformative advancement in hydrogen safety, regulation and sustainability.

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1

Introduction

Hydrogen incidents can occur at any stage of hydrogen's production, transportation, storage or utilisation[1]. There are known catastrophic incidents with hydrogen tanks, such as Korean tank rupture[2], or incidents of a hydrogen tank rupture on industrial premises in Austria[3], as well as incidents with widely spread around the globe compressed natural gas composite storage tanks, including rupture caused by smouldering fire[4],[5],[6]. These incidents underpin the public concern on the use of hydrogen technologies. The total number of hydrogen-powered vehicles, including passenger cars, commercial transport, and material handling machines [7] is currently about 100,000. In just the first half of 2024, more than 5,500 fuel cell vehicles were sold worldwide[8].

Exclusion of high-pressure hydrogen storage tanks rupture in any fire is crucial for public acceptance for obvious reasons. Indeed, it would eliminate hazards of devastating blast waves, fireballs, and projectiles. The problem is of especial concerns for confined spaces as tunnels, underground parking, hydrogen storage enclosures onboard of road vehicles, rail transport, aircrafts, and maritime vessels. Hydrogen storage tank rupture in the worst-case scenario for hydrogen refuelling stations.

Currently, thermally activated pressure relief devices (TPRDs), represent the standard safety technique to mitigate the probability of compressed hydrogen storage systems (CHSS) rupture in a fire. However, TPRDs have significant unacceptable limitations. It may fail to activate in localised or low-intensity fires, e.g. smouldering fires[9,10]. Releases from TPRDs produce thermal and pressure effects that pose hazards and associated risks to people, property and environment [11]. In case of a TPRD activation inside an enclosure like a garage, it may generate overpressures capable of destroying the enclosure by the pressure peaking phenomenon (PPP)[12] discovered in 2010 and characteristic exclusively for light gases such as hydrogen. The way to public acceptance of hydrogen technologies is elimination of what is precepted as "hydrogen explosions", including storage tanks rupture in a fire of any intensity. One option is the breakthrough safety technology of explosion free in any fire self-venting tanks that does not require TPRD as the whole tank surface is working as a "distributed TPRD"[13,14,15]. The technology is based on the microleaks-no-burst (μLNB) concept and is validated by experiments in several EU projects, e.g. SH2APED, HyTunnel-CS, etc.

The scope of this position paper is to address one of the critical issues of hydrogen safety, particularly fire and explosion safety of composite hydrogen storage systems, by advocating for the development of fundamental understanding of the innovative technology, and manufacturing guidance for adoption of self-venting composite hydrogen storage tanks. It highlights the limitations of current TPRD technique in preventing hydrogen tank rupture, as well as it formulates requirements to components and material performance and compatibility for explosion free in any fire self-venting tanks. The position paper defines fundamental studies and research programme for validation of self-venting tanks. This research shall aid regulatory updates and involve close academia-industry collaboration to support the manufacturing of inherently safer self-venting tanks.

The primary goal is to establish a scientific and regulatory framework for manufacturing and deploying self-venting hydrogen storage tanks by addressing key challenges. These include composite and polymer material science, computational modelling of heat and mass transfer, hydrogen safety, fire interactions with CHSS, and experimental validation of self-venting tank prototypes under various fire conditions.

By eliminating hazards and risks associated with traditional TPRD failures, self-venting tanks present a breakthrough in hydrogen storage technology. They provide a more reliable solution for hydrogen-powered vehicles, infrastructure, and industrial use. Adopting this technology not only enhances hydrogen storage safety but also supports the decarbonisation of transport and energy sectors, reinforcing hydrogen's role in a sustainable future.

Key research challenges in developing and deploying self-venting tanks include material selection, understanding thermal degradation, controlling permeability, and designing advanced fire testing protocols. These protocols must account for real-world conditions to meet the demanding regulatory requirement: "hydrogen storage tanks shall not rupture in any fire".

2

Current State of Research

All types of fires, including spill fires, impinging jet fires[16] and smouldering fires, can damage the integrity of onboard hydrogen storage tanks. For example, spill fires can be caused by natural disasters or industrial accidents, such as pipeline leaks, fires, or vehicle collisions. The typical specific heat release rate (HRR divided by the source area, A) for a liquid fuel spill fire is around 1-2 MW/m^2 [17,18,19]. Impinging hydrogen jet fire from nearby storage tank could reach HRR/A=20 MW/m^2 [20]. These values are much higher than the HRR/A levels recommended by the UN Global Technical Regulation No.13 (GTR#13)[21] or the R134[22] fire testing protocol, which suggest values of 0.3 MW/m^2 and 0.7 MW/m^2. The mismatch between the fire intensities in standard test protocols and real fires raises serious safety concerns. The fire resistance rating (FRR) of composite tanks (the time to hydrogen tank rupture in a fire) is highly sensitive to the HRR/A. Research[23] has shown that when the HRR/A is reduced, a hydrogen tank's FRR can increase to tens of minutes, giving enough time to trigger the TPRD and prevent catastrophic rupture. However, this does not rule out the possibility of tank rupture under real fire conditions, where the HRR/A is much higher. The regulated fire test protocol should be revised to account for a full range of real-world fire scenarios, from low-intensity smouldering and spill fires to highly intense fires, such as those involving impinging hydrogen jet flames – a typical incident scenario for CHSS with multiple tanks.

There are known cases of the self-venting behaviour of Type IV tanks. One of such examples is the leak of the composite tanks for LPG [24] in a fire. Such tanks operating at service pressures of 10-20 bar use only a small portion of the critical "load-bearing" composite wall thickness. A similar behaviour was experimentally observed for hydrogen tanks designed for nominal working pressure (NWP) of 700 bar. These tanks are leaking not rupturing in a fire at about 50% state of charge[25]. This behaviour of Type IV tanks was numerically reproduced and explained in study[26]. However, achieving reliable self-venting performance in fully charged standard (conventional) Type IV tanks remains a significant challenge. Explosion free (in any fire) self-venting (TPRD-less) tanks are designed using the innovative microleaks-no-burst (μLNB) concept, which eliminates the need for TPRDs (though their use is not prohibited) by enabling the tank itself to function as a "distributed over surface of tank TPRD" with microchannels for pressure discharge after the liner is melted using the registered invention and know-how.

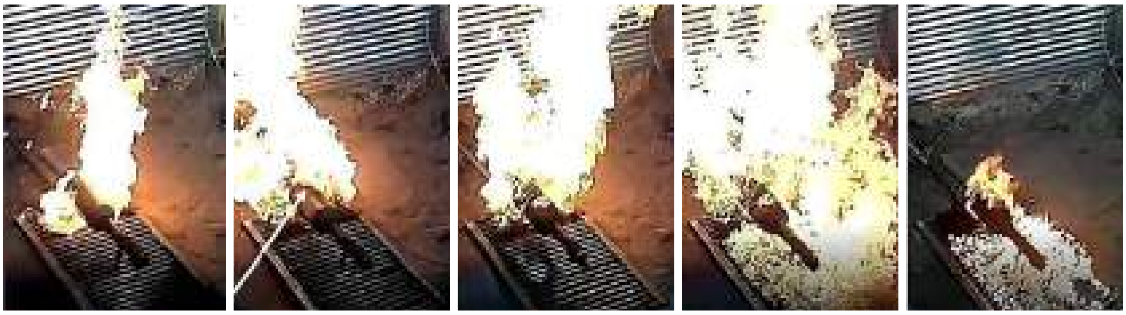
One of currently used engineering solutions to prevent tank rupture along with TPRD is the use of intumescent paint. Intumescent paint protection can be rapidly eroded by high-pressure hydrogen jet fires resulting from impingement of leaks from adjacent storage sources or pipes.

Key achievements and milestones

The design of self-venting (TPRD-less) Type IV hydrogen tanks has been validated through several European and UK projects[27]. These tanks are designed to prevent explosions during fires by using a specialised structure. They have a double-composite wall with a hydrogen-permeable outer layer and a polymer liner that acts as a barrier. The liner can be made from thermoplastic, thermoset, or other suitable polymer materials, depending on compatibility and safety standards. If the tank is exposed to extreme heat, the polymer liner melts, allowing hydrogen to escape through microleaks before the outer composite wall loses its strength. These microleaks form naturally through tiny microchannels in the composite material, similar in size to the reinforcing fibres, i.e. a few microns wide. The self-venting mechanism offers a critical safety advantage over traditional TPRDs. The size of the flammable envelope, the distance to the lower flammability limit (LFL), is directly linked to the leak diameter. Because microchannels are only a few microns wide, the flammable envelope extends just a few centimetres. This ensures hydrogen disperses rapidly, preventing accumulation in enclosed spaces and requiring only minimal ventilation. The self-venting tanks are characterised by the following achievements distinguished from other safety technologies: no blast wave, no fireball, no projectiles, no long flames, no pressure peaking phenomenon in confines spaces, no flammable cloud formation in naturally ventilated enclosures, no life/property loss in case of hydrogen tank affected by any fire. This technology is proposed as a safer alternative for hydrogen storage in road, rail, aviation, and maritime transport. It is also suitable for hydrogen refuelling stations, marine vessel storage, and underground infrastructure such as tunnels and car parks.

The first designed and manufactured prototypes have undergone successful fire testing under conditions exceeding those specified in GTR#13, with HRR/A=1 MW/m^2. Figure 1 shows sequential snapshots from one of the first fire tests on a self-venting tank prototype. The images capture key stages of the process: localised fire initiation, flame appearance, the onset of an engulfing fire, and the final stage with residual resin combustion. Notably, by the end of the process, the hydrogen pressure drops to 1 bar absolute, and there is no visible increase in flame size at the start of hydrogen release through microleaks or afterward.

Figure 1. Self-venting NWP=700 bar tank prototype in localised and engulfing fire portions of HRR/A=1 MW/m^2 intensity [28].



Fire test started
0 s

First isolated flame
3 min

(pressure drops)
10 min 1 s

Engulfing fire starts
10 min 4 s

H2-resin combustion
18 min 10 s

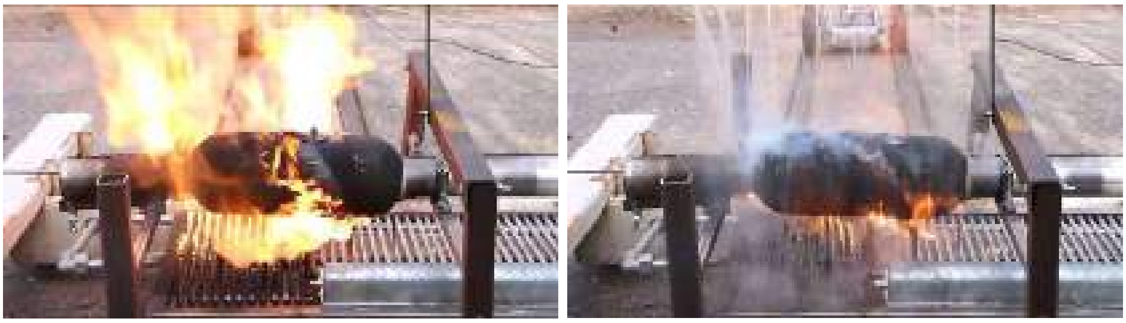
Experiments were carried out on double-composite overwraps using different fibre-resin materials under realistic fire conditions. Glass and basalt fibres were tested as alternatives to carbon fibre and they offered similar safety performance with lower cost. In all cases, the tanks released hydrogen safely until the pressure dropped to atmospheric level.

Protecting public and first responders is a priority. Firefighting strategies may include moving the vehicle away from the fire (simulated in tests by shutting down the burner) or applying water to suppress the flames. Figure 2 demonstrates the technology validation under fire conditions in case of fire suppression by water jets. Hydrogen release from the tank continued safely even after the fire was extinguished and the sprinkler system suppressed the flames. This demonstrates an advantage over TPRD-based systems, as firefighters can respond as in any conventional fire without the need to cool a TPRD to prevent its activation.

Figure 2. Self-venting tank prototype in a fire with flame extinction [29].

Test start

First sign of resin combusting **01:19**



Burner fuel supply stopped, resin is still burning **05:49**

Water sprinkler started **05:55**

Extinction continues, resin is still burning **06:30**

Seconds after sprinkler stopped, combustion is slightly visible (on video) **13:35**

The key achievement was validating the technology under extreme, yet realistic, CHSS conditions of an impinging hydrogen jet fire from a nearby 700-bar tank (see Figure 3). The experiment showed that the outer composite layers of basalt fibre were eroded by the high-momentum hydrogen jet fire. Intumescent paint could not withstand this intensity and would be destroyed within seconds, failing to protect the tank. A TPRD would also be ineffective In such a scenario, if the jet impacted the tank away from its location.

Figure 3. Self-venting tank prototype under extreme impinging jet fire of highest ever intensity of HRR/A=19.5 MW/m^2 from a 700-bar storage tank: left – during fire test, right – aftermath of the prototype composite of tank test [30].

The findings confirm that this breakthrough safety technology gives a step-change in protection for people, property and the environment. To enable its adoption, standard fire test protocols must be updated to cover the full range of scenarios, from low-intensity smouldering and spill fires to high-intensity hydrogen jet fires affecting adjacent tanks in a CHSS. This safety advancement plays a crucial role in increasing public acceptance of hydrogen.

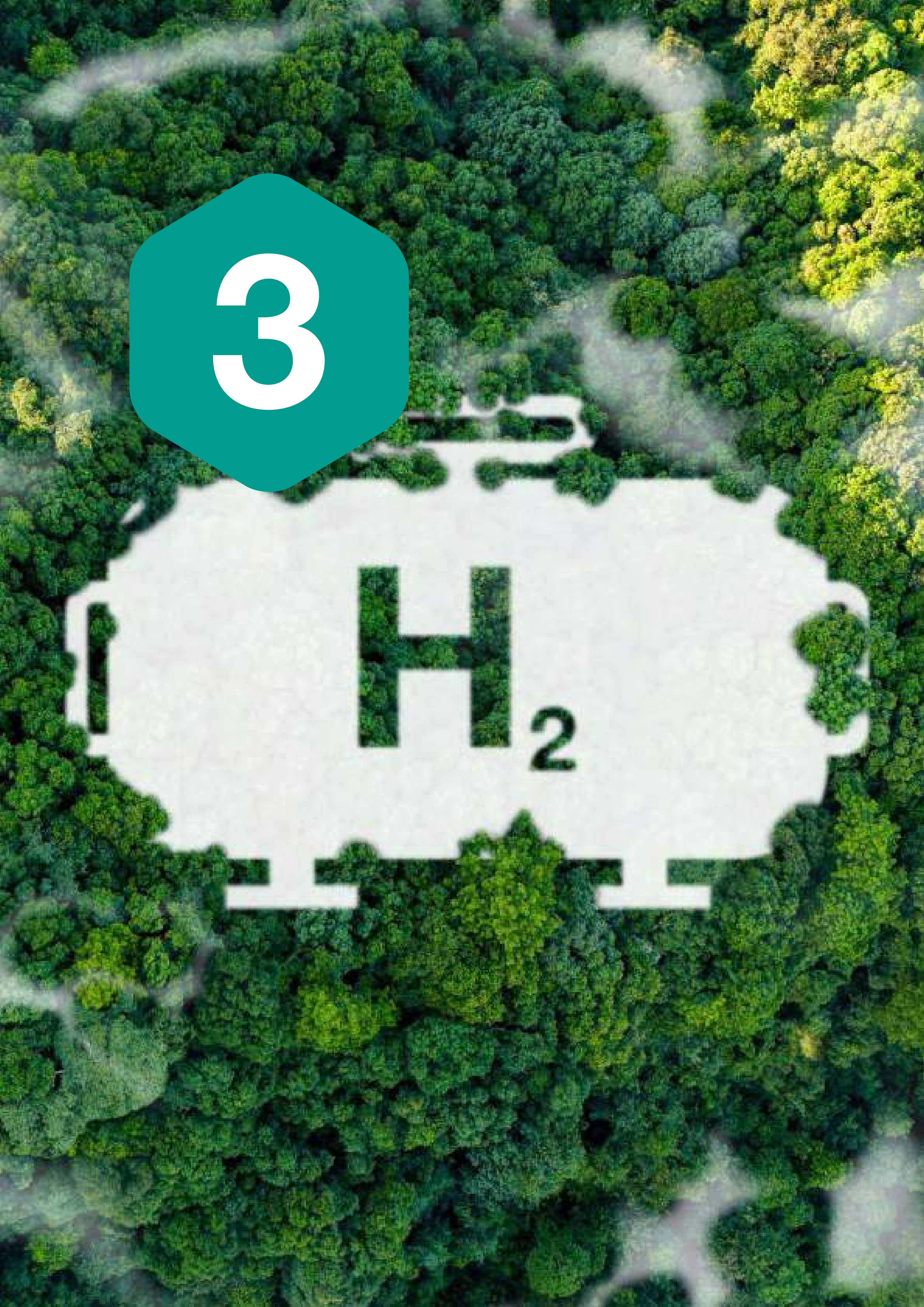
Notable projects:

- UKRI, EPSRC. UK National Clean Maritime Research Hub (MaRes) (EP/Y024605/1).
- Horizon 2020. H2020-JTI-FCH-2020-1. SH2APED: Storage of hydrogen: alternative pressure enclosure development. GA No.101007182.
- H2020, FCH2JU (now Clean Hydrogen Partnership): HyResponder “European Hydrogen Train the Trainer Programme for Responders” (875089).
- Innovate UK. Clean Maritime Demonstration Competition Round 1 (CMDC1): “Northern Ireland Green Seas” (10009311).
- Interreg Atlantic Area, “HYLANTIC Atlantic Network for Renewable Generation and Supply of Hydrogen to promote High Energy Efficiency” (EAPA_204/2016).

- H2020, FCH2JU. “HyTunnel-CS: PNR for safety of hydrogen driven vehicles and transport through tunnels and similar confined spaces”.
- Innovate UK. Clean Maritime Demonstration Competition Round 2 (CMDC2): “Hydrogen Fuel Cell Range Extender” (10041047).
- Invest NI, Centre for Advanced Sustainable Energy (CASE): “Breakthrough safety technologies for hydrogen vessels from Northern Ireland” (PROJECT/A1135).
- Invest NI, Proof of Concept Plus: “Optimisation of explosion-free in fire composite cylinders to industrial requirements” (1703/130130821-1).
- Invest NI, Proof of Concept 629: “Composite tank prototype for onboard compressed hydrogen storage based on novel Ulster’s leak-no-burst safety technology” (1703/130130821).
- EPSRC H2FC SUPERGEN Challenge: “Integrated safety strategies for onboard hydrogen storage systems” (EP/K021109/1).

Current safety technologies have shown effectiveness in fire tests, including scenarios replicating aspects of firefighter interventions and extreme conditions. Prototypes with different fibre-resin composites and liners performed well, but research gaps remain. Materials are still at low TRLs, and their performance and compatibility are uncertain, especially for emerging Type V tanks. Key unknowns include the role of composite porosity, thermal degradation, flame resistance and polymer-liner adhesion. Issues such as liner buckling, delamination and hydrogen permeability also require further study. Existing test methods can give inconsistent results and lack standardisation, but higher pressures and new materials make current protocols less representative of real conditions. Additional work is needed on Joule-Thomson cooling effects, seal reliability and scaling to larger tanks. Addressing these gaps is essential to advance safer composite hydrogen storage systems.

3



Research Challenges

Further research is needed to understand the fundamental physical processes behind this innovative engineering solution. Validating models for designing self-venting Type V and Type IV tanks across various fire scenarios, ranging from smouldering and liquid spills to impinging jet fires, is essential. Testing these tanks in fires of different intensities will build consumer confidence across sectors of the hydrogen economy. At present, no fire testing protocol covers the full range of scenarios, making its development one of the priorities. Introduction of self-venting tanks also creates an opportunity for regulatory updates. Type V tanks, which are less mature than Type IV, do not use a conventional liner. Instead, the composite wall must act as both the load-bearing structure and the gas barrier. In practice, they often include a barrier from non-reinforced tape winding, which improves barrier properties. Without a discrete liner, strain compatibility issues are reduced, improving fatigue performance. However, the safe operating pressures of Type V tanks are still under investigation. Factors including composite layup sequence, fibre architecture, and manufacturing defects remain critical as they significantly influence burst strength and long-term structural integrity [31].

The performance of self-venting tanks depends on fibre and composite thermal properties, liner melting, resin degradation and the flammability of thermoset and thermoplastic materials. As for Type V polymer-based tanks, the key factors include melting point and heat of fusion. Experimental and numerical studies are needed to define thermal conductivity requirements and confirm the ability to withstand fires of varying intensities without failure. The use of flame-retardant additives should also be assessed. Because hydrogen-liner-composite interactions are complex, close collaboration between academia, industry and research institutions is essential. Future work should focus on thermal stability, degradation, reaction kinetics, pyrolysis and optimised flame-retardancy strategies to advance self-venting tank technology.

Another challenge is the adhesion and structural integrity of liners or inner barriers. In fully thermoplastic structures, cohesive bonding is essential, requiring the liner to form a “true weld” with the reinforced structure. When bonding a thermoplastic liner to a thermoset reinforcement, adhesive bonding is needed – an area that requires further investigation.

The permeability of materials is crucial for safety. Micro-voids and defects in the liner can increase hydrogen permeation [32]. Long-term hydrogen exposure may lead to degradation and embrittlement. Permeation measurements must be conducted on a representative sample from a cylinder, with dimensions tailored for compatibility with bench tests. Ensuring the experimental setup minimises or prevents hydrogen leaks is essential for accurate permeation measurements.

Seals in hydrogen storage systems, particularly elastomeric types, can swell under high-pressure hydrogen. This volumetric expansion weakens their structural integrity and increases the risk of extrusion, tearing, failure and leakage. Swelling also alters barrier properties, potentially raising hydrogen permeation. Seal and connection design must therefore meet strict requirements for durability, environmental resistance, vibration, acceleration, refuelling safety and fire safety. Validation should combine extensive experimental testing with computational modelling using validated tools.

TRL vary from low for Type V tanks to TRL 4-6 for Type IV tanks by the end of the project.

The proposed timeline is medium-term 3-5 years. The suggested estimate of the funding is 9M EUR.

4

Rationale for Advancing Research in This Area & Potential Applications

Explosion-free, self-venting hydrogen storage tanks in fires would mark a major step towards public acceptance and sustainability. The use of thermoplastic materials can enable a circular approach to hydrogen tank manufacturing, making production and recycling more efficient. Given the expected increase in hydrogen storage demand, research must prioritise environmentally friendly and cost-effective solutions, covering manufacturing, end-of-life management, and material reuse.

A holistic approach is essential for advancing circular storage systems. While polymers offer recyclability benefits, carbon fibre, being critical for lightweight applications, poses sustainability challenges due to its high CO_2 footprint and limited recyclability. Current carbon fibre composite overwrapped tanks struggle to align with circular economy principles, highlighting the need for innovation in materials and design. A growing demand from sectors such as aerospace and wind energy [33] is driving both price increases and material shortages [34],[35]. The fundamental studies aim to investigate the use of alternative fibres for at least the partial replacement of carbon fibres.

This project will strengthen Europe's leadership by enabling breakthrough hydrogen safety technology. It offers unprecedented safety and cost reduction, positioning Europe ahead of competitors. Building a strong technological base, skilled workforce, and manufacturing capability will drive global demand and market adoption.

The scientific impact of this research and its alignment with the technology advancement goals of EC[36] and CHP[37] is indisputable. The team of inventors and researchers working on different projects devoted to the self-venting tanks has demonstrated significant contributions through internationally leading research in hydrogen safety and advanced materials engineering. Key findings have been, and will continue to be, policy influential, which is in line with the goals of Hydrogen Europe Research: "providing evidence-based research"…"to inform European and national policies related to hydrogen development" [38]. The outcomes of the project will impact existing Regulations, Codes and Standards (RCS), including UN ECE GTR#13 (Phase 3), IMO, ISO/TC197, CEN/CLC/JTC6, etc.

Overview of applications

The research will strongly affect safety through the entire range of hydrogen systems and infrastructure. The inherently safer storage systems will be available for hydrogen storage onboard of passenger cars, heavy-duty vehicles, rail, maritime and aviation systems, as well as stationary applications such as hydrogen refuelling stations, domestic storage, etc.

References

1 Crowl DA, Jo Y-D. The hazards and risks of hydrogen. Journal of Loss Prevention in the Process Industries 2007;20:158–64. https://doi.org/10.1016/j.jlp.2007.02.002.

2 Yonhap. Hydrogen tank explosion kills 2 in Gangneung. The Korea Herald 2019. https://www.koreaherald.com/article/2006624.

3 Collins L. Hydrogen explosion in Austria | "I live more than 3km away… and the blast made my windows shake." HydrogeninsightCom 2023. https://www.hydrogeninsight.com/industrial/hydrogen-explosion-in-austria-i-live-more-than-3km-away-and-the-blast-made-my-windows-shake/2-1-1498784.

4 NJ. WATCH: Garbage truck explodes in fireball, rips hole in nearby house. NJCom 2019. https://www.nj.com/mercer/2016/01/garbage_truck_explosion_damages_hamilton_house.html.

5 Explosions during interventions involving compressed gas powered vehicles | CTIF - International Association of Fire Services for Safer Citizens through Skilled Firefighters. https://ctif.org/news/explosions-during-interventions-involving-compressed-gas-powered-vehicles.

6 Violent Vehicle Fire Explosion Causes Severe Injuries to LAFD Firefighters | Los Angeles Fire Department. https://lafd.org/news/violent-vehicle-fire-explosion-causes-severe-injuries-lafd-firefighters.

7 GDL Groupe. 100,000 hydrogen-powered vehicles worldwide by 2024 2024. https://jdlgroupe.com/en/2024/10/03/100-000-vehicules-hydrogene-dans-le-monde-en-2024/.

8 C. Randall. SNE Research: Only 5,621 new FC vehicles in the first half of the year - electrive.com 2024. https://www.electrive.com/2024/08/16/sne-research-only-5621-new-fc-vehicles-in-the-first-half-of-the-year/.

9 Smouldering coal cargo fire in several holds on bulk carrier Belo Horizonte. GOVUK 2015. https://www.gov.uk/maib-reports/smouldering-coal-cargo-fire-in-several-holds-discovered-when-bulk-carrier-belo-horizonte-arrived-at-its-discharge-port.

10 NJ. WATCH: Garbage truck explodes in fireball, rips hole in nearby house. NJCom 2019. https://www.nj.com/mercer/2016/01/garbage_truck_explosion_damages_hamilton_house.html

11 Molkov V. Fundamentals of hydrogen safety engineering 2012. http://bookboon.com/en/textbooks/mechanics/fundamentals-of-hydrogen-safety-engineering-i.

12 Brennan S, Molkov V. Safety assessment of unignited hydrogen discharge from onboard storage in garages with low levels of natural ventilation. International Journal of Hydrogen Energy 2013;38:8159–66. https://doi.org/10.1016/j.ijhydene.2012.08.036.

13 Molkov V, Kashkarov S, Makarov D. Breakthrough safety technology of explosion free in fire self-venting (TPRD-less) tanks: The concept and validation of the microleaks-no-burst technology for carbon-carbon and carbon-glass double-composite wall hydrogen storage systems. International Journal of Hydrogen Energy 2023. https://doi.org/10.1016/j.ijhydene.2023.05.148.

14 Molkov V, Kashkarov S, Makarov D. Explosion free in fire self-venting (TPRD-less) composite tanks: Performance during fire intervention. International Journal of Hydrogen Energy 2023. https://doi.org/10.1016/j.ijhydene.2023.07.067.

15 Molkov V, Kashkarov S, Makarov D, Fletcher J, Rattigan W. Explosion free in fire self-venting (TPRD-less) Type IV tanks: Validation under extreme impinging 70 MPa hydrogen jet fire conditions. International Journal of Hydrogen Energy 2023. https://doi.org/10.1016/j.ijhydene.2023.09.020.

16 Tamura Y, Takabayashi M, Takeuchi M. The spread of fire from adjoining vehicles to a hydrogen fuel cell vehicle. International Journal of Hydrogen Energy 2014;39:6169–75.

17 Ingason H, Li YZ. Spilled liquid fires in tunnels. Fire Saf J 2017;91:399–406. https://doi.org/10.1016/j.firesaf.2017.03.065.

18 Liu J, Li D, Wang Z, Chai X. A state-of-the-art research progress and prospect of liquid fuel spill fires. Case Stud Therm Eng 2021;28:101421. https://doi.org/10.1016/j.csite.2021.101421.

19 Molkov V, Dadashzadeh M, Kashkarov S, Makarov D. Performance of hydrogen storage tank with TPRD in an engulfing fire. International Journal of Hydrogen Energy 2021. https://doi.org/10.1016/j.ijhydene.2021.08.128.

20 Molkov V, Kashkarov S, Makarov D, Fletcher J, Rattigan W. Explosion free in fire self-venting (TPRD-less) Type IV tanks: Validation under extreme impinging 70 MPa hydrogen jet fire conditions. International Journal of Hydrogen Energy 2023. https://doi.org/10.1016/j.ijhydene.2023.09.020.

21 UNECE. Addendum 13: UN Global Technical Regulation No. 13. Hydrogen and Fuel Cell Vehicles. Amendment 1. 2023. https://unece.org/sites/default/files/2023-07/ECE-TRANS-180-Add.13-Amend1e.pdf.

22 UNECE. Regulation No 134. Uniform provisions concerning the approval of motor vehicles and their components with regard to the safety-related performance of hydrogen fuelled vehicles (HFCV). 2019.

23 Molkov V, Kashkarov S, Makarov D. Explosion free in fire self-venting (TPRD-less) composite tanks: Performance during fire intervention. International Journal of Hydrogen Energy 2023. https://doi.org/10.1016/j.ijhydene.2023.07.067.

24 SEIFERTandSKINNER. Bonfire test on Composite LPG Cylinder. YouTube 2013. https://www.youtube.com/watch?v=AsakH6XT0Ao.

25 Ruban S, Heudier L, Jamois D, Proust C, Bustamante-Valencia L, Jallais S, et al. Fire risk on high-pressure full composite cylinders for automotive applications. International Journal of Hydrogen Energy 2012;37:17630–8. https://doi.org/10.1016/j.ijhydene.2012.05.140.

26 Kashkarov S, Makarov D, Molkov V. Performance of Hydrogen Storage Tanks of Type IV in a Fire: Effect of the State of Charge. Hydrogen 2021;2:386–98. https://doi.org/10.3390/hydrogen2040021.

27 Molkov V, Kashkarov S, Makarov D. Breakthrough safety technology of explosion free in fire self-venting (TPRD-less) tanks: The concept and validation of the microleaks-no-burst technology for carbon-carbon and carbon-glass double-composite wall hydrogen storage systems. International Journal of Hydrogen Energy 2023. https://doi.org/10.1016/j.ijhydene.2023.05.148.

28 Molkov V, Kashkarov S, Makarov D. Breakthrough safety technology of explosion free in fire self-venting (TPRD-less) tanks: The concept and validation of the microleaks-no-burst technology for carbon-carbon and carbon-glass double-composite wall hydrogen storage systems. International Journal of Hydrogen Energy 2023. https://doi.org/10.1016/j.ijhydene.2023.05.148.

29 Molkov V, Kashkarov S, Makarov D. Explosion free in fire self-venting (TPRD-less) composite tanks: Performance during fire intervention. International Journal of Hydrogen Energy 2023. https://doi.org/10.1016/j.ijhydene.2023.07.067.

30 Molkov V, Kashkarov S, Makarov D, Fletcher J, Rattigan W. Explosion free in fire self-venting (TPRD-less) Type IV tanks: Validation under extreme impinging 70 MPa hydrogen jet fire conditions. International Journal of Hydrogen Energy 2023. https://doi.org/10.1016/j.ijhydene.2023.09.020.

31 Air A, Shamsuddoha M, Gangadhara Prusty B. A review of Type V composite pressure vessels and automated fibre placement based manufacturing. Composites Part B: Engineering 2023;253:110573. https://doi.org/10.1016/j.compositesb.2023.110573.

32 Saffers J-B, Makarov D, Molkov VV. Modelling and numerical simulation of permeated hydrogen dispersion in a garage with adiabatic walls and still air. International Journal of Hydrogen Energy 2011;36:2582–8.

33 Carbon fibre: sustained increase in production capacities - JEC. https://wwwjeccompositescom/ 2008. https://www.jeccomposites.com/news/spotted-by-jec/carbon-fibre-sustained-increase-in-production-capacities/.

34 BikeBiz. Carbon fibre shortage could impact on high-end bike sales. BikeBiz 2005. https://bikebiz.mystagingwebsite.com/carbon-fibre-shortage-could-impact-on-high-end-bike-sales/.

35 The future of carbon fiber manufacture 2025. https://www.compositesworld.com/articles/the-future-of-carbon-fiber-manufacture.

36 Hydrogen - European Commission. https://single-market-economy.ec.europa.eu/industry/strategy/hydrogen_en.

37 Mission & Objectives - Clean Hydrogen Partnership. https://www.clean-hydrogen.europa.eu/about-us/mission-objectives_en.

38 Policy – Hydrogen Europe Research. https://hydrogeneuroperesearch.eu/our-activities/policy-working-group/.

A5

The Role of Low-Carbon Hydrogen in Decarbonizing Glass and Ceramic Manufacturing in Europe

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Abstract

The paper investigates the integration of hydrogen as a decarbonization strategy in the European glass and ceramics manufacturing sectors. The primary goal is to analyze the potential, current initiatives, and future opportunities for green H2 adoption, with a focus on reducing sector-specific carbon emissions and supporting the transition to net-zero by 2050. The methodology involves a review of pilot projects, and technological advancements across various sub-sectors, including glass, ceramics, bricks, sanitaryware, and cement, highlighting both successful industrial-scale demonstrations and ongoing feasibility studies. Key insights reveal that H2 can significantly mitigate CO2 emissions, particularly in energy-intensive processes where fossil fuels dominate. Notable pilot projects demonstrate the technical viability of H2 combustion in glass furnaces and ceramic kilns, with some achieving substantial emission reductions and maintaining product quality. However, the study identifies critical challenges: high capital and operational costs, limited H2 supply, the need for technological adaptation, and concerns regarding product quality and safety. The paper concludes that while H2 presents a promising pathway for decarbonization, its widespread adoption will require sustained innovation, policy support, and investment to overcome economic, technical, and regulatory barriers and to ensure the sector's alignment with Europe's carbon neutrality targets.

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1

Introduction

Hydrogen, particularly when produced from renewable sources, is increasingly regarded as a sustainable and eco-friendly energy carrier. Its integration into industrial processes, especially in the manufacturing of glass and ceramics, is attracting significant attention due to escalating environmental concerns and the global drive towards net-zero emissions. In addition, adopting green H2 in industrial processes offers substantial image benefits for companies, particularly as consumer preferences evolve. By 2050, the primary buyers will be today's younger generation, who are developing a strong environmental consciousness and are likely to favour products with minimal environmental impact. Companies that can demonstrate a genuine commitment to sustainability by integrating green H2 will be able to distinguish their products as truly green, enhancing brand reputation and consumer trust. This differentiation is expected to translate into increased market share and customer loyalty, as eco-friendly credentials become a decisive purchasing factor. Another significant advantage for companies using H2 is reduced exposure to fluctuations in fuel prices, which are often driven by volatile international markets. By decreasing reliance on imported fossil fuels, businesses can achieve greater price stability and predictability in their operational costs. This resilience not only safeguards profit margins but also facilitates long-term strategic planning, making companies less vulnerable to geopolitical tensions and supply chain disruptions. Further advantages include compliance with tightening environmental regulations, access to green financing, and improved stakeholder relations. Early adoption of H2 technologies also positions companies as industry leaders, fostering innovation and opening new market opportunities as the global economy transitions towards decarbonisation.

2

Current State of Research

The European ceramics sector currently emits approximately 19 million tonnes of CO2 annually. While this represents a substantial reduction of over 45% since the industry's peak in 2000, it still accounts for about 1% of total European industrial emissions. The primary sources of these emissions include: the combustion of fuels for drying and heating, CO2 released from mineralogical changes in raw materials (e.g., calcination of CaCO3), indirect emissions from electricity generation (cogeneration), and emissions from internal and external logistics. In some highly productive areas, with unfavorable meteorological conditions, slow air exchange due to climatic conditions can lead to legal limits for pollutant emissions being exceeded, posing serious health risks. In response, the European ceramics industry has established ambitious targets to significantly reduce its emissions by 2050, with the ultimate goal of achieving carbon neutrality. The proposed strategy encompasses various approaches, including: reducing process-related emissions, driving innovation to improve manufacturing efficiency, implementing CO2 capture technologies (CCS/CCU), exploring additional carbon removal techniques, and, crucially, utilising green H2 as a fuel. A promising pathway for emission reduction involves using it and waste carbon dioxide from glass and ceramic production to produce synthetic fuels, such as methane. This approach allows many producers to maintain their existing technology, including highly sensitive and efficient thermal machines like spray-dryers and kilns, while significantly lowering net CO2 emissions by converting captured CO2 into methane through a methanation process with green H2 [1].

2.1 Hydrogen project examples

Green H2 has been identified as a key means of mitigating CO2 emissions in the energy-intensive glass and ceramic manufacturing industry, where over 70% of energy currently comes from fossil fuels like natural gas [2-3]. Numerous projects are demonstrating the application and potential of H2 across various sectors. The following tables present some examples of applications.

2.1.1 Glass production.

Project name	Description
H2Glass https://h2-glass.eu/	H2GLASS is driven by 23 strong partners from 8 European countries representing research and industry institutions, major manufacturers from the glass industry. The objectives of the project are different. – Develop the technology stack that will enable 100% H2 combustion in the glass industry. – Validate H2GLASS technology through application in industrial context. – Prove economic and environmental viability of H2GLASS solutions compared to fossil fuels. – Develop IT architecture for automatic control and management and more efficient industrial processes. – Raise public understanding on H2 technology as a solution for decarbonising industrial processes. Transfer technology to other EU energy-intensive industries.
SCHOTT https://www.schott.com/en-gb/news-and-media/media-releases/2024/schott-produces-optical-glass-with-100-percent-hydrogen	After successfully testing glass production with 100% H2 on a laboratory scale, the group Schott has completed the industrial-scale application. For three days, the glass expert melted optical glass in a furnace using the new technology for the first time. Schott reports successful trials of using 35% H2 for industrial-scale glass production.
Pilkington https://www.pilkington.com/en-gb/uk/news-insights/latest/pilkington-uk-plans-to-scale-low-carbon-glass-production-under-pioneering-hydrogen-plans	Pilkington United Kingdom Limited, intends to use green H2 at its site and scale its production of low carbon glass from 2027, under pioneering new plans. The project would enable the company to eliminate 15,000 tonnes/y of carbon from its direct emissions.
H2 project (H2) by Saverglss https://www.saverglass.com/en/csr/actions/hydrogen-project	Saverglass reported successful trials at its hybrid furnace. The project team carried out tests on H2 injection at three different rates: 10%, 20% and 30%.
Hrastnik1860 https://hrastnik1860.com/wp-content/uploads/5.12.23_Hydrogen-bottle-press-release.pdf	In 2023, it reached the significant milestone of using more than 60% of H2 for their combustion needs during glass bottle production. This has led to a reduction of over 30% in CO2 emissions.
DIVINA https://www.spevetro.it/divina-project-research-on-hydrogen-natural-gas-mixed-combustion/?lang=en	Research on H2 – Natural Gas mixed combustion
HyGlass https://www.energy4climate.nrw/en/topics/best-practice/hyglass	By replacing natural gas with H2 in the melting process, a reduction in CO2 emissions of around 3.3 million tonnes could be achieved across Germany as a whole.
Ardagh Glass Packaging-Europe (AGP-Europe) https://www.ardaghgroup.com/2024/ardagh-pioneers-onsite-hydrogen-energy/	Ardagh Glass Packaging-Europe announced that it is now producing green H2 for glass melting via an electrolyser at its facility in Limmared, Sweden. Since testing of the electrolyser began in October 2024, the furnace has successfully combusted 109,000m3 of H2 produced on site, saving 70 tonnes of CO2.
Hynet https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1119899/phase_3_hynet_industrial_fuel_switching.pdf	Hydrogen Firing in a Glass Furnace
COSiMa Saint-Gobain https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1119899/phase_3_hynet_industrial_fuel_switching.pdf	Saint-Gobain announced the launch of the COSiMa project, which aims to investigate the feasibility of using H2 for glass production.

2.1.2 Ceramic Tile Production.

Project name	Description
H2 FACTORY® https://www.irisceramicagroup.com/en/media/iris-ceramica-group-and-edison-next-for-h2-factory-the-first-ceramics-plant-powered-by-green-hydrogen-produced-on-site/	Iris Ceramica Group and Edison Next will develop a production facility that will run on green H2, produced on-site using a cutting-edge custom-designed system. Technical ceramic slabs (3.2 m x 1.6 m x 12 mm thick x sustainability) were produced by using a blend of H2.
Revigrés https://ceramicworldweb.com/en/news/revigres-adopts-new-100-green-complete-production-line	This ceramic tile manufacturer will build a complete production line for 100% green porcelain tiles, consisting of a 7-level horizontal dryer, a TITANIUM®H2 oven using H2.
SITI B&T https://gruppobt.com/en/hydrogen-kilns-within-three-years-siti-bt-research-looking-towards-the-energy-transition/	Siti B&T manufactures a kiln for firing ceramic tiles that initiates a process of gradually replacing traditional methane with a H2-based gas blend. This innovation aims to further reduce the use of fossil fuels and atmospheric emissions.
Sacmi https://sacmi.com/en-US/ceramics/news/19660/The-first-tile-fired-in-a-100-hydrogen-kiln-It-s-from-SACMI	Sacmi produces a 100% hydrogen kiln.

2.1.3 Bricks and Roof Tiles Production.

Project name	Description
HyBrick™ https://www.mbhplc.co.uk/sustainability/hybrick/	Michelmersh has announced plans to conduct a feasibility study to replace natural gas with H2 in the brick-making process. The programme is part of the £1 billion Net Zero Innovation Portfolio (NZIP) which aims to provide funding for low-carbon technologies to decrease the costs of decarbonisation.
Forterra https://www.forterra.co.uk/paving-the-highway-to-hydrogen/	They have completed the first phase of H2 testing at the Measham brickworks in North West Leicestershire. They experimented with 20% H2 mixtures across the whole range of bricks.

2.1.4 Sanitaryware Production.

Project name	Description
Lucideon https://www.iom3.org/resource/ceramics-fired-solely-by-hydrogen.html	Lucideon UK claims it has completed 100% H2 firing of sanitaryware. The test took more than 13 hours at 1,200°C.
SACMI-Riedhammer https://www.sacmi.it/en-US/ceramics/news/16208/Tailor-made-versatility-and-sustainability-SACMI-RH-drives-the-evolution-of-sanitaryware-tunnel-kilns	SACMI-Riedhammer kiln is the first H2-ready solution on the market: the standard machine can run on a H2-gas mix containing up to 20%.

2.1.5 Tableware Production.

Project name	Description
BHS tabletop AG https://tablewareinternational.com/bhs-tabletop-ag-fires-porcelain-using-hydrogen-for-the-first-time/	The company has succeeded in firing porcelain exclusively with hydrogen.

2.1.6 Cement and Refractory.

Project name	Description
Heidelberg Cement Hanson UK https://www.heidelbergmaterials.com/en/pr-01-10-2021	The pilot test used a mix of 100% climate-neutral fuels including H2 for commercial-scale cement manufacture. The proportion of fuels in the cement kiln's main burner was gradually increased to a wholly net zero mix made up of tanker-delivered H2 as well as biomass components and glycerine, generated as by-products of other industries
Cemex Ventures https://www.h2-view.com/story/cemex-to-install-plasma-based-hydrogen-production-tech-at-uk-cement-plant/2117887.article/	The H2 produced by HiiROC (thermal plasma electrolysis) is used as an alternative energy source to fuel clinker production processes.
Tarmac https://www.agg-net.com/news/uk-lime-kiln-in-world-first-net-zero-hydrogen-trial	High-quality lime has been manufactured in the UK using H2 as a fuel alternative to natural gas. The project builds on the company's wider long-term sustainability programme and corporate commitment to deliver net zero by 2050 and cut CO_2 by 45% per tonne of product by 2030.

3

Research Challenges

i) Advantages and Drivers

The push for H2 stems from its potential as a sustainable and eco-friendly energy carrier, crucial for achieving net-zero emissions targets. Its integration is a core strategy for industries, such as the European ceramics sector, to reach carbon neutrality by 2050, significantly contributing to global decarbonisation efforts. Green H2 can substantially mitigate CO2 emissions in energy-intensive processes and offers a pathway to lower net CO2 emissions. The desire to reduce pollutant emissions and improve public health in high-production areas further drives its adoption. Economically, green H2 offers a competitive advantage by enabling the production of environmentally friendly products that appeal to an increasingly eco-conscious market. Furthermore, its development within Europe is seen as a way to drive GDP growth and prosperity, creating new industries and jobs.

ii) Challenges and Barriers

Despite the promising outlook, the integration of H2 into industrial production processes faces several significant “challenges and barriers”.

Economic and Infrastructure Hurdles

For H2 to offer environmental benefits, it must be produced from low-emission sources of climate-altering gases. However, the substantial capital investment and operational expenses required for production plants result in higher costs compared to traditional fuels. Building and storing a H2 production facility makes the overall production process more complex. Furthermore, current production capacity is insufficient to meet even a fraction of the potential demand from energy-intensive industries, highlighting the need for significant scaling up of infrastructure.

Technical and Operational Complexities

Implementing H2 requires the recruitment of specialised personnel to operate facilities, as well as comprehensive training for all staff to ensure proficiency in responding to emergencies like leaks and explosions. Prior to its widespread implementation, a thorough examination of the impact of utilising H2 as a fuel on the final characteristics of products is imperative. It’s essential to maintain the quality and properties of goods currently produced, as directly replacing methane with H2 could compromise the remarkable energy efficiency and product quality achieved by highly sensitive thermal machines like spray-dryers and kilns. The development of all the necessary technologies for introducing H2 into various production processes is also crucial. While some projects demonstrate high technological maturity (TRL 7-9), others are in early stages of development (TRL 1-4), indicating varying levels of readiness across different applications. Current H2 production capacity is insufficient to meet even a fraction of the potential demand from energy-intensive industries. Prior to its implementation, a thorough examination of the impact of utilising H2 as a fuel on the final characteristics of products is imperative. [4-5]

Social and Regulatory Obstacles

The widespread adoption of H2 faces significant social and regulatory obstacles. Public concerns about its safety and the risks associated with its use are prevalent. Misconceptions about H2's flammability and storage can slow acceptance, making education and transparent communication essential. Additionally, the lack of harmonised international standards for production, transport, and usage creates uncertainty for businesses and investors, hindering global market development. Addressing these issues requires coordinated efforts between governments, industry, and communities to build trust and establish clear, universally accepted regulations.

4

Timeline and Resources

The existing information does not permit defining specific timeframes for addressing all the challenges of H2 integration in the glass and ceramics industries. Nevertheless, the European ceramics industry has set ambitious targets to significantly reduce its emissions by 2050 and achieve carbon neutrality. The presence of many projects, some of which are at an advanced stage, suggests that a significant number of plants could be operational in the long term. Much depends on EU and industrial policies to promote the ecological transition. In order to achieve net-zero emissions by 2050, there needs to be sustained, incremental innovation across decarbonisation technologies. This trajectory requires a long-term commitment to development and implementation that is aligned with globally recognised climate goals. Decarbonisation depends on continuous, phased technological and infrastructural advancements. Initiatives must prioritise scalable solutions that evolve alongside policy frameworks and market readiness to ensure measurable progress towards mid-century targets. It remains complex to quantify the exact funding requirements for emerging technologies. Projects supported in some countries amount to €1.2 billion. This figure serves as a benchmark, not a definitive sum, reflecting the scale of the resources required to overcome technical and commercial barriers. Significant public and private investments are already accelerating low-carbon innovation. Crucially, public financing acts as a financial multiplier, reducing project risk and mobilising private capital on a large scale. This synergy must be expanded strategically to bridge funding gaps and drive widespread adoption.

5

Rationale for Advancing Research in This Area & Potential Applications

Green H2 offers a multifaceted solution for the ceramics and glass industries, addressing key sustainability issues, societal benefits, economic impacts and strategic goals.

Sustainability and environmental benefits:

As a sustainable and eco-friendly energy carrier, it is essential for achieving net-zero emissions targets. Integrating it is a core strategy for the European ceramics industry to reach carbon neutrality by 2050, and it will make a significant contribution to global decarbonisation efforts. Green H2 can substantially mitigate CO_2 emissions in energy-intensive processes, providing a pathway to lower net emissions by converting waste carbon dioxide into synthetic fuels.

Societal benefits

Reducing pollutant emissions is particularly important in areas with high production rates, where slow air exchange can cause legal limits for pollutants to be exceeded, leading to serious health consequences for residents. Cleaner air directly improves public health and quality of life. Furthermore, investing in H2 technologies can foster innovation and create new jobs in the research, development and manufacturing sectors.

Economic impacts

Adopting green H2 provides a significant competitive advantage. It enables the production of environmentally friendly products that appeal to an increasingly eco-conscious consumer base. Ceramic products are also inherently energy-efficient in use (e.g. bricks, refractories and double/triple glazing). Certifying products made with green H2 could significantly enhance a brand's image, appealing particularly to wealthy, environmentally conscious customers who may be willing to pay more, opening up new premium market segments. Furthermore, developing H2 technologies in Europe will boost GDP and prosperity, creating new industries and strengthening the continent's competitive position.

Alignment with strategic goals

The drive to integrate green H_2 aligns directly with ambitious global decarbonisation goals and the carbon neutrality targets set by major industries. This strategic alignment demonstrates a commitment to future-proofing the industry and meeting international climate obligations. It also enhances energy security by diversifying energy sources and reducing reliance on volatile fossil fuel markets.

Potential Applications.

Hydrogen can be applied as a fuel directly or as a component in mixed fuels for various high-temperature industrial processes within glass and ceramic production:

Glass Production: H2 can be used in furnaces for melting primary ingredients and recycled glass at temperatures typically ranging from 1,500–1,700°C.

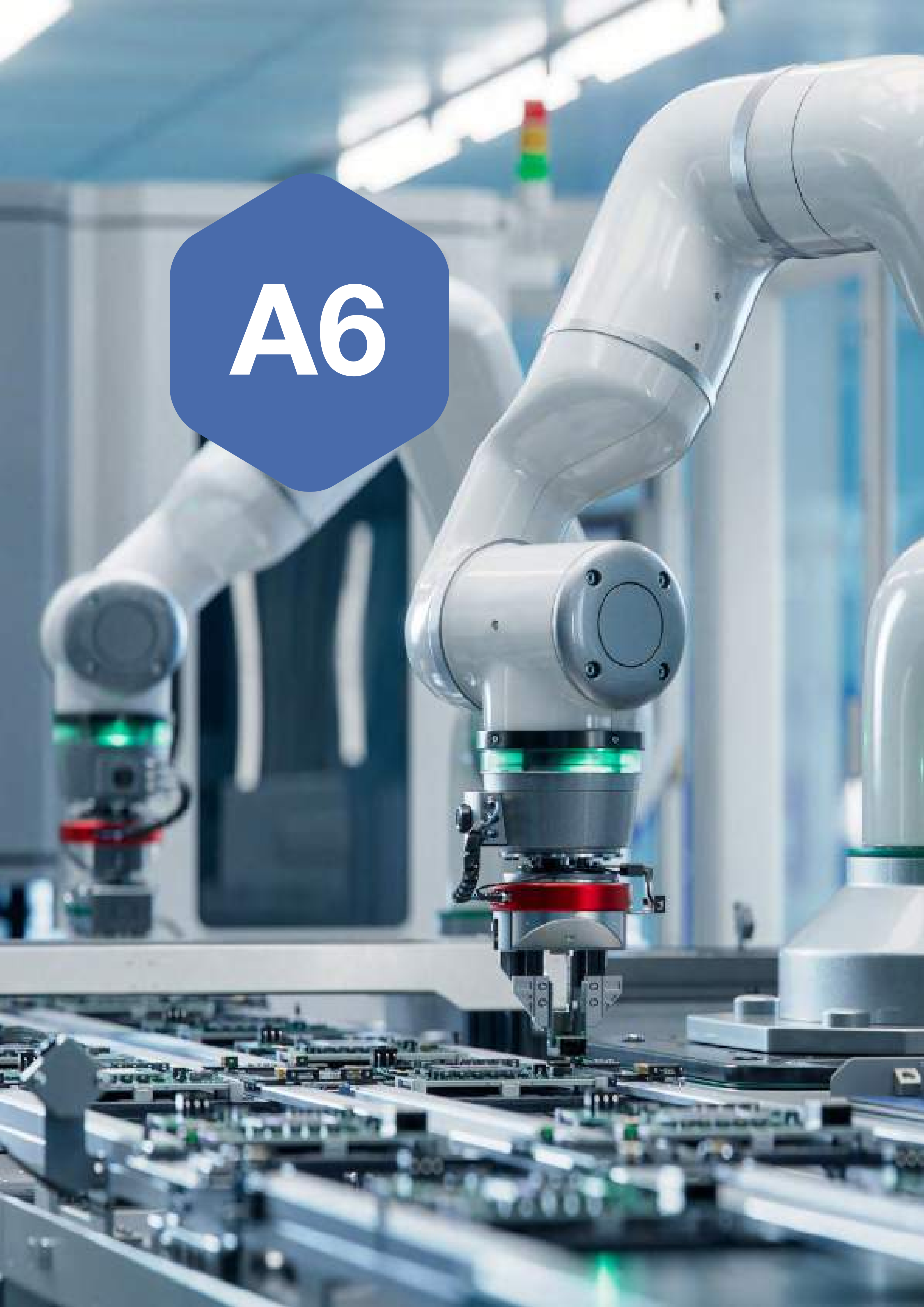
Ceramic and Concrete Production: It is suitable for firing in kilns across various ceramic sub-sectors, including:

Ceramic	Firing temperature
Glass	1500–1700°C
Tiles	1050–1230°C
Bricks and roof tiles	950–1100°C
Sanitaryware and tableware	1000–1400°C
Cement clinker and ceramic refractories	1450-1500°C

Synthetic Fuel Production. Green H2 can be combined with waste carbon dioxide from glass and ceramic production to create synthetic fuels such as methane, methanol, or dimethyl ether. This innovative approach allows manufacturers to significantly reduce their carbon footprint without requiring major modifications to existing key equipment like spray-dryers and kilns [6-8].

References

1. European Ceramic Industry Association, CERAMIC ROADMAP TO 2050 FOR THE WELL-BEING OF A RESILIENT, CLIMATE NEUTRAL EUROPE, https://www.ceramicroadmap2050.eu/wp-content/uploads/2024/01/ceramic-roadmap-to-2050.pdf (accessed May 16, 2025)
2. Glass Alliance, What is Glass, (n.d.). https://glassallianceeurope.eu/the-world-of-glass/ (accessed May 16, 2025).
3. A. Schmitz, J. Kamiński, B. Maria Scalet, A. Soria, Energy consumption and CO2 emissions of the European glass industry, Energy Policy 39 (2011) 142–155. https://doi.org/10.1016/J.ENPOL.2010.09.022.
4. DISCOVER “CERAMIC TILE TECHNOLOGY” (VOLUME II) | SACMI, (n.d.). https://sacmi.com/en-US/Ceramics/Tiles/SACMI-Tiles-Lab/Ceramic-tile-technology (accessed May 16, 2025).
5. Monfort, Eliseo & Mezquita, Ana & Granel, R. & Vaquer, E. & Escrig, A. & Miralles, A. & Zaera, V.(2010). Analysis of energy consumption and carbon dioxide emissions in ceramic tile manufacture. Boletín de la Sociedad Española de Cerámica y Vidrio. 49.
6. G.U. Fayomi, S.E. Mini, O.S.I. Fayomi, A.A. Ayoola, Perspectives on environmental CO2 emission and energy factor in Cement Industry, IOP Conf Ser Earth Environ Sci 331 (2019). https://doi.org/10.1088/1755-1315/331/1/012035.
7. P. Riyakad, S. Chiarakorn, Energy Consumption and Greenhouse Gas Emission from Ceramic Tableware Production: A Case Study in Lampang, Thailand, Energy Procedia 79 (2015) 98–102. https://doi.org/10.1016/J.EGYPRO.2015.11.483.
8. M.P. Desole, L. Fedele, A. Gisario, M. Barletta, Life Cycle Assessment (LCA) of ceramic sanitaryware: focus on the production process and analysis of scenario, International Journal of Environmental Science and Technology 21 (2024) 1649–1670. https://doi.org/10.1007/S13762-023-05074-6.



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Challenges in Manufacturing Structurally Stable Ceramic Membranes

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Abstract

Structurally stable ceramic membranes are pivotal for advancing hydrogen technologies, enabling efficient energy conversion, separation, and chemical processing under demanding conditions. Despite their superior thermal, chemical, and mechanical resilience, the large-scale deployment of ceramic membranes remains constrained by significant manufacturing and mechanical stability challenges. Key limitations include defect formation during shaping and sintering, multi-layer co-sintering issues, porosity control across multiple length scales, and brittleness under thermal and mechanical loads. This position paper analyzes these challenges, emphasizing the critical interplay between material composition, microstructure, macro-geometry, and processing strategies. We highlight emerging solutions, including multi-phase ceramic composites, high-entropy oxides, graded and hierarchical porous structures, advanced macro-geometries, and hybrid manufacturing approaches integrating additive manufacturing with conventional techniques. Furthermore, the integration of multi-scale modeling and AI-driven material design offers a pathway to accelerate the discovery of high-performance, durable membranes while optimizing fabrication protocols. By addressing both material and process innovations, this work provides strategic guidance for developing next-generation ceramic membranes tailored for hydrogen applications, supporting durable, efficient, and scalable hydrogen technologies.

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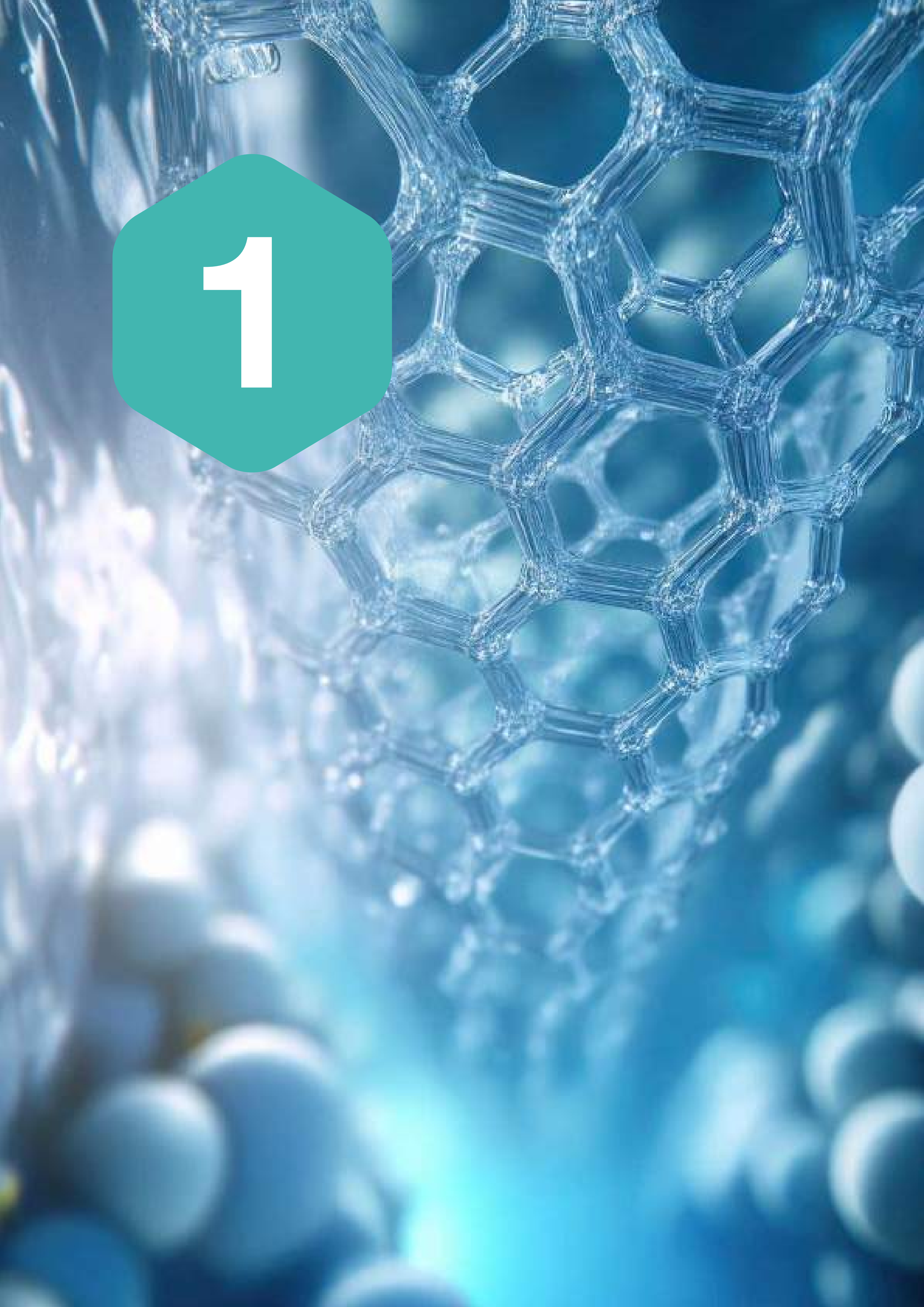


1

Introduction

The development of structurally stable membranes is crucial for advancing hydrogen technologies in Europe, enabling efficient energy conversion, separation, and chemical processing. Ceramic membranes stand out for their thermal and chemical stability, tailored selectivity, and efficient transport properties (permeability, ionic or mixed ionic-electronic conductivity), making them ideal for electrochemical applications and increasingly relevant in selected pressure-driven processes. Their enhanced structural integrity - and, in some cases, engineered multiscale porosity ranging from nano- to micro- and mesopores - further supports advanced functionality across diverse hydrogen-related applications, including production, purification, energy conversion, and storage. In fuel and electrolysis cells, as well as catalytic reactors and separation systems, structurally stable membranes with tailored gas-tightness or controlled porosity improve performance and extend longevity, benefiting stationary and mobile power generation and enhancing hydrogen or chemicals production efficiency. Pore architecture enables selective hydrogen extraction, improves reforming yields, and contributes to energy savings and process sustainability. Integrated into industrial systems and energy storage platforms like power-to-gas, ceramic membranes support grid stability and promote the widespread adoption of hydrogen as a clean energy carrier.

Despite their advantages, the large-scale deployment of ceramic membranes is constrained by significant manufacturing and mechanical stability challenges, which directly impact their reliability, efficiency, and cost-effectiveness. Achieving structurally stable membranes remains a key challenge in next-generation hydrogen technologies. Manufacturing processes like shaping, casting, additive manufacturing, sintering, and co-sintering often introduce defects, porosity variations across scales, and residual stresses, leading to mechanical failure and compromising gas-tightness, ionic conductivity, and durability. Additionally, ceramic membranes are prone to cracking, delamination, and thermal expansion mismatches, especially under thermal cycling, mechanical loads, and steam exposure, limiting their real-world applicability in hydrogen systems.

This position paper aims to analyze the key challenges in manufacturing structurally stable ceramic membranes for hydrogen applications, focusing on both material and process limitations. It presents an overview of ceramic membrane materials, highlights key manufacturing and mechanical stability challenges, and underscores the pivotal role of multiscale porosity in enabling high-performance operation. The exclusive focus on ceramic membranes is warranted by their exceptional thermal, chemical, and mechanical robustness, which renders them uniquely suitable for high-temperature and harsh-environment conditions. By contrast, alternative membrane types - such as polymeric or AgPd membranes - are already well established, with mature manufacturing routes and proven performance in low-temperature applications. Including such membranes would unnecessarily broaden the scope and dilute the technical depth dedicated to ceramics. The paper emphasizes the need for innovative solutions and reinforcement strategies, including new material compositions, optimized porous architectures, advanced macro-geometries, etc., to improve membrane durability and performance. By addressing these aspects, it provides expert insights to accelerate innovation, shape research priorities, and offer strategic recommendations for EU research initiatives, fostering multidisciplinary collaboration and stronger industry-research partnerships.

2

Overview of Ceramic Membrane Materials for Hydrogen Applications

Membrane material selection is a critical determinant of performance, durability, and manufacturability in hydrogen technologies - and is ultimately dictated by the specific application. Selecting the appropriate material ensures high efficiency, long-term stability, and scalable production, making it central to next-generation hydrogen systems[1,2]. Ceramic membranes are typically based on ionic conductors (oxygen-ion, proton, co-ionic)[3], mixed ionic-electronic conductors[4], or porous ceramic structures[5], each offering distinct transport or separation properties suited to specific operational demands.

- Oxygen ion conductors (e.g., Yttria-Stabilized Zirconia (YSZ), Gadolinia-Doped Ceria (GDC)) enable oxygen ion transport at elevated to high temperatures (≥700 °C for YSZ; ≥550 °C for GDC) and are widely used in solid oxide fuel and electrolysis cells (SOFCs/SOELs).
- Proton-conducting ceramics (e.g., Y-substituted $BaZrO_3$/$BaCeO_3$ (BZCY), $La_{5.5}WO_{12-\delta}$ (LWO)) enable proton transport at intermediate to elevated temperatures (400-650°C), making them suitable for protonic ceramic fuel and electrolysis cells (PCFCs/PCCELs), electrochemical membrane reactors, hydrogen pumps.
- Co-ionic conductors (e.g., $BaCe_{0.5}Zr_{0.3}Y_{0.2}O_3-\delta$ perovskites, $Ba_7Nb_4MoO_{20}$-based perovskite-related oxides) enable simultaneous oxygen ion and proton conduction, offering unique advantages for membrane reactors and electrochemical devices operating in mixed gas environments or under steam (reforming, co-electrolysis, chemical looping).
- Mixed ionic-electronic conductors (MIECs) (e.g., perovskite-based materials such as LSCF ($La_{0.6}Sr_{0.4}Co_{0.2}Fe_{0.8}O_3-\delta$), BSCF ($Ba_{0.5}Sr_{0.5}Co_{0.8}Fe_{0.2}O_3-\delta$), LWO) combine electronic conductivity and oxygen-ion or proton conductivity, making them ideal for pressure-driven oxygen or hydrogen separation processes and membrane reactors.
- Porous ceramic membranes (e.g., alumina, silica, titania) offer high surface area, tunable porosity, and excellent thermal and chemical resistance, making them suitable for demanding applications. They are widely employed in hydrogen purification and as membrane reactors for processes such as steam methane reforming (SMR), ammonia decomposition, and the water–gas shift (WGS) reaction. In addition, advanced materials like graphene and ceramic–graphene composites are increasingly explored to enhance

permeability and selectivity. Functional layers (e.g., palladium-based or proton-conductive coatings) further enable selective transport and catalytic conversion, supporting hybrid concepts that integrate separation and reaction in a single step.

Material properties such as thermal stability, mechanical integrity, electrical conductivity, hydrogen flux, chemical resistance etc., vary significantly across ceramic membrane classes, directly influencing their suitability for specific hydrogen applications. As outlined in Table 1, key limitations, including challenging processability, moderate mechanical strength, and low reproducibility, continue to hinder the development and large-scale deployment of structurally stable membranes.

Table 1. Comparative overview of major types of ceramic membranes, including graphene-based porous membranes, relevant to hydrogen applications, emphasizing performance trade-offs and key fabrication challenges affecting structural stability, scalability, and industrial deployment.

Membrane Type	Stability			Conductivity	Manufacturing			Key applications
	Therm.	Chem.	Mech.		Processability	Reproducibility	Scalability	
Oxygen ion conductors	H	M to H	H	M to H (O^{2-})	Good	H	H	SOFCs, SOECs, Membrane reactors
Proton conductors	M	M	M	M to H (H^+)	Challenging	L to M	L to M	PCFCs, PCCELs, Membrane rectors, Hydrogen separation, purification, sensors, pumps, Hydrogen recovery
Co-ionic conductors	M to H	M	M	M to H (O^{2-}, H^+)	Challenging	Under development	Emerging	Membrane reforming, co-electrolysis, chemical looping
MIECs	M	L to M	M	H (O^{2-}, e^-) M (H^+, e^-)	Moderate to Good	M	M	Membrane reactors, oxygen/ hydrogen separation
Porous (e.g., based on graphene, alumina, silica, titania)	M to H (M, H, M, M to H)	M to H (H, H, M, H)	H (VH in plane, H, L to M, M)	Not applicable	Excellent (Challenging, E, good but brittle at high T, good)	H (L, H, M, M to H)	H (L to M, H, M, M to H)	Hydrogen purification, separation, (nano)-filtration, pervaporation, catalytic membrane reactors, sensing

VH: very high; H: high; M: moderate; L: low.

The specified material-related limitations, alongside critical raw material dependency and complex manufacturing requirements, underscore the urgent need for innovation in membrane design and processing. The following chapter examines these challenges in detail, with a focus on structural optimization, scalable fabrication methods, and sustainable material strategies to enable next-generation hydrogen membrane technologies. Future progress will depend on optimizing material compositions, tailoring microstructures, and advancing fabrication techniques to enhance both performance and scalability in industrial hydrogen applications.

3

Current Challenges in Manufacturing: Formulation, Shaping and Processing

Manufacturing structurally stable ceramic membranes is hindered by a set of interconnected challenges spanning formulation, shaping, and processing. A critical difficulty lies in **controlling porosity across multiple length scales**, which is essential for enabling gas transport, mechanical integrity, and functional performance. The widespread use of pore-forming agents adds complexity and introduces risks such as swelling, gas entrapment, and residual impurities, all of which compromise membrane performance. In parallel, **defect formation during thermal treatment** (drying, sintering), such as warping, delamination, or cracking, commonly results from poor green strength and inhomogeneous shrinkage, while many advanced functional ceramics exhibit **limited formability or poor phase compatibility**, further complicating their shaping. Conventional methods like tape casting and extrusion struggle with achieving **geometric precision and scalability for complex architectures. Additive manufacturing** (AM) offers a promising route for fabricating membranes with integrated porous-dense domains and tailored geometries, but it remains **immature for thin, functional ceramics**. Key limitations include low resolution, slow build rates, and limited material compatibility, while high costs and lack of standardization in post-processing continue to hinder industrial adoption. Moreover, the absence of robust hybrid workflows that combine the scalability of conventional techniques with AM's design flexibility, alongside unresolved reproducibility issues, further delays scale-up. Beyond th**ese, additional shaping-related issues further constrain progress. Rheological control** of ceramic slurries or pastes is critical during casting and printing; poor dispersion, viscosity instability, or particle sedimentation can lead to film inhomogeneity, edge defects, and local stress accumulation. Likewise, in multilayer membrane architectures, ensuring **interlayer compatibility during green processing (i.e., in the unsintered state)** is essential to prevent delamination, interfacial stress, or mechanical failure prior to sintering. In addition to the previously outlined issues, further formulation and shaping-related challenges continue to constrain the reliable production of ceramic membranes. An improperly optimized particle size distribution can result in poor **packing density and local inhomogeneities** in the green body, undermining both mechanical stability and porosity control. In additive manufacturing, the formulation of printable ceramic inks or pastes remains a bottleneck; achieving the required rheological properties without compromising extrusion stability, layer adhesion, or feature resolution is a complex task. Moreover, during tape casting or direct deposition, **interaction with**

carrier substrates frequently causes film tearing, wrinkling, or edge defects upon release, particularly in ultra-thin or large-area membranes. **Environmental factors** such as ambient humidity and temperature also exert a strong influence on slurry behavior, drying kinetics, and green body uniformity, requiring tightly controlled processing conditions to avoid variability and defect formation. **Sintering** is a crucial step in ceramic membrane fabrication, playing a key role in achieving dense, defect-free structures with the necessary mechanical strength, optimized ionic conductivity, and gas-tightness. Through high-temperature treatment, sintering enables particle bonding and densification, reducing porosity and enhancing structural integrity. However, improper sintering can lead to excessive or uncontrolled grain growth, microcracking, or residual stress accumulation, severely compromising membrane performance. Achieving optimal sintering conditions requires precise control of temperature, heating profile, and atmosphere to balance densification and mechanical stability. Too low a temperature results in **insufficient densification**, leading to poor mechanical strength and high permeability, while excessively high temperatures can cause over-sintering, grain growth, or phase decomposition, ultimately reducing thermal and chemical stability. Furthermore, different ceramic compositions exhibit varying sintering kinetics, making it challenging to define a universal sintering protocol applicable to all materials used in hydrogen-related applications. An even greater challenge arises in **co-sintering**, which is required for multi-layered ceramic membranes that combine functional layers with different compositions, microstructures, and properties. Integrating several ceramic layers requires precise control over shrinkage rates, thermal expansion mismatches, interface stability, and sintering compatibility. If these factors are not carefully managed, co-sintering can lead to delamination, interfacial defects, segregation of undesired secondary phases, or residual stress-induced cracking, reducing both mechanical stability and functionality. To overcome these challenges, advancements in sintering aids, optimized thermal profiles, and alternative densification methods such as electric field-assisted sintering, cold (aka hydrothermal) sintering and light-assisted (e.g., laser) sintering are being explored. These techniques offer improved densification, phase content and grain size control, reduced sintering times, and enhanced interfacial bonding, providing promising solutions for manufacturing robust, high-performance ceramic membranes for hydrogen applications. Digital approaches (e.g., finite element modeling, phase-field simulations, machine learning) simulating the evolution of properties during the sintering process, alongside a systematic set of experiments for validation, would further accelerate developments in the field.

Beyond the control of the material's composition and structure, the manufacturing process itself also requires improvements. Processing of ceramics is in general a laborious, multi-step, time- and energy-intensive process, and thus rather inefficient and costly. New sintering technologies hold great promise to boost the efficiency of these manufacturing processes, while offering additional process parameter space for better tuning of the membranes' performance. The majority of these technologies is, however, still requiring research and development.

These combined challenges underscore the need for integrated solutions that bridge material formulation, advanced shaping strategies, precise process control, and digital approaches, laying the groundwork for scalable, high-performance ceramic membranes for hydrogen technologies.

To accelerate progress, it is crucial to merge the established expertise of traditional shaping techniques, such as tape casting and extrusion, known for their scalability and reliability, with the design flexibility and geometric precision offered by additive manufacturing and emerging sintering techniques. This integrative approach enables the co-fabrication of complex architectures, graded porosity, and multi-functional membrane structures, offering a more effective pathway toward scalable, cost-efficient production tailored to next-generation hydrogen applications.

4

Current Challenges in Mechanical Stability of Manufactured Membranes

Ceramics are intrinsically brittle, a characteristic that often limits their structural applications unless specific toughening mechanisms are intentionally incorporated. One such case relevant for ceramic membranes is yttria-stabilized zirconia (YSZ), which can achieve enhanced toughness at intermediate Y-doping levels (partially stabilized zirconia). However, most ceramics used in membrane technologies remain highly susceptible to cracking. The complex geometries and demanding operating conditions of ceramic membranes expose them to mechanical failure during both fabrication and service.

During processing, critical steps such as drying, binder and pore former removal, and especially sintering can introduce cracks, voids, and delamination. These defects typically arise from mismatches in shrinkage rates across the different layers of the membrane structure, leading to localized stress concentrations at their interfaces. In operation, additional challenges include mismatches in thermal expansion coefficients and the accumulation of thermomechanical fatigue, which can lead to cracking and delamination.

Such vulnerabilities significantly limit the operational lifespan and reliability of ceramic membranes, preventing them from reaching their full potential in terms of durability and service temperatures. To address these limitations, robust mechanical characterization methods are essential. However, testing the thermomechanical stability of ultrathin, brittle membranes presents its own set of challenges. In situ testing techniques that capture behavior across multiple length scales are especially valuable, as they help identify the critical scale at which failure originates and propagates. Tools such as digital image correlation and high-temperature in situ mechanical testing, combined with advanced simulations that account for fracture, are also instrumental.

There is a general need for a comprehensive redesign of ceramic membranes for hydrogen applications, addressing both macroscale geometry and mesoscale (microstructural features at the 1–100 µm scale) architecture (microstructural features at the 1–100 µm scale) architecture to reduce stress concentrations. At the same time, there is a growing demand for standardized, reliable, and accessible mechanical testing protocols to guide material development and ensure performance consistency.

5

Call for New Compositions, Porous Structures, Macro-Geometries and Manufacturing Strategies

To overcome the structural and mechanical limitations of ceramic membranes in hydrogen applications, advancements in material composition, porosity engineering, and geometric design are essential. Novel material compositions, optimized porous structures, and innovative macro-geometries can significantly enhance mechanical stability, durability, and overall membrane performance. New and hybrid manufacturing techniques also need to be envisioned to enable the realization of such innovative material concepts. Furthermore, multi-scale modeling and AI-driven material design present new opportunities for accelerating the development of high-performance membranes tailored to specific operational conditions.

5.1 Novel Material Compositions for Enhanced Structural Stability

Current ceramic membranes suffer from fracture susceptibility, thermal expansion mismatches, and chemical degradation, particularly under cyclic thermal and mechanical loads. The development of multi-phase ceramic composites, such as perovskite-based proton conductors reinforced with high-strength oxides (e.g., $BaZrO_3$-ZnO or BCZY-Al_2O_3 composites), can enhance mechanical resilience. Similarly, graded materials with transition layers between different phases can help reduce stress concentrations and improve overall durability. Alternatively, engineering the interfaces between the membrane layers has high potential to minimize structural stability issues. Further reinforcement strategies, including fiber- or whisker-reinforced ceramics, nanostructured composites, or glass–ceramic hybrids, could provide additional toughness and thermal shock resistance.

Moreover, doping strategies can be optimized to balance ionic conductivity and mechanical strength. For example, rare-earth doping in zirconates and cerates enhances both proton mobility and chemical stability, reducing degradation in CO_2- and H_2O-rich environments. The integration of high-entropy oxides (HEOs) is another promising avenue, as these materials offer superior phase stability, reduced grain growth, and tunable ionic conduction properties. In addition, multi-cation perovskites, fluorite-type oxides, and defect-engineered solid solutions represent attractive design directions for combining chemical robustness with enhanced transport performance.

5.2 Porous Structures for Improved Mechanical Integrity

Porous architectures play a crucial role in balancing mechanical strength and functional performance, especially in composite and multi-layered membranes. Tailoring porosity at multiple scales - nano, micro, and meso - can help mitigate thermal stress buildup, enhance gas diffusion, and prevent mechanical failure. Tunable multiscale porosity can offer fine control over gas permeability, transport properties, stress distributions, fracture behavior, and thermal expansion mismatches.

New processing techniques, such as freeze casting (ice templating), colloidal assembly, scaffold 3D-printing, and sacrificial templating, enable precise control over pore size distribution and connectivity, showing great potential to improve both mechanical stability and performance in hydrogen applications.

5.3 Innovative Macro-Geometries for Performance Stability

Beyond material composition and porosity, macro-structural design plays a key role in improving mechanical resilience and operational stability. Traditional flat-sheet membranes often suffer from stress concentration and structural fragility, whereas engineered geometries can better accommodate thermal and mechanical stresses.

- Honeycomb structures distribute mechanical loads more evenly, reducing stress points and improving durability.
- Tubular configurations enhance thermal shock resistance and scalability for large-scale applications.
- Non-flat (wavy or roughened) interfaces prevent stress concentrations and promote interlocking.

- Layered architectures with graded porosity optimize both gas diffusion and structural support, enhancing long-term performance.

AM and advanced ceramic shaping techniques allow the fabrication of complex geometries, offering new possibilities for multi-functional membrane designs tailored for specific hydrogen applications.

5.4 New and Hybrid Manufacturing Methods

New and hybrid manufacturing methods hold great promise to overcome the limitations of casting and production of membranes with a discrete number of layers, with limited control over their nano- and microstructures.

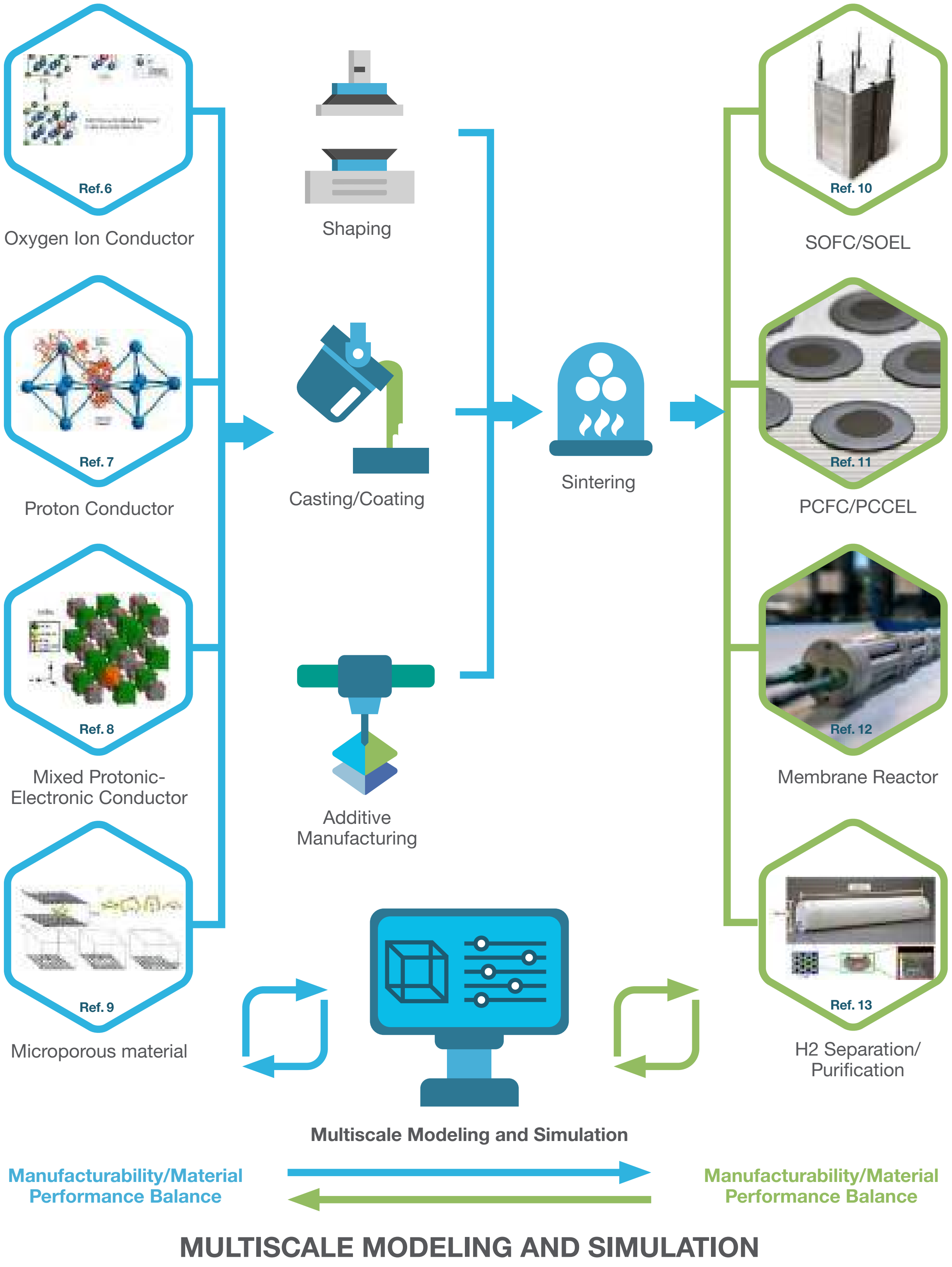
AM enables the fabrication of novel meso- and micro-scale geometries that enhance structural integrity, optimize gas permeability, and improve material efficiency. A wide array of AM techniques is now being explored for ceramic processing. These include material jetting, known for its high resolution and versatility albeit slower speed; binder jetting, which offers scalability and broad material compatibility despite lower resolution; and material extrusion or direct writing, which provide cost-effective and flexible solutions with moderate precision. Vat photopolymerization, although still immature for many ceramic compositions, can deliver very high resolution.

In parallel, advanced nano- and micromanufacturing methods such as colloidal assembly, templating, and freeze casting are increasingly used to introduce hierarchical porosity with great precision. These methods contribute to improved mechanical performance through the development of geometries that optimize stress distribution, and they even allow the incorporation of toughening mechanisms.

At the densification stage, innovative sintering technologies that rely on solvents (cold sintering), electric fields and currents (Field-Assisted Sintering Technique/Spark Plasma Sintering (FAST/SPS); Ultrarapid-High-temperature Sintering, (UHS), flash sintering), lasers (selective laser sintering) or light (photonic sintering, blacklight sintering) provide a new level of control over structural evolution. By tailoring heating rates and mass transfer mechanisms, these approaches allow multiscale manipulation of membrane architectures, preserving the intricate features created during earlier processing stages.

To fully exploit these capabilities, it is essential to adapt and integrate these advanced manufacturing and sintering techniques into the underutilized ceramic materials required for specific hydrogen-related functionalities.

Figure 1. Integrated approach for the fabrication and performance optimization of ceramic membranes for hydrogen applications. This depiction highlights examples and does not represent all possible materials, technologies, or final products.



5.5 The Potential of Multi-Scale Modeling and AI-Driven Material Design

The integration of multi-scale modeling and AI-driven material design can accelerate the discovery of new compositions and structures while optimizing their manufacturing feasibility. Machine learning algorithms can rapidly analyze large datasets to predict optimal dopant concentrations, microstructural configurations, and mechanical performance under various conditions. Computational simulations, such as finite element analysis (FEA) and density functional theory (DFT), can guide design choices before experimental trials, reducing development time and costs. Multiscale and multiphysics modeling can also capture the manufacturing processes, and efficiently streamline experiments, allowing the gaining of new insights in the driving process parameters, and a significant decrease of time- and energy-intensive experimental campaigns. An integrated approach of those digital tools with experimental validation and shared collection of measured data on material properties and resulting performance would aid an acceleration of material development.

By leveraging novel materials, tailored porosity, innovative macro-geometries, and computational design tools, the next generation of ceramic membranes can achieve unprecedented structural stability, efficiency, scalability, paving the way for durable and high-performance hydrogen technologies (Fig. 1).

6

Conclusions and Recommendations

To overcome the challenges of ceramic membrane fabrication, novel material compositions, optimized multi-scale porosity, and innovative macro-geometries are essential. These advancements will enhance the mechanical stability and performance of membranes for hydrogen technologies.

Material Composition and Structural Design: A critical analysis of the currently used materials, plus the exploration of multi-phase ceramic composites and high-entropy oxides can provide paths to improve mechanical resilience while maintaining high functional performance. Engineering the interfaces between layers and employing graded materials can help mitigate structural instability and thermal expansion mismatches.

AM Potential: The integration of AM with traditional shaping techniques and nano/micromanufacturing methods can allow for more precise control over membrane architecture, enabling the creation of complex geometries and tailored porosity at nano, micro, and meso-scales.

Improved Co-Sintering Methods: New sintering technologies offer more flexibility and control in densification processes. These methods can better preserve the intricate features introduced by AM and nano/microstructuring techniques, while preventing cracking and delamination issues during fabrication.

AI and Multi-Scale Modeling: Leveraging AI-driven material design and multi-scale modeling will accelerate the development of new materials and optimize manufacturing processes. These tools can predict optimal compositions and processing conditions, reducing trial-and-error experimentation and speeding up the material development cycle.

Future Research and Collaboration: The successful realization of durable, high-performance ceramic membranes for hydrogen applications will require ongoing collaboration between academia, industry, and policy-makers, for the definition of common relevant research ambitions and supporting out-of-the-box, fundamental research ideas[14]. Multidisciplinary efforts will be key to addressing the manufacturing and stability challenges that hinder widespread adoption, while a coordinated, cross-sectoral approach will be vital to unlock the full potential of ceramic membrane technologies in the hydrogen economy.

References

1 Das, C., & Bose, S. (2017). Advanced Ceramic Membranes and Applications (1st ed.). CRC Press. https://doi.org/10.1201/9781315165530

2 Ivanova, M. E., Ricote, S., et al. Chapter, “Doping: Properties, Mechanisms and Applications”; Series: Materials Science and Technologies, Physics Research and Technology, 221-276. Edt Yu, L., Nova Sci Publ (2013) ISBN: 978-1-62618-097-0

3 Bilbey, B., et al. (2025). Wiley Interdisciplinary Reviews: Energy and Environment. https://doi.org/10.1002/wene.70010

4 Chen, G., Feldhoff, A., et al., Adv. Funct. Mater. 32 (2022) 2105702. https://doi.org/10.1002/adfm.202105702

5 Lee, H.J., Ha, JH., Lee, J. et al. J. Korean Ceram. Soc. 60 (2023) 760–780. https://doi.org/10.1007/s43207-023-00311-7

6 M. Lo Faro, A.S. Aricò, chapter 9 in Membranes for Clean and Renewable Power Applications, Editor(s): Annarosa Gugliuzza, Angelo Basile, Woodhead Publishing, (2014) 237-265, ISBN 9780857095459, h ttps://doi.org/10.1533/9780857098658.4.237

7 Kreuer, K. D., Annu. Rev. Mater. Res. 33 (2003) 333-359. https://doi.org//10.1146/annurev.matsci.33.022802.091825

8 Fantin, A., et al., Solid State Ionics, 306 (2017) 104-111. https://doi.org/10.1016/j.ssi.2017.04.005

9 Wasalathilake, K. C., et al., RSC Adv., 8 (2018) 2271-2279. https://doi.org/10.1039/C7RA11628D

10 https://elcogen.com/products/solid-oxide-stacks-for-fuel-cell-systems/

11 Ivanova, M. E., self-developed PCCEL specimens for testing, private archive

12 https://www.greencarcongress.com/2022/07/20220730-sintef.html

13 Cao, Z., et al., Separations, 9 (2022) 47, https://doi.org/10.3390/ separations9020047

14 https://erc.europa.eu/news-events/magazine-article/editorial-stronger-europe-starts-science

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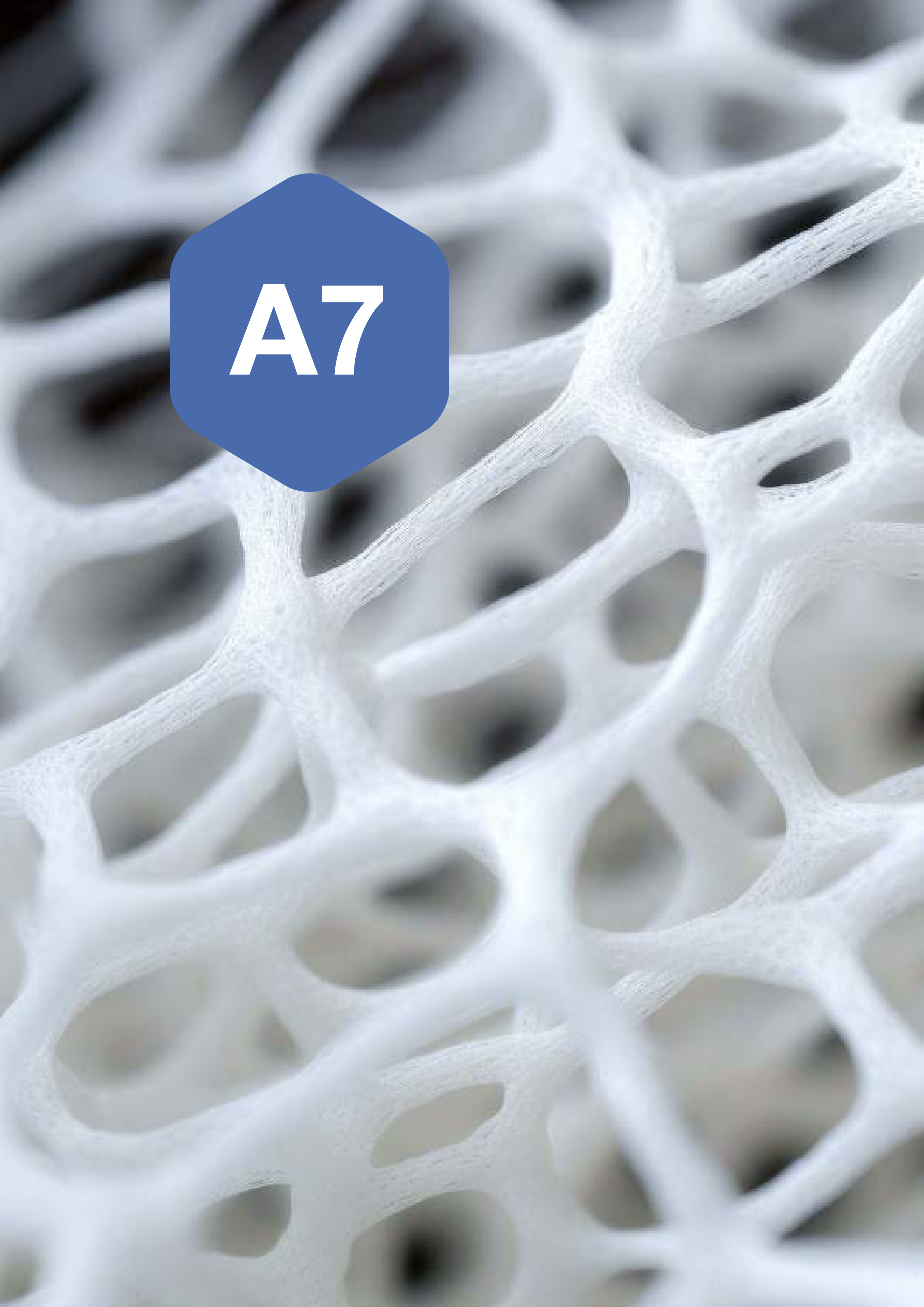

From Detection to Substitution: Scientific Challenges of PFAS in Hydrogen Technologies

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Abstract

Per- and polyfluoroalkyl substances (PFAS) are widely used in hydrogen technologies, particularly as perfluorosulfonic acid (PFSA) in proton exchange membrane (PEM) fuel cells and electrolysers, due to their chemical stability, hydrophobicity, and ion-conducting properties. However, these same properties pose environmental and regulatory challenges, as PFAS are persistent, bioaccumulative, and potentially toxic. This review provides a comprehensive overview of PFAS in the hydrogen sector, examining degradation pathways, emission sources across production, use, and end-of-life stages, and the associated environmental and analytical challenges. Current research highlights the emission of fluoride ions and polymer fragments during device operation, but substantial knowledge gaps remain regarding emissions from manufacturing, recycling, and nanoparticle release. Strategies for mitigating PFAS-related risks, including effluent filtration and alternative fluorine-free membranes and ionomers, are discussed, alongside the technological, chemical, and operational hurdles associated with their implementation. By mapping current scientific understanding and outstanding research needs, this review aims to guide efforts toward environmentally responsible, sustainable hydrogen technologies while reducing reliance on PFAS.

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1

Introduction

Per- and polyfluoroalkyl substances (PFAS) are a class of synthetic chemicals valued for their chemical and thermal stability, hydrophobicity, and resistance to degradation. These properties make them integral to numerous industrial applications, including hydrogen technologies, where perfluorosulfonic acid (PFSA)—a PFAS subclass—is widely used in polymer electrolyte membranes and electrocatalyst layers for proton exchange membrane (PEM) fuel cells and electrolysers. However, the very same properties that make PFAS ideal for energy conversion components also raise environmental and regulatory concerns due to their persistence, bioaccumulation potential, and emerging links to adverse health and ecological effects.[1]

In recent years, growing scrutiny over PFAS has triggered regulatory developments and intensified scientific inquiry into their lifecycle impacts across technologies.[2] While some research in the hydrogen sector has focused on degradation pathways and the release of fluoride and fluorinated organic fragments during device operation, PFAS emissions also occur at other lifecycle stages, including production, manufacturing, and end-of-life handling. Furthermore, substantial knowledge gaps remain on the path to fully understand degradation processes and the development of adequate analytical tools—particularly in the context of electrolysers, upstream emissions, nanoparticle formation, and long-term environmental behaviour. Simultaneously, it is imperative to advance research on filtration technologies aimed at preventing emissions, as well as on the identification and development of alternative materials that can replicate the unique functional properties required for various components within fuel cells and electrolysers.

This paper provides a comprehensive overview of the current state of research on PFAS in the hydrogen sector. It examines degradation mechanisms and emission profiles, explores sources of PFAS release across the production–use–disposal chain, reviews the environmental and analytical challenges, and surveys emerging mitigation and substitution strategies. By mapping the scientific progress and outstanding research challenges, this review aims to inform ongoing efforts to manage PFAS-related risks and accelerate the development of safe, sustainable hydrogen technologies.

2

Current State of Research

Degradation of H2 technologies and link with emissions

Polymer electrolytes in fuel cells and electrolysers are for the most part relying on perfluorosulfonic acid (PFSA) in both the membrane and electrocatalyst layers. It is highlighted, however, that the PFSAs implemented in the membrane and in the electrocatalyst layers have to satisfy different requirements.[3] PFSAs for membranes must yield a high proton conductivity (to minimize ohmic drops) and a low gas permeability (to maximize durability). On the other hand, PFSAs for electrocatalyst layers must exhibit a high gas permeability to facilitate mass transport. PFSA consists of a fluorocarbon-based backbone with perfluoroethereal side chains terminated by sulfonic acid groups and are classified as polyfluoroalkyl substances (PFAS). The use of PFAS has come under scrutiny due to their exceptionally high stability.[4] This stability, however, makes them also almost irreplaceable in PEM fuel cells and electrolysers.

Despite their remarkable stability, it has been known that the degradation of PFSA leads to the emission of fluorine containing compounds early on. In fact, the emission of fluoride ions has been suggested as a metric to monitor fuel cell and electrolyser membrane degradation in 1990 and used as such ever since.[5] The underlying degradation mechanism is based on the generation of radicals from hydrogen peroxide, the latter formed either as a byproduct of the electrode processes or from gas crossover. Depending on the site of chemical attack as well as general polymer structure, it has been assumed in the past that the majority of emitted fluorine is in the form of fluoride ions or HF.[6] However, more recent data shows that besides fluoride ions, substantial amounts of polymer fragments are emitted as well.[7–9] A significant amount of data has been collected on fuel cells and, to some extent, electrolysers operating under conditions that selectively allow for a high level of crossover and in general favour the generation of radicals. Such conditions are achieved under the OCV hold tests proposed by the US Department of Energy.[10,11] While these degradation pathways only have limited transferability to real applications, where countermeasures are specifically taken to prevent harmful conditions, similar results have been replicated under operation.[9,12]

Throughout literature, a dependency of the emission of fluorinated species as well as fluoride (and their respective ratios) on time, conditions and materials has been recorded and it is clear that there are underlying influencing factors that need to be carefully considered.[7,8,13] For example, it was found that an initial chain cleavage can lead to the formation of more degradation-susceptible carbonyl end groups, which allow for consecutive chain unzipping as proposed by Coms et al..[6]

While much research has been dedicated to enhancing the understanding of membrane degradation, it is worth noting that the same or similar compounds are used in the electrocatalyst layers as well. Such PFSA can undergo degradation, which leads to the emission of fluorinated species just the same. The proton-exchange membrane, on the other hand, typically does not only include the proton-conducting ionomer, but also chemical and mechanical stabilisers, with PTFE being one of them. In addition, layers such as the microporous layer, the gas diffusion layer or the porous transport layer are commonly treated with PTFE in order to modulate their hydrophobicity and thus the water management in a fuel cell or in an electrolyser. Processing aids can also contain fluorine. These perfluorinated compounds can degrade as well, contributing to the overall emission of fluorinated compounds [A].

Sources of emissions during the production, usage and recycling

As of today, research into PFAS emissions in the hydrogen industry has primarily focused on the operation of electrochemical cells—namely fuel cells and electrolysers. These studies typically examine degradation products released under accelerated aging conditions or stress tests.[15–17] However, PFAS contamination has also been detected in the environment near chemical industry sites, indicating a broader range of emission sources requiring attention.[18,19]

The production stage is a critical but underexplored contributor of PFAS emissions. This includes the synthesis of PFSA-based ionomers, membrane fabrication, electrocatalyst ink formulation, and the manufacturing of catalyst-coated membranes (CCMs). Mechanical processes such as the fabrication of membrane-electrode assemblies (MEAs) and the assembly of cell stacks—especially during sealing component integration—can cause abrasions and an unintentional particle release.

Environmental monitoring has revealed elevated PFAS levels around industrial production sites, emphasizing that significant emissions may occur during manufacturing and not only during use.[18] These findings call for a more detailed assessment of upstream PFAS sources in hydrogen technologies.

During operation, PFAS-based materials are subjected to chemical and mechanical stresses. The aggressive electrochemical environment found in fuel cells and electrolysers can lead to degradation, while pressure fluctuations and flow dynamics may gradually release PFAS into effluent streams.

At end-of-life system disassembly, disposal, or recycling introduces additional risks. Me-

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[A] From conversation notes with Ian T. Cousins, Juliane Glüge and Amanda Rensmo, see also: Dalmijn, Joost; Glüge, Juliane; Scheringer, Martin; Cousins, Ian T. (2024): Emission inventory of PFASs and other fluorinated organic substances for the fluoropolymer production industry in Europe. In Environmental Science: Processes & Impacts 26 (2), pp. 269–287. DOI: 10.1039/D3EM00426K.

chanical handling may damage PFAS-containing components, and chemical recycling could release harmful substances if not properly managed. These aspects remain insufficiently studied.

Environmental impact of PFAS and analytical techniques for their detection

The monitoring of fluoride ions – which are detectable by common analytical techniques such as high-performance liquid chromatography and ion chromatography (HPLC/IC) or fluoride ion-selective electrodes (F-ISE) – already poses many challenges. The applicable techniques require substantial volumes of sample, especially if sample preparation (e.g., due to a complex matrix) is needed. In addition, such techniques are time-consuming and equipment-intense, giving neither the possibility for finely time-resolved monitoring of emissions nor straightforward possibilities for online monitoring.

At the same time, the decomposition of PFSA is known to lead not only to the emission of fluoride ions, which occur naturally in salt form, but also of the much more concerning polymer fragments as shown in recent work by Yandrasits et al.,[7,8] who use liquid chromatography and mass spectroscopy (LC-MS), IC as well as combustion ion chromatography (CIC) to allow for a more holistic understanding of the degradation products. However, although the detection and identification of some of the fragments obtained upon PFAS and PFSA degradation is progressing, the heterogeneity and low concentrations of such fragments under regular operation remains an unsolved challenge for analytical techniques.

PFAS capture and avoiding emissions

Polymers belonging to the perfluorosulfonic acid (PFSA) subclass of PFAS are widely used as both ion-exchange membranes and electrocatalyst layer ionomers in state-of-the-art proton exchange membrane fuel cells and electrolysers. In the last decade, the development of fluorine-free aromatic hydrocarbon (AH)-type alternatives to PFSAs has been at the centre of significant research interests. Compared to PFSAs, AHs often involve trade-offs, notably reduced stability against radical-induced degradation, resulting in a shorter in-device lifespan. Among AH-type materials, sulfonated polyphenylenes are the only ones that exhibit a sufficient chemical stability and performance in comparison with PFSAs.[20,21] However, their use in energy conversion devices remains limited to low TRL. Given that PFSA cannot be replaced by alternative materials in the short- and middle-term, it is crucial to focus on understanding and mitigating emissions into natural water bodies resulting from the chemical-induced degradation of PFSA-based materials.

Various remediation techniques exist, that are based on the separation and/or destruction of PFAS that are already present in natural waters.[22] For low PFAS concentrations, typical of natural water bodies, concentration-based methods are often more cost-effective due to the higher energy demand and complex infrastructure (i.e., due to scalability issues) required for destruction-based approaches. Several high-TRL remediation technologies that are based on PFAS concentration are currently being developed to effectively remove PFAS contaminants from various water bodies or landfills, and include: (i) foam fractionation;[23,24] (ii) filtration over granular activated carbons;[25] and (iii) adoption of ion exchange resins.[26,27] The limited selectivity of these methods often necessitates specific material compositions or frequent filter regeneration. Recently, an approach comprising a fluorinated anion-exchange membrane-based sorbent achieved a removal efficiency of over 98% for 11 different types of PFAS, demonstrating its potential for advancing to higher TRLs.[28]

Alternatives to PFSA-based membranes and ionomers and implications of alternative technologies on fuel cell technologies

Over the last decades, numerous fluorine-free proton-exchange membranes have been investigated as alternatives to Nafion for use in fuel cell and electroylser technologies, including poly(arylene ether ketones),[29] poly(arylene ether sulfones),[30] polyimides,[31] poly(arylene sulfone sulfides),[32] and poly(phenylenes).[21]

Recent advances in the field of fluorine-free PEMs have led to drastically improved performance and durability of these alternative membranes, with recent reports showing comparable results to PFSA. Qelibari et al. employed a sulfonated poly(phenylene sulfone) (sPPS) membrane in a single-cell proton exchange membrane water electrolyser, demonstrating a performance of 3.2 A/cm^2 at 1.8 V and stable operation for 650 hours with a degradation rate of 80 μV/h.[33] Adamski et al. [21] and Yazili et al. [34] employed poly(phenylene) and poly(phenylene sulfone) membranes, respectively, in single-cell PEMFCs, demonstrating a similar performance in comparison to PFSA. These studies also demonstrate an improved durability compared with PFSA under accelerated stress tests consisting of an extended open circuit voltage hold at 90 °C and 30 %RH. A recent study, however, has shown that this accelerated stress test designed for PFSA-based membranes is not appropriate for hydrocarbon-based membranes due to the different degradation mechanisms affecting the latter.[35] To definitively prove the durability of non-fluorinated membranes in fuel cell applications, it is imperative that future studies perform extended “in-situ” drive cycles under real operating conditions.

While a steady output of high-quality research investigating alternative fluorine-free PEMs in electrochemical hydrogen technologies has been ongoing since the 1990s, the Clean Hydrogen Joint Undertaking (CH JU) has recently highlighted this area of research as a key topic in the impeding uncertainty surrounding the use of PFAS-based materials in Europe. In 2023, the SUSTAINCELL (101101479) and HIGHLANDER (101101346) projects kicked off, where part of the activities will be dedicated to the development of fluorine-free membranes and ionomers. In 2024, the CH JU launched a call dedicated to the development of non-fluorinated components for fuel cells and electrolysers (HORIZON-JTI-CLEANH2-2024-05-02), where three projects will begin in 2025 : PROMISERS (101192151), FASTCH2ANGE (101192325), and ECOPEM (101192366).

The recent advances in fluorine-free PEM research have led to the commercialization of a few different membranes and ionomers, mainly through Ionomr Innovations (Canada) and Toray (Japan). Additionally, Ionysis (Germany) is focusing on producing membrane electrode assemblies (MEAs) with PFAS-free materials. Many of the largest European polymer manufacturers also have ongoing R&D initiatives to develop fluorine-free membranes and ionomers. Despite the recent flurry of commercial interest in fluorine-free materials, there are currently no commercially available proton exchange membrane fuel cells or electrolysers which incorporate these alternative materials. This points to the fact that many challenges remain to be overcome and must be addressed through low TRL research.

PFAS & Sealing technologies for H_2 applications

Within the hydrogen value chain, fluoropolymers—such as FKM, FFKM, and PTFE—and fluorinated elastomers (commonly referred to as fluoroelastomers) are currently employed in gaskets and sealing components in most electrolyser and fuel cell types. These materials are also integral to components of hydrogen transport and distribution infrastructure, including regulator membranes, meters, and valves. Their exceptional properties, including high thermal and chemical resistance, non-wetting and non-sticking properties, and low friction coefficients, render them essential for meeting the stringent performance criteria of hydrogen applications. In particular, their use is critical to ensuring high levels of tightness and minimizing fugitive emissions from both static and dynamic sealing systems. Ongoing research has been investigating the behaviour of these polymers under high-pressure hydrogen environments in both static and dynamic sealing contexts.[36,37]

3

Research Challenges

Degradation of H_2 technologies and link with emissions

To this day, the combination of limited availability of analytical techniques, low concentration and heterogeneity of the degradation products make their identification difficult and in particular limit the possibilities for time-resolved detection and identification as well as online monitoring beyond the emission of fluoride ions. In addition, there is scientific consensus that the underlying degradation mechanisms are not fully and sufficiently understood as the exact interplay between operating conditions and degradation emission products remains unknown. Furthermore, much of the work on the detection and identification of PFSA degradation products has been conducted based on fuel cells, with far less information available for electrolysers.

Sources of emissions during the production, usage and recycling

There is a significant knowledge gap regarding the nature, quantity, and environmental impact of PFAS emissions as well as their relation to fluoride emissions across all lifecycle stages of hydrogen technologies. While fluoride ions and polymer fragments are known degradation products in the use phase, much less is understood about emissions during production and recycling. Particularly concerning are bioavailable compounds for which data is scarce, despite their potential ecological and toxicological relevance.

Analytical challenges further complicate the issue. Many PFAS compounds occur at trace levels, within complex matrices, or as nanoparticles—forms that current methods struggle to detect reliably. This limits our ability to characterize emissions and assess their associated risks.

To address these challenges, future research should focus on closing key knowledge gaps by generating robust data, enhancing analytical methods, and investigating emission pathways and material behaviour. At the same time, mitigation strategies—such as filtration, material recovery, and cleaner production and recycling processes—must be developed and validated. The overarching goal is to understand and reduce PFAS-related risks, enabling the environmentally responsible use of hydrogen technologies.

Environmental impact of PFAS and analytical techniques for their detection

The OECD identified more than 4 700 individual PFAS-related CAS numbers, referring to compounds in commercial use and often with an unknown impact on the environment and human health, but often also with little to no alternative.[38–40] To add to the complexity, there are also limited means to detect these compounds individually, as standards are missing and non-targeted approaches for detection are time time-consuming. In comparison studies between the extractable organic fluorine and known, selected fluorinated organic compounds, in some cases only 10% of species could be identified, highlighting the limited possibilities in analytics available today.[41,42] An additional challenge lies in the fact that emissions are not only in the form of broken-down polymer fragments in liquid or gaseous phase, but also in the form of highly bioavailable nanoparticles (K. Schreyer, "Conversation notes Kristin Schreyer and Jörg Feldmann (University of Graz)." 2024). Currently, there are no techniques able to detect these particles and their potential emission from fuel cells and electrolysers is unexplored.

PFAS capture and avoiding emissions

PFAS capture is challenging due to several factors summarized below.[43] The high stability of carbon-fluorine bonds makes PFAS highly resistant to destruction-based approaches and poses challenges for long-term waste management in methods that focus on PFAS concentration. PFAS include thousands of compounds with varying chain lengths and chemical structure (e.g., functional groups), complicating the development of uniform removal strategies. PFAS are often present at extremely low concentrations, i.e., ppt levels, requiring highly efficient removal technologies complemented by highly sensitive analytical techniques for detection. Standard water treatment methods (e.g., coagulation and flocculation) are ineffective at these concentrations. Most high-TRL approaches face challenges with capture efficiency, as PFAS compounds of different chain lengths exhibit significantly different mobility and adsorption behaviour. Moreover, the presence of other inorganic or organic contaminants aggravates the selectivity issue and necessitates frequent adsorbent regeneration (or replacement), resulting in increased operational costs. PFAS-selective sorbents show a high selectivity; however, they contain fluorinated constituents, which are necessary for halogen-bonding interactions with the target compounds. Moreover, evolving regulations make it difficult to select optimal long-term solutions, requiring constant adaptation of existing technologies.

Effluent filtration of energy conversion devices may address several of the challenges outlined above: it enables targeted removal of PFAS directly at the source, before its discharge into the environment and its subsequent dilution. Moreover, the effluent typically contains higher concentrations of target contaminants and lower concentrations of background contaminants compared to natural waters, making the removal process more effective and selective.

The use of PFAS-selective sorbents in effluent filtration provides a more targeted and efficient approach for PFAS removal, demonstrating promising potential as a long-term solution for PFAS remediation.[44] However, challenges related to filter durability, cost, and the management of concentrated PFAS waste must be addressed to advance the TRL of this approach. The latter issue might be alleviated for instance by combining filtration with already existing high TRL destruction-based approaches.

Alternatives to PFSA-based membranes and ionomers

One of the main considerations for the development of non-fluorinated ionomers is that the sulfonic acid groups tethered to a hydrocarbon backbone do not exhibit the same super-acidity of those tethered to a perfluorinated backbone. Consequently, non-fluorinated ionomers require a much higher density of sulfonic acid groups (i.e., higher ion exchange capacities – IECs) to achieve similar proton conductivities as PFSA ionomers. The high density of sulfonic acid groups, however, also leads to increased water absorption by the membrane and electrocatalyst layer ionomers, resulting in excessive swelling and a reduced mechanical stability. The lack of proven stability has been a major challenge in the area of non-fluorinated ionomer development. Additionally, the incorporation of fluorine-free ionomer binders in the electrocatalyst layer is a significant challenge due to unmitigated swelling, low gas permeability, potential electrocatalyst poisoning/deactivation through interactions with the phenyl groups, and the potential for electrochemical oxidation of phenyl groups at elevated potentials in electrolyser applications.

These new materials will also require re-thinking some of the approaches to fuel cell and electrolyser state-of-health monitoring, as well as degradation mitigation strategies.

PFAS & Sealing technologies for H_2 applications

Despite the progresses made so far significant research gaps remain, particularly concerning the development of per- and polyfluoroalkyl substances (PFAS)-free alternatives. Further research and development are needed to design and evaluate new sealing materials and configurations that can meet or exceed current in-service performance specifications. This includes the establishment of dedicated characterization methods and testing platforms to accurately assess material behaviour under operational conditions. Prioritizing the development of sustainable, high-performance alternatives to PFAS-based materials is essential to ensure safety, reliability, and environmental compliance in both static and dynamic hydrogen sealing applications.

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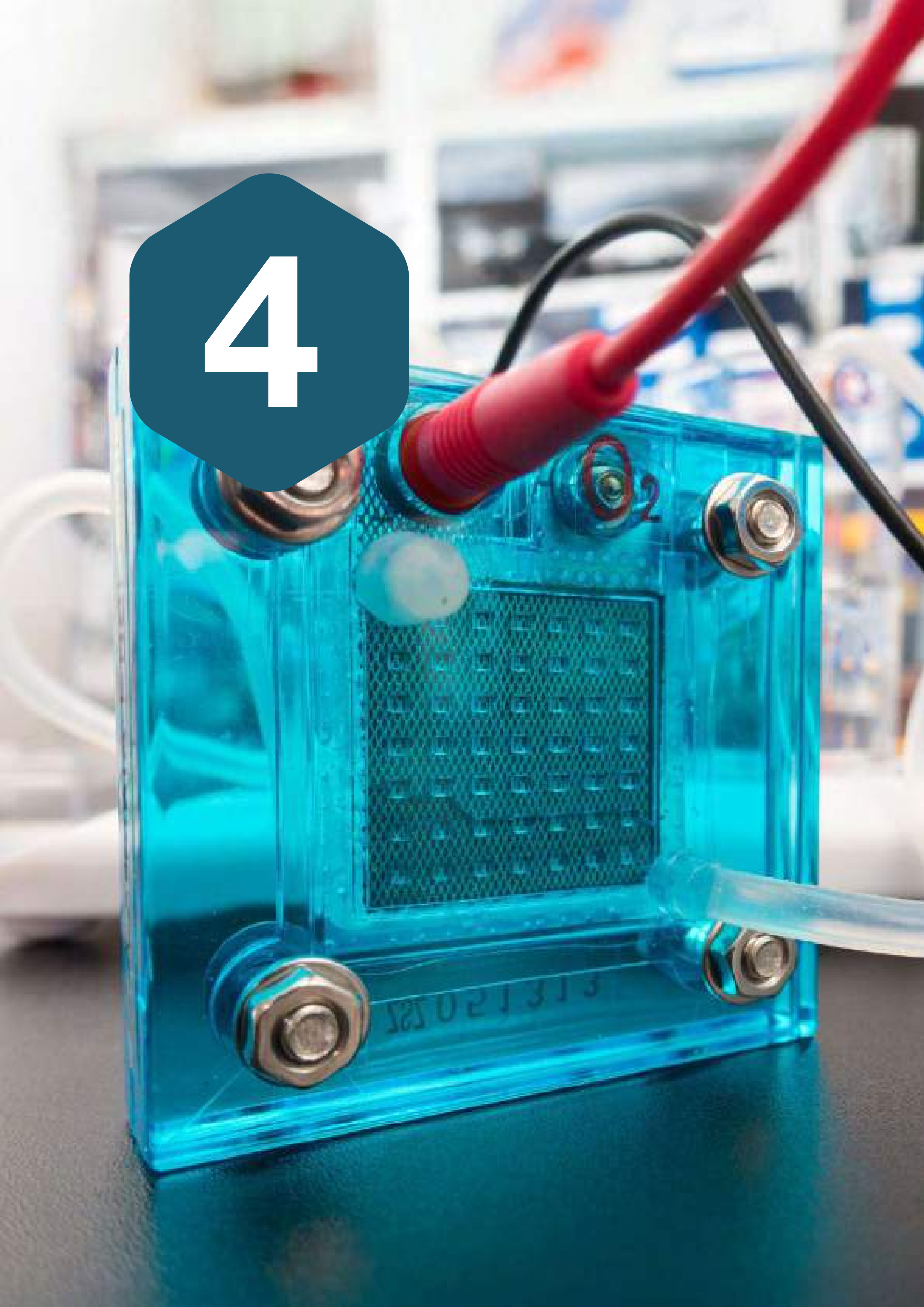

Timeline and Resources

Degradation of H_2 technologies and link with emissions

Research regarding the better linkage between material selection, operating conditions and the emission of fluorinated species is already underway. However, due to the complexity of the topic and the multitude of influencing factors, it is evident that it will not be possible to answer the linked research questions in the short term. With growing means for analysis, identification and quantification of fluorinated species, the mechanistic understanding of the underlying degradation mechanisms is expected to improve. Furthermore, the in-depth understanding of the harmful conditions is also expected to accelerate the integration of novel, non-fluorinated ionomers.

Sources of emissions during the production, usage and recycling

Establishing a comprehensive understanding of PFAS emissions across the entire lifecycle of hydrogen technologies is a long-term objective. This effort is challenged by the complexity and cost of sampling and analytical techniques, particularly when dealing with trace concentrations and diverse PFAS compounds. However, certain aspects require immediate attention: in particular, emissions from systems during operation should be assessed as soon as possible. Early monitoring capabilities would allow for the identification of critical emission pathways and enable retrofitting or mitigation measures in existing systems where necessary.

In the short to medium term, focused studies on emissions during recycling and dismantling processes are also essential. These areas remain underexplored but are increasingly relevant as more systems approach end-of-life. Without proper understanding and controls, there is a risk that such systems could contribute to significant environmental harm.

Environmental impact and analytical techniques

It is evident that the development of analytical techniques and reliable test procedures is mandatory in order to fully understand the emission pathways and the potential environmental risks. This is a concern that reaches far beyond hydrogen technologies, but also impacts them directly. A close exchange between different fields and the early validation of novel analytical techniques for their suitability for hydrogen technologies is crucial for a fast adoption.

PFAS capture and avoiding emissions

There is a significant increase in the use of proton exchange membrane (PEM) electrolysers and fuel cells, driven by the global shift towards clean energy, hydrogen production and use. In the absence of high-TRL alternative materials to PFSA-type polymers, their capture needs to be addressed in the medium term. Low-TRL solutions already exist that can be further developed.

Alternatives to PFSA-based membranes and ionomers

With the recent support of the CH JU, at least five European projects focused on the development of fluorine-free membranes and ionomers will be complete before 2030, potentially providing promising materials demonstrated up to TRL 4. Any materials developed within this period, however, must undergo an extensive qualification and demonstration period in operational fuel cell and electrolyser stacks run in realistic conditions. Concerted efforts between industry and research partners will be required to bring low TRL research developments through to market-ready solutions in a timely manner. In parallel, it is imperative that low TRL research continues to be funded to ensure innovation does not remain stagnant in favour of only upscaling the most promising state-of-of-the-art solutions.

References

1 Lohmann, R.; Cousins, I. T.; DeWitt, J. C.; Glüge, J.; Goldenman, G.; Herzke, D.; Lindstrom, A. B.; Miller, M. F.; Ng, C. A.; Patton, S.; Scheringer, M.; Trier, X.; Wang, Z. Are Fluoropolymers Really of Low Concern for Human and Environmental Health and Separate from Other PFAS? *Environ. Sci. Technol.* 2020*, 54* (20), 12820–12828. https://doi.org/10.1021/acs.est.0c03244.

2 Paladin, G.; Manzardo, A.; Nale, A.; Negro, E.; Di Noto, V. A Comparative Life Cycle Assessment of Pt Nanoalloy/Carbon Nitride/Graphene Electrocatalysts for PEMFC Stacks. *Chemical Engineering Journal* 2025*, 505*, 159251. https://doi.org/10.1016/j.cej.2025.159251.

3 Braaten, J. P.; Kariuki, N. N.; Myers, D. J.; Blackburn, S.; Brown, G.; Park, A.; Litster, S. Integration of a High Oxygen Permeability Ionomer into Polymer Electrolyte Membrane Fuel Cell Cathodes for High Efficiency and Power Density. *Journal of Power Sources* 2022*, 522*, 230821. https://doi.org/10.1016/j.jpowsour.2021.230821.

4 Pemberton, E. Poly- and Perfluoroalkyl Substances (PFAS): Sources, Pathways and Environmental Data - Chief Scientist's Group Report, No. August, p. 110, 2021. https://assets.publishing.service.gov.uk/media/611e31fbd3bf7f63b19cea2d/Poly-_and_perfluoroalkyl_substances_-sources_pathways_and_environmental_data_-_report.pdf.

5 Baldwin, R.; Pham, M.; Leonida, A.; McElroy, J.; Nalette, T. Hydrogenoxygen Proton-Exchange Membrane Fuel Cells and Electrolyzers. *Journal of Power Sources* 1990*, 29* (3–4), 399–412. https://doi.org/10.1016/0378-7753(90)85013-3.

6 Coms, F. D. The Chemistry of Fuel Cell Membrane Chemical Degradation. *ECS Trans.* 2008*, 16* (2), 235–255. https://doi.org/10.1149/1.2981859.

7 Yandrasits, M. A.; Komlev, A.; Kalstabakken, K.; Kurkowski, M. J.; Lindell, M. J. Liquid Chromatography/Mass Spectrometry Analysis of Effluent Water from PFSA Membrane Fuel Cells Operated at OCV. *J. Electrochem. Soc.* 2021*, 168* (2), 024517. https://doi.org/10.1149/1945-7111/abe56a.

8 Yandrasits, M. A.; Marimannikkuppam, S.; Lindell, M. J.; Kalstabakken, K. A.; Kurkowski, M.; Ha, P. Ion Chromatography and Combustion Ion Chromatography Analysis of Fuel Cell Effluent Water During Open Circuit Voltage. *J. Electrochem. Soc.* 2022*, 169* (3), 034526. https://doi.org/10.1149/1945-7111/ac5d96.

9 Bodner, M.; Marius, B.; Schenk, A.; Hacker, V. Determining the Total Fluorine Emission Rate in Polymer Electrolyte Fuel Cell Effluent Water. *ECS Trans.* 2017*, 80* (8), 559–563. https://doi.org/10.1149/08008.0559ecst.

10 Kuhnert, E.; Heidinger, M.; Sandu, D.; Hacker, V.; Bodner, M. Analysis of PEM Water Electrolyzer Failure Due to Induced Hydrogen Crossover in Catalyst-Coated PFSA Membranes. *Membranes* 2023*, 13* (3), 348. https://doi.org/10.3390/membranes13030348.

11 *Fuel Cell Technical Team Roadmap*; None, 1220127, 6361; 2013; p None, 1220127, 6361. https://doi.org/10.2172/1220127.

12 Takasaki, M.; Nakagawa, Y.; Sakiyama, Y.; Tanabe, K.; Ookubo, K.; Sato, N.; Minamide, T.; Nakayama, H.; Hori, M. Degradation Study of PFSA Polymer Electrolytes: Approach from Decomposition Product Analysis. *ECS Trans.* 2009*, 17* (1), 439–447. https://doi.org/10.1149/1.3142773.

13 Birkner, L.; Foreta, M.; Rinaldi, A.; Orekhov, A.; Willinger, M.-G.; Eichelbaum, M. Dynamic Accelerated Stress Test and Coupled On-Line Analysis Program to Elucidate Aging Processes in Proton Exchange Membrane Fuel Cells. *Sci Rep* 2024*, 14* (1), 3999. https://doi.org/10.1038/s41598-024-54258-8.

14 Edjokola, J. M.; Heidinger, M.; Niroumand, A. M.; Hacker, V.; Bodner, M. Chemical Oxidation-Induced Degradation in Gas Diffusion Layers for PEFC: Mechanisms and Performance Implications. *J. Electrochem. Soc.* 2024*, 171* (9), 094507. https://doi.org/10.1149/1945-7111/ad790a.

15 Lange, T.; Dietrich, M.; Schlottmann, H.; Valkov, V.; Mackert, V.; Radev, I.; Hoster, H. Investigating PFAS Emissions of Light- and Heavy-Duty Fuel Cell Electric Vehicles. *Journal of Power Sources Advances* 2025*, 32*, 100171. https://doi.org/10.1016/j.powera.2025.100171.

16 Von Tettau, P.; Thiele, P.; Mauermann, P.; Wick, M.; Tinz, S.; Pischinger, S. Per- and Polyfluoroalkyl Substances in Proton Exchange Membrane Fuel Cells — A Review. *Journal of Power Sources* 2025*, 630*, 236104. https://doi.org/10.1016/j.jpowsour.2024.236104.

17 Höglinger, M.; Kartusch, S.; Eder, J.; Grabner, B.; Macherhammer, M.; Trattner, A. Advanced Testing Methods for Proton Exchange Membrane Electrolysis Stacks. *International Journal of Hydrogen Energy* 2024*, 77*, 598–611. https://doi.org/10.1016/j.ijhydene.2024.06.118.

18 Teymoorian, T.; Delon, L.; Munoz, G.; Sauvé, S. Target and Suspect Screening Reveal PFAS Exceeding European Union Guideline in Various Water Sources South of Lyon, France. *Environ. Sci. Technol. Lett.* 2025*, 12* (3), 327–333. https://doi.org/10.1021/acs.estlett.4c01126.

19 Dalmijn, J.; Glüge, J.; Scheringer, M.; Cousins, I. T. Emission Inventory of PFASs and Other Fluorinated Organic Substances for the Fluoropolymer Production Industry in Europe. *Environ. Sci.: Processes Impacts* 2024*, 26* (2), 269–287. https://doi.org/10.1039/D3EM00426K.

(20) Miyake, J.; Taki, R.; Mochizuki, T.; Shimizu, R.; Akiyama, R.; Uchida, M.; Miyatake, K. Design of Flexible Polyphenylene Proton-Conducting Membrane for next-Generation Fuel Cells. *Sci. Adv.* 2017*, 3* (10), eaao0476. https://doi.org/10.1126/sciadv.aao0476.

(21) Adamski, M.; Skalski, T. J. G.; Britton, B.; Peckham, T. J.; Metzler, L.; Holdcroft, S. Highly Stable, Low Gas Crossover, Proton-Conducting Phenylated Polyphenylenes. *Angew Chem Int Ed* 2017*, 56* (31), 9058–9061. https://doi.org/10.1002/anie.201703916.

(22) Wanninayake, D. M. Comparison of Currently Available PFAS Remediation Technologies in Water: A Review. *Journal of Environmental Management* 2021*, 283*, 111977. https://doi.org/10.1016/j.jenvman.2021.111977.

(23) Buckley, T.; Karanam, K.; Han, H.; Vo, H. N. P.; Shukla, P.; Firouzi, M.; Rudolph, V. Effect of Different Co-Foaming Agents on PFAS Removal from the Environment by Foam Fractionation. *Water Research* 2023*, 230*, 119532. https://doi.org/10.1016/j.watres.2022.119532.

(24) Stevenson, P.; Karakashev, S. I. Commercial-scale Removal of Short-chain PFAS in a Batch-wise Adsorptive Bubble Separation Process by Dosing with Cationic Co-surfactant. *Remediation Journal* 2024*, 34* (1), e21767. https://doi.org/10.1002/rem.21767.

(25) Cantoni, B.; Turolla, A.; Wellmitz, J.; Ruhl, A. S.; Antonelli, M. Perfluoroalkyl Substances (PFAS) Adsorption in Drinking Water by Granular Activated Carbon: Influence of Activated Carbon and PFAS Characteristics. *Science of The Total Environment* 2021*, 795*, 148821. https://doi.org/10.1016/j.scitotenv.2021.148821.

(26) Woodard, S.; Berry, J.; Newman, B. Ion Exchange Resin for PFAS Removal and Pilot Test Comparison to GAC. *Remediation Journal* 2017*, 27* (3), 19–27. https://doi.org/10.1002/rem.21515.

(27) Dixit, F.; Dutta, R.; Barbeau, B.; Berube, P.; Mohseni, M. PFAS Removal by Ion Exchange Resins: A Review. *Chemosphere* 2021*, 272*, 129777. https://doi.org/10.1016/j.chemosphere.2021.129777.

(28) Yang, Z.; Zhu, Y.; Tan, X.; Gunjal, S. J. J.; Dewapriya, P.; Wang, Y.; Xin, R.; Fu, C.; Liu, K.; Macintosh, K.; Sprague, L. G.; Leung, L.; Hopkins, T. E.; Thomas, K. V.; Guo, J.; Whittaker, A. K.; Zhang, C. Fluoropolymer Sorbent for Efficient and Selective Capturing of Per- and Polyfluorinated Compounds. *Nat Commun 2024, 15* (1), 8269. https://doi.org/10.1038/s41467-024-52690-y.

(29) Iulianelli, A.; Basile, A. Sulfonated PEEK-Based Polymers in PEMFC and DMFC Applications: A Review. *International Journal of Hydrogen Energy* 2012*, 37* (20), 15241–15255. https://doi.org/10.1016/j.ijhydene.2012.07.063.

30 Park, K. T.; Chun, J. H.; Kim, S. G.; Chun, B.-H.; Kim, S. H. Synthesis and Characterization of Crosslinked Sulfonated Poly(Arylene Ether Sulfone) Membranes for High Temperature PEMFC Applications. *International Journal of Hydrogen Energy* 2011*, 36* (2), 1813–1819. https://doi.org/10.1016/j.ijhydene.2010.02.019.

31 Lee, S.; Jang, W.; Choi, S.; Tharanikkarasu, K.; Shul, Y.; Han, H. Sulfonated Polyimide and Poly (Ethylene Glycol) Diacrylate Based Semi-interpenetrating Polymer Network Membranes for Fuel Cells. *J of Applied Polymer Sci* 2007*, 104* (5), 2965–2972. https://doi.org/10.1002/app.25966.

32 Titvinidze, G.; Kreuer, K.; Schuster, M.; De Araujo, C. C.; Melchior, J. P.; Meyer, W. H. Proton Conducting Phase-Separated Multiblock Copolymers with Sulfonated Poly(Phenylene Sulfone) Blocks for Electrochemical Applications: Preparation, Morphology, Hydration Behavior, and Transport. *Adv Funct Materials* 2012*, 22* (21), 4456–4470. https://doi.org/10.1002/adfm.201200811.

33 Qelibari, R.; Ortiz, E. C.; Van Treel, N.; Lombeck, F.; Schare, C.; Münchinger, A.; Dumbadze, N.; Titvinidze, G.; Klose, C.; Vierrath, S. 74 Mm PEEK-Reinforced Sulfonated Poly(Phenylene Sulfone)-Membrane for Stable Water Electrolysis with Lower Gas Crossover and Lower Resistance than Nafion N115. *Advanced Energy Materials* 2024*, 14* (5), 2303271. https://doi.org/10.1002/aenm.202303271.

34 Yazili, D.; Marini, E.; Saatkamp, T.; Münchinger, A.; De Wild, T.; Gubler, L.; Titvinidze, G.; Schuster, M.; Schare, C.; Jörissen, L.; Kreuer, K.-D. Sulfonated Poly(Phenylene Sulfone) Blend Membranes Finding Their Way into Proton Exchange Membrane Fuel Cells. *Journal of Power Sources 2023, 563*, 232791. https://doi.org/10.1016/j.jpowsour.2023.232791.

35 Han, Z.; Nemeth, T.; Yandrasits, M.; Ren, H.; Bangay, W.; Saatkamp, T.; Gubler, L. Hydrocarbon Proton Exchange Membranes for Fuel Cells: Do We Need New Chemical Durability Testing Protocols? *ACS Electrochem.* 2025*, 1* (5), 588–598. https://doi.org/10.1021/acselectrochem.4c00123.

36 Menon, N. C.; Kruizenga, A. M.; Alvine, K. J.; San Marchi, C.; Nissen, A.; Brooks, K. Behaviour of Polymers in High Pressure Environments as Applicable to the Hydrogen Infrastructure. In *Volume 6B: Materials and Fabrication*; American Society of Mechanical Engineers: Vancouver, British Columbia, Canada, 2016; p V06BT06A037. https://doi.org/10.1115/PVP2016-63713.

37 Simmons, K. L.; Kuang, W.; Burton, S. D.; Arey, B. W.; Shin, Y.; Menon, N. C.; Smith, D. B. H-Mat Hydrogen Compatibility of Polymers and Elastomers. *International Journal of Hydrogen Energy* 2021*, 46* (23), 12300–12310. https://doi.org/10.1016/j.ijhydene.2020.06.218.

38 Buck, R. C.; Korzeniowski, S. H.; Laganis, E.; Adamsky, F. Identification and Classification of Commercially Relevant Per- and Poly-Fluoroalkyl Substances (PFAS). *Integrated Environmental Assessment and Management* 2021*, 17* (5), 1045–1055. https://doi.org/10.1002/ieam.4450.

39 OECD. *Summary Report on the New Comprehensive Global Database of Per- and Polyfluoroalkyl Substances (PFASs)*; OECD Series on Risk Management of Chemicals; OECD, 2018. https://doi.org/10.1787/1a14ad6c-en.

40 Lim, X. Tainted Water: The Scientists Tracing Thousands of Fluorinated Chemicals in Our Environment. *Nature* 2019*, 566* (7742), 26–29. https://doi.org/10.1038/d41586-019-00441-1.

41 Heuckeroth, S.; Nxumalo, T. N.; Raab, A.; Feldmann, J. Fluorine-Specific Detection Using ICP-MS Helps to Identify PFAS Degradation Products in Nontargeted Analysis. *Anal. Chem.* 2021*, 93* (16), 6335–6341. https://doi.org/10.1021/acs.analchem.1c00031.

42 Koch, A.; Kärrman, A.; Yeung, L. W. Y.; Jonsson, M.; Ahrens, L.; Wang, T. Point Source Characterization of Per- and Polyfluoroalkyl Substances (PFASs) and Extractable Organofluorine (EOF) in Freshwater and Aquatic Invertebrates. *Environ. Sci.: Processes Impacts* 2019*, 21* (11), 1887–1898. https://doi.org/10.1039/C9EM00281B.

43 Leung, S. C. E.; Wanninayake, D.; Chen, D.; Nguyen, N.-T.; Li, Q. Physicochemical Properties and Interactions of Perfluoroalkyl Substances (PFAS) - Challenges and Opportunities in Sensing and Remediation. *Science of The Total Environment* 2023, *905*, 166764. https://doi.org/10.1016/j.scitotenv.2023.166764.

44 He, Y.; Cheng, X.; Gunjal, S. J.; Zhang, C. Advancing PFAS Sorbent Design: Mechanisms, Challenges, and Perspectives. *ACS Mater. Au* 2024, *4* (2), 108–114. https://doi.org/10.1021/acsmaterialsau.3c00066.

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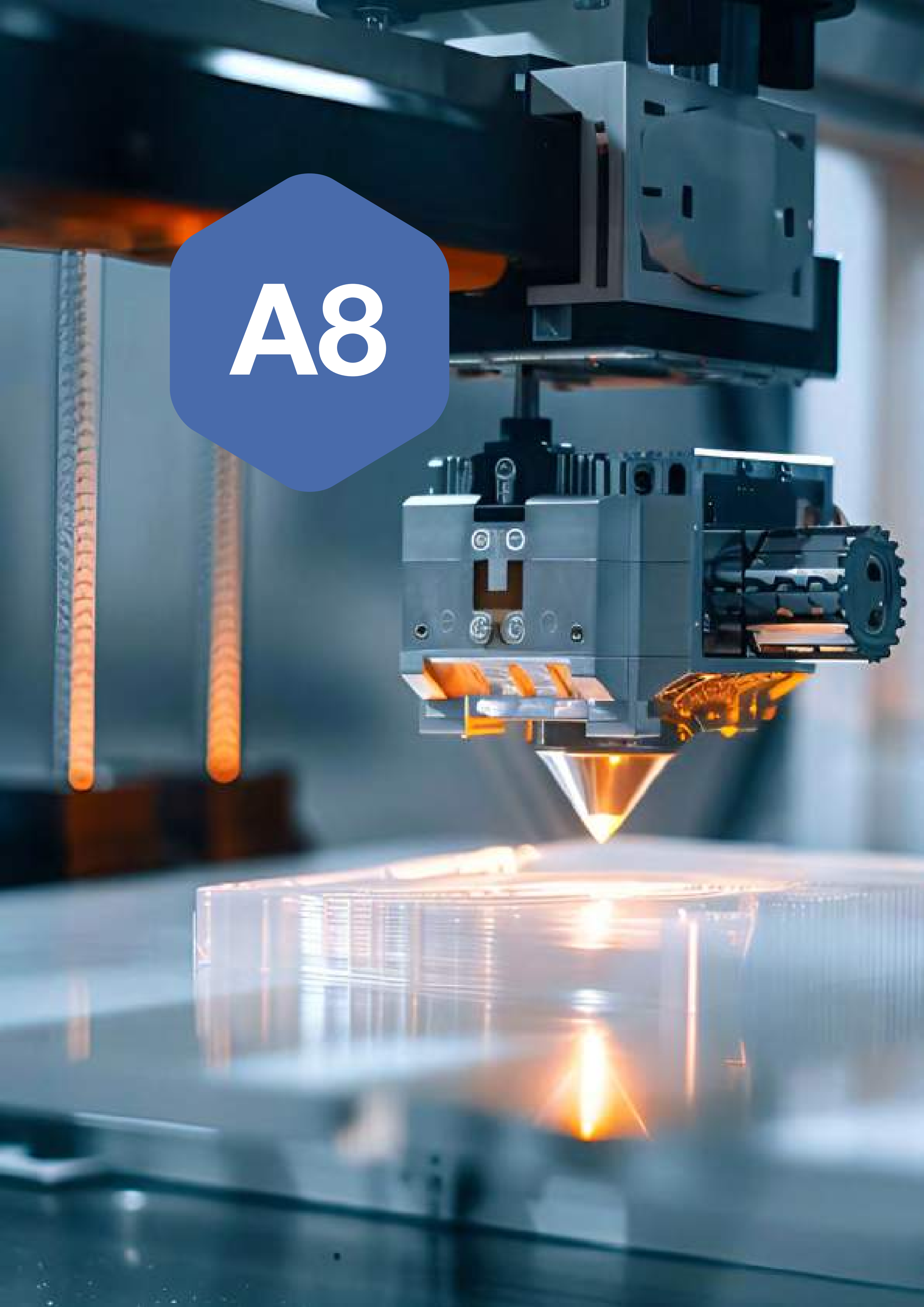

Non-Conventional and Advanced Sustainable Manufacturing Technologies for Fuel and Electrolytic Cells

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Abstract

The integration of non-conventional and advanced sustainable manufacturing technologies into the production of fuel cells and electrolytic cells represents a paradigm shift towards enhanced efficiency, reduced costs, and greater environmental compatibility. This paper explores the current state of research, key challenges, and future directions in this rapidly evolving field, emphasizing the transformative potential of additive manufacturing and other innovative techniques. By examining the strategic, economic, environmental, and societal implications, this analysis aims to provide a comprehensive rationale for advancing research and development in this area, aligning with broader EU policy frameworks and sustainable energy goals.

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1

Introduction

This position paper evaluates novel manufacturing approaches to increase the efficiency and sustainability of fuel cells and electrolyzers. A primary goal is to identify advanced production methods that reduce costs while maintaining high component quality at large scale [1]. For example, high-throughput techniques (e.g., additive manufacturing and roll-to-roll fabrication) can improve process efficiency, yield, and cut material waste, thereby lowering manufacturing costs. These innovations are essential because conventional manufacturing may struggle to maintain quality as production volumes rise.

The scope of this paper includes both additive and non-additive non-conventional manufacturing technologies, examining their technical potential, economic and environmental benefits, and readiness for industrial deployment. The analysis also considers policy actions that can accelerate their adoption, especially in alignment with European energy and industrial strategies.

Moreover, the paper emphasizes the strategic importance of developing cutting-edge fuel cell and electrolyzer production capabilities within the EU [2]. By advancing domestic manufacturing, the EU can reduce dependence on foreign suppliers and create high-tech jobs, thereby supporting economic growth. This aligns with broader EU policies (such as the Net-Zero Industry Act) that aim to strengthen industrial competitiveness and energy resilience. In sum, advancing advanced manufacturing in the hydrogen sector will accelerate decarbonization and reinforce the EU's leadership in renewable energy technologies. Fuel cells and electrolysers are foundational technologies in the hydrogen economy. Table 1 and 2 summarise the main technologies used for the manufacture of fuel and electrolytic cells.

Table 1: Fuel Cell Technologies

(PEMFC proton exchange membrane fuel cell; AEMFC alkaline anion- exchange membrane fuel cell; SOFC solid oxide fuel cell; PCFC protonic ceramic fuel cell; PAFC phosphoric acid fuel cell; MCFC molten carbonate fuel cell)

Type	Temp. °C)	Ion	Fuel	Notes
PEMFC	60–80	H^+	H_2	Low-T, Pt-based, compact, mobile use
AEMFC	40–80	OH^-	H_2, NH_3	Low-cost, non-noble, early-stage
SOFC	600–900	O^{2-}	H_2, CO, CH_4	High-T, fuel-flexible, stationary/CHP
PCFC	400–600	H^+	H_2, NH_3	Mid-T, ceramic proton conductor
PAFC	150–220	H^+	H_2, reformate	Legacy tech, reliable but bulky
MCFC	600–700	CO_3^{2-}	H_2, CH_4, CO	Large-scale CHP, corrosive electrolyte

Table 2: Electrolyser Technologies

AEL alkaline electrolyzer; PEMEL proton exchange membrane electrolyzer; AEMEL alkaline anion- exchange membrane; SOEC solid oxide electrolyzer cell

Type	Temp. (°C)	Ion	Catalyst	Notes
AEL	60–90	OH^-	Ni, Co	Mature, low-cost, lower H_2 purity
PEMEL	50–80	H^+	Pt, Ir	High-purity H_2, compact, costly
AEMEL	40–70	OH^-	Ni, Co, Mn	Low-cost potential, emerging
SOEC	600–850	O^{2-}	Ni, LSM	Highest efficiency, uses heat, complex system

2

Current state of research

A variety of traditional manufacturing techniques are currently employed in the production of fuel cell and electrolyzer components. These include spray coating, tape casting, screen printing, hot pressing, die coating, and slot die coating. These methods are widely adopted due to their maturity, relative simplicity, and availability of industrial equipment [1]. However, despite their established nature, they present significant challenges in terms of scalability, cost, material efficiency, and environmental impact, especially when applied to high-throughput and precision-demanding applications.

2.1 Challenges and Limitations

Traditional manufacturing processes often struggle with scaling to large production volumes, which can lead to increased costs and compromised efficiency. Many of these methods rely on subtractive or batch processes, resulting in substantial material waste—particularly critical when using high-cost or rare materials. Achieving uniformity and structural integrity is also difficult with multi-step processes, especially when assembling multilayered components such as MEAs (membrane electrode assemblies) or complete cells.

Catalyst Layers: are typically deposited by spraying catalyst ink onto a gas diffusion layer (GDL) or directly onto the membrane. This method faces multiple challenges: i) ***Cost***: The catalyst layer accounts for a major share of total fuel cell costs due to the use of noble metals like platinum; the MEA can contribute up to 60% of the total cost [1]; ii) ***Efficiency***: Spraying often results in inhomogeneous distribution and low catalyst utilization. Structure optimization, particularly of the catalyst layer, is essential to increase the utilization ratio of Pt [3]; iii) ***Environmental Impact***: Solvent-based inks and the energy-intensive nature of the process contribute to environmental concerns. **MEA:** critical components in PEMFCs, are usually fabricated through hot-pressing, using either a catalyst-coated membrane (CCM) or catalyst-coated substrate (CCS) configuration [1]. Key limitations include: i) ***Cost***: MEAs remain one of the most expensive components in stack [1]; ii) ***Process Sensitivity***: The hot-pressing process requires tight control over time, temperature, and pressure; iii) ***Non-homogeneity***: Non-continuous deposition can lead to layer delamination, inhomogeneity, and performance variability [4]. **Bipolar Plates:** essential for electrical conduction and gas separation, are often produced by machining graphite or corrosion-resistant metals. Limitations include: i) ***Machinability and Cost***: Graphite is fragile and hard to machine, while metals like Ti, Nb, and Au are durable but expensive; ii) ***Durability***: Even stainless steel may corrode under anode-side conditions, releasing contaminants that reduce system performance.

2.2 General Limitations of Traditional Methods

Traditional manufacturing has broader drawbacks: i) ***High Cost***: Expensive materials (platinum catalysts, specialized membranes) [1] and energy-intensive processes drive up costs; ii) ***Scalability***: Many conventional techniques are difficult to scale up for high-volume production; iii) ***Material Waste***: These processes often generate significant waste of costly materials [5]; iv) ***Environmental risks***: Hazardous chemicals (e.g. NiO in solide oxide cells (SOCs) or $Ni(OH)_2$ in AEM and high energy use contribute to environmental impact [5].

3

Research challenges:

3.1 Background: Non-Conventional and Advanced Sustainable Manufacturing Technologies

While non-conventional manufacturing techniques have shown promising results in lab-scale applications, several technical and implementation challenges must be addressed to enable industrial adoption [1]. To address these limitations, several EU-funded initiatives have explored next-generation manufacturing processes for fuel cell and electrolyzer components. Projects such as ***MAMA-MEA***, ***VOLUMETRIQ***, ***GAIA***, have demonstrated successful scaling of digital fabrication techniques, novel material formulations, and automated MEA production with improved yield and reduced cost. For example, the MAMA-MEA project focused on scalable inkjet-based deposition for catalyst layers, while GAIA explored continuous-line production compatible with Clean Hydrogen JU targets. These emerging processes—especially additive manufacturing (AM), roll-to-roll coating, and digital slurry deposition—have demonstrated improved material efficiency and design flexibility. However, most techniques remain at Technology Readiness Level (TRL) 3–4, meaning they are currently validated in laboratory settings but require significant optimization and upscaling for full industrial deployment. Meeting Clean Hydrogen JU's 2030 Key Performance Indicators (KPIs)—including high throughput (100,000–500,000 m^2 yr^{-1}), reproducibility above 95%, and scrap rates below 5%—will necessitate a coordinated effort to bring these methods to TRL 7–9 [6]. In this context, non-conventional manufacturing technologies are not only a promising alternative but also a strategic necessity for the hydrogen economy. Their development is key to lowering system costs, reducing environmental impact, and ensuring Europe's technological sovereignty.

3.2 Additive Manufacturing

Additive manufacturing enables the production of fuel cell and electrolyzer components with tailored geometries, improved catalyst utilization, and reduced material waste (see Table 2 [7]). Yet, open challenges include: i) ***Microstructural control***: especially in ceramics, achieving defect-free sintering and desired porosity remains difficult, ii) ***Standardization***: there is a lack of standardized inks, pastes, and process parameters for functional fuel cell layers, iii) ***Scale-up***: most AM techniques are limited in throughput and consistency; few are currently suited for roll-to-roll or automated high-volume lines.

Table 2: Summary of Additive Manufacturing Methods Employed for Fuel Cell Component Production

Technology	Description	Fuel Cell Type	Ref
Inkjet Printing	Droplet-based digital deposition	PEM, SOCs	[4]
Material Extrusion	Thermoplastic filament printing	PEM, SOCs	[8]
Vat Photopolymerization	Laser-curing of photopolymers	PEM, SOCs	[9]
Slurry-Based Printing	Layered ceramic/metal slurries	SOCs	[10]
Powder Bed Fusion	Laser melting/sintering of powders	AEM, PEM, SOCs	[11]
Binder Jetting	Liquid binder deposition + sintering	Full units	[12]

3.3 Other Non-Conventional Techniques

Beyond additive manufacturing, innovative non-additive techniques are gaining attention for their potential in fuel cell and electrolyser fabrication. Methods such as ultrasonic spray, electrospray, electrospinning, centrifugal casting, and electrodeposition offer unique capabilities for fabricating thin films, structured layers, and functional coatings. These approaches could be further explored for integration into roll-to-roll or continuous-line manufacturing systems, enabling scalable high-throughput production while maintaining material precision and performance.

4

Timeline and Resources

The industrial adoption of non-conventional manufacturing technologies for fuel cells and electrolyzers requires a phased roadmap addressing TRL progression, process integration, supply chain, and regulatory alignment.

Short Term (1–3 years)

- Raise TRL from 3–4 to 5–6 via pilot-scale demonstrations;
- Optimize AM and hybrid processes (e.g., inkjet, binder jetting);
- Standardize printable materials and introduce initial in-line metrology;
- Launch industrial–academic consortia on key components.
  Estimated funding: €15–20M per topic, with public-private co-financing and early infrastructure investment.

Medium Term (3–5 years)

- Integrate non-conventional methods into continuous lines (e.g., roll-to-roll + AM);
- Validate under industrial conditions with automation and process control;
- Conduct LCA and recyclability studies;
- Strengthen EU supply chains for materials and precursors.
  Estimated funding: €30–50M per program, covering demo-scale lines, skills development, and digital monitoring.

Long Term (5–10 years)

- Deploy TRL 8–9 manufacturing platforms meeting Clean Hydrogen JU KPIs;
- Scale to commercial gigafactories for MEAs and SOCs;

Establish regional manufacturing hubs and align with global standards.
Estimated funding: >€100M (public + private), including CAPEX, regulatory support, and alignment with EU funding programs.

5

Rationale for Advancing Research in This Area & Potential Applications

The shift toward non-conventional and advanced sustainable manufacturing technologies for fuel cells and electrolyzers is not only technically justified but strategically essential for achieving the EU's climate and industrial policy goals. Advancing research in this field addresses several intertwined imperatives: economic competitiveness, sustainability, energy security, and industrial leadership.

5.1 Strategic and Economic Rationale

The European Union's ambition to become a global leader in hydrogen technologies requires not only innovation in device design, but also scalable, cost-effective, and environmentally sustainable production processes. Traditional manufacturing methods are no longer sufficient to meet the projected deployment volumes, cost targets, and flexibility needs of emerging hydrogen markets.

Non-conventional approaches—such as additive manufacturing (AM), inkjet printing, roll-to-roll coating, and hybrid deposition—enable: i) *Reduced dependency on scarce materials*, such as platinum and iridium, through more efficient catalyst utilization and optimized layer architectures [5]; ii) *Lower production costs*, via automation, digital process control, and high-throughput fabrication [3]; iii) *Adaptability for different volumes and formats*, supporting diverse fuel cell and electrolyzer configurations; iv)

Enhanced European manufacturing sovereignty, through localized, modular, and digital production strategies aligned with the Net-Zero Industry Act and REPowerEU.

These innovations will support job creation (up to one million hydrogen-related jobs by 2030) and build competitive advantage in the clean tech manufacturing sector.

5.2 Environmental and Societal Impact

Non-conventional manufacturing techniques significantly improve the environmental performance of hydrogen technologies, making them more attractive for large-scale deployment and public procurement. Key benefits include: i) *Minimized material waste* via precise deposition (e.g., inkjet, slurry printing, binder jetting) and near-net-shape production [7]; ii) *Reduced energy consumption*, especially compared to legacy solvent-based or high-temperature processes; iii) *Smaller carbon footprint*, enabled by leaner manufacturing, fewer process steps, and potential integration with circular economy practices. These factors contribute to improved lifecycle performance and help meet EU decarbonization targets, especially when coupled with green hydrogen production.

5.3 Application Potential

Non-conventional manufacturing methods unlock design flexibility and production agility across a wide spectrum of applications, including: *Transport*: PEMFCs and AEMFCs for hydrogen-powered vehicles (cars, trucks, buses, trains); *Stationary power and heat*: SOFC-based combined heat and power (CHP) systems for residential, commercial, and industrial use; *Industrial decarbonization*: SOECs for high-efficiency hydrogen and e-fuel production from renewable heat; *Portable systems*: Compact PEM units for off-grid, military, or backup power; *Chemical and fertilizer production*: High-temperature electrolysis enabling green ammonia and synthetic fuels. The deployment of non-conventional techniques supports rapid prototyping, customized geometries, and high-durability components—tailored to specific sectoral needs.

5.4 Alignment with EU Policy Frameworks

The advancement of non-conventional manufacturing technologies directly supports the objectives of several key EU initiatives: i) *The Clean Hydrogen JU SRIA*, especially targets for manufacturability, recyclability, and TRL progression; ii) *The Green Deal and Fit for 55*, which require clean technology scale-up and emissions reductions across sectors; iii) *The Net-Zero Industry Act*, which prioritizes the establishment of European clean-tech manufacturing capacity; iv*) The Circular Economy Action Plan*, advocating for resource efficiency, waste minimization, and design for reuse/recycling. In conclusion, investment in this field is not only a technological necessity but a strategic imperative. Advancing non-conventional manufacturing will accelerate hydrogen deployment, enhance European industrial competitiveness, and deliver tangible societal and environmental benefits.


CO2
H2
CO2

6

Conclusion and Recommendations

Non-conventional and advanced manufacturing technologies offer transformative potential for the production of fuel cells and electrolyzers by reducing costs, improving performance, and enhancing sustainability. However, their widespread adoption requires overcoming implementation challenges, such as supply chain risks, safety standards, and infrastructure gaps; through collaborative efforts among industry, academia, and policy-makers. To accelerate deployment, we recommend the following: i) ***Cost reduction:*** Minimize the use of critical raw materials (e.g., platinum, iridium) and scale advanced, efficient manufacturing methods; ii) ***Performance and durability:*** Target higher power density, improved efficiency, and long-term reliability [7] to ensure commercial viability; iii) ***Sustainability:*** Reduce waste, emissions, and energy use by adopting circular economy practices and recycling strategies; iv) ***Technological advancement:*** Support integration of additive manufacturing, automation, and high-throughput techniques such as inkjet printing and roll-to-roll coating [4], [7]; v) ***Infrastructure investment:*** Focus on developing durable, lightweight components for hydrogen storage and distribution**;** vi) ***Collaboration and funding:*** Promote public-private partnerships and transnational R&D projects, supported by targeted funding and subsidies; vii) ***International standards:*** Establish and align standards to ensure safety, interoperability, and regulatory clarity; viii) ***Regulatory clarity:*** Streamline legislation to boost investor confidence and enable predictable market conditions; ix) ***Demand-side policies:*** Introduce mandates (e.g., minimum green hydrogen shares) to foster long-term market stability and investment.

Through coordinated action along these strategic lines, a resilient, efficient, and clean hydrogen economy can be achieved.

References

1 G. Paixão da Costa, D. M. E. Garcia, T. H. Van Nguyen, P. Lacharmoise, and C. D. Simão, “Advancements in printed components for proton exchange membrane fuel cells: A comprehensive review,” *Int J Hydrogen Energy*, vol. 69, pp. 710–728, Jun. 2024, doi: 10.1016/j.ijhydene.2024.05.072.

2 J. R. C. K. O. T. Quailan Homann, “The Case for Recalibrating Europe’s Hydrogen Strategy - REGlobal - Opinion & Perspective.” Accessed: Jun. 06, 2025. [Online]. Available: https://reglobal.org/the-case-for-recalibrating-europes-hydrogen-strategy/

3 P. Liu, D. Yang, B. Li, C. Zhang, and P. Ming, “Recent progress of catalyst ink for roll-to-roll manufacturing paired with slot die coating for proton exchange membrane fuel cells,” *Int J Hydrogen Energy*, vol. 48, no. 51, pp. 19666–19685, Jun. 2023, doi: 10.1016/J.IJHYDENE.2023.02.022.

4 A. Willert, F. Z. Tabary, T. Zubkova, P. E. Santangelo, M. Romagnoli, and R. R. Baumann, “Multilayer additive manufacturing of catalyst-coated membranes for polymer electrolyte membrane fuel cells by inkjet printing,” *Int J Hydrogen Energy*, vol. 47, no. 48, pp. 20973–20986, Jun. 2022, doi: 10.1016/J.IJHYDENE.2022.04.197.

5 J. C. Ho, E. C. Saw, L. Y. Y. Lu, and J. S. Liu, “Technological barriers and research trends in fuel cell technologies: A citation network analysis,” *Technol Forecast Soc Change*, vol. 82, no. 1, pp. 66–79, Feb. 2014, doi: 10.1016/J.TECHFORE.2013.06.004.

6 “Clean Hydrogen JOINT UNDERTAKING (Clean Hydrogen JU) WORK PROGRAMME 2025”.

7 R. Singh ***et al.***, “Advances in additive manufacturing of fuel cells: A review of technologies, materials, and challenges,” *Sustainable Materials and Technologies*, vol. 43, p. e01317, Apr. 2025, doi: 10.1016/J.SUSMAT.2025.E01317.

8 M. Cannio ***et al.***, “Smart catalyst deposition by 3D printing for Polymer Electrolyte Membrane Fuel Cell manufacturing,” *Renew Energy*, vol. 163, pp. 414–422, Jan. 2021, doi: 10.1016/J.RENENE.2020.08.064.

9 N. Kostretsova, A. Pesce, M. Nuñez, A. Morata, M. Torrell, and A. Tarancón, “Self-Supported Solid Oxide Fuel Cells by Multimaterial 3D Printing,” *ECS Meeting Abstracts*, vol. MA2021-03, no. 1, p. 13, Jul. 2021, doi: 10.1149/MA2021-03113MTGABS.

10 K. Mirzaee Fashalameh, Z. Sadeghian, and R. Ebrahimi, “A high-performance planar anode-supported solid oxide fuel cell with hierarchical porous structure through slurry-based three-dimensional printing,” 2022, doi: 10.1016/j.jallcom.2022.165406.

11 C. J. Netwall, B. D. Gould, J. A. Rodgers, N. J. Nasello, and K. E. Swider-Lyons, “Decreasing contact resistance in proton-exchange membrane fuel cells with metal bipolar plates,” *J Power Sources*, vol. 227, pp. 137–144, Apr. 2013, doi: 10.1016/J.JPOWSOUR.2012.11.012.

12 S. J. Ha, Y. K. Lee, K. C. Jeong, Is. S. Ryu, H. G. Kim, and J. Y. Park, “Binder jetting and melt infiltration for ceramic-metal fuel fabrication,” *Ceram Int*, vol. 50, no. 22, pp. 48583–48591, Nov. 2024, doi: 10.1016/J.CERAMINT.2024.09.206.

A9

Development of IGF Code for hydrogen Providing comprehensive scientifically based safety recommendations for maritime applications

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Abstract

The decarbonisation of the maritime sector requires a transition to hydrogen as a clean fuel, yet the absence of a comprehensive regulatory framework remains a major barrier. The International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels (IGF Code), originally developed for liquefied natural gas, provides only limited “alternative design” provisions for hydrogen that are insufficient to address its specific hazards. Key risks, including high flammability, rapid dispersion, embrittlement effects and boil-off from cryogenic storage, need hydrogen-specific safety principles, including new paradigms and new engineering solutions, in some instances. The IGF Code requires revision of its goals and provisions to cover hydrogen’s buoyancy, storage enclosures, redundancy systems and fuel cell applications. This position paper identifies the critical knowledge gaps and technological bottlenecks that hinder the development of scientifically based regulations, codes, and standards (RCS) for hydrogen-fuelled vessels. Fundamental research is urgently required to advance ventilation strategies, safe storage concepts, fire and explosion prevention, and inherently safer technologies such as self-venting tanks. Additional challenges include bunkering protocols, under-deck storage safety, double-walled piping integrity, and zero boil-off solutions for liquid hydrogen. The efforts by classification societies (DNV, LR, ABS) and EU projects (e-SHyIPS, HyShip, FLAG-SHIPS and more) represent important milestones, yet they are still fragmented and not fully prepared for global adoption. Absence of a common shared understanding of the alternative design process among stakeholders, can possibly force each project team to “repeat baseline safety assessments” and increase costs and slow a regulatory approval. A coordinated international research programme is needed to underpin the development of hydrogen provisions within the IGF Code, elevate key technologies to TRL 4–6, and support the safe, efficient, and cost-effective deployment of hydrogen in maritime applications. Achieving this will strengthen public trust, accelerate decarbonisation, and ensure Europe’s leadership in clean maritime transport.

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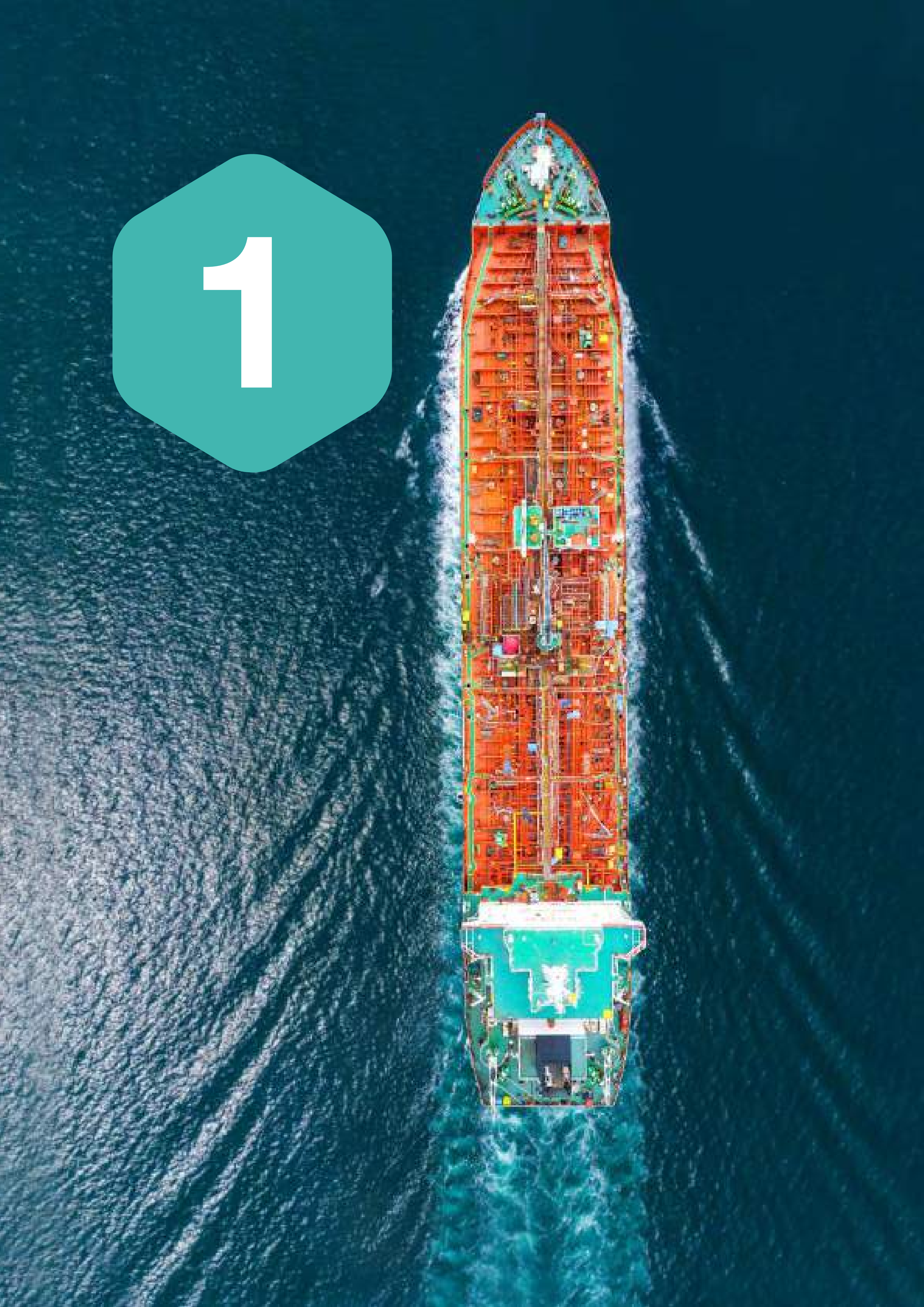
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Introduction

Fundamental research is essential to support pre-normative work that shapes international regulations, codes, and standards (RCS) in fast-evolving industries. In the maritime sector, current safety RCS lag behind industrial needs. The IGF Code permits "alternative design" for hydrogen, which requires equivalent functional safety, but this is a concept rather than practical guidance. Significant knowledge gaps and technological bottlenecks in hydrogen safety engineering must be addressed before effective adoption. The lack of hydrogen-specific provisions in the IGF Code hinders both safety and the wider deployment of hydrogen-powered vessels, despite urgent decarbonisation demands.

This topic highlights the importance of fundamental research that should underpin the development by RCS of the International Maritime Organization (IMO)[1]. To enable the safe and efficient adoption of hydrogen as a maritime fuel, a dedicated regulatory framework tailored to hydrogen-specific hazards and associated risks, and breakthrough safety technologies and innovative engineering solutions are urgently required.

This position paper aims to inform decision-makers and funders about the critical challenges in deploying inherently safer maritime applications, due to the gap in regulatory coverage under the IGF Code for hydrogen. The scope of the paper is to highlight the need to close existing knowledge gaps and technological bottlenecks through fundamental research. The IGF Code, designed for LNG, must be revised to address hydrogen-specific risks. Key hazards include high flammability, permeability, embrittlement, and buoyancy, which demand improved ventilation, leak prevention, and safety zones. Provisions are also needed for fuel cells, redundancy systems, storage, and fuel quality, drawing on land-based standards. Fire suppression, explosion prevention and emergency shutdown protocols must be adapted to hydrogen's unique properties. There is a need for a comprehensive update of the IGF Code to integrate hydrogen-specific design, operational, and safety standards[2].

It is essential to meet all stakeholders' expectations for the safety of hydrogen-fuelled ships, to build public trust and support the deployment of hydrogen technologies in the maritime sector. There is no thorough, shared understanding among stakeholders, including hydrogen-powered vessel designers, about the scope of the alternative design approval process. This makes regulatory approval difficult and demands significant investment as each time a new project team must ".a new project team could undertake redundant development, without added value". Behind these difficulties are numerous knowledge gaps, e.g. on design of ventilation systems, hydrogen storage enclosures, use of other hydrogen systems under deck, etc. Fragmenting safety research across different projects to save costs has proven ineffective. To address this, the full spectrum of stakeholders should be brought together.

Several critical research gaps must be addressed for the safe deployment of hydrogen technologies in maritime applications. Firstly, ventilation systems with complex duct geometries need a dedicated investigation. An improper design can lead to hazardous accumulation of hydrogen, in the event of a release. Further research is also required to identify and qualify materials for hydrogen technologies, such as those used in fuel cells, that are suitable for harsh maritime environments.

Secondly, safety gaps include the need for strategies to manage emergency hydrogen releases and better understanding of jet fire and unignited release behaviour. Research must address thermal and pressure effects from delayed ignition and the deflagration-to-detonation transition (DDT) in non-uniform hydrogen-air mixtures, with thresholds defined for shipboard scenarios. Storage enclosures must be protected against incidental jet fires, and the risk of tank rupture in any fire must be eliminated. This is now achievable with self-venting tank technology, validated across fire intensities from spill fires to extreme impinging jet flames.

Lastly, systemic and operational challenges increase due to the existence of hydrogen systems using compressed gaseous hydrogen (CGH2) and liquid hydrogen (LH2). This includes the need for comprehensive safety provisions covering both shore-based and offshore operations, such as bunkering procedures, ship-to-shore interfaces and debunkering procedures.

2

Current State of Research

Due to the lack of detailed hydrogen safety guidelines from the IMO, classification societies have independently established regulatory frameworks for hydrogen storage on vessels. Particularly, Lloyd's Register (LR) introduced the first set of classification rules for hydrogen fuel in 2023[3], outlining specific technical and safety requirements for ships utilising hydrogen as a fuel source. The regulations serve to bridge the existing gap in the IMO's current IGF Code. Also, Det Norske Veritas (DNV) published the first set of classification rules for hydrogen fuel in July 2024[4]. The Maritime Technologies Forum report[5] examines the viability of hydrogen as a zero-emission fuel in alignment with the IMO's strategy for the reduction of GHG emissions from ships by 2050. The report highlights the limited operational experience within the maritime sector regarding hydrogen as both cargo and fuel, while also recognising the increased safety risks associated with its application as a fuel compared to LNG. The IMO has been developing guidelines for the safe design of hydrogen-fuelled ships, with the guidelines to be presented by Sub-Committee on Carriage of Cargoes and Containers (CCC) [6]. The publication of guidelines is targeted for 2025[7] and the Interim Guidelines for the Safety of Ships Using Ammonia as Fuel developed by the CCC Sub-Committee, were issued by the IMO [8], marking a regulatory milestone providing goal-based, non-mandatory provisions (aligned with the IGF Code and SOLAS) to support the uptake of ammonia-fuelled ships.

More provisions to IGF Code related to hydrogen are also targeted to be introduced by the correspondence group in 2025. However, more joint efforts at the international level are required, including researchers and experts who specialise professionally in hydrogen safety. A Comité Européen de Normalisation (CEN) workshop Agreement (CWA) was achieved in 2024 on developing guidelines for integrating hydrogen propulsion systems based on fuel cells into passenger ships from the early design stages[9]. These recommendations aim to assist in risk assessments by utilising existing standards and are based on findings from the EU e-SHyIPS project [10]. The project developed guidelines for integrating hydrogen technologies into maritime passenger transport. It involved vessel redesigns to assess the feasibility of gaseous and liquid hydrogen propulsion, supported by hydrostatic/hydrodynamic analyses and CFD simulations of gas dispersion and explosion scenarios. Experimental work validated fuel cell components through inclination, materials and corrosion testing. The project also proposed bunkering strategies, conducted risk assessments, and identified gaps in the IGF Code, leading to preliminary recommendations for regulatory adaptation.

Unlike the IGF Code, the American Bureau of Shipping (ABS) Guide for Fuel Cell Power Systems for Marine and Offshore Applications[11] explicitly addresses hydrogen, yet its provisions largely reference the IGF Code. The DNV Handbook[12] includes hydrogen storage onboard. CGH2 at 70 MPa is more technologically mature but has a lower energy density compared to LH2, requiring larger storage volumes. LH2 offers a higher energy density, making it more suitable for long-haul applications. However, its liquefaction process is energy-intensive, it requires advanced insulation to minimise boil-off losses (which can be as high as 1~5% per day[13]), and it poses additional safety concerns related to extremely low temperatures.

Proper, scientifically based guidelines for ventilation systems and inherently safer technologies are crucial to prevent the accumulation of flammable hydrogen-air clouds. The safety principles for hydrogen fuel supply systems are outlined in the published DNV class rules for the use of hydrogen as fuel onboard ships[14]. These rules emphasise that ventilation of hazardous enclosed spaces should not serve as the primary safety barrier. Instead, the primary objective should be the prevention of a flammable atmosphere, thereby mitigating the risk of fire or explosion at its source. This can be achieved through the implementation of inerting or vacuum-insulated containment strategies, depending on whether the system utilises compressed gaseous or liquefied hydrogen.

Hydrogen ventilation is one of the most critical safety challenges in in maritime applications. Ventilation systems that are not properly designed may cause ignition and catastrophic explosions. A Risk-based approach is being adopted to tackle this, e.g. the ongoing revision of DNV's Handbook for Hydrogen Fuelled Vessels, which applies computational fluid dynamics (CFD) analyses and quantitative risk assessment (QRA) to develop design criteria for ventilation and fire safety. Contemporary multiphase CFD tools now allow simulations of ventilation interacting with fire suppression or unignited releases, however, they demand experimental validation on realistic vessel configurations. Full-scale experiments, e.g. those carried out by DNV[15], are important to establish detonation thresholds and support the development and refinement of the models. Such experiments also inform the integration of storage systems with leak and explosion assessments to ensure that there is no further incident escalation. Results can provide the scientific basis for regulatory approval.

To eliminate hazards and associated risks of compressed hydrogen storage systems (CHSS) rupture and potential catastrophic consequences, the innovative solution, such as explosion free in any fire self-venting tanks[16,17,18], can be used. These innovative solutions can remove previously applied expensive measures such as blast wave panels and explosion-proof enclosures.

Due to its cryogenic nature, LH2 storage requires maintaining extremely low temperatures to minimise boil-off losses. Ongoing research has identified several engineering approaches to manage boil-off[19,20,21], such as improved insulation and pressure control techniques. One promising concept is helium refrigeration for reducing losses through advanced thermal control. However, these approaches require further validation in maritime conditions.

Hydrogen bunkering research, including full-system simulations of hydrogen refuelling stations (HRS) for CGH2[22] and LH2[23] should address transparent and inherently safer bunkering protocols. The protocols must address the regulated limits for bunkering parameters and develop recommendations on reduction of temperature non-uniformity for CGH2[24]. The currently developed and validated modelling tools enable the design of detailed bunkering protocols, considering onboard storage conditions (residual pressure, hydrogen temperature, tank properties), bunkering system components (piping, valves, precooling, dispensers), and onshore storage parameters (pressure, volume, number of tanks).

Key achievements and milestones

As described above, the IMO is advancing safety guidelines for the use of hydrogen as a marine fuel. However, numerous knowledge gaps and technological bottlenecks remain, these should first be addressed through fundamental research to formulate new norms and guidelines. Nonetheless, the maritime industry has achieved meaningful milestones in the use of hydrogen technologies, demonstrating its commitment to zero-emission solutions. Norway introduced the MF Hydra[25], the world's first liquid hydrogen-powered ferry, classed by DNV. Equipped with two 200 kW fuel cells, it demonstrates the possibility of hydrogen propulsion in maritime transport; and there are more known cases of developed maritime transport powered by hydrogen. By 2024, the Antwerp/Flanders Port Training Center provided maritime education to more than 20000 trainees covering topics such as green hydrogen applications[26]. This effort shows the role of knowledge sharing in enhancing hydrogen. In parallel, Japan launched HydroBingo [27], which a hydrogen-powered passenger ferry with similar technological advancements and reinforcing global journey toward hydrogen adoption in maritime transport. In 2025 HD Korea Shipbuilding & Offshore obtained Approval in Principle from DNV for its pioneering vacuum-insulated large-capacity LH_2 tank technology[28]. This is an advancement on resolving the difficulties of expanding hydrogen storage for maritime applications, their safety and efficiency.

The tangible ongoing work contributing to development of technical requirements to the ship design, safe hydrogen handling and the use of hydrogen as fuel for power generation on board ships, is reflected in the rules and guidelines introduced by classification societies (LR, Bureau Veritas[29] etc). DNV has been proactive in establishing frameworks for the safe implementation of hydrogen in maritime applications. In 2021, DNV published the "Handbook for Hydrogen-fuelled Vessels," which offers a roadmap towards safe hydrogen operations using fuel cells. This handbook details how to navigate the complex requirements for design and construction and covers critical aspects of safety and risk mitigation, engineering details for CHSS, and implementation phases for maritime applications. However, it does not provide specific guidance for the onboard storage of CGH2, cryo-compressed hydrogen (CcH2), or LH2. Current DNV ventilation regulations do not account for the pressure peaking phenomenon (PPP), a critical safety phenomenon characteristic only of hydrogen[30], but describe this from gas inerting point of view, whereby the procedure needs to be designed using CFD. There is a lack of understanding around the hazards and associated risks related to explosions (deflagrations, detonations, storage tank rupture). For example, the standard by National Fire Protection Association, NFPA 2, referenced in DNV Handbook, only considers hydrogen jet flames and does not assess explosion hazards and risks.

There are also recommendations[31] for IGF Code, whereby it should be expanded to explicitly address hydrogen safety, with new chapters covering storage, energy conversion, and safety protocols. Ship-specific risk assessments must be developed, incorporating lessons from land-based hydrogen regulations. CFD simulations should be used to assess ventilation, gas dispersion, and explosion risks. Collaboration between maritime authorities, classification societies, and industry stakeholders is essential to establish comprehensive international guidelines. Implementing these measures will ensure the safe adoption of hydrogen in shipping, supporting global decarbonisation goals.

The development of self-venting tanks represents a key milestone in advancing inherently safer hydrogen storage in maritime transport and infrastructure. Such innovative tanks indeed are a breakthrough in fire safety by preventing storage rupture during exposure to fires. Their design can eliminate the main causes of catastrophic consequences, e.g. blast waves, projectiles or long flames triggered by a thermally activated pressure relief device (TPRD), while still allowing for hydrogen release under extreme conditions. This represents a paradigm shift in risk mitigation for hydrogen storage systems, both onboard and onshore.

Hydrogen leakage, dispersion and possible accumulation in enclosures pose very serious challenges for the design of effective ventilation systems. These can be intensified by dynamic marine conditions, including vessel motion and external weather effects that can influence hydrogen flow and potentially ventilation performance. Understanding the behaviour of hydrogen under these conditions requires advanced CFD modelling to design practical engineering solutions, especially when it comes to enclosures or during releases from vent stacks. Under-deck storage configurations need proper, robust ventilation integration to prevent hazardous accumulation and reduce the risk of ignition. The IGF Code and IGC Code specify a minimum of 30 air changes per hour (ACH), but this value is not based on scenario-specific consequence modelling. The further research is needed to determine optimal ACH values for a range of realistic hydrogen release rates and system configurations. The configuration and grouping of vent ducts and stacks must be optimised through fundamental studies and simulation-based design. The work on inherently safer CGH2 storage for maritime applications should include material-focused studies to confirm long-term integrity, performance under varying marine conditions and integration with ship specific ventilation and containment systems. Advancing this technology to a higher TRL requires coordinated experimental and numerical investigations well aligned with real-world maritime applications. To achieve long-term safety and operational efficiency, further fundamental research is required into zero boil-off technologies for LH2 storage, where helium refrigeration is a leading candidate. This research must address technical feasibility, integration into vessel systems and performance under variable marine conditions. Bunkering operations have additional challenges that require development of inherently safer and standardised protocols. These efforts across conceptual design, numerical simulation and experimental validation are important to elevate the technologies to higher TRLs and support their wider adoption in maritime applications.

Notable projects:

- FCH2 JU. e-SHyIPS: Ecosystemic knowledge in Standards for Hydrogen Implementation on Passenger Ship (101007226) [32].
- FCH2 JU. HyShip: Demonstrating Liquid Hydrogen for The Maritime Sector (101007205).
- FCH2 JU. FLAGSHIPS (826215) [33].
- FCH2 JU. MARANDA: Marine Application of a New Fuel Cell Powertrain Validated in Demanding Arctic Conditions. (735717) [34].
- FCH2 JU. H2PORTS: Implementing Fuel Cells and Hydrogen Technologies in Ports. (826246) [35].
- Horizon 2020. HySeas III. (769417) [36].
- Interreg Atlantic Area. HYLANTIC Atlantic Network for Renewable Generation and Supply of Hydrogen to promote High Energy Efficiency (EAPA_204/2016) [37].
- Innovate UK. Clean Maritime Demonstration Competition Round 1 (CMDC1): “Northern Ireland Green Seas” (10009311).
- Innovate UK. Clean Maritime Demonstration Competition Round 2 (CMDC2): “Hydrogen Fuel Cell Range Extender” (10041047).
- UKRI, EPSRC. UK National Clean Maritime Research Hub (MaRes) (EP/Y024605/1) [38].
- Norwegian Research Council. H2Maritime: H2Maritime Project.
- U.S. EERE. MarFC: Maritime Hydrogen Fuel Cell Project [39].
- California Air Resources Board. LCTI: Zero-Emission Hydrogen Ferry Demonstration [40].

3

Research Challenges

One of the key challenges is the design of ventilation systems for scenarios from permeation and allowed standard leak rates for connections to more challenging to tackle incidents with loss of containment, particularly in the context of under-deck storage and fuel piping. The fundamental research should investigate different scenarios of hydrogen leaks/release. This includes but is not limited to: releases inside, below-deck, where hydrogen can be trapped in “pockets”; transition to vent stack, outside releases from masts/ducts, and dispersion, including the cases when a marine vessel experiences heave or pitching and rolling. The latter could be challenging due to vessel motions, potentially leading to a flammable concentration entering the ventilation system or adjacent compartments with ignition sources. The weather conditions, e.g. wind gusts, could affect the ventilation efficiency and hydrogen dispersion.

Hydrogen releases from piping or pressure relief devices can ignite via electrostatic discharge, causing jet fires and explosion hazards. In confined or poorly ventilated spaces, ignition may lead to deflagration or even DDT, depending on enclosure size, pressure, and ventilation. Understanding these dynamics is crucial for effective mitigation. Numerical simulations can assess ventilation and fire suppression but require validation through full-scale testing. However, large-scale hydrogen explosion experiments are limited due to potential destruction. Combining full-scale experiments with modelling improves predictive accuracy, particularly for ventilation-fire suppression interactions, enhancing mitigation strategies and hydrogen safety.

For CGH2 tanks placed in compartments beneath the deck, an alternative safety measure involves inerting the entire hold space surrounding the CHSS. This approach could effectively suppress reactive conditions, thereby mitigating potential hazards. Fundamental studies would help understand hydrogen combustion in low-oxygen atmosphere that would underpin development inert gas filling strategies and formulate quantitative recommendations.

The design of large-scale LH2 storage tanks remains a work in progress, necessitating improved insulation and safer transfer systems. Both CGH2 and LH2 systems demand double-walled piping and robust venting systems to detect a leak and mitigate pressure build-up and accidental leaks. The design of the piping plays an important role in the safety of the entire system. A detailed study of combustion dynamics within double-walled piping systems is essential for provision of this piping integrity. Establishing the minimum structural strength required for the outer tubing to maintain gas-tight integrity and exploring strategies to contain explosion propagation within vent stacks are necessary. Understanding the conditions under which deflagration transitions to detonation is crucial for determining appropriate design pressures for secondary containment barriers.

One of the primary safety concerns associated with LH2 storage tanks is hydrogen boil-off. While leakage can be negligible due to the necessity of maintaining a vacuum within the double-walled tank structure, boil-off hydrogen can escape through the valve system. Mitigating or eliminating boil-off is essential not only to enhance cost-effectiveness, operational efficiency, and the vessel sailing range but also to address safety risks, particularly in confined storage environments such as under-deck compartments. There should be a design that could decrease heat flux from the surroundings, hence fundamental research on achieving a zero boil off must be undertaken. This could involve the use of a helium refrigeration, which should be studied numerically and validated experimentally.

The bunkering of onboard storage systems presents significant economic and safety challenges. The future research should tackle hydrogen temperature non-uniformity and novel approaches to pressure ramps that could underpin establishing standardised protocols that enhance the intrinsic safety and operational efficiency of the bunkering process while optimising time efficiency.

This position paper elucidates and stresses the need to undertake fundamental research, one of the objectives of which is identification and critical analyse of knowledge, technology, and regulatory gaps, including limitations of ventilation, bunkering, handling unignited and ignited releases in confined spaces and safety of under-deck hydrogen storage, prevention and mitigation of pressure and thermal effects in unscheduled conditions. The future research should also aim to support a standardised risk analysis framework to underpin the design and approval of novel solutions. Such framework would serve as a robust decision-support tool, demonstrating that proposed solutions comply with risk acceptance criteria in the current regulatory and operational context before the establishment of more standardised alternatives.

Activities are expected to achieve TRL between 4 and 6 by the end of research.

The proposed timeline for this topic is medium-term 3 years. The suggested estimate of the funding is €5M.

4

Rationale for Advancing Research in This Area & Potential Applications

Whilst maritime shipping is critical to the European economy and one of the most energy-efficient forms of transport, it is also a significant and growing contributor to atmospheric greenhouse gases. The ambition of this research is in line with the European Green Deal[41] including "Fit to 55" package[42], which aim to address the barriers to decarbonisation of the maritime sector. The research will strengthen Europe's leadership in decarbonising waterborne transport and stimulate its transition to green energy through elaborated decision-making procedures for the selection of an appropriate alternative fuel for a particular maritime application.

The research will aid to address key technical and economic barriers to decarbonisation in the shipping sector by improving the safety, feasibility, and public acceptance of hydrogen as a maritime fuel. It will enhance understanding of hydrogen behaviour, mitigating perceived hazards and promoting broader social acceptance of hydrogen powered maritime sector. Inherently safer hydrogen technologies will not only reduce pollutants such as NOx but also establish new markets for hydrogen-compatible construction materials and material testing, supported by potential amendments to maritime RCS.

The research outcomes will strengthen the European economy and its leadership in the area. This advancement would position Europe ahead of competitors by achieving an unprecedented level of safety and cost reduction. Establishing a robust technological foundation, a skilled workforce, and the capability to manufacture competitive commercial products would drive global demand and market adoption. The potential for the impact of this research is non-doubtful, as it aligns with the European industrial strategy, namely supporting clean hydrogen[43] and ambitions of CHP[44]. The key findings will be influential in shaping policy, aligning with the objectives of HER[45]. The findings of a low-TRL research will extend beyond maritime applications, with potential spill-over benefits for other hydrogen-powered heavy-duty transport sectors. By addressing fundamental challenges, this work will contribute to the broader adoption of hydrogen as a clean energy solution in transport and beyond.

Overview of applications

This research will support the decarbonisation of maritime-related industries dependent on hydrogen storage, particularly maritime applications such as hydrogen-powered maritime vessels and transport applications (e.g. cargo ships, bulk carriers, ferries, passenger vessels, tugboats etc.) and port equipment (e.g. hydrogen fuel cell forklifts, terminal tractors, yard trucks etc.). Additionally, it will benefit stationary applications such as HRS for maritime vessels and onshore power supply systems.

References

1 International Code of Safety for Ship Using Gases or Other Low-flashpoint Fuels (IGF Code). https://www.imo.org/en/ourwork/safety/pages/igf-code.aspx .

2 Georgopoulou C, Di Maria C, Di Ilio G, Cigolotti V, Minutillo M, Rossi M, et al. On the identification of regulatory gaps for hydrogen as maritime fuel. Sustainable Energy Technologies and Assessments 2025;75:104224. https://doi.org/10.1016/j.seta.2025.104224.

3 LR issues world's first rules for hydrogen fuel | LR 2023. https://www.lr.org/en/knowledge/horizons/june-2023/lr-issues-worlds-first-rules-for-hydrogen-fuel/.

4 Now available: July 2024 edition of the DNV class rules for ships and offshore units. DNV 2024. https://www.dnv.com/news/now-available-july-2024-edition-of-the-dnv-class-rules-for-ships-and-offshore-units/.

5 Bahtić F. MTF explores hydrogen bunkering gaps as IMO prepares guidelines for safe ship design. Offshore Energy 2024. https://www.offshore-energy.biz/mtf-explores-hydrogen-bunkering-gaps-as-imo-prepares-guidelines-for-safe-ship-design/.

6 Progress on safety guidelines for hydrogen- and ammonia-fuelled ships. https://www.imo.org/en/MediaCentre/Pages/WhatsNew-1968.aspx.

7 IMO CCC 10: interim guidelines for ammonia and hydrogen as fuel. DNV 2024. https://www.dnv.com/news/imo-ccc-10-interim-guidelines-for-ammonia-and-hydrogen-as-fuel/.

8 IMO issues interim guidelines for safety of ammonia-fuelled ships 2025. https://www.bimco.org/news-insights/bimco-news/2025/03/27-ammonia/.

9 CEN Workshop E-Shyips on 'Pre-normative plan for H2 applications to passenger ships - Guidelines for H2 passenger ships from the early stage of design.' CEN-CENELEC 2024. https://www.cencenelec.eu/news-and-events/news/2024/workshop/2024-06-14-e-shyips/.

10 Clean Hydrogen Partnership. Ecosystemic knowledge in Standards for Hydrogen Implementation on Passenger Ship (e-SHyIPS) 2024. https://www.clean-hydrogen.europa.eu/projects-dashboard/projects-repository/e-shyips_en.

11 American Bureau of Shipping, 2019. ABS guide for fuel cell power systems for marine and offshore applications.

12 DNV, 2021. Handbook for Hydrogen-fuelled Vessels, 1st Edition. Ed, MarHySafe JDP Phase 1. https://www.dnv.com/maritime/publications/handbook-for-hydrogen-fuelled-vessels-download/

13 Zhang T, Uratani J, Huang Y, Xu L, Griffiths S, Ding Y. Hydrogen liquefaction and storage: Recent progress and perspectives. Renewable and Sustainable Energy Reviews 2023;176:113204. https://doi.org/10.1016/j.rser.2023.113204.

14 Now available: July 2024 edition of the DNV class rules for ships and offshore units. DNV 2024. https://www.dnv.com/news/now-available-july-2024-edition-of-the-dnv-class-rules-for-ships-and-offshore-units/.

15 Crewe R. CostFX - Full-scale explosions of gaseous hydrogen jets in congestion | H2tools | Hydrogen Tools 2024. https://h2tools.org/document/costfx-full-scale-explosions-gaseous-hydrogen-jets-congestion.

16 Molkov V, Kashkarov S, Makarov D. Breakthrough safety technology of explosion free in fire self-venting (TPRD-less) tanks: The concept and validation of the microleaks-no-burst technology for carbon-carbon and carbon-glass double-composite wall hydrogen storage systems. International Journal of Hydrogen Energy 2023. https://doi.org/10.1016/j.ijhydene.2023.05.148.

17 Molkov V, Kashkarov S, Makarov D. Explosion free in fire self-venting (TPRD-less) composite tanks: Performance during fire intervention. International Journal of Hydrogen Energy 2023. https://doi.org/10.1016/j.ijhydene.2023.07.067.

18 Molkov V, Kashkarov S, Makarov D, Fletcher J, Rattigan W. Explosion free in fire self-venting (TPRD-less) Type IV tanks: Validation under extreme impinging 70 MPa hydrogen jet fire conditions. International Journal of Hydrogen Energy 2023. https://doi.org/10.1016/j.ijhydene.2023.09.020.

19 Choi M, Jung W, Lee S, Joung T, Chang D. Thermal Efficiency and Economics of a Boil-Off Hydrogen Re-Liquefaction System Considering the Energy Efficiency Design Index for Liquid Hydrogen Carriers. Energies 2021;14:4566. https://doi.org/10.3390/en14154566.

20 Shakir U. Toyota shows off its latest big idea for cold hydrogen vehicles. The Verge 2024. https://www.theverge.com/2024/11/18/24299725/toyota-liquid-hydrogen-self-pressurizer-gr-corolla-h2.

21 Yan Y, Li S, Zheng S, Zhou Y, Yu J, Wei W, et al. A Boil-Off Gas Control Scheme for Liquid Hydrogen Transportation: Risk Assessment Framework and Proactive Release Control System 2024. https://doi.org/10.2139/ssrn.5027472.

22 Ebne-Abbasi H, Makarov D, Molkov V. CFD model of refuelling through the entire equipment of a hydrogen refuelling station. International Journal of Hydrogen Energy 2024;53:200–7. https://doi.org/10.1016/j.ijhydene.2023.12.056.

23 Molkov V, Ebne-Abbasi H, Makarov D. Liquid hydrogen refuelling at HRS: Description of sLH2 concept, modelling approach and results of numerical simulations. International Journal of Hydrogen Energy, Volume 93, 3 December 2024, Pages 285-296. https://doi.org/10.1016/j.ijhydene.2024.10.392.

24 Xie H, Makarov D, Kashkarov S, Molkov V. Comparative analysis of CFD models to simulate temperature non-uniformity during hydrogen tank refuelling. International Journal of Hydrogen Energy 2024;70:715–28. https://doi.org/10.1016/j.ijhydene.2024.05.047.

25 megabite. MF Hydra sails on zero-emission liquid hydrogen. Norled 2023. https://www.norled.no/en/mf-hydra-sails-on-zero-emission-liquid-hydrogen/.

26 APEC pioneers green hydrogen training in the maritime sector. http://www.mundomaritimo.cl/noticias/apec-pioneers-green-hydrogen-training-in-the-maritimesector?utm_medium=email&utm_campaign=newsletter.

27 HydroBingo – World's first hydrogen ferry starts operating in Japan. Baird Maritime / Work Boat World 2021. https://www.bairdmaritime.com/passenger/ferry/vessel-review-hydrobingo-worlds-first-hydrogen-ferry-starts-operating-in-japan.

28 DNV Awards Approval in Principle (AiP) to KSOE for vacuum-insulated large-scale liquefied hydrogen tank technology. DNV 2025. https://www.dnv.com/news/dnv-awards-approval-in-principle-to-ksoe-for-vacuum-insulated-large-scale-liquefied-hydrogen-tank-technology/.

29 Bureau Veritas unveils Rules for hydrogen-fuelled ships | Marine & Offshore. https://marine-offshore.bureauveritas.com/newsroom/bureau-veritas-unveils-rules-hydrogen-fuelled-ships.

30 Brennan S, Molkov V. Safety assessment of unignited hydrogen discharge from onboard storage in garages with low levels of natural ventilation. International Journal of Hydrogen Energy 2013;38:8159–66. https://doi.org/10.1016/j.ijhydene.2012.08.036.

31 Georgopoulou C, Di Maria C, Di Ilio G, Cigolotti V, Minutillo M, Rossi M, et al. On the identification of regulatory gaps for hydrogen as maritime fuel. Sustainable Energy Technologies and Assessments 2025;75:104224. https://doi.org/10.1016/j.seta.2025.104224.

32 Clean Hydrogen Partnership. Ecosystemic knowledge in Standards for Hydrogen Implementation on Passenger Ship (e-SHyIPS) 2024. https://www.clean-hydrogen.europa.eu/projects-dashboard/projects-repository/e-shyips_en.

33 DEMONSTRATING LIQUID HYDROGEN FOR THE MARITIME SECTOR | HyShip | Projekt | Fact Sheet | H2020. CORDIS | European Commission. https://cordis.europa.eu/project/id/101007205.

34 Marine application of a new fuel cell powertrain validated in demanding arctic conditions | MARANDA | Projekt | Results | H2020. CORDIS | European Commission. https://cordis.europa.eu/project/id/735717/results.

35 Implementing Fuel Cells and Hydrogen Technologies in Ports | H2Ports | Projekt | Results | H2020. CORDIS | European Commission. https://cordis.europa.eu/project/id/826339/results.

36 Realising the world's first sea-going hydrogen-powered RoPax ferry and a business model for European islands | HySeas III | Projekt | Fact Sheet | H2020. CORDIS | European Commission. https://cordis.europa.eu/project/id/769417.

37 Atlantic network for renewable generation and supply of hydrogen to promote high energy efficiency. KeepEu. https://keep.eu/projects/19341/Atlantic-network-for-renewa-EN/.

38 UK National Clean Maritime Research Hub. https://gtr.ukri.org/projects?ref=EP%2FY024605%2F1.

39 Maritime Fuel Cell Generator Project: 2018 – 2023. US Hydrogen Alliance. https://www.ushydrogenalliance.org/news/maritime-fuel-cell-generator-project%3A-2018-%E2%80%93-2023

40 LCTI: Zero-Emission Hydrogen Ferry Demonstration Project | California Air Resources Board. https://ww2.arb.ca.gov/lcti-zero-emission-hydrogen-ferry-demonstration-project.

41 Delivering the European Green Deal - European Commission. https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/delivering-european-green-deal_en.

42 Fit for 55: Delivering on the proposals - European Commission. https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/delivering-european-green-deal/fit-55-delivering-proposals_en.

43 Hydrogen - European Commission. https://single-market-economy.ec.europa.eu/industry/strategy/hydrogen_en.

44 Mission & Objectives - Clean Hydrogen Partnership. https://www.clean-hydrogen.europa.eu/about-us/mission-objectives_en.

45 Policy – Hydrogen Europe Research. https://hydrogeneuroperesearch.eu/our-activities/policy-working-group/.

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Research and Technology Infrastructures

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Introduction

The REPowerEU Strategy set out the aim of producing 10 million tonnes of renewable hydrogen and importing 10 million tonnes of the same by 2030. By 2050, renewable hydrogen is to cover around 10% of the EU's energy needs, significantly decarbonising energy-intensive industrial processes and the transport sector. Thus, renewable and low-carbon hydrogen stands as a key component in the EU's strategy within the energy transition, net-zero, and sustainable development.[1] Beyond that, hydrogen must be produced, stored, transported and distributed via efficient and sustainable technologies, minimising or even omitting critical and strategic raw materials as well as environmentally harmful substances while respecting strict safety rules. As solutions for this are either not sufficiently developed or do not exist at all, **production, transport, storage and usage need intensified research and development.[2]**

Already in 2021, the European Research Area (ERA) policy agenda identified **Research and Technology Infrastructures (RTIs)** as being crucial elements of European Research and Innovation (R&I) ecosystems, providing essential platforms for bridging the gap between research and market applications.[3] This position is promoted by the European Association of Research and Technology Organisations (EARTO) in its recommendations for the implementation of an EU strategy on technology infrastructures.[4] In September 2024, the EC published two reports on (i) a detailed analysis of European, national and regional initiatives, strategies and programmes addressing investments in Technology Infrastructures,[5] and (ii) mapping of the existing landscape of Technology Infrastructures in clean and renewable energy technologies.[6]

The significance of RTIs has been repeatedly underscored in strategic documents such as the Draghi report[7] (*'increased funding and stronger coordination is required to develop world-leading research and technological infrastructures'*), the Letta report[8] ('a key pillar of the fifth freedom is the empowerment of our research infrastructures') and the Heitor report[9] (*'Research and Technology infrastructures should be prioritised throughout Europe in order to foster the European RD&I ecosystem, attract and retain researchers'*). Most recently, the EC Communication on 'A Competitiveness Compass for the EU' from January 2025 establishes competitiveness as one the EU's overarching principles for action, so that tomorrow's technologies, services and clean products are invented, manufactured and marketed in the EU. The availability of support and investment for R&I is a key issue holding back the growth of tech start-ups and particularly for early-stage technologies that have game-changing potential. In this context, access to research and technology infrastructures for innovative companies is a key element.**[10]**

2

Research and Technology Infrastructures: Context and Status

The European Union needs to develop a robust ecosystem of infrastructures supporting research, innovation and technology development that enable businesses to advance, scale and commercialise their innovations efficiently. Research Infrastructures (RIs) and Technology Infrastructures (TIs) are essential in this ecosystem, offering advanced facilities and expertise.

RIs and TIs complement each other with RIs focusing, but not exclusively so, on fundamental and applied research and TIs on technology development, testing, scale-up and deployment. Additionally, companies can invest in and build **industrial infrastructures** as part of their operations, which are understood as facilities developed typically with a focus on a specific product, technology or production process within an individual company, such as industrial demonstrators.[11] Thus, the capacities and services provided by RIs and Tis, on one hand, and industrial infrastructures and demonstrators, on the other hand, are complementary to each other by covering different steps needed for the scale up of technologies towards industrial processes and manufacturing.

2.1 Research Infrastructures

Research Infrastructures (RIs) are facilities that provide resources and services for research communities to foster innovation and achieve excellence in their fields. They include the associated human resources, major equipment or sets of instruments, knowledge-related facilities such as collections, archives or scientific data infrastructures, computing systems, and communication networks. They can be 'single sited', 'virtual' or 'distributed', are usually open to external users and, where relevant, may be used beyond research, for example for education or public services.[12]

2.2 Technology Infrastructures

Following the updated definition provided by the Expert Group on Technology Infrastructures (EGTI), Technology Infrastructures (TIs) are:[13]

'(…) facilities, equipment, capabilities and resources required to develop, test, upscale and validate technology. They enable and accelerate technological innovations towards societal/market adoption, fostering industrial competitiveness. They provide a wide range of capacities and services from pre-competitive applied research services, through demonstration and validation of technology, up to small-scale production. They include, amongst others, test beds, demonstration and testing facilities, pilot lines or living labs, usually embedded within non-profit research and technology organisations, universities active in technology fields or technology centres, which are open to private and public users. They can be public, semi-public or privately owned, physical or digital. '

Examples of TIs range from facilities to develop electrolyser stacks to biogas plants, cleanroom facilities for chip production to test areas for automated shipping or road traffic safety solutions, from wind tunnels to testbeds for multi-functional nano-composites, or from multi-material 3D printing to thermo-plastics and industrial robotics. Regarding hydrogen, there are, amongst others, currently two Open Innovations Test Beds (OITBs) active : *CleanHyPro*[14] and *H2Shift*[15]. In addition, TIs related to hydrogen are hosted by several RTOs in Europe and strategically analysed by the *RITIFI*[16] project.

3

RIs, TIs and industrial infrastructures in the hydrogen innovation ecosystem

In 2024, the EC launched an online survey addressed to diverse enterprise types and industrial ecosystems such as SMEs, very small enterprises and large companies, amongst others, from the key sectors of mobility, health, aerospace and defence, digital, energy, electronics, agri-food, and construction. While the majority of enterprises participating in the survey (80%) declared that they use TIs, **90% of the enterprises active in the area of electrolysers and fuel cells considered not to have adequate TIs to support their technology development plans**. Moreover, the related share of companies in the areas of micro/nano electronics and photonics (71%) and carbon capture and storage (70%), which are both closely linked to hydrogen, came in second and third, respectively. The mentioned reasons for why the offer of TI services is not sufficient were – most importantly – that **there are simply not enough TIs**, and – secondly – that **access to TIs are too complicated for industrial users**, and – thirdly – that **they are inconveniently located**, wherein missing relevance for industrial needs or missing state-of-the-art were comparably important reasons.[17]

According to the enterprises, **making existing TIs more visible by offering (better) insights into their services, as well as active dissemination of up-to-date information,** would be the most important elements to increase their usage of TIs. In this context, related inventories or roadmapping exercises to date include the mapping of the existing landscape of TIs in clean and renewable energy technologies by the EC[18], as well as the mapping of hydrogen RIs and TIs through Hydrogen Europe Research .

At the EU Member States level, dedicated support for TIs is currently focusing on fields such as **hydrogen**, semiconductors, ICT, advanced materials, and most recently on AI[19],[20]. On the other hand, the EU Hydrogen Strategy mentions ‘*pilot lines to test new solutions or perform early product validation*’ as a priority area for collaboration between Member States and local and regional authorities[21], and the proposal for a Critical Raw Materials Act highlights the need for R&I for a sustainable materials value chain[22].

In 2024, Hydrogen Europe Research published a Research Position Paper ‘For a long-term perspective impact of European research and industrial sectors’[23], pointing towards the importance of RTIs for ‘*fostering innovation and enabling breakthrough technologies, especially in scaling up manufacturing capacity for hydrogen-related industries*’.

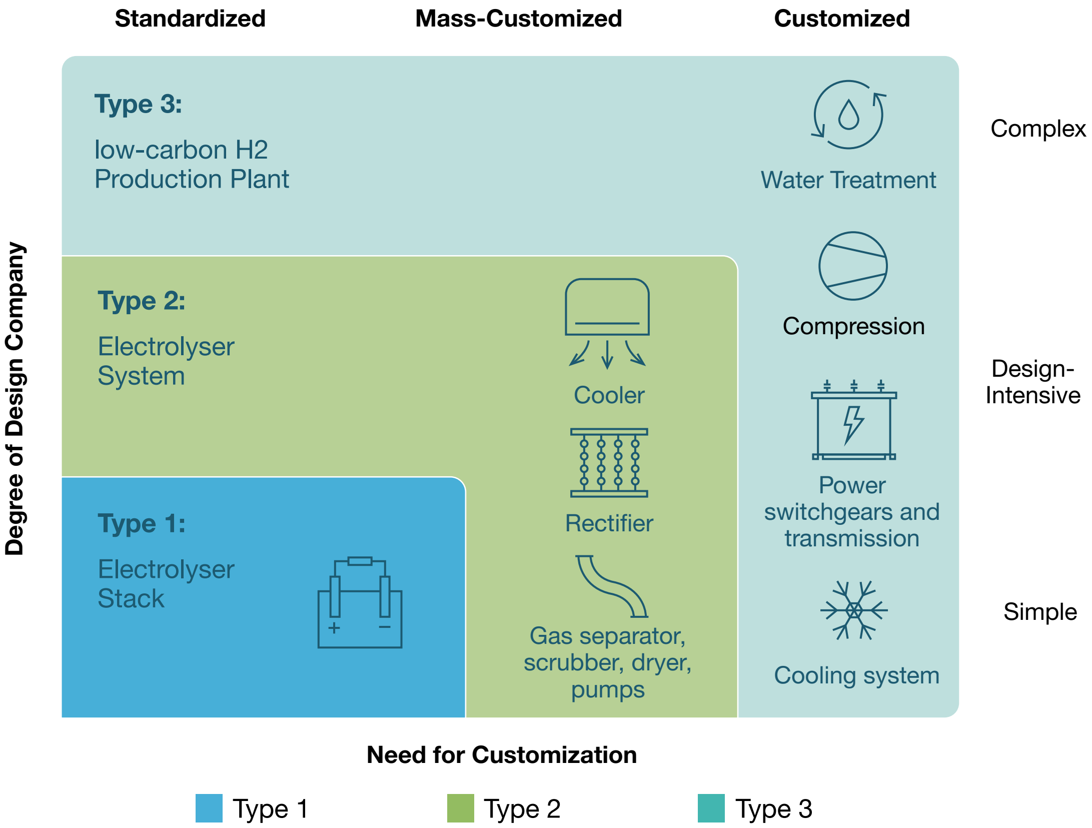
3.1 Accelerating technology development for the hydrogen economy

The European Union needs to advance a variety of hydrogen technologies if it wants to achieve carbon neutrality by 2050, focusing on scaling up renewable and low-carbon hydrogen production, storage, and distribution. Thus, a wide range of different technologies, with varying Technology Readiness Levels (TRLs), has to be covered. For example in the area of renewable hydrogen production, at higher TRLs, one focus is on water electrolysis using renewable electricity, with a particular emphasis on upscaling electrolyser technologies such as Alkaline Electrolysis (AEL), Anion/Proton Exchange Membrane Electrolysis (AEMEL/PEMEL), and Solid Oxide Electrolysis (SOEL) and Protonic Ceramic Electrolysis (PCEL). Beyond water electrolysis, many technologies such as direct solar-driven or biological processes are still at lower TRLs requiring substantial R&I efforts to achieve commercial readiness. On the other hand, scaling up production capacity, improving cost competitiveness, and establishing robust distribution infrastructure are key areas requiring coordinated efforts. As such, **besides the need for policy action to improve the accessibility of RTIs, user(technology)-focused services and capabilities are necessary to improve the applicability of RTIs and facilitate their collaboration with users**.

Based on a thorough literature review[24] of experience rates[25] of low-carbon technologies, a technology typology has been developed that explains systematic differences in technologies' experience rates by distinguishing these technologies based on (i) their design complexity and (ii) the extent to which they need to be customised. Accordingly, energy technologies are grouped into three types (*'Type 1/ 2/ 3'*), which have significant implications, such as, for example, the way the individual technologies and their costs develop, respectively, and therefore require different roles of national and international innovation and deployment policies.

Based on such *'Type 1/ 2/ 3 technologies'*, Doyle et al. developed an approach to map renewable hydrogen production plants towards a combination of these technology types (see figure 1)[26], building on the fact that a renewable or low-carbon hydrogen production plant essentially combines the (theoretical) simplicity and scalability of a mass-produced technology (electrolysers) with the complexity and customisation of an industrial-scale system. **This approach may therefore act as a guideline for the (strategic) planning and coordinated establishment of hydrogen-related research, technology and even industrial infrastructures, and to improve their accessibility and applicability.**

Figure 1: Green hydrogen production plant as a combination of Type 1, 2, and 3 technologies[27].



Adapted from Ramboll, “Achieving affordable green hydrogen production plants”, 2023.

Type 1 technologies: Standardised components

Type 1 technologies such as (i) electrolyser or fuel cell stacks, (ii) components of multipurpose Hydrogen Refuelling Station (HRS) systems, or (iii) pipeline components, are comparably “simple” and mass-producible, and expanding production capacity will most likely lead to cheaper products.

Studies[28],[29] by policymakers, trade associations and industry often assign learning curves from the solar PV industry to predict the potential cost decline of electrolysers and ultimately the cost of renewable hydrogen based on the scaling of manufacturing. A recent academic study[30] compared forecasted and actual learning rates across solar PV, Li-ion batteries, and PEM electrolysers, and concluded that each of these technologies had demonstrated cost declines in line with Wright’s Law (i.e. costs drop as a power law of cumulative production). However, the PEM dataset was significantly limited.

Nevertheless, although electrolyser manufacturing capacity doubled in 2023 to reach 25 GW/yr,[31] electrolysers CAPEX and levelized costs of renewable hydrogen were rising due to other macroeconomic trends and seemingly despite those announcements.[32] Given the huge demand for electrolysers in the renewable and low-carbon hydrogen-powered energy transition, it may still be assumed that **stack components** exhibit a sustained

5-20% year over year decline for the next decade, depending on stack technology (AEL, PEMEL, AEMEL, or SOEL).[33]

This can only be achieved if sufficient public and private investments are streamlined into R&I capacities, facilities and services. Related key objectives include (i) reducing the loading factors of the most expensive/critical minerals, (ii) increasing the efficiency to reduce energy needs and footprint per unit of hydrogen production, and (iii) improving reliability and lifetime via reducing degradation and poisoning processes.

When it comes to **testing and evaluating cells and (short) stacks**, there is still a huge variety of technology concepts, devices (cell assembly, cell area, stacking, etc.) and testing procedures. **Thus, RTIs applying harmonised testing protocols, clear codes, technical regulations, standards and related Pre-Normative Research are needed to prevent delays in technology deployment**. Harmonisation and certification schemes for hydrogen technologies and their components are required to guarantee on the quality of the commercial and novel technologies and components.[34] In this context, the *STASHH* project[35] developed an open standard for heavy-duty fuel-cell modules to kick-start the use of hydrogen in the heavy-duty mobility sector, which standard has been transformed into a pre-normative work in the IEC TC105.

Type 2 technologies: Mass-customised systems

Electrolysers or electrolyser systems are more than their stacks, and thus can be referred to a type-2 technology that relies on a mix of mass-produced products, also called BOS (‘Balance of System’) components, which are type-1 technologies such as stacks, rectifiers, switchgears, gas separators, etc. Electrolyser systems are therefore more complex and customised than the stack inside. Moreover, the requirements for the BOS components, such as the power electronics and water or gas purification systems, may depend on the region, location, and project design.

Original Equipment Manufacturers (OEMs) usually develop and deliver an electrolyser system with the required specifications, whereas the available systems (AEL, PEMEL, AEMEL, or SOEL) can vary widely regarding BOS components. Especially power electronics such as transformers and rectifiers have been shown to be the key limiting factor for stack and system size, currently staying at the 2-5 MW range.[36] **Thus, accelerated and increased R&I activities for these components are strongly needed.**

In terms of testing and evaluation, such OEM electrolyser systems are more applicable, since they are mostly containerised and to a certain extend ‘plug-and-play’. **Challenges for TIs often arise from the large system size, necessitating sufficient electrical connection power, water supply and/or gas storage/usage capabilities. RTIs should also be able to address the electrical components of electrolyser systems, especially rectifiers or even fully DC-powered systems.**

Moreover, in manufacturing, these type 2 technologies require more than increased production volume to unlock significant cost reductions, such as, amongst others, the standardisation of electrolyser offerings , comprising more integrated and cohesive solutions with better integrated and improved BOS components. Beyond that, electrolysers systems for very large plants are made of several stacks/modules and, thus, the technology-specific standardisation of such stacks/modules will accelerate and accordingly reduce the costs of the entire project lifecycle, from design and engineering to procuring the necessary equipment and building the plant.

Type 3 technologies: Customised components for hydrogen production plants and end-use

A renewable or low-carbon hydrogen production facility usually contains an electrolyser or hydrogen production system, the balance of plant (BOP) components as well as multiple process loops that connect with the outside environment (such as the water, electrical, heat and gas streams). **These interfaces make the plants highly customised to their specific location and thus reduce the impact of learning and scale.** Moreover, the produced hydrogen must be supplied into an offtake infrastructure such as storage of different types (tanks, caverns, pipelines) or power-to-X processes, wherein, amongst others, the grid interconnection, the water systems, and the gas systems including the gas transport and storage infrastructure have to be considered.

Many of these factors interact not only with real infrastructure systems (e.g. the grid, the gas network) but also with a cascading system of national and local laws. So, at the plant level, technologies are so complex and customised in their design that they require collaboration across OEMs, developers, operators, end-users, financiers, regulators, local authorities and governments to unify the enabling environment for these technologies.

For hydrogen production, this will require the harmonisation of certification for hydrogen origin and regulatory frameworks for permitting and safety, the definition of interconnection standards and tariffs, and enhanced industry coordination on R&I, maybe even based on industrial infrastructures.

3.2 Materials development and AI Applications

Advanced material development plays a crucial role in hydrogen technology development, especially in type 1 technologies and e.g. storage, transportation (pipelines) or end-use technologies. In this context, the first three R&I priorities as defined by the new Co-Programmed HE partnership *'Innovative Advanced Materials for Europe' (IAM4EU)* are directly addressing hydrogen production, conversion and storage.[37] Moreover, recent advances in AI show promise in generating scientific breakthroughs in areas such as materials science where models can be trained on large datasets of existing examples.[38]

In February 2024, the EC published its Communication on *'Advanced Material for Industrial Leadership'*, **underscoring the need for more accessible TIs and better connections between existing infrastructures in different Member States**.[39]

4

Implementation Challenges and Proposed Actions

Fragmentation Across Member States

Evidence shows that the availability of TIs in clean and renewable energy technologies in the EU is fragmented and geographically imbalanced. There are often no overarching coordination mechanisms to oversee investments in TIs in Europe and no roadmapping or long-term investment planning[40].

To improve cooperation and overcome fragmentation, the promotion of such infrastructures can act as **vehicles for attracting and growing talent** and **create deep-tech innovation R&I ecosystems** within the infrastructures and beyond (e.g. between different types of infrastructures and/ or companies).

Regarding the hydrogen sector, **Hydrogen Europe Research conducted a mapping of RTIs** and set up a **RI&TI Working Group**[41] in order to "coordinate *a mapping exercise with a technology-oriented approach at the EU level, building upon national and institutional initiatives, set up through existing structures and coordinated at the European level".*[42] **A technology-type-focused value-chain approach** is promoted in order to create structured, business-oriented ecosystems near enterprise clusters, and fostering regional innovation. For this, the partnerships with its private partners, such as Hydrogen Europe Research, could provide a format for future road-mapping.

Regulatory and Funding Issues

To ensure the sustainability of TIs in the long run, support often needs the combination of public and private funding streams to cover various needs underpinned by relevant skills and expertise in the planning and creation phase as well as during implementation, upgrade and decommissioning. These funding streams can range from fully regional public funding to a multi-level combination of different funding schemes. **TI operators face difficulties finding instruments to cover their capital investment needs and support the operational use of TIs for actors with lower financial capacity**, such as SMEs. Moreover, outdated and stringent regulations in high-tech sectors hinder smooth operation and access.

Under Horizon 2020, the EU invested around €1.2 billion in research and TI projects, while the European Regional Development Fund (ERDF) has provided, during the 2014-2020 programmes, over €16 billion for building or upgrading RTIs. **Hydrogen Eu-**

rope Research strongly encourages the European Commission to maintain and consolidate this impetus in the forthcoming financial framework, amongst others by creating a dedicated EU funding scheme to support large-scale investments and operational costs of TIs and pool resources at the EU level. In addition, exploiting synergies and joint investments between institutional, regional, national, European and global funding streams can mobilize further investment in needed TIs, e. g. via the sectoral acts proposed in the Competitiveness Compass

Awareness, Use and Accessibility

Many enterprises lack awareness of the TI landscape and its benefits, resulting in underutilisation of the TIs and their services. Moreover, SMEs and startups, particularly in less economically developed regions, encounter significant barriers to accessing TI resources. These barriers include high usage fees, lack of geographical proximity, and insufficient awareness of available facilities. Finally, ambiguous and diverse access rules discourage engagement with TIs, wherein concerns about intellectual property (IPR) protection and data security further deter users, especially those worried about the risk of misappropriation.

Under Horizon 2020, around €21 billion were allocated to research and innovation support services that foster the exploitation and development of technologies, in particular by SMEs[43]. **Hydrogen Europe Research strongly encourages the European Commission to maintain and consolidate this impetus in the forthcoming financial framework, and to foster SMEs' access to RTIs by enhancing and incentivising the use of support instruments.**

To improve the awareness, each RI and TI should provide clear and transparent information on the infrastructure, its standardised services, and the support that can be provided. This would enable enterprises, particularly SMEs, to learn about TIs outside of their field of expertise and about available funding opportunities. Moreover, these infrastructures should provide training for SMEs on innovation management, technology transfer, IPR and data management.

RIs and TIs should be developed and organised on the basis of a technology-type-focused value-chain approach, ideally in the form of joint infrastructure frameworks between different types of infrastructures, to create structured, business-oriented ecosystems near enterprise clusters and industry infrastructures, and fostering regional innovation.

The digitalisation of infrastructures will be enabled by AI, and remote testing and simulation platforms can help to overcome physical barriers and expand access to distributed facilities as long as they are fully implemented in the communication and access strategy.

Market Alignment and Adaptability

Some RIs and TIs service offerings may not fully align with end-user needs, leading to a gap with market demand, thus lacking clear, industry-aligned business models, resulting in inefficiencies, fragmented efforts and inadequate services. Related pricing models often fail to address SMEs and start-ups financial constraints, creating further access barriers. This is particularly true in fast evolving technology fields, where rapid technological advancements require adaptable infrastructures and well-trained staff.

Go-to-market strategies should be developed, prioritising industry engagement to drive commercialisation and innovation. A business-oriented R&D approach should be chosen that is agile and responds to changing market demands. Seamless collaboration between technology providers and end-users should be established to improve the pathways of RIs towards industry. For a forthcoming European coordination body on TIs, the perspective of industry as TI users and research community as TI operators must be safeguarded. **Hydrogen Europe Research strongly encourages the European Commission to support this by European funding instruments such as the collaborative projects in HEU Pillar II.**

5

Summary

Renewable and low-carbon hydrogen technologies require the development of Research, Technology, and Industrial Infrastructures to bridge the gap between research, innovation, and market adoption, thereby reducing the time-to-market for innovative solutions and enhancing Europe's industrial competitiveness.

Yet many companies lack knowledge of the facilities and services they could use to develop, validate or scale up their technologies, or face barriers in accessing them. Despite growing demand, existing infrastructures are often insufficient, difficult to access, or poorly aligned with industrial needs. This limits the ability of enterprises – especially startups and SMEs – to develop, test, and scale breakthrough technologies.

To accelerate progress, the European Union must build a more connected and responsive ecosystem that supports the full development cycle of hydrogen technologies, from research to commercial deployment. This includes improving visibility and accessibility of infrastructures, strengthening collaboration across regions and sectors, and ensuring regulatory and funding frameworks that are fit for purpose.

By aligning infrastructure investment with R&I and market needs, fostering innovation ecosystems near enterprise clusters, and simplifying access and support for companies, the European Union can unlock the full potential of hydrogen technologies. This will not only drive competitiveness but also contribute meaningfully to the EU's climate and energy goals.

References

1 https://energy.ec.europa.eu/topics/eus-energy-system/hydrogen_en

2 Hydrogen Europe Research: Advancing Hydrogen Technologies, Key Research and Innovation Priorities (2024); https://hydrogeneuroperesearch.eu/

3 EC: ERA Policy Agenda, Overview of actions for the period 2022-2024, 2021

4 JRC-EARTO: Recommendations for the Implementation of an EU Strategy on Technology Infrastructures, 2022

5 EC: Policy Landscape Supporting Technology Infrastructures in Europe, 2024

6 EC: Mapping of Technology Infrastructures supporting Clean and Renewable Energy Industries in Europe, 2024

7 EC: The Draghi report: A competitiveness strategy for Europe (2024); https://commission.europa.eu/document/download/97e481fd-2dc3-412d-be4c-f152a8232961_en?filename=The%20future%20of%20European%20competitiveness%20_%20A%20competitiveness%20strategy%20for%20Europe.pdf

8 E. Letta: Much More Than a Market (2024); https://www.consilium.europa.eu/media/ny3j24sm/much-more-than-a-market-report-by-enrico-letta.pdf

9 EC: Align Act Accelerate. Research, Technology and Innovation to boost European Competitiveness (2024); doi:10.2777/9106236

10 EC, DG Research and Innovation: Towards a European Policy for Technology Infrastructures (2025); doi:10.2777/0876395

11 EC, DG Research and Innovation: Towards a European Policy for Technology Infrastructures (2025); doi:10.2777/0876395

12 EC, DG Research and Innovation: Towards a European Policy for Technology Infrastructures (2025); doi:10.2777/0876395

13 EC, DG Research and Innovation: Towards a European Policy for Technology Infrastructures (2025); doi:10.2777/0876395

14 https://cleanhypro.eu/

15 https://cordis.europa.eu/project/id/101137953

16 https://ritifi.eu/clean-hydrogen/

17 EC, DG Research and Innovation: Towards a European Policy for Technology Infrastructures (2025); doi:10.2777/0876395

18 EC: Mapping of Technology Infrastructures supporting Clean and Renewable Energy Industries in Europe, 2024

19 EC: Policy Landscape Supporting Technology Infrastructures in Europe, 2024

20 https://digital-strategy.ec.europa.eu/en/policies/ai-factories

21 EC: "A hydrogen strategy for a climate-neutral Europe", COM/2020/301 final, 2020

22 EP and EC: Proposal for establishing a framework for ensuring a secure and sustainable supply of critical raw materials; COM (2023)160.

23 Hydrogen Europe Research: Advancing Hydrogen Technologies, Key Research and Innovation Priorities, 2024

24 A. Malhotra and T. S. Schmidt: Accelerating Low-Carbon Innovation, Joule 4 (11), 2020

25 "Experience curves" describe the cost dynamics of (low-carbon) technologies, according to which a technology's cost decreases by a fixed percentage for each doubling of its cumulative installed capacity.

26 E. Doyle et al.: Achieving affordable green hydrogen production plants, 2023

27 E. Doyle et al.: Achieving affordable green hydrogen production plants, 2023

28 S. Revinova et al.: Forecasting Development of Green Hydrogen Production Technologies Using Component-Based Learning Curves. Energies 16(11): 4338, 2023

29 International Energy Agency: Global Hydrogen Review 2022, 2022

30 R. Way et al.: Empirically grounded technology forecasts and the energy transition, Joule 6 (9), 2022

31 International Energy Agency: Global Hydrogen Review 2024, 2024

32 L. Collins: Green hydrogen price in Europe unlikely to fall below €5/kg by 2030, putting off potential offtakers: analyst, Hydrogen Insight, 2023

33 H. Böhm et al.: Estimating future costs of power-to-gas – a component-based approach for technological learning, International Journal of Hydrogen Energy. 44. 30789-30805, 2019

34 Hydrogen Europe Research: Advancing Hydrogen Technologies, Key Research and Innovation Priorities, 2024; https://hydrogeneuroperesearch.eu

35 https://stashh.eu/

36 E. Doyle et al., Rambold: Achieving affordable green hydrogen production plants, 2023

37 Innovative Advanced Materials-Initiative: Innovative Advanced Materials for Europe, 2024

38 A. Toner-Rodgers: Artificial Intelligence, Scientific Discovery, and Product Innovation, MIT, 2024

39 European Commission: Advanced Material for Industrial Leadership, 2024

40 European Commission: Policy Landscape Supporting Technology Infrastructures in Europe, 2024

41 Hydrogen Europe Research, https://hydrogeneuroperesearch.eu/rt-infrastructures, last accessed 05/2025

42 European Commission: Policy Landscape Supporting Technology Infrastructures in Europe, 2024

43 Technology Infrastructures Commission Staff Working Document – European Commission, Directorate General for Research and Innovation, Publications Office of the European Union, 2019

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