Position Paper

Hydrogen Europe Research

Advancing Hydrogen Technologies

Key Research and Innovation Priorities

A roadmap for pioneering research projects

November 2024

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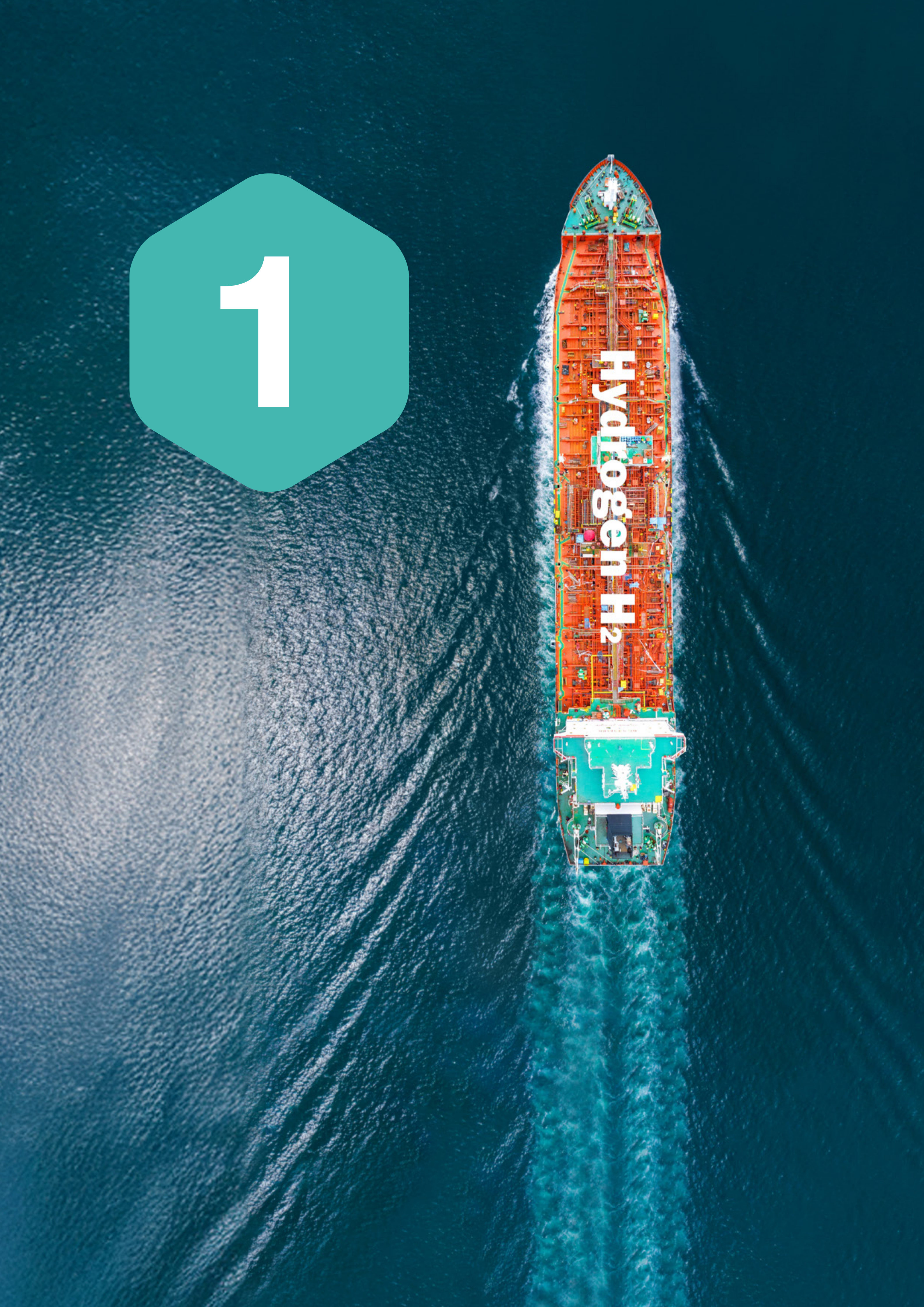

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Foreword

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
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

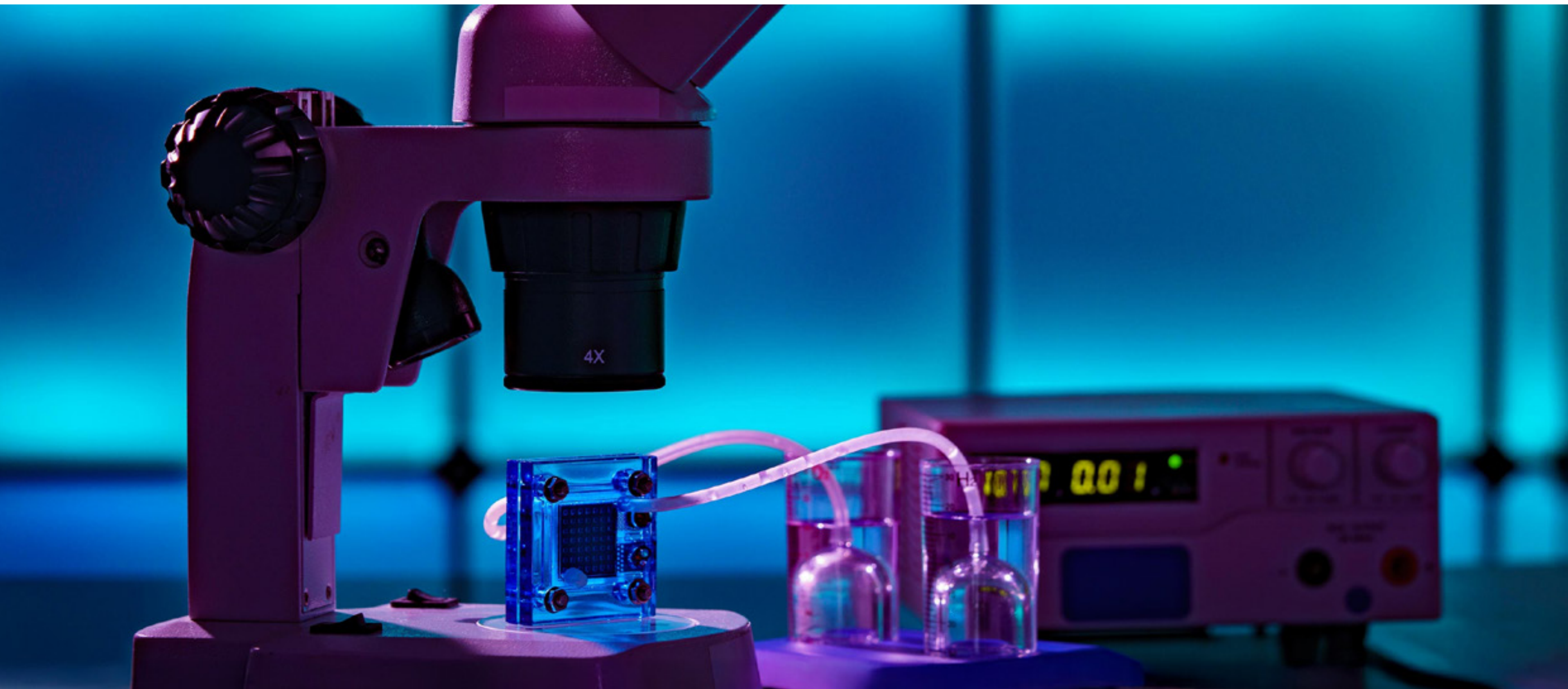
Innovative Cell and Stack Designs for Electrolysis

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.

Hydrogen Europe Research

> 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.

Hydrogen Europe Research

> 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.

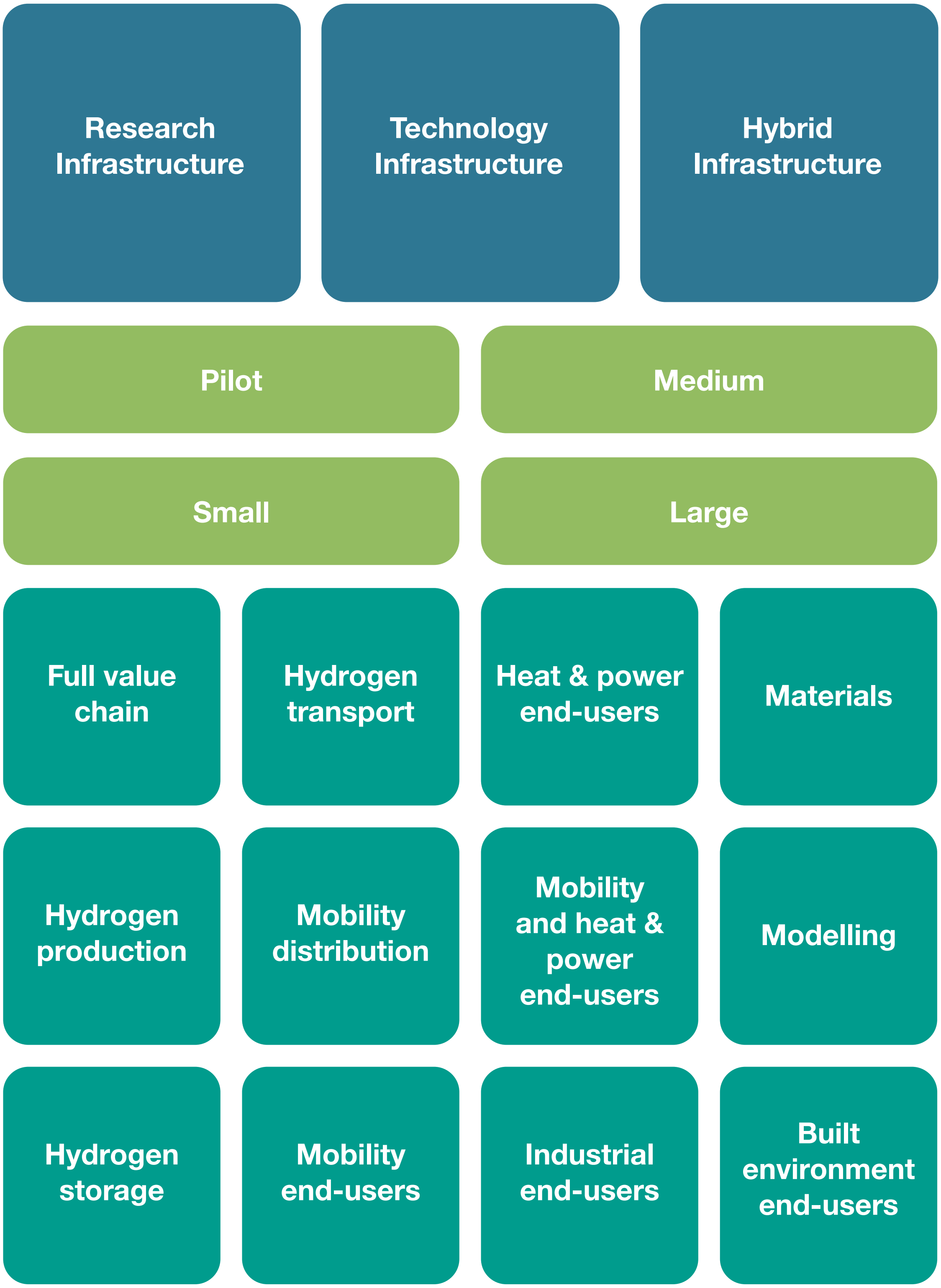
Ludwig Jörissen,
Technical Committee Leader Hydrogen Supply Chain

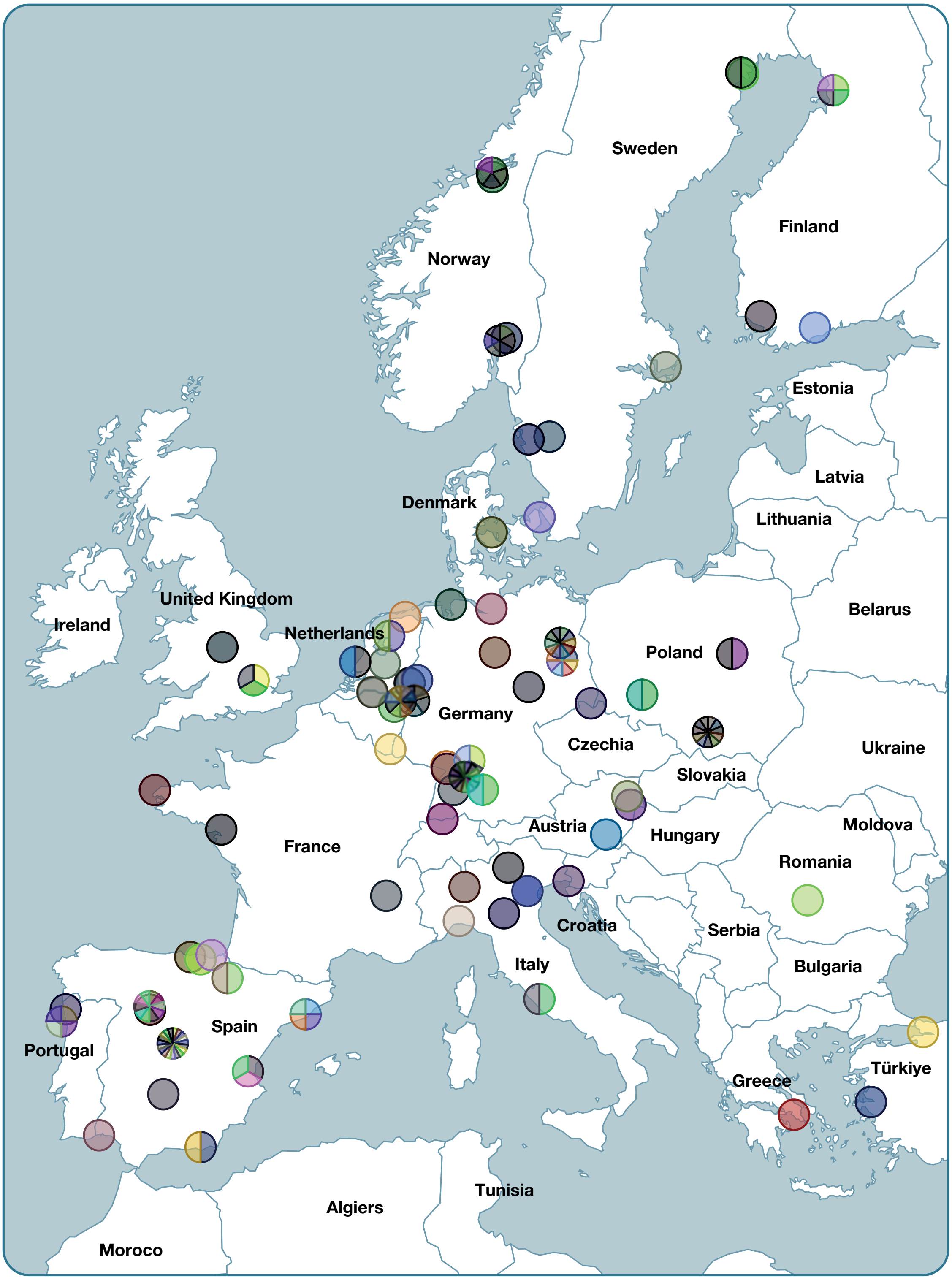
4.5 Research and Technology Infrastructures

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

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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.

www.hydrogeneuroperesearch.eu

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