European Commission

Joint Research Centre

Ensuring safe hydrogen fuel operations: Lessons learned and safety considerations for industry operations

Summary of an expert webinar exchange,
9 October 2024

Van Wijk, L., Wood, M., Moretto, P.

2026

This document is a publication by the Joint Research Centre (JRC), the European Commission's science and knowledge service. It aims to provide evidence-based scientific support to the European policymaking process. The contents of this publication do not necessarily reflect the position or opinion of the European Commission. Neither the European Commission nor any person acting on behalf of the Commission is responsible for the use that might be made of this publication. For information on the methodology and quality underlying the data used in this publication for which the source is neither Eurostat nor other Commission services, users should contact the referenced source. The designations employed and the presentation of material on the maps do not imply the expression of any opinion whatsoever on the part of the European Union concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries.

The Joint Research Centre: EU Science Hub
https://joint-research-centre.ec.europa.eu

JRC144097
EUR 40656

PDF ISBN 978-92-68-38188-5 ISSN 1831-9424 doi:10.2760/4976910 KJ-01-26-121-EN-N

Luxembourg: Publications Office of the European Union, 2026

© European Union, 2026

The reuse policy of the European Commission documents is implemented by the Commission Decision 2011/833/EU of 12 December 2011 on the reuse of Commission documents (OJ L 330, 14.12.2011, p. 39). Unless otherwise noted, the reuse of this document is authorised under the Creative Commons Attribution 4.0 International (CC BY 4.0) licence (https://creativecommons.org/licenses/by/4.0/). This means that reuse is allowed provided appropriate credit is given and any changes are indicated.

For any use or reproduction of photos or other material that is not owned by the European Union permission must be sought directly from the copyright holders.

How to cite this report: Van Wijk, L., Wood, M., and Moretto, P., *Ensuring safe hydrogen fuel operations: Lessons learned and safety considerations for industry operations - Summary of an expert webinar exchange, 9 October 2024,* Publications Office of the European Union, Luxembourg, 2026, https://data.europa.eu/doi/10.2760/4976910, JRC144097.

Contents

Abstract 2

Acknowledgements 3

1 Introduction 4

1.1 The JRC hydrogen fuel risk webinar series 4

1.2 Structure and highlights of the third hydrogen fuel risks webinar 5

1.3 Summary of key discussion themes 6

2 Presentations 7

2.1 JRC MAHB – Setting the scene 7

2.2 JRC - Lessons learned from hydrogen accidents JRC 8

2.3 DNV – Hydrogen research 9

2.4 Energy Institute - Safety research (Safety research outlook and programme for the hydrogen economy) 10

2.5 VDI - Technical standards 11

2.6 Air Product - Emergency response 14

2.7 Air Liquide - Safety and regulatory aspects for large-scale hydrogen deployment 14

2.8 CEPSA - Expanding hydrogen production capacity 15

3 Key findings and suggestions 17

4 Conclusions 20

References 21

List of figures 22

Abstract

This report provides a synthesis of discussions held during the third webinar in the series addressing hydrogen fuel risks, organised by the European Commission's Joint Research Centre (JRC) in partnership with the Organisation for Economic Co-operation and Development (OECD), on 9 October 2024. Valuable insights were provided into the critical aspects of hydrogen infrastructure development, focusing on safety challenges, regulatory frameworks, stakeholder engagement, and risk mitigation strategies.

In response to global strategies aimed at reducing dependence on carbon-based fuels, numerous countries are promoting investments in alternative energy sources, notably hydrogen fuels. Hydrogen is an abundant and versatile resource that plays a crucial role in chemical manufacturing and oil refining. However, its use is associated with flammability and explosiveness risks, necessitating the implementation of appropriate safety controls to mitigate potential hazards, particularly in large-scale applications. Both industry and government have significant roles in minimising adverse impacts related to the introduction of new hydrogen fuel applications and infrastructure on workers and surrounding communities.

The webinar facilitated exchanges between industry stakeholders and regulators from EU and OECD member countries, addressing the main challenges associated with hydrogen-related risks. This initiative is particularly relevant given the rapid expansion of hydrogen fuel projects currently undergoing or soon to enter regulatory review processes. The discussions encompassed an overview of various hydrogen fuel technologies and their proposed applications, alongside risk management considerations pertinent to inspectors, local authorities, and regulatory agencies responsible for permitting and oversight.

Key findings from the webinar highlight the need for harmonised international safety standards, enhanced monitoring and detection systems, improved emergency response protocols, and comprehensive stakeholder engagement. It was noted that the main challenge remains the consolidation of safety distances approaches to consequence modelling. This publication summarises the main insights collected from these exchanges, serving as a critical platform for dialogue that enables stakeholders to collaboratively address the complexities of hydrogen fuel risks and regulatory considerations. The webinar is part of a series organised by the JRC to provide competent authorities with the necessary knowledge to address emerging risks linked to hydrogen fuels and other alternative energy sources.

This report summarises the main conclusions drawn from the webinar. It does not necessarily reflect the official positions or the views of the OECD or of the European Commission. The report has not been reviewed by the OECD's Working Party on Chemical Accidents nor the OECD's Chemicals and Biotechnology Committee.

Acknowledgements

The authors express their sincere gratitude to all participants of the Hydrogen Fuel Risks Webinar 3 for their engagement and contributions during the discussions. Special recognition is given to the Organisation for Economic Co-operation and Development (OECD) for facilitating the inclusion of diverse perspectives from non-EU countries and experts, which enriched the overall dialogue. Moreover, the invaluable contributions of the Technical Advisory Group are acknowledged, for their critical role in guiding the structure of the webinar series to address a wide range of critical issues related to emerging hydrogen fuel risks. The dedication of the Technical Advisory Group members in generously sharing their national insights and innovative tools has been beneficial in addressing specific challenges within the evolving hydrogen sector.

1 Introduction

The third webinar in the Hydrogen Fuel Risks series, titled Hydrogen Fuel Risks Webinar 3, was held on 9 October 2024. Organised in collaboration with the Major Accident Hazards Bureau (MAHB) of the European Commission's Joint Research Centre (JRC) and the Organisation for Economic Co-operation and Development (OECD), the event brought together over 400 participants, including representatives from industry, regulatory bodies, and research institutions. In all, 41 countries were represented in the webinar, including 23 EU and 28 OECD member countries, plus Argentina, Bosnia-Herzegovina, India, Iran, Kosovo, Montenegro, Philippines, Singapore, and Ukraine. Contributions were made by experts from organisations such as Air Products, the Energy Institute, VDI, Air Liquide, and Compañía Española de Petróleos (Cepsa).

As the concluding event in a structured series facilitated by the JRC, the webinar focused on the safety challenges, regulatory frameworks, and strategies for deploying hydrogen technologies in a rapidly evolving energy landscape. The discussions aimed to foster dialogue among stakeholders, share insights on risk management, and promote collaboration to ensure the safe and sustainable development of hydrogen technologies.

This report provides a detailed analysis of the key themes, findings, and recommendations that emerged during the webinar.

1.1 The JRC hydrogen fuel risk webinar series

Hydrogen has emerged as a critical clean energy carrier in the global transition to a decarbonised energy system. Its potential to decarbonise hard-to-abate sectors, such as transportation, heavy industry, and power generation, has driven significant investment and innovation across industry. However, hydrogen's unique properties, such as its low ignition energy and wide flammability limits, its potential to embrittle steel, and its low boiling point (for cryogenic storage), pose safety challenges that must be addressed to enable its safe and widespread adoption.

The webinar series was initiated in response to growing inquiries from EU and OECD discussions, as well as questions from Seveso inspectors, regarding risk assessment methodologies for new hydrogen applications. The series aimed to bring together industry experts, regulators, and researchers to assess hydrogen technologies, evaluate associated risks, and examine the evolving regulatory landscape.

There have been four webinars on hydrogen fuel risks. In addition to the webinar 3 described in this report, the following additional webinars have taken place:

Webinar 1 – foundations and ongoing projects (15 September 2023)

Focused on introducing either ongoing or planned hydrogen fuel projects and discussing technical investigations to ensure safe operations. Authorities and researchers shared updates on initiatives to enhance hydrogen accessibility and safety.

Participation: 60+ participants from 24 EU and OECD countries

Webinar 2 – safety, inspections, and regulatory challenges (14 February 2024)

Building on the discussions from the first webinar, Webinar 2 addressed hydrogen-related risks, regulatory challenges, and the rapid evolution of hydrogen applications. Emphasis was placed on engaging stakeholders beyond the process safety community to ensure broader awareness and collaboration.

Participation: 198 from 23 EU countries, 28 OECD countries, and four additional countries (Argentina, Kenya, Moldova, Philippines, Singapore)

Webinar 3 – process safety and strategic deployment (9 October 2024)

The third webinar explored process safety concerns, standardisation needs, and strategies for deploying hydrogen technologies responsibly. The session highlighted the importance of balancing safety, efficiency, and environmental accountability while fostering collaboration among stakeholders.

Participation: 410+ from 23 EU and 28 OECD countries and other countries

Webinar 4 – Focus on exchange with policymakers and ammonia safety (11 March 2025, Final report not yet published)

This webinar fostered an exchange with the EU level energy policy actors on challenges raised by regulators in Webinars 1 and 2. The second part of the webinar focused on new initiatives to ensure safety with large NH_3 storage associated with hydrogen fuel distribution and production.

Participants: 289 participants from 21 EU countries, 28 OECD countries, and six additional countries (Argentina, Bahrain, Philippines, Singapore, Ukraine, and United Arab Emirates).

Detailed agendas, presentations, and reports from each webinar are available online on the home page of the Hydrogen Fuel Risks Webinar Series.

1.2 Structure and highlights of the third hydrogen fuel risks webinar

The third webinar presented a comprehensive industry perspective on hydrogen risks and standards development, alongside ongoing research efforts. Key representatives from industry and standards organisations discussed practical challenges, safety concerns, and solutions, stressing the need to align safety practices with technological innovation for scalable hydrogen deployment. Case studies of hydrogen-related incidents were shared by the Joint Research Centre (JRC), providing detailed analyses of root causes, impacts, and safety lessons to enhance risk management.

In addition, the webinar highlighted some important challenges, as indicated below:

- DNV underscored the complexity of transitioning to a hydrogen-based energy system aimed at net-zero emissions by 2050, underscoring the extensive research and safety measures required due to new technologies, operators, interfaces, and processes across the hydrogen value chain.
- The Energy Institute presented an analysis of hydrogen safety, focused on its unique physical and chemical properties compared to hydrocarbons like methane, and the implications for tailored safety strategies.

- The Association of German Engineers (VDI) outlined a harmonised standardisation roadmap to address technical and safety challenges, aiming to align national, European, and international standards to prevent fragmentation, reinforce EU leadership, build public trust, and accelerate market integration.

- Air Products described its operational safety protocols and emergency response measures for hydrogen systems, drawing on extensive experience with high-pressure gaseous and liquid hydrogen. Emphasis was placed on lessons learned, robust design, and disciplined operational practices.

- Air Liquide summarised its efforts to harmonise safety standards, particularly regarding safety distances and technical aspects of hydrogen infrastructure development, reflecting its extensive experience in handling hydrogen and its active role in standardisation.

1.3 Summary of key discussion themes

The webinar provided a thorough overview of industry efforts to overcome hydrogen safety and standardisation challenges, facilitating the safe and effective integration of hydrogen technologies into the energy system. It also highlighted recent advancements in hydrogen technologies and their critical role in the clean energy transition. Key discussion themes included:

- **Safety challenges and risk management**

  Emphasis was placed on the development of safety protocols and risk management strategies tailored to the unique hazards of hydrogen. Ensuring safety throughout the entire hydrogen value chain was recognised as a primary concern.

- **Regulatory challenges**
  The need for effective regulatory frameworks that balance risk mitigation with innovation and large-scale deployment was discussed. Harmonisation of standards emerged as essential to reduce barriers and ensure consistency across jurisdictions.

- **Collaboration and stakeholder engagement**
  Cross-sector cooperation involving industry, government, and academia was identified as vital to addressing technical, safety, and regulatory issues. Transparent communication and public engagement were highlighted as key factors in building trust and promoting acceptance of hydrogen technologies.

In addition, the webinar expanded understanding of hydrogen's physical properties and provided insights into the hydrogen value chain, including production methods, distribution, and storage infrastructure.

The webinar also highlighted that there is substantial work ahead to achieve alignment of technical standards to ensure operational integrity and safety throughout the value chain. The industry has led development of strategies to address these gaps, but it is a work in progress and the timeline needed to fulfil all the gaps identified is still unclear.

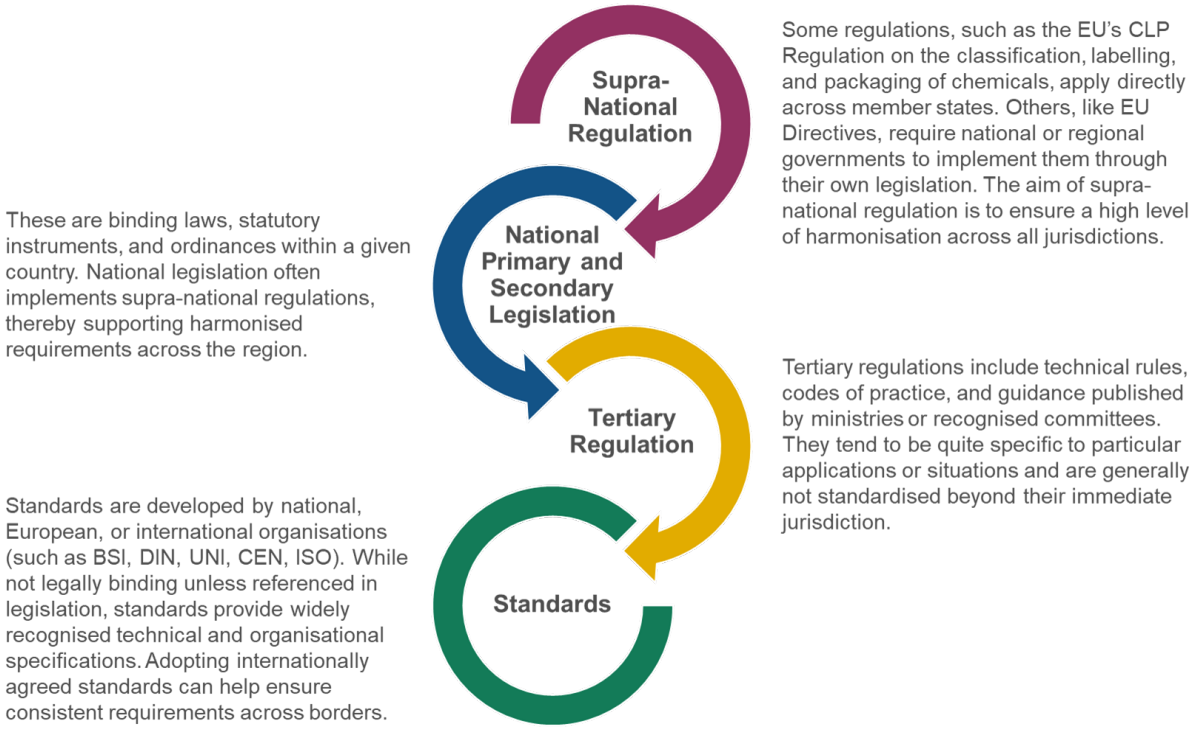
2 Presentations

This chapter provides concise summaries of the speakers' presentations delivered during the webinar, highlighting insights, technical advancements, and strategic initiatives across the hydrogen industry. The summaries capture the scope of research, safety considerations, regulatory developments, and operational experiences essential for advancing a safe and sustainable hydrogen economy.

2.1 JRC MAHB – Setting the scene

MAHB highlighted key safety challenges and regulatory considerations for the safe hydrogen technology deployment. While established hydrogen legislation and safety standards exist for traditional uses, they are not fully adapted to address the challenges posed by new applications, locations, and actors. This discrepancy creates for new operators, emphasising the need for coordinated regulatory efforts and effective communication among stakeholders to develop clear, enforceable guidelines tailored to emerging hydrogen uses.

Figure 1 Regulatory frameworks governing hydrogen spans supranational, national, and local levels



Source: Mark Hailwood (presented in Wood, 2024)

Hydrogen's unique properties demand robust risk assessments and effective emergency preparedness. There is a need to develop standardised emergency procedures and consolidated response plans, based on the latest research.

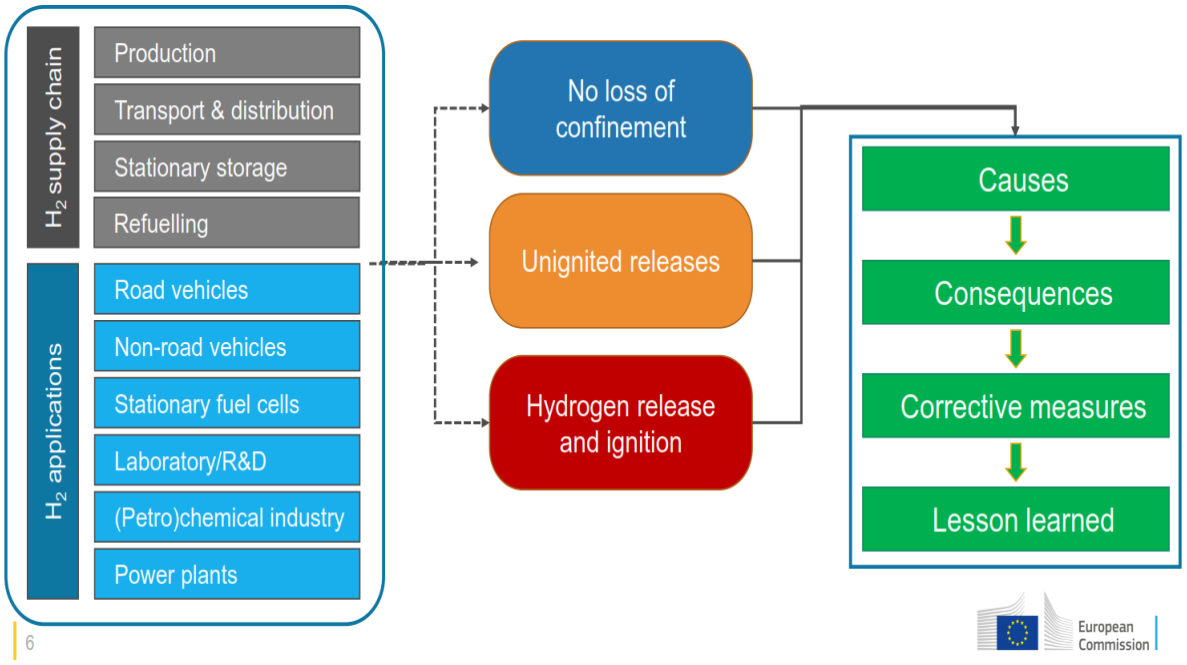
Broader safety efforts should include refined risk assessments that consider community impacts to build public trust. Advancing leak detection and flexible emergency plans that evolve with technology are essential. Recommendations emphasise tailored legislation, stronger collaboration among regulators, industry, and safety bodies, plus expanded training and knowledge sharing. Research on hydrogen's effects on materials like pipelines is critical for safe operations, and lessons from chemical and petroleum sectors can enhance safety.

The regulatory framework illustrated in **Figure 1** spans supranational, national, and local levels, each with distinct responsibilities that collectively support safe deployment. EU legislation such as the Seveso Directive and ClP Regulation set harmonised safety and classification standards. National governments adapt these into binding laws and technical standards, while regional codes and guidelines vary, complicating compliance. Local authorities enforce site-specific safety through permits, assessments, and emergency planning. This multi-tiered system ensures comprehensive hydrogen safety management frameworks across contexts.

2.2 JRC - Lessons learned from hydrogen accidents JRC

The JRC presented the Hydrogen Incident and Accident Database (HIAD 2.1, updated September 2023), a comprehensive repository documenting hydrogen-related accidents occurred in the EU and globally. As illustrated in **Figure 2,** HIAD incident reports provide insights on causes, consequences, release scenarios, and lessons learned, supporting enhanced risk management, system design, and operational protocols amid hydrogen's energy transition expansion.

Figure 2 Structure of the database HIAD



Source: Moretto and Smedberg, 2024

Analysis of HIAD data reveals the multifactorial nature of hydrogen incidents, with 62% attributed to management and human factors. For example, a fire caused by mechanical damage to an underground hydrogen pipeline during excavation (Incident #891)[1] illustrated how inadequate communication about pipeline locations can lead to significant risks. Another incident (Incident #174) involving hydrogen coolant transfer at a power plant highlighted the consequences of poor maintenance, flawed safety design, and failure to learn from previous events. Similarly, a fire on a hydrogen tube trailer truck (Incident #1025), triggered by brake system defects causing tire

[1] Numbers refer to incident numbers in the HIAD database https://minerva.jrc.ec.europa.eu/en/shorturl/capri/hiadpt

overheating, exposed vulnerabilities in vehicle maintenance and material reliability. These cases exemplify how minor contributing factors can align to create major hazards, consistent with James Reason's "Swiss Cheese Model" of accident causation.[2]

Key take-away: JRC highlighted the role of learning from incidents to strengthen hydrogen safety culture. HIAD and associated case studies underscore hydrogen safety's complexity and the indeed for ongoing improvements in design, operations, and emergency response, aligned with regulatory frameworks that integrates these lessons into evolving standards.

2.3 DNV – Hydrogen research

Dan Allason of DNV presented a comprehensive analysis of hydrogen safety, leveraging decades of research and operational experience. He emphasised hydrogen's distinct physical and chemical properties relative to hydrocarbons like methane, and their implications for hazard mitigation and safe energy integration.

Hydrogen's low density yields volumetric flow rates about 2.8 times greater than methane for equivalent turbulent leaks, which can give rise to larger flammable clouds. Its mass energy density is 2.4 times that of methane, with comparable initial energy release rates. Hydrogen flames exhibit high stability and proximity to release points due to elevated burning velocity and wide flammability limits, reducing flame blow-off but increasing explosion risk in confined spaces. Flame temperatures exceed methane's by approximately 200°C, challenging material integrity and fire management.

In enclosed spaces, buoyancy-driven mixing accelerates hydrogen accumulation above release points, reaching explosive concentrations faster than methane. Accurate modelling of such scenarios is essential for accurate hazard assessment and safety planning.

The DNV presentation also addressed the issue of public scepticism linked to hydrogen's novelty and historic incidents like the Hindenburg disaster, underscoring the need for transparent communication, education, and visible safety measures to build societal trust.

Mr. Allason advocates a proactive risk management approach incorporating quantitative risk assessments tailored to hydrogen's detonation potential, guiding mitigation via catalytic burners, oxygen sensors, and advanced ventilation. Simulation tools, such as dispersion and explosion models, are essential for optimising safety design and mitigating risks. Stakeholder collaboration and clear communication remain paramount for public acceptance.

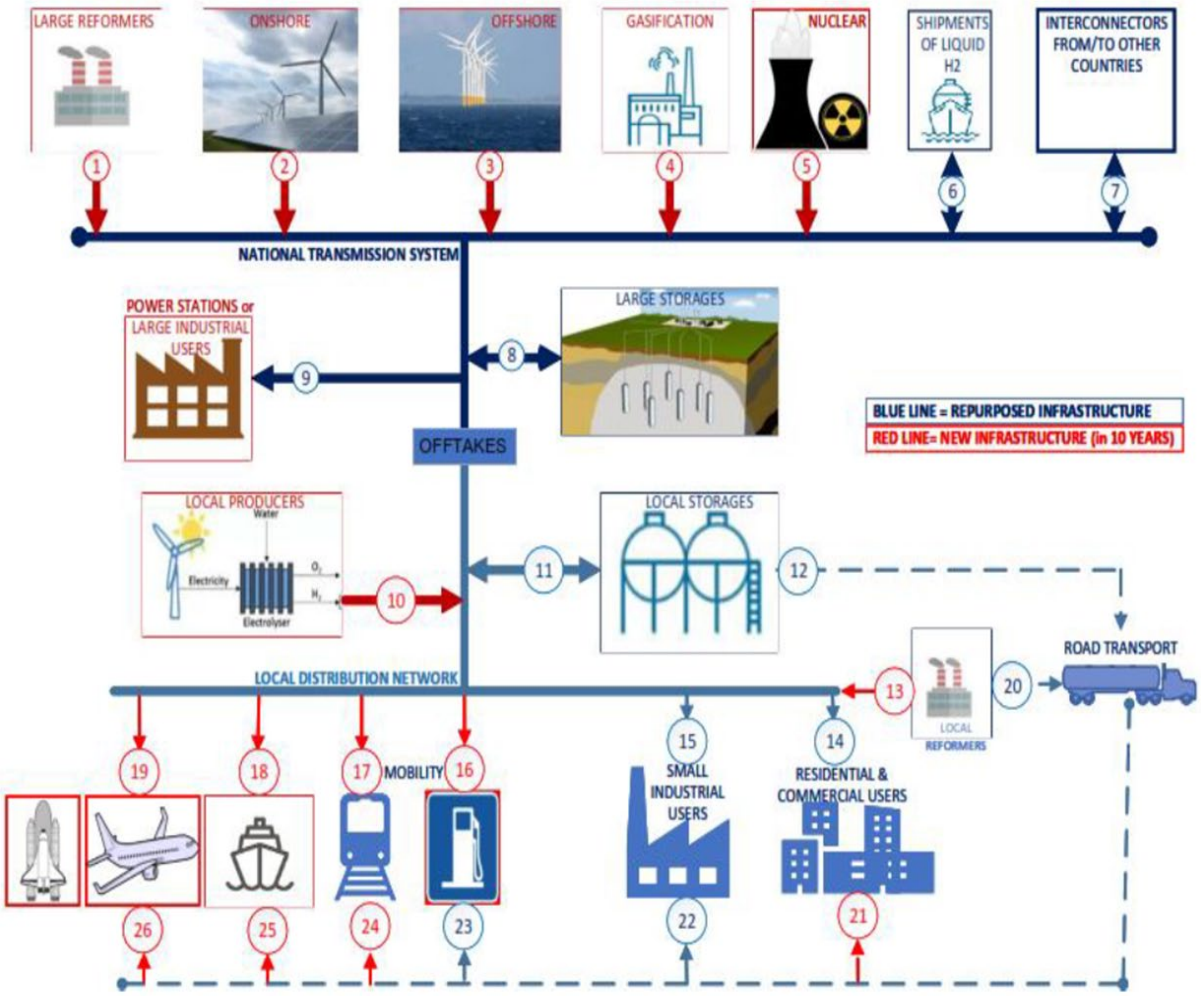
Key take-away: DNV's research highlights engineering innovation, predictive modelling, and public engagement as critical to resolving hydrogen-specific safety challenges, enabling its safe, efficient integration into energy systems and supporting the transition to a hydrogen economy with assured public confidence.

[2] For the full analysis of the HIAD data, see Wen, J. X., M. Marono, P. Moretto, E. Reinecke, P. Sathiah, E. Studier, E. Vyazmina and D. Melideo, 2022, Statistics, lessons learned and recommendations from analysis of HIAD 2.0 database, International Journal of Hydrogen Energy, Volume 47, Issue 38, 1 May 2022, Pages 17082-17096, https://doi.org/10.1016/j.ijhydene.2022.03.170

2.4 Energy Institute – Safety research (Safety research outlook and programme for the hydrogen economy)

Mark Scanlon of the Energy Institute (EI) outlined the extensive safety research needed to support the hydrogen economy's net-zero transition by 2050, as shown in **Figure 3.** The emerging hydrogen value chain introduces complex safety and environmental challenges due to new technologies, operators, and interfaces, demanding rigorous safety management and comprehensive regulatory frameworks beyond traditional industrial hydrogen systems.

Figure 3 National systems view of the hydrogen value chain



Source: Scanlon, 2024

Current legislation like the Seveso Directive and the UK Control of Major Hazards (COMAH) Regulation cover emerging onshore hydrogen facilities but lack provisions for large-scale storage, transport, overpressure protection, leak detection, compression, hydrogen blending in gas pipelines, and corrosion in repurposed infrastructure. Offshore hydrogen production remains regulated under general hazardous fluid rules, rather than the Offshore Safety Directive, highlighting regulatory gaps.

EI is updating process safety standards (e.g., EI 3015[3], EI 3314[4]) to address gaseous and liquid hydrogen risks and passive fire protection, but research gaps persist. Its technical committee of over 1,000 experts is developing guidelines to close these gaps. However, limited expertise and fragmented stakeholder coordination cause inconsistent safety practices across technology readiness levels.

The presentation indicated that EI was carrying out an assessment in phases. For example, 2024 covered understanding and addressing technical challenges for the deployment of a hydrogen economy, while 2025 was provisionally expected to target technical challenges for the hydrogen economy (e.g., the maturity and service supply chain. These assessments will identify potential gaps and weaknesses in the current standards frameworks and also strategies for addressing them.

The hydrogen safety landscape is fragmented, involving multiple organisations across research, standards, and skills development working in parallel across various technology readiness stages. High-level coordination is essential to harmonise efforts and ensure consistent industry-wide safety practices.

EI's research priorities span the entire value chain, focusing on safety cases for large-scale storage and transport, safe separation distances, high-pressure system validation, advanced leak detection, pipeline materials, and hydrogen integration into existing systems. Phase 2 research (completion 2025) targets vulnerabilities in isolation systems, pressure valves, custody transfer, and infrastructure interfaces.

Mr. Scanlon emphasised stakeholder collaboration to address skills shortages and align academia, industry, and regulators. Training programmes for hydrogen operators are prioritised from 2024 onward, reflecting the value chain's complexity. Large projects like the EU Hydrogen Backbone, aiming to transport 130 million tonnes annually, illustrate the scale and need for sustained innovation.

Key take-away: EI stressed that realising a hydrogen-based energy system requires continuous research, innovation, and global collaboration. While progress is underway, robust safety frameworks and standards remain a work in progress. EI is committed to leading these efforts, but coordinated international action is vital for safe, efficient hydrogen deployment as a cornerstone of the net-zero transition and a commitment to these efforts over the long term is essential..

2.5 VDI - Technical standards

Kevin Hares of the Association of German Engineers (VDI) outlined a comprehensive Standardization Roadmap addressing technical and safety challenges in hydrogen deployment. The roadmap seeks to harmonise national, European, and international standards to avoid fragmentation, reinforce EU leadership, build public trust, and accelerate market integration.

Though hydrogen technologies are established, scaling and novel applications demand updated safety protocols and regulations. Developed collaboratively with German partners (DIN, DKE, DVGW) and funded by the German Federal Ministry for Economic Affairs and Climate Action (BMWK), the

[3] EI 3015 EI Model code of safe practice Part 15: Area classification for installations handling flammable fluids

[4] EI 3314 Guidance on passive fire protection for process and storage plant and equipment

roadmap covers all practical aspects of operations, that is, facility and equipment design, personnel training and certification, quality assurance and safety, within the value chain (production, storage, distribution and transport, and consumer and industrial uses).

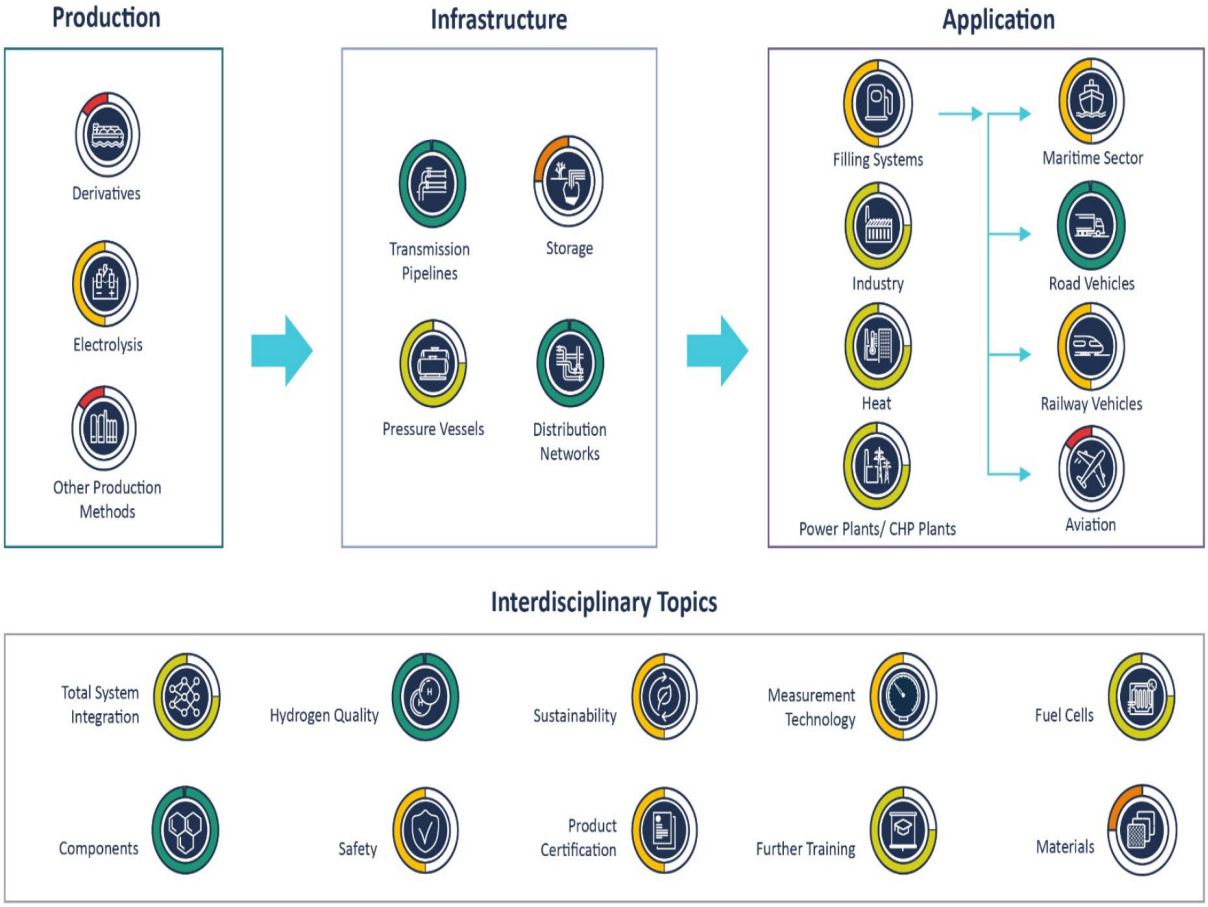
The establishment of the Roadmap involved 39 working groups and over 600 experts from industry, academia, and government, guided by a steering committee prioritizing strategy and resources. To meet urgent needs, 38 immediate projects address electrolyser safety, personnel training and certification, and interoperability of refuelling stations and pipelines.

The Roadmap divides the standardisation path in three phases: analysis, recommendation, and implementation. The analysis phase consists of a review of approximately 1,000 relevant standards, identifying about 300 needing updates on hydrogen release safety, dispersion modelling, risk assessment, electrolyser safety, refuelling station compatibility, and hydrogen blending in gas pipelines. (See **Figure 4**.) The recommendation phase identifies standardisation projects (e.g., adapting VDI 3783-2 for hydrogen hazard identification), including validation and testing methods to inform the standardisation process. Mr. Hares emphasised that many revisions would require additional research on hydrogen properties in application. The implementation phase launches funded projects at national, European, and international levels to ensure harmonised progress. The roadmap describes the results of a needs analysis of each standardisation subtopic, followed by recommendations for meeting the needs identified and options for implementing these recommendations. The process of revising the standards was foreseen to take place over a period of several years.

Notably, the VDI approach aims to integrate safety into technical standards using various mechanisms, such as separation distances, leak prevention, and the incorporation of hydrogen-specific risk management principles. These elements are integrated within standards governing component compatibility and high-pressure systems, thereby ensuring a comprehensive framework for managing hydrogen-related risks. For example, current projects address electrical protection for large electrolysers, vehicle and refuelling station compatibility, and risk-based blending standards. Moreover, emphasis on interoperability supports scalability by enabling seamless integration of transport, storage, and end-use systems, including repurposed gas infrastructure. VDI also aligns German standards with CEN/CENELEC[5] and ISO/IEC frameworks to promote global market acceptance and reduce fragmentation.

[5] European Committee for Standardization/European Committee for Electrotechnical Standardization

Figure 4 Technical rule framework



Source: Hares, 2024

Mr. Hares acknowledged challenges in achieving implementation of roadmap recommendations, including expert shortages delaying progress, the complexity of harmonising safety with technical standards, and extensive stakeholder coordination required across governance levels.

VDI's efforts complement the Energy Institute's safety research, focusing on technical standards while EI targets safety frameworks. Recent advances include updated electrolyser safety and electrical protection standards, interoperability standards for vehicles and refuelling infrastructure, and training guidelines to ensure consistent operational and safety practices.

A second version of the Standardization Roadmap Hydrogen Technologies will further specify and consolidate the existing Roadmap. The final version of the Roadmap will be published at the end of 2025.

Key take-away: VDI's Roadmap, due in 2025, systematically analyses standardisation gaps and fosters stakeholder collaboration, providing a robust framework for harmonised hydrogen standards. The roadmap recommendations support safe, interoperable, and scalable hydrogen deployment, important for the sustainable energy transition. The timeline for achieving the roadmap objectives is not yet clear, but implementation of many recommendations is already underway.

2.6 Air Product - Emergency response

Derek Miller from Air Products detailed the company's operational safety and emergency response protocols for hydrogen systems, based on extensive experience with high-pressure gas and liquid hydrogen. Air Products has several decades of experience in managing hydrogen risks safely. The presentation's focus was on Air Products' specific practices rather than proposing universal standards.

Mr. Miller compared the safety profiles of high-pressure gas versus liquid hydrogen systems. High-pressure gas systems pose leak and rupture hazards due to numerous fittings and stored energy, requiring rigorous design and maintenance. Liquid hydrogen systems, with welded construction, double-wall cryogenic vessels, and automatic emergency isolation, offer improved containment and reduced leak risks, underscoring the critical role of design integrity and operational discipline.

Storage and transport safety challenges were illustrated through case studies. A liquid hydrogen transport truck collision highlighted the need for robust emergency isolation and vehicle safety features. A rupture disc failure in a gas system underscored the importance of regular inspection and maintenance of pressure relief devices. These incidents informed Air Products' continuous refinement of safety practices.

Emergency response protocols emphasise hydrogen's unique hazards, i.e., low ignition energy, wide flammability range, and cryogenic risks. Automatic isolation systems in liquid hydrogen setups enable rapid leak containment. Specialised, ongoing training for emergency responders is essential, reflecting lessons learned from real-world incidents.

Mr. Miller acknowledged that Air Products' protocols are tailored to its operations and may not universally apply across the hydrogen industry. The complexity of hydrogen systems demands strict design standards, maintenance, and specialised training. He also highlighted gaps in current training frameworks and the need for continual skill development as hydrogen technologies evolve.

Key take-away: Air Products' presentation emphasised robust design, meticulous maintenance, and targeted training as pillars of hydrogen safety. Drawing on operational experience, Air Products' practices demonstrate the importance of continuous improvement in safety and emergency preparedness within the hydrogen industry.

2.7 Air Liquide - Safety and regulatory aspects for large-scale hydrogen deployment

Dr Elena Vyazmina, Regulations Codes and Standards (RCS) Expert at Air Liquide, serves as manager of the IEA[6] TCP H2 Task 43 (Safety & RCS for Large-scale Deployment) and is a member of the European Hydrogen Safety Panel. In her presentation, she outlined Air Liquide's extensive expertise in hydrogen safety and detailed the company's proactive efforts to address regulatory and safety challenges associated with the large-scale implementation of hydrogen technologies.

A central theme of the presentation was the harmonisation of safety standards, with particular attention to interoperability, the establishment of appropriate safety distances, and the importance of stakeholder engagement for effective infrastructure development. Dr Vyazmina highlighted Air

[6] International Energy Agency (IEA)

Liquide's collaboration in major international standardisation bodies and active involvement in ISO TC 197[7], CEN-CENELEC, and EIGA[8] and CGA[9]. This involvement aims harmonising safety distance methodologies for gaseous and liquid hydrogen applications such as electrolysers, refuelling stations, marine bunkering, and large liquid hydrogen storage (exceeding 10 tonnes). These safety distances refer specifically to technical standards for the safe siting and operation of hydrogen installations within industrial sites. They do not necessarily extend to land-use planning (LUP) considerations, which are subject to separate regulatory frameworks and national policies. These standardisation efforts under IEA Task 43 aim to establish global baseline safety practices that accommodate regional risk tolerances and industrial practices, while recognising the distinction between technical safety standards and LUP requirements.

IEA TCP H2 Task 43 is currently developing a harmonised safety distance methodology by reviewing existing practices in North America, Asia, Australia, and Europe. The Task Group has identified three principal inconsistencies in current methodologies:

1. Inconsistent harm criteria: There is significant variation in thermal radiation thresholds (10–40 kW/m²) and overpressure limits (50–140 mbar).
2. Variation in leak scenario definitions.
3. Divergent explosion severity thresholds, particularly regarding concentration levels.

Furthermore, there is no unified approach for defining worst-case events, such as explosions in gas–liquid separators or electrolysers involving hydrogen–oxygen mixtures.

To address these issues, IEA TCP H2 Task 43 is preparing position papers proposing harmonised methodologies for various case studies, including electrolyser safety, explosion severity limits, liquid hydrogen storage, and safety distances for multi-fuel refuelling points (drawing on the MultHYfuel project). Air Liquide's participation in research programmes further supports the development of refined safety measures and risk management strategies, particularly for sectors such as marine bunkering and hydrogen refuelling stations.

Dr Vyazmina emphasised that effective stakeholder collaboration, including regulators, industry, research institutions, and first responders, is essential to ensure the development of coordinated, scientifically robust, and globally applicable safety standards.

Key takeaway: Air Liquide's technical leadership and global engagement are instrumental in addressing critical safety gaps and promoting the harmonisation of standards. Continued research, collaboration, and standardisation are vital to support the safe and widespread adoption of hydrogen within the evolving hydrogen economy.

2.8 CEPSA – Expanding hydrogen production capacity

Jorge Martinez outlined CEPSA's strategic focus on green hydrogen and biofuels to advance the energy transition. Central is the €3 billion "Positive Motion" initiative, Europe's largest green hydrogen

[7] ISO/TC 197 - Hydrogen technologies

[8] European Industrial Gases Association (EIGA)

[9] Compressed Gas Association (CGA)

project, aligned with Europe's decarbonisation goals. Strategic partnerships, including a green hydrogen corridor with the Port of Rotterdam, support CEPSA's net-zero CO2 target by 2050. CEPSA is also building Southern Europe's largest second-generation biofuel plant.

CEPSA's safety framework employs rigorous risk management, using HAZOPs and QRAs to achieve ALARP risk levels. Asset integrity is maintained with a focus on hydrogen-specific hazards. Operator training addresses risks like invisible flames and high pressures, while digital twins simulate hazards to enhance safety planning. Safety culture is reinforced through audits and continuous improvement.

Key safety measures include effective ventilation and advanced detection systems. Lessons from incidents (Porsgrunn 1985, Gangneung and Sandvika 2019) have driven mitigation strategies such as catalytic burners, oxygen detectors, independent ventilation zones, and ATEX compliance. Dispersion modelling defines safety zones and optimises risk control.

Key take-away: CEPSA's emphasised the substantial investments, partnerships, and advanced safety measures as relevant to its role in Europe's hydrogen economy. By addressing technical and safety challenges, CEPSA aims to deliver sustainable, scalable hydrogen infrastructure supporting decarbonisation and the energy transition.

3 Key findings and suggestions

The speakers emphasised the importance of regulatory and safety standards in the safe deployment of hydrogen technologies. Industry experts, regulators, and researchers concurred on the necessity of a coordinated global approach to harmonise safety standards and address the unique risks posed by hydrogen. Central to safe deployment of hydrogen is the technological maturity of hydrogen systems and the development of comprehensive, consistent safety frameworks that span the entire hydrogen value chain.

Key findings:

- Hydrogen's unique properties, such as its wide flammability range, low ignition energy, and high diffusivity, pose significant safety challenges, especially in confined spaces where the formation of an explosive atmosphere is facilitated by presence of obstacles to hydrogen diffusion and effects of explosions can are more severe .
- Safety risks span the hydrogen value chain, including electrolysis plants (e.g., hydrogen-oxygen crossover, membrane degradation), pipelines (e.g., excavation damage, embrittlement, corrosion), refuelling stations (e.g., jet fires, leak explosions, interoperability), and cryogenic storage (e.g., thermal stress, boil-off, pressure build-up).
- Established regulatory frameworks, including the Seveso Directive and the Pressure Equipment Directive, provide robust oversight for hydrogen facilities in the EU. Existing regulations have supported the safe operation of hydrogen facilities for several decades, especially within the chemicals and refining sectors. However, challenges persist in harmonising technical standards and developing hydrogen pipeline networks. These issues primarily concern the standardisation process and the consolidation of consequence modelling approaches, rather than regulatory fragmentation or inconsistency.
- International standards (ISO[10], IEC[11]) provide foundational guidance, but regional and national standards vary widely, with countries progressing toward harmonisation but lacking a unified framework. Moreover, the upscaling of technologies (e.g., large electrolysers, fuel cells, transport of large quantity of hydrogen) as well as innovative solutions (e.g. new membranes) are insufficiently covered by existing regulations, complicating integration.
- For these reasons, it is important that stakeholders work together across industries and across jurisdictions to promote safety and reliability across the supply chain. In addition, the involvement of all stakeholders is essential to assure an open market, leverage economies of scale, and facilitate transnational applications.
- Standardisation needs to include unified guidelines for material compatibility, pressure relief, explosion protection, leak detection, safety distances, risk assessment, change management, training, and emergency response. In many areas, additional research is needed to inform the development of new safety standards. In praticular, addressing knowledge gaps through

[10] Internatonal Organisation for Standardisation

[11] International Electrotechnical Commission

experimental research on hydrogen behaviour and high-risk scenarios (e.g., electrolyser explosions) is critical for refining risk mitigation.

- The historical record of incidents shows that deployment of hydrogen technologies has become safe and reliable in recent years in many existing applications. Nevertheless, the same record highlights the importance of understanding and managing the specific risks that hydrogen poses for specific applications. Moreover, continuous improvement in design, operational protocols, communication, and maintenance. It is particularly important to learn from incidents and foster a robust safety culture with open communication in regard to problems and failures.
- The dangerous properties of hydrogen manifest in different ways depending on the conditions of use. Hence, new uses of hydrogen and use in new contexts should be studied carefully to address safety considerations effectively. New uses of hydrogen as a fuel can achieve the same level of safety as existing uses may be possible to achieve with an equivalent commitment to understanding and managing the risks.
- Technical challenges include developing hydrogen-resistant materials, improving seals, enhancing monitoring systems, and advancing leak detection, pressure regulation, and automated safety systems. In particular, advancing safety technologies require investment in real-time leak detection, cryogenic safety, and materials resistant to extreme temperatures.
- Harmonising technical standards and safety practices at the international level is essential to establish consistent safety benchmarks and support the coordinated deployment of hydrogen. While regulatory harmonisation is already advanced within the EU, differences in regulatory approaches between regions, such as the US and EU, make international harmonisation of regulations less feasible. Focusing on standardisation offers a more practical path towards global consistency in hydrogen safety.
- Industry has developed strategies for aligning current safety and technical standards. However, the landscape is complex and affects many stakeholders. In many cases, updating standards to meet future demands for hydrogen fuel will require significant investment of time and money in research and collaboration to achieve full functionality and safety of all operations.

Suggestions for safety enhancement:

- Establish and adopt standardised approaches to consequence modelling and risk assessment to ensure consistency in safety evaluations, inform technical standards, and support effective regulatory oversight across jurisdictions.
- Collaborative efforts are essential to identify and prioritise research needs to address existing gaps in knowledge related to hydrogen safety as well as to inform the development of standards, risk assessments, and technical specification
- Update and unify international, regional, and national standards to encompass emerging hydrogen technologies and applications, prioritizing interoperability and compatibility.
- Enhance public education and transparent communication to build societal trust and acceptance of hydrogen technologies.

- Strengthen risk assessment methodologies, operational procedures, and continuous training programmes for operators, technicians, and emergency responders.
- Promote collaboration among international organisations, regulators, industry, and academia to align safety requirements, technical specifications, and personnel qualifications.
- Invest in advanced safety technologies, including predictive leak detection, risk analysis tools, fail-safe designs, and automated safety systems to reduce human error.
- Establish robust incident reporting systems and knowledge-sharing platforms to facilitate continuous learning and safety culture development.
- Address gaps in emergency response protocols, large-scale electrolyser safety, and liquid hydrogen handling through targeted research and standardisation.
- Foster a strong safety culture within organisations managing hydrogen technologies via regular audits, education, and awareness campaigns.
- Incorporate design improvements such as hydrogen-resistant materials, redundant venting, explosion-proof electrical equipment, and robust venting and flaring protocols.
- Utilise digital tools like digital twins and dispersion modelling to simulate hazard scenarios and optimise safety planning.
- Engage stakeholders, including regulators, first responders, and the public, in transparent dialogue to support societal acceptance and effective deployment.

4 Conclusions

The webinar underscored the complexity of the hydrogen value chain and the extensive research and development needed to address safety, environmental, and operational challenges. Despite progress through collaboration and standards development, substantial knowledge gaps persist. Effective deployment of hydrogen as a key element of the net-zero transition requires coordinated action among industry, regulators, researchers, and emergency responders.

Hydrogen's unique properties, such as its wide flammability range, low ignition energy, and material compatibility issues, demand specialised risk assessments and tailored safety management across the value chain, including electrolysis plants, pipelines, refuelling stations, and cryogenic storage. The JRC's Hydrogen Incident and Accident Database (HIAD) highlights the critical role of learning from past incidents to build a robust safety culture through continuous system improvements. DNV's insights emphasise engineering innovation and predictive modelling to address hydrogen-specific safety challenges while maintaining public confidence.

While existing regulatory frameworks, such as those governing the chemical and refining industries, have effectively supported hydrogen safety for decades, emerging applications in heavy transport, maritime, and aviation present new challenges that may not be fully addressed by current standards and regulations. Targeted updates and harmonisation of safety standards are therefore important to ensure regulatory consistency, facilitate international deployment, and reduce adoption barriers. The VDI standardisation roadmap, expected by 2025, systematically identify and addresses these sector-specific gaps, fostering stakeholder collaboration and providing a framework for harmonised standards that ensure safety, interoperability, and global coordination. Air Liquide is also contributing by addressing methodological gaps relevant to large-scale hydrogen deployment in these new applications.

A major barrier remains the insufficient coordination among regulatory bodies, industry, and researchers. Enhanced collaboration is essential for comprehensive safety coverage and consistent practices. The Energy Institute stresses that overcoming hydrogen's complexities requires sustained research, innovation, and international cooperation, particularly addressing material science, leak detection, and high-risk scenarios such as electrolyser explosions. Operational experience from Air Products and CEPSA illustrates the necessity of robust design, meticulous maintenance, specialised training, and integration of advanced safety technologies.

Public engagement extending beyond industry and regulators to first responders and the general public is vital. Transparent communication and demonstrable safety measures build societal trust, which is crucial for hydrogen's successful integration. Inclusive dialogue and education should emphasise safety and environmental benefits.

Overall, safe and scalable hydrogen integration depends on continuous innovation, collaboration, adherence to best practices, harmonised safety standards, technical advancements, a strong safety culture, and transparent public engagement. By embracing these measures, the hydrogen sector can overcome fragmentation, enhance safety, and fulfil its potential as a cornerstone of a sustainable, decarbonised energy future.

References

Allason, D., 2024, Hydrogen Safety - key considerations and learning from hydrocarbons, Hydrogen Fuel Risks Webinar Part 3, Webinar Series organised by JRC and OECD, 8 October 2024

Hares, K., 2024, Building a Safe Hydrogen Economy: The Role of Standardization, Hydrogen safety risk challenges for new projects in CEPSA, Hydrogen Fuel Risks Webinar Part 3, Webinar Series organised by JRC and OECD, 8 October 2024
https://minerva.jrc.ec.europa.eu/en/shorturl/minerva/oecdstandardizationroadmappdf

Martínez, J., 2024, Hydrogen safety risk challenges for new projects in CEPSA, Hydrogen Fuel Risks Webinar Part 3, Webinar Series organised by JRC and OECD, 8 October 2024 https://minerva.jrc.ec.europa.eu/en/shorturl/minerva/ue_safety_hydrogen_8102024_rev1pdf

Miller, D., 2024, Risk comparison between high pressure gas and liquid hydrogen, Hydrogen Fuel Risks Webinar Part 3, Webinar Series organised by JRC and OECD, 8 October 2024

Moretto, P. and E. Smedberg, 2024, European incidents database HIAD, 8 October 2024 https://minerva.jrc.ec.europa.eu/en/shorturl/minerva/jrcpt3rd_seminar_jrc_lessons_learnt_pdfpdf

Scanlon, S., 2024, Readiness of safety and environmental protection knowledge for a hydrogen energy economy, Hydrogen Fuel Risks Webinar Part 3, Webinar Series organised by JRC and OECD, 8 October 2024
https://minerva.jrc.ec.europa.eu/en/shorturl/minerva/scanlonoecdhydrogenmark_scanlonenergy_institutecompressed_picturespdf

Vyazmina, E., 2024, Safety and regulatory aspects for the large-scale hydrogen deployment - Building a sustainable, low-carbon society, Hydrogen Fuel Risks Webinar Part 3, Webinar Series organised by JRC and OECD, 8 October 2024
https://minerva.jrc.ec.europa.eu/en/shorturl/minerva/vyazminahydrogen_fuel_riskspdf

Wood, M. H., 2024, Hierarchy of hydrogen safety regulations, norms and standards, Hydrogen Fuel Risks Webinar Part 3, Webinar Series organised by JRC and OECD, 8 October 2024 https://minerva.jrc.ec.europa.eu/en/shorturl/minerva/hierarchy_of_hydrogen_safety_regulations_normspdf

List of figures

Figure 1 Regulatory frameworks governing hydrogen spans supranational, national, and local levels 7

Figure 2 Structure of the database HIAD 8

Figure 3 National systems view of the hydrogen value chain 10

Figure 4 Technical rule framework 13

Getting in touch with the EU

In person

All over the European Union there are hundreds of Europe Direct centres. You can find the address of the centre nearest you online (european-union.europa.eu/contact-eu/meet-us_en).

On the phone or in writing

Europe Direct is a service that answers your questions about the European Union. You can contact this service:

— by freephone: 00 800 6 7 8 9 10 11 (certain operators may charge for these calls),
— at the following standard number: +32 22999696,
— via the following form: european-union.europa.eu/contact-eu/write-us_en.

Finding information about the EU

Online

Information about the European Union in all the official languages of the EU is available on the Europa website (european-union.europa.eu).

EU publications

You can view or order EU publications at op.europa.eu/en/publications. Multiple copies of free publications can be obtained by contacting Europe Direct or your local documentation centre (european-union.europa.eu/contact-eu/meet-us_en).

EU law and related documents

For access to legal information from the EU, including all EU law since 1951 in all the official language versions, go to EUR-Lex (eur-lex.europa.eu).

EU open data

The portal data.europa.eu provides access to open datasets from the EU institutions, bodies and agencies. These can be downloaded and reused for free, for both commercial and non-commercial purposes. The portal also provides access to a wealth of datasets from European countries.

Science for policy

The Joint Research Centre (JRC) provides independent, evidence-based knowledge and science, supporting EU policies to positively impact society

Scan the QR code to visit:

The Joint Research Centre: EU Science Hub
https://joint-research-centre.ec.europa.eu

Publications Office
of the European Union