Clean Hydrogen Partnership

European Commission

PROGRAMME REVIEW REPORT 2025

https://www.clean-hydrogen.europa.eu/
e-mail: info@clean-hydrogen.europa.eu
tel: +32 2 221 81 48; +32 2 221 84 10

Communication & Press:
e-mail: communications@clean-hydrogen.europa.eu

EU Science Hub https://joint-research-centre.ec.europa.eu

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Clean Hydrogen Partnership

PROGRAMME REVIEW
REPORT 2025

EUROPEAN PARTNERSHIP

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LIST OF ACRONYMS

AEL	Alkaline Electrolysis/Electrolyser
AEMEL	Anion Exchange Membrane Electrolysis/Electrolyser
AI	Artificial intelligence
AST	Accelerated Stress Tests
AWP	Annual Working Plan
BEV	Battery Electric Vehicle
BoP	Balance of Plant
CAJU	Clean Aviation Joint Undertaking
CAPEX	Capital expenditure
CHP	Combined heat and power
CINEA	European Climate Infrastructure and Environment Executive Agency
CRM	Critical Raw Materials
DOE	Department of Energy
EHSP	European Hydrogen Safety Panel
EIS	Electrochemical Impedance Spectroscopy
EoL	End of Life
EPRI	Electric Power Research Institute
EU	European Union
FC/FCS	Fuel Cell/Fuel Cell System
FCB	Fuel Cell Bus
FCT	Fuel Cell Truck
FCEV	Fuel Cell Electric Vehicle
FCH JU	Fuel Cells and Hydrogen Joint Undertaking in the 7th R&I Framework programme, from 2008 to 2013.
FCH 2 JU	The second Fuel Cells and Hydrogen Joint Undertaking from 2014 to 2020, under the H2020 R&I Framework programme (now replaced by the Clean Hydrogen Joint Undertaking).
FCHPP	Fuel Cell Hybrid PowerPack
FCPS	Fuel Cell Power Systems
FP7	EU's 7th framework programme
GA	Grant agreement
GDL	Gas diffusion layer
GH2	Green Hydrogen Organisation
GHG	Greenhouse Gases
H2020	Horizon 2020
HE	Horizon Europe
HER	Hydrogen Evolution Reaction
HFTO	Hydrogen and Fuel Cell Technologies Office
HHV	Higher Heating Value
HDV	Heavy-duty Vehicle
HRS	Hydrogen Refuelling Station
HT	High Temperature
IATA	International Air Transport Association

IEA	International Energy Agency
IEC	International Electrotechnical Commission
IPHE	International Partnership for Hydrogen in the Economy
IRENA	International Renewable Energy Agency
ISA	International Solar Alliance
ISO	International Organisation for Standardisation
JRC	Joint Research Centre of the European Commission
JU	Joint Undertaking
KPI	Key Performance Indicator
LCA	Life Cycle Assessment
LCSA	Life Cycle Sustainability Assessment
LH_2	Liquid Hydrogen
LOHC	Liquid Organic Hydrogen Carrier
LT	Low Temperature
m-CHP	micro-CHP
MA	Managing Authorities
MAIP	FCH JU's Multi-Annual Implementation Plan (2008-2013)
MAWP	FCH 2 JU's Multi-Annual Work Plan (2014-2020)
MCFC	Molten Carbonate Fuel Cell
MDPC	Monitoring, Diagnostic, Prognostic and Control Tool
MEA	Membrane Electrode Assembly
METI	Ministry of Economy, Trade and Industry
MGT	Micro-gas turbines
MHV	Materials handling vehicles
MoC	Memoranda of Cooperation
NEDO	New Energy and Industrial Technology Development Organization
NFPA	National Fire Protection Association
NG	Natural gas
NREL	National Renewable Energy Laboratory
OEM	Original equipment manufacturer
ORR	Oxygen Reduction Reaction
O&M	Operational and maintenance
PACF	Phosphoric Acid Fuel Cell
PC	Photocatalytic
PCC	Proton Conducting Ceramic Electrochemical Cells
PCCEL	Proton Conducting Ceramic Electrolysis/Electrolyser
PDA	Project Development Assistance
PEC	Photoelectrochemical
PEFCR	Product Environmental Footprint Category Rules
PEM	Proton Exchange Membrane
PEMEL	Proton Exchange Membrane Electrolysis/Electrolyser
PEMFC	Proton Exchange Membrane Fuel Cell
PFAS	Perfluoroalkyl and Polyfluoroalkyl Substances
PGM	Platinum Group Metals
PNR	Pre-Normative Research

PSA	Pressure Swing Adsorption
PTFE	Polytetrafluoroethylene
PV	Photovoltaic
QRA	Quantitative Risk Assessment
R&I	Research and Innovation
R&D	Research and Development
RCS	Regulations, Codes and Standards
REE	Rear Earth Element
RES	Renewable Energy Sources
rSOC	Reversible Solid Oxide Cell
SAF	Sustainable Aviation Fuel
SBA	Single Basic Act
SME	Small and medium-sized enterprise
SMR	Steam methane reforming
SoA	State-of-the-art
SOEC	Solid Oxide Electrolyser Cell
SOEL	Solid Oxide Electrolysis/Electrolyser
SOFC	Solid Oxide Fuel Cell
SRIA	Strategic Research and Innovation Agenda of the Clean Hydrogen JU
STH	Solar to hydrogen
TCO	Total Cost of Ownership
TIM	Tools for Innovation Monitoring
TRL	Technology readiness level
	TRL 1–basic principles observed
	TRL 2–technology concept formulated
	TRL 3–experimental proof of concept
	TRL 4–technology validated in lab
	TRL 5–technology validated in a relevant environment (industrially relevant environment in the case of key enabling technologies)
	TRL 6–technology demonstrated in a relevant environment (industrially relevant environment in the case of key enabling technologies)
	TRL 7–system prototype demonstration in operational environment
	TRL 8–system complete and qualified
	TRL 9–actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies, or in space)
TRUST	Technology Reporting Using Structured Templates
TPRD	Thermal Pressure Relief Device
UHS	Underground hydrogen storage
UPS	Uninterruptible Power Supply

EXECUTIVE SUMMARY

Hydrogen is positioned as a key element of the European Union's strategy to reduce greenhouse gas emissions by 55% by 2030 and to achieve climate neutrality by 2050. The Clean Hydrogen Joint Undertaking (JU) builds on the achievements of its predecessors, the Fuel Cells and Hydrogen (FCH) and Fuel Cells and Hydrogen 2 (FCH 2) JUs, by advancing research and innovation in renewable hydrogen production, storage, distribution, end-use applications, and cross-cutting areas. To ensure alignment with EU policy objectives and to track progress across projects, the JU conducts an annual programme review that includes the annual data collection, the annual technical assessment, and the *Programme Review Report* (i.e., the present report).

The Joint Research Centre of the European Commission (JRC) has been entrusted with the annual performance of the programme technical assessment based on the data collected from projects by the Programme Office. This assessment, which in 2025 covered 114 ongoing projects distributed across eight thematic pillars, along with 28 projects from the 2024 call, lies at the core of this *Programme Review Report*.

In Pillar 1, with 38 projects, the focus is on renewable hydrogen production through the advancement of electrolysers and alternative technologies. Considerable progress has been made in Proton Exchange Membrane (PEMEL) and Solid Oxide Electrolyser (SOEL) technologies, with emerging developments in Proton Conducting Ceramic (PCCEL) and Anion Exchange Membrane (AEMEL) electrolysers. Low-temperature electrolysis technologies are advancing rapidly but continue to face challenges in durability, efficiency, and cost, while solar-to-hydrogen production, despite its conceptual promise, is still far from achieving the efficiency required for large-scale deployment. A persistent reliance on critical raw materials remains a structural weakness across all production technologies, making standardisation, harmonised testing, and certification tools essential to support industrial uptake.

Pillar 2, with 24 projects, addresses the storage and distribution of hydrogen, including compression, purification, separation, and transportation using approaches such as compressed and liquid hydrogen as well as chemical carriers. Several innovative advances have been achieved, but performance indicators have often proven overly ambitious compared to the maturity of the technologies and the available resources. To ensure steady progress towards commercialisation, future initiatives will require more realistic targets and a careful balance between breakthrough concepts and incremental improvements.

In Pillar 3, with 27 projects, attention focuses on transport applications of hydrogen and fuel cell technologies. Previous JU programmes successfully demonstrated market-ready passenger cars, buses, and medium-duty trucks, yet significant effort is still required in harder-to-decarbonise areas such as heavy-duty road vehicles, maritime, aviation, rail, and off-road applications. Demonstration projects are producing valuable operational data, but this information is not being systematically integrated into regulatory and standardisation frameworks, which slows down market uptake.

Pillar 4, with 16 projects, supports renewable and flexible hydrogen-based heat and power solutions, ranging from household systems to large-scale power plants. The portfolio covers stationary fuel cells, gas turbines, boilers, and burners designed to run on either pure hydrogen or transitional blends with natural gas. Despite the significant technical achievements, results from completed projects are not always exploited or scaled up. A more deliberate strategy of building on existing outcomes and conducting proof-of-concept demonstrations with commercial products could accelerate deployment in real-world contexts.

In Pillar 5, with 16 projects, the programme addresses cross-cutting issues essential to mass-market adoption. These include safety, pre-normative research, standards, sustainability, recycling, eco-design, education, and public awareness, with the 2025 addition of international cooperation to strengthen Europe's global role in hydrogen. Educational materials have been successfully developed and disseminated, but the transition from project-level outputs to regulatory and standardisation frameworks remains underdeveloped.

Pillar 6, with 17 projects, is centred on the development of Hydrogen Valleys, i.e., integrated regional ecosystems that cover the entire hydrogen value chain while fostering market creation and regulatory innovation. While these valleys have become a flagship of the EU hydrogen strategy, most projects remain in early stages and are challenged by complexity, scale, and stakeholder coordination. Tailored performance indicators, de-risking measures, and robust contingency planning will be crucial for maintaining momentum and ensuring success.

In Pillar 7, with 1 project, efforts are directed at strengthening the hydrogen technology supply chain, which the European Commission has identified as strategic for Europe. European companies currently hold leadership positions in many areas of hydrogen production, component manufacturing, and system integration, but global disruptions have exposed vulnerabilities in availability, costs, and delivery times. A more structured approach, including systematic analyses of completed projects, workshops connecting supply chain experts and OEMs, and requirements for multiple suppliers of critical components, will help build resilience and reduce dependence on single sources.

Finally, Pillar 8, with 3 projects, sustains a steady flow of early-stage scientific knowledge in areas that conventional three-year projects struggle to cover. These projects address three critical challenges: reducing dependence on scarce or unsustainable materials such as PGMs and PFAS, advancing novel hydrogen storage materials, and deepening understanding of durability and performance mechanisms. Yet, systematic quantification of critical material use across the hydrogen value chain and harmonised durability targets are still lacking, limiting the ability to evaluate substitution strategies and long-term sustainability.

Overall, the Programme Review constitutes an important activity for the assessment and communication of the Clean Hydrogen JU Programme and the achievements of the supported projects, providing valuable insights into the state of hydrogen technologies and the challenges towards their implementation. The 2025 review demonstrates substantial progress across all eight pillars, advancing hydrogen production, distribution, transport, heat and power, cross-cutting issues, hydrogen valleys, supply chain resilience, and fundamental research.

1. INTRODUCTION

Hydrogen (H_2) is emerging as a key pillar of the global energy transition, offering a versatile and clean energy carrier that can complement renewable sources and reduce reliance on fossil fuels. Its potential to provide large-scale energy storage and to balance the intermittency of renewables further underlines its importance in building a resilient and secure low-carbon energy system.

As the EU works towards achieving climate neutrality by 2050, hydrogen offers a sustainable solution to reduce emissions not only in the power sector but also in hard-to-abate sectors such as energy-intensive industries (e.g., steel, chemicals, and cement) and mobility (e.g., heavy-duty vehicles, rail, and maritime). Recognising both the opportunities and challenges, the EU has embedded hydrogen into its policy framework through the European Green Deal and the "Fit for 55" package, which aim to cut greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels. These initiatives promote investment in renewable hydrogen production, infrastructure development, and cross-border cooperation to ensure that hydrogen can be deployed at scale across the EU.

The EU has been supporting research and innovation (R&I) in hydrogen technologies, ensuring sustained progress in this strategic field. Through the Fuel Cells and Hydrogen (FCH) and Fuel Cells and Hydrogen 2 (FCH 2) Joint Undertakings (JUs), the EU successfully showcased hydrogen's viability as a clean energy carrier and the efficiency of fuel cells (FCs) as energy conversion systems. Building on these achievements, the Clean Hydrogen Joint Undertaking (Clean Hydrogen JU) is advancing this work by prioritising renewable hydrogen production, as well as its storage, distribution, and end-use applications. Thanks to the JU's continuous efforts, several technologies have reached or come closer to maturity (e.g., buses, vans, material-handling vehicles, and refuelling stations), and high-profile projects have been developed in promising applications (e.g., e-fuels for aviation, hydrogen in rail, and the maritime sector), closing the knowledge gap and supporting uptake in the European energy system. EU-funded projects also contributed to the acknowledgement of the necessary adjustments in regulation, codes and standards for allowing the production and utilisation of hydrogen in the EU. As a result, the EU has achieved global leadership in certain future technologies, notably electrolysers, hydrogen refuelling stations (HRS), and megawatt-scale FCs.

The multi-annual programme of the Clean Hydrogen JU is described in its Strategic Research and Innovation Agenda (SRIA)[1]. Compared to the Multi-Annual Work Programmes (MAWPs)[2] of its predecessors, it contains a much broader set of activities in all areas and applications where hydrogen is expected to play a role, across energy, transport, building, and industrial end-uses. Simultaneously, it is expected that the Clean Hydrogen JU will closely collaborate with other partnerships, and in synergy with other EU, national and regional research funding programmes, it will help strengthen and integrate EU scientific capacity to accelerate the development and improvement of advanced, market-ready clean hydrogen applications.

The Clean Hydrogen JU has an initial budget of EUR 1 billion for the period 2021-2027, complemented by at least an equivalent amount of private investment coming from the private members of the JU and an additional EUR 200 million, aiming to double the number of hydrogen valleys across Europe as part of REPowerEU[3]. Additional contributions from the UK, a country associated with Horizon Europe, are expected to further increase the initial JU budget.

1 Strategic Research and Innovation Agenda 2021-2027

2 Multi-annual Implementation Plan (MAIP) for 2008-2013 under FP7, Multi-Annual Work Programme (MAWP) for 2014-2020 under H2020.

3 REPowerEU Plan, COM(2022) 230.

2. PURPOSE AND SCOPE OF THE PROGRAMME REVIEW

The periodic Programme Review constitutes a critical process to ensure that the Clean Hydrogen JU remains fully aligned with the strategic priorities defined in the Single Basic Act (SBA)[4], and further detailed in its Strategic Research and Innovation Agenda (SRIA) for 2021–2027. This process is performed similarly to the Clean Hydrogen JU's predecessors, the FCH JU and FCH 2 JU, which relied on multi-annual work plans such as the Multi-Annual Implementation Plan (MAIP)[5] under FP7 (2008–2013) and the Multi-Annual Work Plan (MAWP)[6] under Horizon 2020 (2014–2020).

The Programme Review's primary purpose is to monitor progress against long-term research and innovation objectives[7] for fuel cells and hydrogen technologies in Europe, assessing performance through quantitative key performance indicators (KPIs) described in the multi-annual plans, such as cost, durability, and efficiency. It was first introduced in 2011 and was initially carried out by external experts from both European and international research and industry, alongside members of the FCH 2 JU Scientific Committee. As of 2017, the JRC has been entrusted with the programme review exercise under a multi-annual framework contract signed with the FCH 2 JU, following up on a recommendation[8] by the European Commission's Internal Audit Service, thus marking the start of a more systematic review process.

Data collection is coordinated by the Programme Office, drawing on structured reporting platforms, project deliverables, and targeted surveys. In the past two years, two upgraded tools have been used for the data collection: in 2024, the survey was replaced by the Suite CRM application, which contains the project's fiches[9], and in 2025, the Technology Reporting Using Structured Templates (TRUST)[10] was replaced by the Clean Hydrogen Knowledge Hub, which aims to incorporate all project data and information into a single database.

Based on the collected data, the JRC produces a comprehensive assessment which evaluates annual progress towards SRIA technology KPIs, identifies potential gaps, and formulates recommendations for improving the programme's effectiveness. These insights, enriched by major international reports and developments in the global hydrogen landscape, form the basis for the Programme Review.

By integrating these diverse inputs, the Programme Review goes beyond monitoring, offering a holistic picture of the programme's performance and context. Its findings feed directly into the preparation of future Annual Work Programmes (AWPs), shaping research priorities and the design of upcoming calls for proposals.

4 Council Regulation (EU) 2021/2085 of 19 November 2021 establishing the Joint Undertakings under Horizon Europe (https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32021R2085).

5 MAIP, Clean Hydrogen JU website

6 MAWP, Clean Hydrogen JU website

7 On top of the horizontal objectives of FP7 and H2020, common to all Programmes

8 Final audit report on performance management of the FCH 2 JU activities (Internal Audit Service report: IAS.A2-2016-FCH 2 JU-003).

9 https://www.clean-hydrogen.europa.eu/knowledge-management/annual-data-collection_en#project-fiche

10 https://www.clean-hydrogen.europa.eu/knowledge-management/annual-data-collection_en

3. ANNUAL PROGRAMME TECHNICAL ASSESSMENT BY JRC

The annual programme technical assessment carried out by the JRC is a core activity that draws on project data provided by the Clean Hydrogen JU, the expertise of JRC specialists, and close exchanges with JU staff, particularly project officers and the knowledge management team. It results in an internal report that not only highlights project impacts and outcomes but also identifies gaps against SRIA objectives and offers recommendations to strengthen programme implementation. The present Programme Review report is largely based on the findings of this assessment, which are reflected primarily in Chapter 5 and the Annex.

The 2025 annual programme technical assessment includes all ongoing[11] projects in the period January 2024 to March 2025, up to the 2020 calls, and the first Horizon Europe projects of the 2022 calls[12]. Although the agreements for the projects of the 2024 call were signed too recently to have produced any outcomes, they have also been analysed based on the content of their project fiches in order to give them visibility and forecast their possible impacts against the related SRIA targets.

The current annual programme technical assessment therefore covers 114 projects: 33 H2020 projects and 81 HE projects. Additionally, there are 28 projects from the 2024 call that do not have technology KPIs to report yet, but were nevertheless considered for the programme review report. In line with the new programme structure of the Clean Hydrogen JU, explained in the SRIA, all projects have been assigned to eight pillars that cover a wide range of topics and related activities:

- Pillar 1: Renewable hydrogen production
- Pillar 2: Hydrogen storage and distribution
- Pillar 3: Hydrogen end-uses: transport applications
- Pillar 4: Hydrogen end-uses: clean heat and power
- Pillar 5: Cross-cutting issues
- Pillar 6: Hydrogen valleys
- Pillar 7: Supply chain
- Pillar 8: Strategic research challenges

Moreover, as part of the legacy projects of H2020, the Clean Hydrogen JU is continuing certain activities and applications. To better map the different current and possible future activities of the JU, a set of research areas[13], which groups projects covering related topics, is used. This split is presented in Table 1 below.

11 'Ongoing' means between project start date and project end date.

12 HORIZON-JTI-CLEANH2-2022-1 and HORIZON-JTI-CLEANH2-2022-2 calls: https://www.clean-hydrogen.europa.eu/call-proposals-2022_en

13 These research areas are the basis of the annual programme technical assessment performed by JRC.

Table 1: Research areas and topics per pillar of projects reviewed

PILLARS	RESEARCH AREAS	RESEARCH TOPICS
1) Renewable hydrogen production	1 – Low temperature electrolysis	Projects targeting AEL, PEMEL, and AEMEL
	2 – High temperature electrolysis	Projects targeting SOEL and PCCEL
	3 – Other routes of renewable Hydrogen production	Projects covering reformer development for distributed hydrogen production and thermochemical hydrogen production are covered in this review
2) Hydrogen storage and distribution	4 – Underground storage	Projects targeting the feasibility, risks, and impact of H_2 underground storage
	5 – Aboveground storage	currently not covered by any projects
	6 – Hydrogen refuelling stations	Projects addressing reliability and availability issues indicated by the operation of existing HRS
	7 – Liquid Hydrogen carriers	Projects focusing on the improvement of the round-trip efficiency of conversion and system cost
	8 – Liquid Hydrogen storage	Projects developing concepts for liquid hydrogen storage tanks
	9 – Compression, purification, and metering solutions	Projects demonstrating the feasibility of direct separation of H_2 from NG and material research on proton-conducting ceramic electrochemical cells (PCC)
	10 – Hydrogen in the natural gas grid	Projects assessing the effect of H_2 on transmission (high-pressure) NG pipeline
	11 – Improving existing hydrogen transport means	Projects focusing on the improvement of the transportation and storage of LH_2 in shipping
	12 – Hydrogen distribution (pipelines)	currently not covered by any projects
3) Hydrogen end-uses: transport applications	13 – Building Blocks	Project focusing on material, design, and system optimisation for LT and HT PEMFC
	14 – Heavy Duty Vehicles, including Busses/Coaches	Projects addressing the optimisation of BoP components and architectures design to meet HDV needs. Validation of the technology in real operational conditions
	15 – Waterborne Applications	Project focusing on improving access to the market for hydrogen, its derivatives, and FCs, initially on smaller vessels
	16 – Rail Applications	Projects with the objective of enabling hydrogen to be recognised as the leading option for trains on non-electrified routes or partially electrified routes
	17 – Aeronautics applications	Projects addressing the optimisation of BoP components and architectures design to meet aviation needs
	18 – Cars	currently not covered by any projects

PILLARS	RESEARCH AREAS	RESEARCH TOPICS
4) Hydrogen end-uses: clean heat and power	19 – μ-CHP	currently not covered by any projects
	20 – Commercial Size CHP	Demonstration projects for commercial size CHP using SOFC and HT PEMFC
	21 – Industrial Size CHP	Projects exploiting PEMFC technology at industrial size
	22 – Off-grid/back up/genset	currently not covered by any projects
	23 – Turbines, boilers and burners	Projects explore the combustion of hydrogen, ammonia, and natural gas in gas turbines and boiler burners, with a focus on retrofitting existing fossil fuel-based infrastructure to be compatible with hydrogen.
	24 – Other Research Areas	Exploration projects for the utilization of biogas fed with a SOFC-CHP system and use of EIS technology for monitoring & diagnostic purposes.
5) Cross-cutting issues	25 – Education and Public Awareness	Projects aiming to increase knowledge and awareness in the public and at educational level
	26 – Safety, Pre-Normative Research (PNR) and Regulations, Codes and Standards (RCS)	Projects performing research activities to lay down a suitable RCS for hydrogen while contributing to ensuring a safe roll-out of the technologies
	27 – Sustainability, Life Cycle Sustainability Assessment (LCSA), recycling and eco-design	Projects laying down the foundations for more sustainable and circular technologies
	28- International Cooperation	Projects aiming at developing long-term partnerships across the hydrogen supply chain
6) Hydrogen valleys	29 – Hydrogen valleys	Projects developing H_2 integrated system when favourable conditions at industrial or geographical point of view
7) Supply chain	30 – Manufacturing for stationary applications	Projects addressing the optimisation of materials and/or BoP components and architectures design to meet stationary application needs
	31 – Manufacturing for transport applications	Projects addressing the optimisation of BoP components and architectures design to meet transport application needs
8) Strategic research challenges	32 – Strategic Research Challenge	Projects focusing on the reduction of CRM usage, lifetime improvement of systems by modelling, degradation analysis, and advanced materials for hydrogen tanks

4. OPERATIONAL BUDGET IMPLEMENTATION

4.1. OVERVIEW

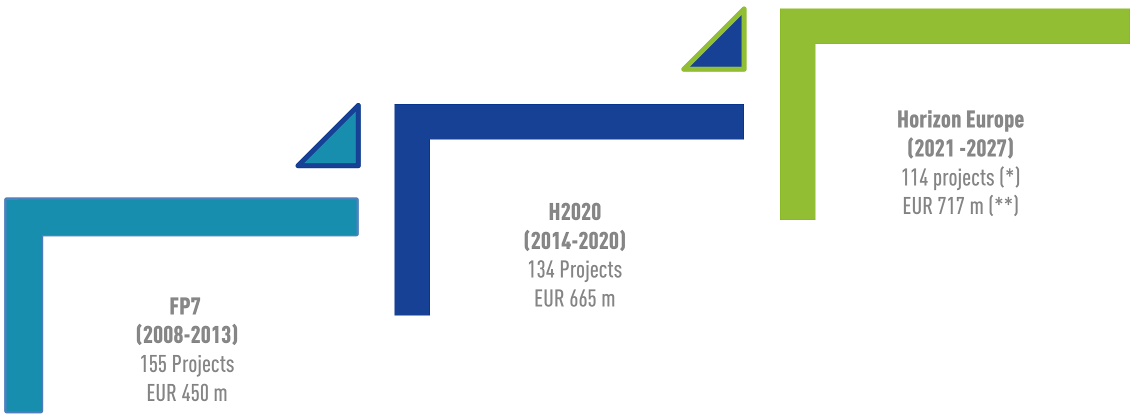
The Clean Hydrogen JU, established under the Horizon Europe Programme, was created to continue and expand the work of its successful predecessors, Fuel Cells and Hydrogen Joint Undertakings (FCH and FCH 2 JU). With a clear mandate to build on their achievements, the Clean Hydrogen JU has taken over all remaining contracts from the earlier programmes, including all grant agreements (GAs), ensuring continuity of actions and results.

Under the FP7 and H2020 programmes, the FCH and FCH 2 JUs played a pivotal role in advancing research and innovation (R&I) in hydrogen technologies. Their collective impact includes EUR 1.12 billion in European Union funding invested across 289 hydrogen and fuel cell projects, along with an additional EUR 17.25 million allocated for the procurement of strategic studies.

To further accelerate innovation in the sector, the Clean Hydrogen JU operates with a European Union financial contribution of up to EUR 1 billion. This is matched by at least EUR 1 billion in contributions from the JU's members, as mandated by Articles 76 and 77 of the Single Basic Act (SBA). In addition, under the REPowerEU Plan, the European Commission has committed an extra EUR 200 million to the programme, with the aim of doubling the number of Hydrogen Valleys across Europe.

The new programme has seen significant progress. To date, 114 projects selected under the 2022, 2023, and 2024 Calls have signed GAs, representing a combined commitment of EUR 717 million, which is more than half of the EUR 1.2 billion operational budget available through 2027. The programme has also been strengthened by an additional EUR 5.61 million earmarked for further studies and analytical work. Figure 1 illustrates the level of overall implementation of the Clean Hydrogen JU Programme as of 2024, including the legacy of previous Joint Undertakings and the continued scale-up under Horizon Europe.

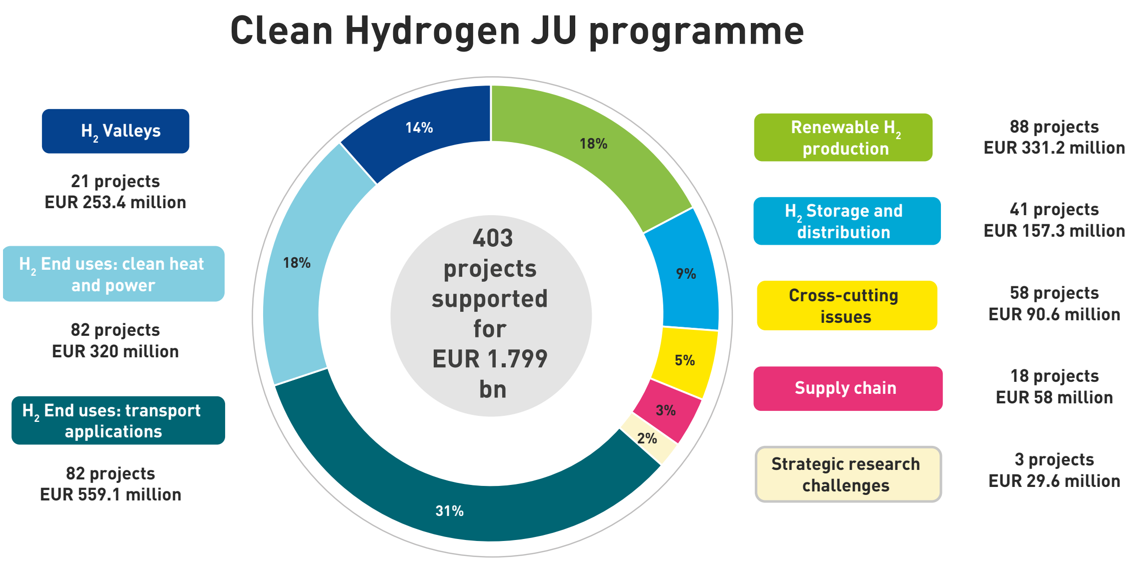
Figure 1: EU contribution to the implementation of MAIP 2008-2013, MAWP 2014-2020 and SRIA 2021-2027



(*) Projects with signed GAs (Calls 2022, 2023,2024)
(**) Out of 1.2bn of the overall programme operational budget, including foreseen funding for hydrogen valleys from the REPowerEU Plan
Source: Clean Hydrogen JU

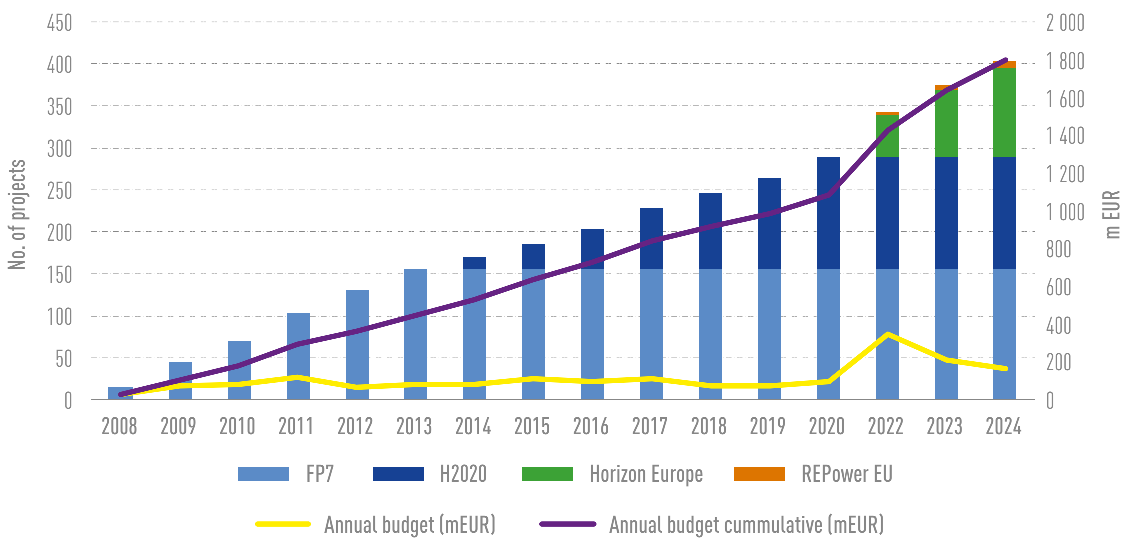
Overall, the Clean Hydrogen JU has contributed a total of EUR 1.799 billion in funding, supporting 403 completed and ongoing projects. Figure 2 and Figure 3 provide a detailed breakdown of these projects and the operational budget allocated for their implementation, organised by SRIA Pillar and by year over the period 2008–2024.

Figure 2: Projects supported by the Clean Hydrogen JU per pillar and annual financial contribution (2008-2024)



Source: Clean Hydrogen JU.

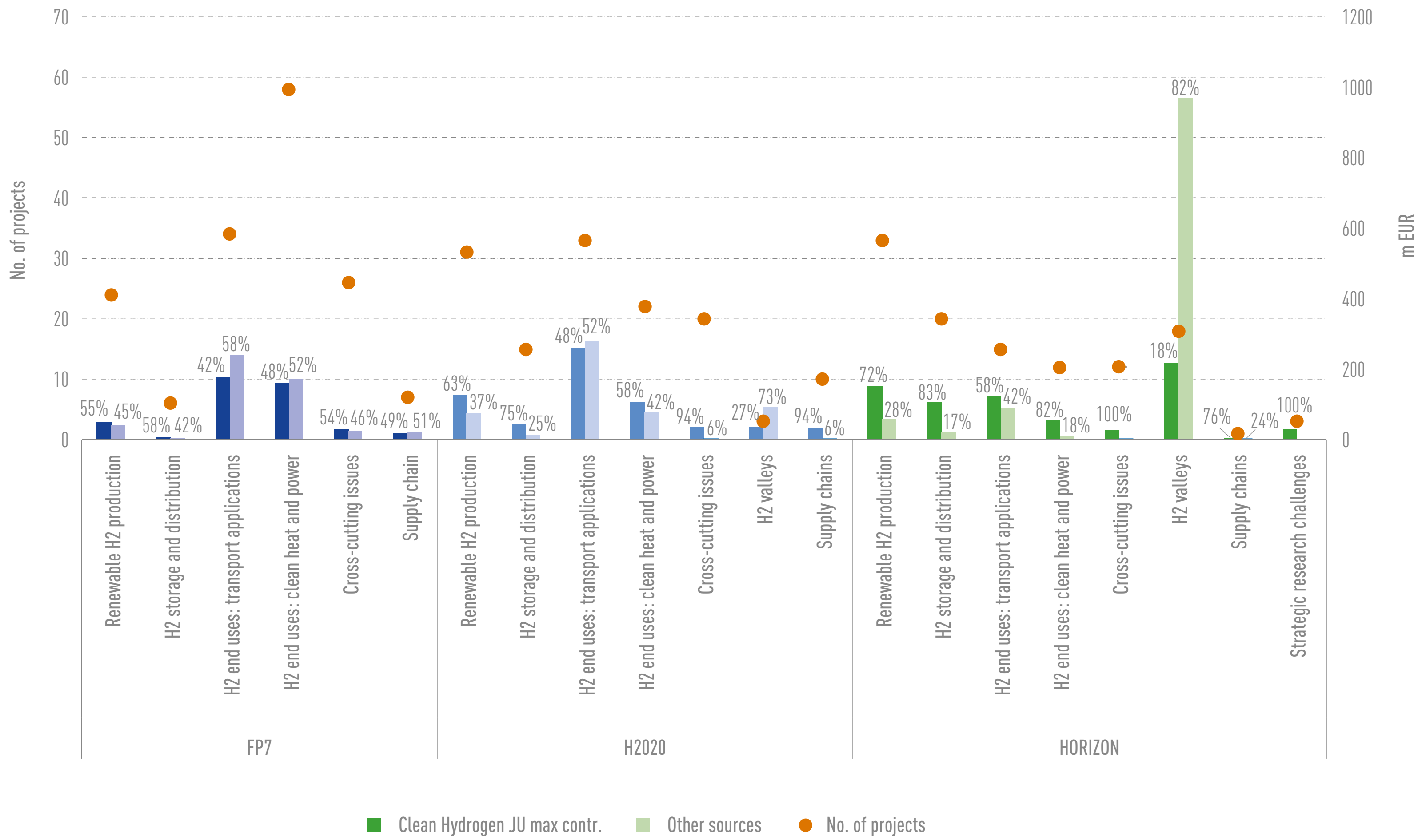
Figure 3: Annual financial contribution of the Clean Hydrogen JU (2008-2024)



Source: Clean Hydrogen JU.

In addition to the substantial financial support provided by the European Union through both the legacy and current Clean Hydrogen JU programmes, the private sector has also contributed significant resources. These additional investments have played a key role in implementing the programme and supporting project activities across various research and innovation (R&I) areas, thereby amplifying the overall impact on hydrogen and fuel cell technologies. Figure 4 presents a breakdown of the total financial contributions by programme and review pillar, highlighting the different sources of funding.

Figure 4: Number of projects and financial contribution of both Clean Hydrogen JU and private funding (utilised or planned) per SRIA pillar (2008-2024)

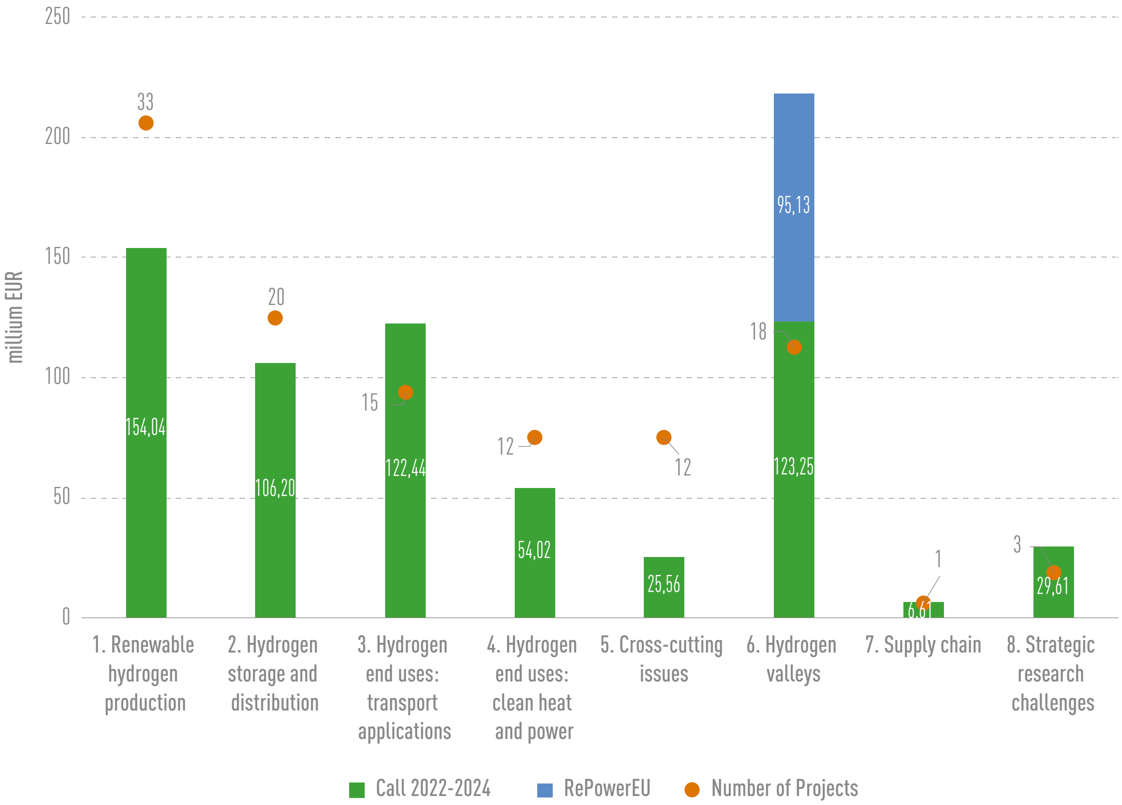


Source: Clean Hydrogen JU.

4.2. PREVIOUS CALLS (2022-2024)

As previously noted, the implementation of the JU Programme has been strategically advanced in its early phases. Including the 2024 Call, over EUR 717 million (out of the total EUR 1.2 billion budget) has already been committed through grant agreements, covering 114 projects and related operational activities. Among the SRIA Pillars, Hydrogen Valleys have received the largest share of funding, with EUR 123.2 million allocated. This amount is further supported by an additional EUR 95.1 million from the REPowerEU plan, as part of its EUR 200 million top-up. Figure 5 provides an overview of the distribution of these commitments by SRIA Pillar and shows the number of projects formalised under Horizon Europe from the 2022 to 2024 Calls.

Figure 5: Financial contribution of Clean Hydrogen JU and number of projects from Calls 2022 and 2024 with signed GAs per SRIA pillar



Source: Clean Hydrogen JU.

4.3. CALL 2025

The year 2025 began with an important milestone for the Clean Hydrogen JU: the publication of a new Call for Proposals on January 15. This call is expected to lead to the launch of a new group of projects, with grant agreements anticipated by the end of the year. In total, up to EUR 184.5 million in operational funding has been made available to support these upcoming initiatives.

Call 2025 includes 20 research and innovation topics, covering a wide range of areas along the hydrogen value chain, as well as horizontal priorities. The funding is distributed as follows:

- Renewable Hydrogen Production: 7 topics, EUR 40 million
- Hydrogen Storage and Distribution: 3 topics, EUR 16 million

- Transport: 3 topics, EUR 17 million
- Heat & Power: 1 topic, EUR 5 million
- Cross-Cutting: 3 topics, EUR 6.5 million
- Hydrogen Valleys: 2 topics, EUR 80 million (+ EUR 80 million top-up from REPowerEU Plan investment)

In addition, the total budget includes EUR 20 million from United Kingdom appropriations, which are intended to support projects placed on reserve lists. These funds will be allocated in line with the strategic priorities set by the Clean Hydrogen JU's Governing Board.

4.4. PROGRAMME REVIEW PROJECT CLASSIFICATION

The 2025 Programme Review report encompasses all projects that were active at any point during 2024. This includes both mature Horizon 2020 projects that remained ongoing or concluded during the year, as well as Horizon Europe projects from the 2024 Call, which are being assessed for the first time by the JRC. As many of these newer projects are still in their early stages and have yet to demonstrate significant progress toward their objectives, this report provides a brief overview of their concepts and expected impacts. This approach offers contextual insight aligned with the SRIA and sets a baseline for comparison in future Programme Reviews.

A total of 142 projects were active in 2024, representing a combined budget of nearly EUR 1 billion. Table 2 presents their distribution across the SRIA Pillars and identifies those included in the current Programme Review.

Table 2: MAWP/SRIA pillars reviewed

SRIA pillar	Programme	No. of projects	Total JU funding in million EUR
Pillar 1 – Renewable H_2 production	H2020	6	36.20
	HE	32	144.09
Pillar 2 – H_2 storage and distribution	H2020	5	15.99
	HE	19	86.21
Pillar 3 – H_2 end-uses: transport applications	H2020	12	111.80
	HE	15	122.44
Pillar 4 – H_2 end-uses: clean heat and power	H2020	4	11.23
	HE	12	54.02
Pillar 5 – Cross-cutting issues	H2020	4	7.49
	HE	12	25.56
Pillar 6 – H_2 valleys	H2020	2	30.00
	HE	15	192.56
Pillar 7 – Supply chain	HE	1	6.61
Pillar 8 – Strategic research challenges	HE	3	29.61
	Total	142	873.81

Source: Clean Hydrogen JU.

5. REVIEW OF PROGRAMME PILLARS

5.1. PILLAR 1: RENEWABLE HYDROGEN PRODUCTION

Currently, the majority of hydrogen produced in the EU still comes from fossil fuels, mainly through steam methane reforming (SMR) and coal gasification. Yet hydrogen holds vast potential as a clean energy carrier and chemical feedstock and is expected to have a significant role in the EU's future energy mix. Achieving cost-competitive renewable hydrogen requires scaling up electrolyser technologies, alongside emerging methods that use direct sunlight, while driving down costs and improving efficiency.

The projects in pillar 1 aim at enhancing the performance and durability of electrolysers via the development of advanced materials, innovative components, and a deeper understanding of degradation mechanisms, as well as reducing dependence on critical raw materials (CRMs).

The main technology funded under this pillar is electrolysis. This pillar supports higher-Technology Readiness Level (TRL) technologies such as Alkaline Electrolysers (AEL), Proton Exchange Membrane Electrolysers (PEMEL), and Solid Oxide Electrolysers (SOEL), alongside emerging lower-TRL technologies such as Anion Exchange Membrane Electrolysers (AEMEL) and Proton Conducting Ceramic Electrolysers (PCCEL). The remaining projects focus on alternative production technologies such as biomass gasification and solar-to-hydrogen production.

Overview of Research Areas

Low-Temperature Electrolysis: Low-temperature water electrolysis technologies include alkaline electrolysers (AEL), proton exchange membrane electrolysers (PEMEL), and anion exchange membrane electrolysers (AEMEL).

To date, 11 JU-funded projects have advanced the development of AEL, with some also addressing PEMEL. These efforts have led to a reduction in energy consumption per kilogram of hydrogen, bringing most projects close to target values. Regarding the SRIA 2024 targets, most of them are met, except for the technology's durability, which still remains a concern.

PEMEL technology has been explored through 18 JU-funded projects, some of which have concurrently worked on AEL. Projects under other pillars, such as hydrogen valleys and HRS, have also contributed to this RA. Scaling up to multi-MW PEMEL systems was initially a significant challenge, but progress has been made. Some projects are on track to meet not only the 2024 KPIs but also certain 2030 SRIA targets.

AEMEL technology, which uses a solid electrolyte and non-PGM catalysts to produce high-purity hydrogen, is still at a relatively low TRL. Of the seven projects exploring this pathway, three JU-funded initiatives (i.e., CHANNEL, ANIONE, and NEWELY) have reported KPI results from single-cell testing. These projects show encouraging progress toward the 2024 SRIA targets, though system operation and maintenance (O&M) costs continue to present a significant hurdle.

High-Temperature Electrolysis: High-temperature water electrolysis technologies include Solid Oxide Electrolysers (SOEL), alongside emerging lower-TRL technologies such as Anion Exchange Membrane Electrolysers (AEMEL) and Proton Conducting Ceramic Electrolysers (PCCEL).

To date, SOEL technology has been advanced through 14 JU-funded projects, addressing most of the revised MAWP targets. However, compared with AEL and PEMEL, SOEL remains less mature, with fewer projects progressing to higher TRLs. Aside from system O&M costs, the best-performing projects in 2024 have reported values close to, or already meeting, the SRIA 2024 targets. PCCEL technology, which operates at intermediate temperatures of 500–700°C to limit material degradation and external heat demand, is still at a low TRL.

Other Routes of Renewable Hydrogen Production: The routes of renewable hydrogen production covered in this research area include biomass gasification (HYIELD project) and solar-to-hydrogen (STH) (HYSELECT and PH2OTOGEN projects). Given their recent start dates, the projects are not yet expected to be contributing to programme level achievements. However, HYSELECT has yet to identify the technology for heat recovery and gas purification.

State-of-the-art

Low-Temperature Electrolysis: According to the IEA Global Hydrogen Review[14], the global water electrolyser capacity reached 1.4 GW in 2023, with China contributing nearly 70% of the capacity in committed projects. Projections suggest that global capacity could expand to approximately 520 GW by 2030, although only 4% of this is currently financed or under construction. In the past year, 6.5 GW of electrolyser capacity was financed, with projects primarily in China (40%) and Europe (32%), focusing on producing hydrogen for industrial use and transportation fuels. Some projects faced cancellation due to uncertainties around demand, regulations, financing, and licensing issues. Additionally, electrolyser manufacturing capacity doubled to 25 GW annually, with 60% based in China. Most installed capacity in 2023 used alkaline technology (over 60%), followed by PEM technology (22%). Significant developments in 2024 included the commissioning of a 50 MW electrolyser in the USA and a 10 MW electrolyser in Hungary, alongside the start of a 24 MW PEM electrolyser in Norway for ammonia production. The capital expenditure (CAPEX) for alkaline and PEM electrolysers is estimated at 2000 USD/kW and 2450 USD/kW in the USA and Europe, compared to 750-1300 USD/kW for installations in China.

The development of low-temperature water electrolysis technologies, including AEL, PEMEL, and AEMEL, has shown significant progress, though challenges remain in optimising these systems fully. AEL technology faces major concerns around durability and lifespan, requiring further improvements for long-term use. PEMEL has successfully scaled up to multi-megawatt systems, marking significant progress. The focus remains on achieving cost efficiency and better performance, although challenges like energy consumption and system reliability persist. Improved catalyst materials, membrane technology, and cell design are helping reduce energy use. For PEMEL, reducing the use of costly precious metals in catalysts is a priority. Efforts to enhance cost-effectiveness involve improving system durability, reducing component costs, and improving system designs. AEL research is aimed at creating more durable components and increasing electrode lifespan, with studies into material stability and degradation. As demand for large-scale hydrogen production increases, scaling up electrolysis technologies from lab to industrial scales, integrating them with renewable energy sources, and managing power fluctuations are key areas of research. Some manufacturers also propose pressurised alkaline systems; for example, Green Hydrogen Systems[15] electrolyser operates under 35 barg[16], Sunfire's pressurised electrolyser operates 10-MW modules under 30 barg[17], similarly to De Nora's DragonFly system[18]. Among the projects funded by CINEA, the SEAWORTHY project[19] is developing groundbreaking technology capable of providing dispatchable offshore power. This is achieved through the use of a 4.3 MW wind turbine and an 800 kW wave energy converter, with the ultimate goal of generating hydrogen onboard for the power-to-X market using a 1 MW electrolyser.

High-Temperature Electrolysis: SOE technology offers improved efficiency, especially when integrated with processes that supply high-purity steam, making it ideal for industries such as chemicals, fertilisers, and steel

14 https://iea.blob.core.windows.net/assets/89c1e382-dc59-46ca-aa47-9f7d41531ab5/GlobalHydrogenReview2024.pdf

15 This company went bankrupt; see at https://www.hydrogeninsight.com/electrolysers/green-hydrogen-systems-to-file-for-bankruptcy-after-selling-key-technology-assets-to-rival-thyssenkrupp-nucera/2-1-1835946?zephr_sso_ott=pXCFHY

16 Our System Technology | Green Hydrogen Systems

17 Pressurized Alkaline Electrolyzers (AEL) Sunfire

18 Dragonfly® System | De Nora

19 floatingpowerplant.com

production, as well as refineries with surplus low-grade heat. It can also be used at geothermal and nuclear plants, where permitted. High-Temperature Electrolysis technologies, such as SO Electrolysers (SOELs) and Proton-Conducting Ceramic Electrolysers (PCCELs), operate efficiently at high temperatures but face challenges with material degradation in stacks due to factors like temperature, pressure, and load fluctuations. Despite these issues, High-Temperature Electrolysis technology could reduce hydrogen production costs due to its energy efficiency at temperatures above 600°C. However, degradation can lead to component failures, necessitating replacements. Achieving long lifetimes is possible, but practical testing for such durations is challenging, highlighting the need for Accelerated Stress Testing (AST) and modelling to predict technology lifetimes. To scale up SOEL technology, the cell area and current density need to be increased, and more cells should be added to the stack to expand capacity to several megawatts. Multiple stacks could then be combined to form blocks of tens of megawatts, reducing the duplication of balance-of-plant components and leading to lower capital costs for SOEL systems.

In the USA, Bloom Energy has tested a 4 MW SO electrolyser[20], with an annual manufacturing capacity of around 2 GW[21]. Fuel Cell Energy, in partnership with the Idaho National Laboratory, is testing a 250 kW SO electrolyser system that utilises waste heat from a nuclear power plant to generate steam for the daily production of 150 kg of hydrogen.[22] The Korea Institute of Energy Research developed an 8 kW SO electrolyser, and Mitsubishi Heavy Industries in Japan operates a 400 kW test module for gas turbine co-firing demonstrations. Globally speaking, the technology has not yet reached TRL 8-9 in every part of the world. Scaling up and improvements are still needed globally. The rSOC technology is advancing and currently at TRL 5, with support from the U.S. Department of Energy's National Energy Technology Laboratory, aiming to progress to Level 6 on parity with, e.g., the SWITCH project (see Section 5.4). Key challenges remain, including stack-module size, durability, and operational cycle issues for Solid Oxide Electrolysis Cell (SOEC) manufacturers before commercialisation is feasible.

Other Routes of Renewable Hydrogen Production: Internationally, various alternative hydrogen production methods are under investigation, though they often possess a significantly lower TRL compared to electrolysis and, in some instances, encounter substantial technical challenges. Biomass gasification emerges as a promising pathway with a relatively high TRL of 6-7 and the potential for low costs. Thermal integration, explored by the HYIELD project, may be crucial for enhancing efficiency. However, this approach is hindered by the limited availability of suitable feedstock and the complexities involved in sorting municipal waste. Photocatalytic hydrogen production is met with considerable technical and practical obstacles, including low STH efficiency, material degradation, and scalability issues. Although photocatalytic (PC) routes are less complex compared to photoelectrochemical (PEC) processes, PEC offers advantages such as easier gas separation and higher efficiency. Current laboratory-scale PC systems achieve only 1-2% STH, with even lower efficiencies in outdoor tests, indicating that this technology is unlikely to play a significant role in renewable hydrogen production in the next twenty years. Thermochemical cycles continue to face major challenges, but they may eventually offer low-cost hydrogen solutions. For instance, a UK study (HyTN)[23] identified the sulphur-iodine and hybrid sulphur cycles as the most promising, with potential hydrogen costs projected to be less than a British pound per kilogram by 2050.

Programme highlights

Regarding low-temperature electrolysis, high-TRL demonstration projects have validated electrolyser performance in diverse and challenging environments, gaining strong visibility. A large-scale demonstration of clean hydrogen deployment in carbon-intensive industry was conducted by the REFHYNE project, which was completed in June 2024. At Shell's Wesseling refinery, a 10 MW PEM electrolyser manufactured by ITM was successfully commissioned and operated. The system was fully integrated into refinery operations, responding dynamically to fluctuations in power prices and hydrogen demand.

20 See at https://hydrogentoday.info/en/bloom-energy-shell-electrolysers

21 See at https://www.renewableenergyworld.com/energy-storage/bloom-expands-electrolyzer-production-capacity-to-2-gw

22 See at https://www.hydrogenfuelnews.com/fuelcell-energy-electrolyzer/8569602

23 https://assets.publishing.service.gov.uk/media/64678f30628371000c3a8919/HYS2115_NNL_Final_Feasibility_Report__Public_.pdf

The ADVANCEPEM initiative demonstrated 2,000 hours of continuous testing of membrane electrode assemblies (MEAs). At the same time, the DJEWELS and HOPE projects carried out short-stack and full-scale trials that helped resolve earlier issues of performance loss and degradation. In parallel, HYPRAEL focused on dimensionally stable electrodes and tested new component concepts under standard operating conditions, with the ambition of designing next-generation alkaline electrolysis (AEL) systems suited for demanding environments.

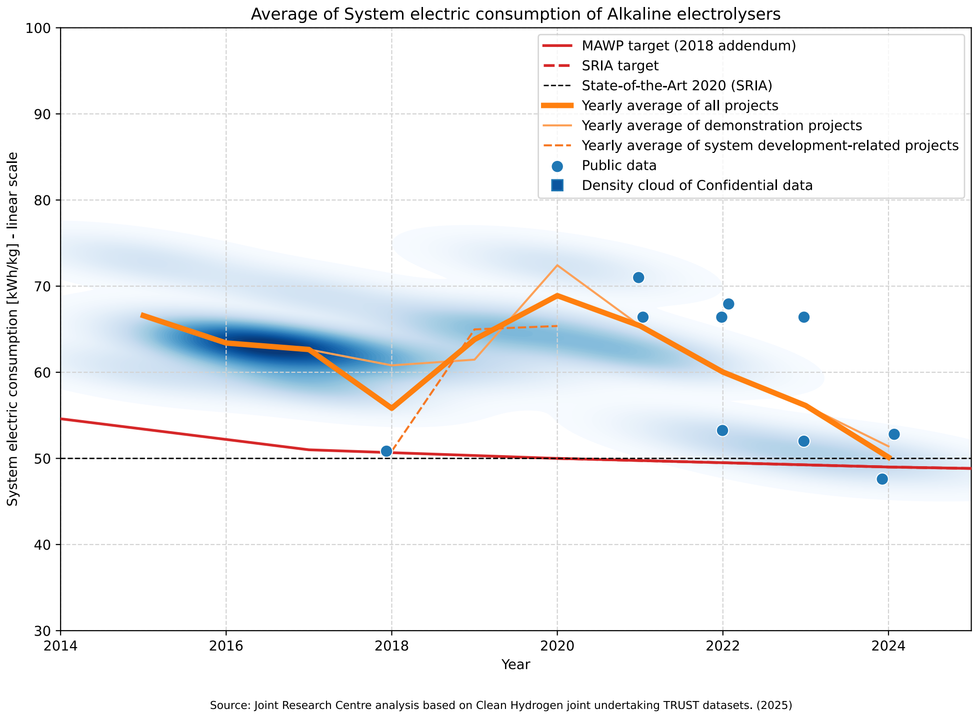
For AEL, the HYPRAEL project reports an electricity consumption of 48 kWh/kg of hydrogen, a system CAPEX of 450 EUR/kW, and an O&M cost of 40 EUR/(kg/d)/yr. Despite meeting the SRIA 2024 targets for electricity consumption, current density, CAPEX, O&M costs, and hot idle ramp time, the SRIA 2024 targets for stack degradation, use of CRM, and cold start ramp time remain unachieved/unaddressed by newcomer projects. However, it should be noted that, due to the fact that some of the projects target PGM-free catalyst coatings, the use of CRMs might not be reported.

For PEM electrolysis the use of CRM has decreased significantly, from an average of about 0.74 mg/W to 0.15 mg/W. Energy consumption has reduced from 60.5 kWh/kg of hydrogen to 53.8 kWh/kg of hydrogen. The average degradation rates have improved, dropping from about 0.25% per 1000 hours of operation to around 0.13% per 1000 hours. Moreover, current density has improved to 3.0 A/cm², up from 2.3 A/cm², meeting even the 2030 SRIA target. Meeting the 2024 SRIA target of 700 EUR/kW and the SRIA 2030 target of 500 EUR/kW for CAPEX could only be reached by one of the projects.

AEMEL technologies advanced significantly, with three JU-funded projects raising TRLs and paving the way for new initiatives on PFAS-free membranes and lower CAPEX. A machine-learning method was also introduced to fine-tune membrane composition, paving the way toward what may become the first recombination catalyst without PGMs (AEMELIA project).

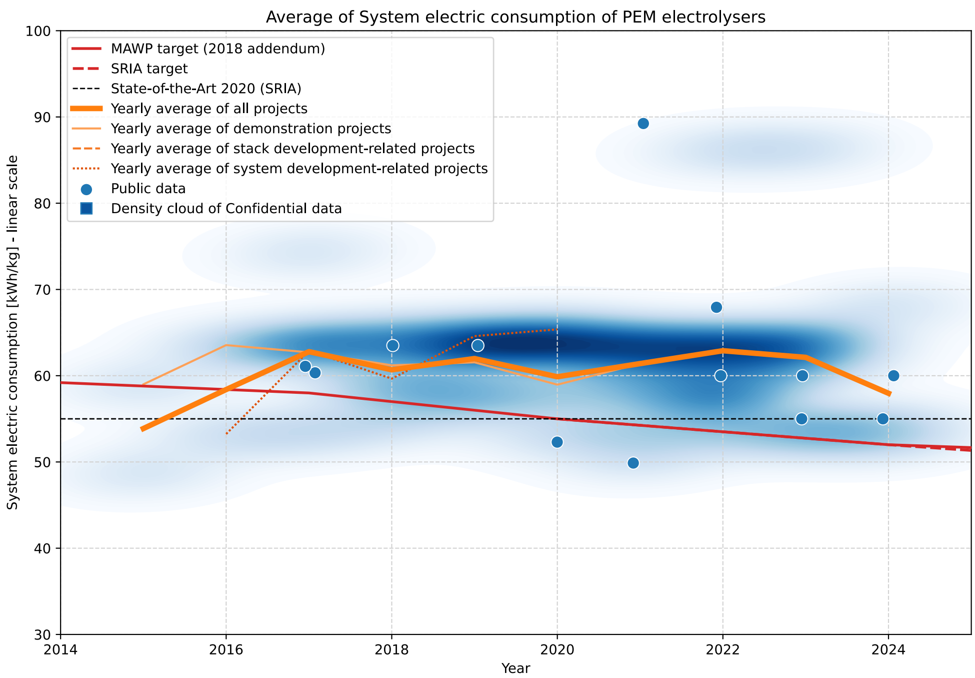
The average electrical consumption of Alkaline, PEM and AEM electrolysers developed by projects under this RA is shown in Figure 6, 7, and 8. Over the past four years, the majority of alkaline electrolyser deployed in projects have, on average, exceeded their SRIA targets for system electric energy consumption, measured in kWh/kg of hydrogen produced. In contrast, projects deploying PEM, and AEM electrolyser, similarly to SO electrolysers, have predominantly met or nearly met their respective SRIA targets for this category. Notably, there is a downward trend in energy consumption across all four types of electrolyser, with the most significant improvements observed in projects using AEM electrolyser.

Figure 6: Average of system electric consumption of Alkaline electrolysers



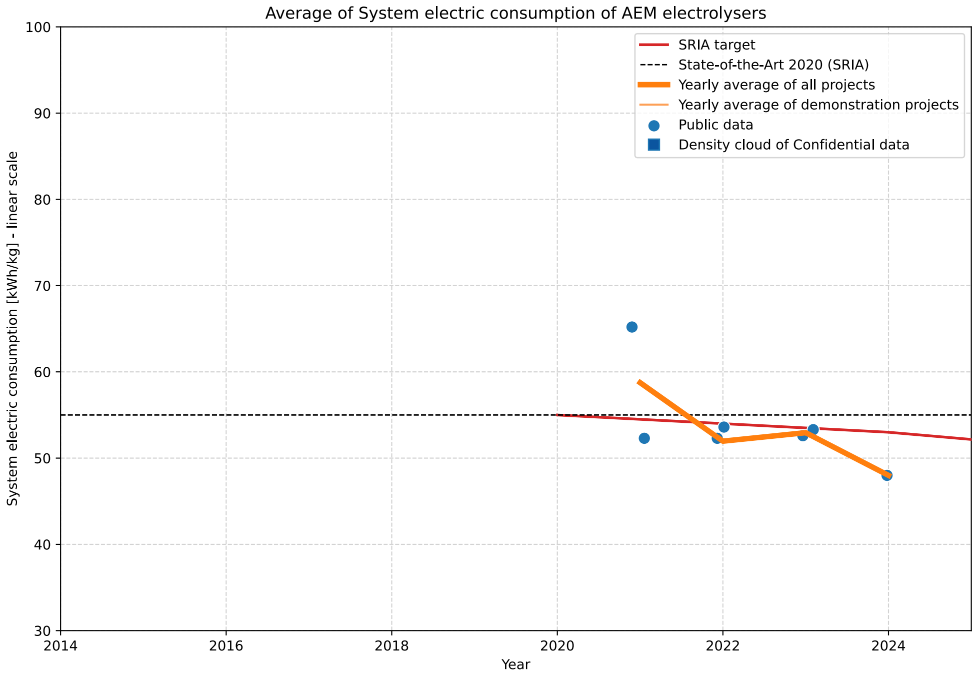
Source: Joint Research Centre analysis based on TRUST data (2025). Note: MAWP and SRIA targets are overlapping.

Figure 7: Average of system electric consumption of PEM electrolysers



Source: Joint Research Centre analysis based on TRUST data (2025). Note: MAWP and SRIA targets are overlapping.

Figure 8: Average of system electric consumption of AEM electrolysers

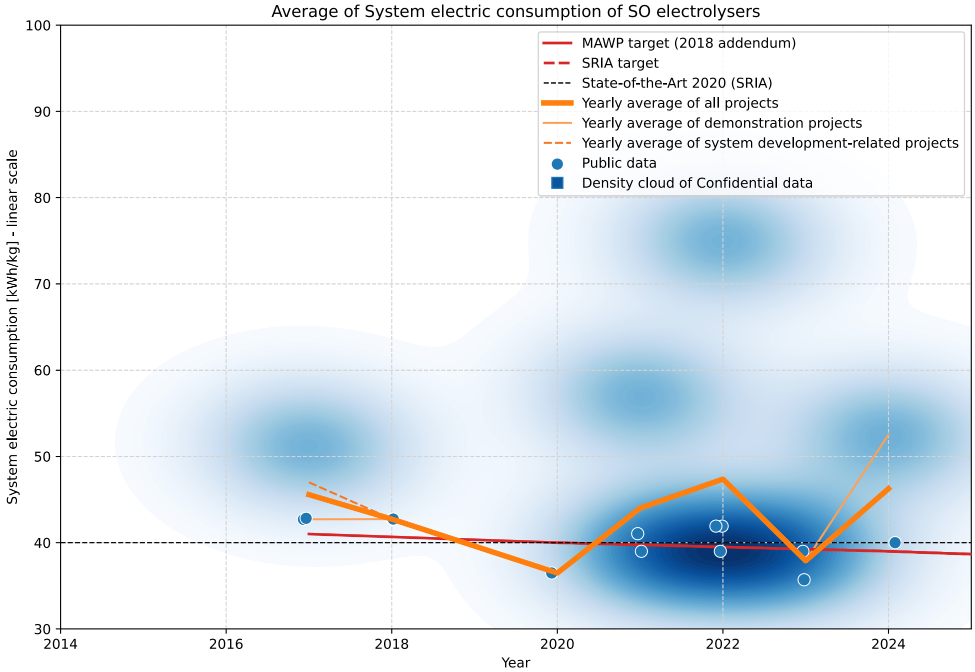


Source: Joint Research Centre analysis based on TRUST data (2025). Note: MAWP and SRIA targets are overlapping.

In high-temperature electrolysis, though only limited changes in achievements were reported, two out of ten indicators improved compared to the 2024 review. Specifically, system O&M cost and current density have now been achieved by the best-performing project, while round-trip electrical efficiency and heat demand at nominal capacity remain unachieved or unexplored in SO electrolyser projects. The cold start ramp time continues to be out of reach for all projects. Among the remaining parameters, a notable improvement is the significant decrease in the average electrical consumption of SOELs implemented in this RA. Most projects have already achieved or are very close to their SRIA targets in this category, with the consistent downward trend in energy consumption underscoring the enhanced efficiency of the developed electrolysers.

It is worth mentioning that the average electrical consumption of SOELs implemented by the projects in this RA, presented in Figure 9, further decreased. Most projects have largely achieved or closely approached their designated SRIA targets for this category. A consistent decline in energy consumption over time highlights the enhanced efficiency of the developed electrolysers.

Figure 9: Average of system electric consumption of SO electrolysers



Source: Joint Research Centre analysis based on TRUST data (2025). Note: MAWP and SRIA targets are overlapping.

Overall, SOEL has scaled to the megawatt level, demonstrating competitiveness for large-scale renewable hydrogen production and benefiting from waste heat integration. Sunfire successfully delivered a 2.6 MW SO electrolyser installed at the Neste refinery in Rotterdam (MultiPHLY project). The REACTT project focused on understanding and mitigating degradation mechanisms in SO electrolysis and reversible solid oxide cell (rSOC) stacks. Using online monitoring, it addressed performance losses under high-current and transient conditions, and further developed its Monitoring, Diagnostic, Prognostic, and Control (MDPC) tool. In parallel, the OUTFOX project made significant progress in producing and testing industrial-scale solid oxide cells, achieving performance results in line with the SRIA current density target of 0.85 A/cm².

Finally, solar-based hydrogen production continues to be explored, further diversifying clean hydrogen pathways. The HYSELECT concept appears to address a critical challenge in solar hydrogen production by decoupling the energy/heat collection process from the chemical reactor. This approach reduces heat transfer losses and corrosion while allowing for the use of more optimised materials. However, HYSELECT has yet to identify the technology for heat recovery and gas purification.

Gap Analysis – Main JRC Recommendations

The Clean Hydrogen JU is laying a strong foundation for advancing electrolyser technologies, particularly PEMEL and SOEL, in line with the EU hydrogen strategy for large-scale sustainable production. Support is also directed to PCCEL and AEMEL, which may offer benefits for specific applications as well as to alternative pathways for hydrogen production. Overall, continued emphasis is needed on both low-TRL research to enable next-generation solutions and first-of-a-kind demonstrations to accelerate industrial uptake.

Low-Temperature Electrolysis: Low-temperature water electrolysis technologies (AEL, PEMEL, and AEMEL) are advancing rapidly, yet important optimisation challenges remain. A careful and tailored use of artificial intelligence (AI) and dedicated datasets is encouraged to optimise material discovery, electrochemical screening, and manufacturing processes, reducing critical raw material and PFAS use. European-wide approval procedures and permitting guide for 'energy transition' projects should be considered. Deployment of the MDPC tool for stack degradation monitoring, open-access databases with structured test metadata, and standardised material synthesis routes are advised to improve reproducibility, predictive maintenance, and innovation. For electrolyser demonstrations integrated into industrial processes, comprehensive risk assessments with realistic timelines and contingency planning involving all stakeholders, third parties, and subcontractors, are essential. Industry partners from key projects (Djewels, ENDURE, EPHYRA, PEACE, SEAL-HYDROGEN, ADVANCEPEM, HOPE, HERAQCLES, and HYPRAEL projects) should be encouraged to engage in ISO TC 197 SC 1 standardisation activities, contributing their expertise on safety and operational experience. Finally, R&D funding for well-established AEL technologies should be prioritised only for highly innovative approaches that significantly improve hydrogen yield, gas purity, reduce costs, or enhance electrolyser flexibility.

High-Temperature Electrolysis: Compared to AEL and PEMEL, SOEL technology is still less advanced, with fewer funded projects reaching higher TRLs. The smart use of AI and AI-based tools remains largely absent, despite their potential to support design, engineering, and testing processes, thereby optimising R&D and reducing future expenses. Equally, although EU harmonised test methods and protocols are often required in call topic descriptions, not all projects consistently apply them when defining their specific testing frameworks. The MDPC tool, developed under the REACTT project to monitor stack degradation, has yet to be employed more widely across other relevant initiatives, leaving an underexploited opportunity for predictive degradation assessment. Furthermore, a critical gap is the absence of a KPI on the use of CRMs as catalysts, particularly rare earth elements used in the anodes and cathodes, where market ramp-up is driving demand. In addition, test data management remains insufficiently coordinated. Although projects report selected results through deliverables and publications, much of the non-proprietary data is not structured for open access or easy comparability. Metadata on material synthesis, essential for ensuring reproducibility and supporting disruptive findings, is often incomplete, limiting broader uptake and cross-project synergies.

To address these shortcomings, several actions are needed. A consolidated, circular-oriented European supply chain must be developed to ensure economic viability, resource efficiency, and resilience while supporting the cost-effective manufacture and operation of HT electrolysis systems. Greater use of AI in R&D should be encouraged to enhance component development and optimise system operation. A new KPI on CRM use in electrolysers should be introduced to monitor and mitigate critical material dependencies. The MDPC tool should be adopted more widely, supported by targeted dissemination efforts such as dedicated webinars for testing institutes. Moreover, all non-proprietary test data, complete with metadata on conditions, processes, and instrumentation, should be systematically collected in an open-access database, with proprietary data released after embargo periods. Enhanced comparability in material synthesis could be achieved through standardised, automated synthesis routes where feasible. Stronger industrial partnerships, established before project initiation, would help mitigate partner dependencies and facilitate cross-comparisons of performance in identical industrial configurations. Synergies with ongoing certification efforts, such as CertifHy, and active participation in international standardisation activities should be reinforced to ensure European projects contribute to and benefit from evolving global norms in electrolysis testing and guarantees of origin. Finally, existing testing protocols, such as those developed by Hy-Spire for O-SOE and P-SOE cells, should be leveraged in international standardisation efforts, and project consortia are encouraged to contribute expertise to committees such as IEC TC 105 MT 206 and WG 107.

Alternative Methods of Hydrogen Production: Solar-to-hydrogen (STH) technologies, including HYSELECT and PH2OTOGEN, face challenges in achieving plant-level efficiency and durability targets, with current systems unlikely to meet the 10% STH needed for low-cost hydrogen. Gaps include limited progress on non-PGM catalysts and the need to prioritise material optimisation over premature field testing. To address these challenges, JRC recommends focusing on basic research to advance STH efficiency and reduce costs, increasing support for sustainable biomass gasification, and integrating carbon capture where feasible. Additionally, comprehensive assessments of municipal and industrial waste streams should guide the allocation of resources to the most sustainable and effective hydrogen production pathways. Adequate funding reflecting the ambitious objectives of thermochemical cycle projects is essential to ensure meaningful technological progress in this research area.

5.2. PILLAR 2: HYDROGEN STORAGE AND DISTRIBUTION

The REPowerEU plan and the European hydrogen strategy highlight the critical importance of hydrogen storage and distribution in accelerating the uptake of renewable hydrogen across Europe. The plan sets a target of importing 10 million tonnes of hydrogen by 2030, complementing an additional 10 million tonnes expected to be produced within Europe. To achieve this, the hydrogen strategy underscores the need for a robust logistical infrastructure capable of transporting hydrogen from regions with high renewable energy potential to demand centres throughout the continent.

A variety of storage and transport solutions are available, and the SRIA promotes a diversified, technology-neutral approach to support multiple options. These technologies collectively form the foundation of a comprehensive EU-wide hydrogen logistics network.

Overview of Research Areas

Pillar 2 of the programme addresses a wide spectrum of distribution challenges, including storage, compression, purification, separation, and transportation. Each of these areas can be approached through multiple technological solutions, such as compressed or liquid hydrogen, chemical carriers, and systems of varying scales. The maturity of these technologies differs, with some already well-developed and others still in early stages of R&D, reflecting the diverse and evolving nature of hydrogen distribution innovation.

For clarity and readability, the project (NICOLHy) under the research area “liquid hydrogen storage” will be combined with those categorized as “liquid hydrogen carriers” throughout the chapter. Additionally, due to notable thematic overlaps between the “liquid hydrogen carriers” projects and those focused on “improving existing hydrogen transport means,” these groups will be merged. The SRIA also includes the research areas “aboveground storage” and “hydrogen distribution (pipelines),” for which no projects are currently active.

Underground Hydrogen Storage: The most commonly used formations for underground hydrogen storage (UHS) are salt caverns, rock caverns, depleted gas fields, and aquifers. UHS has seen significant advancements in recent years. From a technical side, both salt cavern and porous reservoir have shown progress, but there are still challenges to overcome. Given that large-scale underground hydrogen storage in salt caverns is already at a higher TRL, the SRIA primarily focuses on lowering costs and identifying best practices and viable business cases for integrating renewable hydrogen production with underground storage.

The project HYUSPRE has significantly advanced the understanding of UHS, enhancing the technical knowledge of storage operations. The project explored the feasibility of large-scale renewable hydrogen storage in porous reservoirs across Europe using a combination of laboratory experiments and integrated modelling approaches. It validated open-source reservoir modelling software capable of simulating coupled flow, geochemical, and microbiological processes, and developed an interactive GIS story map to visualise hydrogen storage potential across European porous reservoirs. These tools provide accurate predictions of hydrogen behaviour at selected sites, supporting strategic decision-making. Complementary projects, FRHYGE and EUH2STARS, focus on demonstrating hydrogen storage in salt caverns and depleted gas fields, with EUH2STARS targeting TRL 8 by the end of the decade, building on Austria’s TRL 6 pilot facility operated by RAG.

Overall, this research area demonstrates strong integration of basic research, modelling, geological surveys, and practical testing. Projects like HYSTORIES and HYUSPRE have considerably advanced the state of the art for porous rock storage, generating extensive knowledge that is accessible through public deliverables and tools. These efforts collectively provide a solid foundation for scaling up underground hydrogen storage and informing future deployment strategies.

Hydrogen in the natural gas grid: In Europe, significant efforts are focused on distributing large volumes of hydrogen via pipelines, encompassing the injection of hydrogen into the existing natural gas grid, repurposing natural gas pipelines for 100% hydrogen transport, and constructing dedicated hydrogen pipelines. This research area primarily addresses the first two objectives.

Safety remains a central concern, with research targeting material compatibility with hydrogen and advanced leak detection. Projects like CANDHY and PILGRHYM are expected to provide valuable input to these standardisation efforts. While current hydrogen regulations mainly focus on safety concerns, work is still needed to address hydrogen's climate impact as an indirect greenhouse gas. Policies aimed at limiting hydrogen leakages beyond safety considerations would represent a significant step toward integrating environmental considerations into hydrogen pipeline operations. In this direction, OPTHYCS focuses on developing and validating sensor technologies across multiple case studies, which can directly support NHyRA's efforts (from Pillar 5) in establishing robust measurement methods and protocols for quantifying hydrogen releases. Shared partners, such as GERG and Enagás, are expected to facilitate effective communication and knowledge transfer between the projects, enhancing coordination and ensuring that insights from sensor validation inform hydrogen release quantification strategies.

Liquid H_2 storage, Liquid H_2 carriers, improving existing hydrogen transport means: Transporting gaseous hydrogen over long distances presents notable challenges because of its low volumetric energy density, requiring substantial investment in delivery infrastructure. For distances exceeding 3,000 km, pipelines are generally less cost-effective than alternatives such as shipping compressed or liquid hydrogen, or using chemical carriers. Among these options, liquid hydrogen is particularly attractive due to its high gravimetric and volumetric energy density, though technical hurdles remain, including minimizing energy consumption during liquefaction and managing boil-off.

Liquid hydrogen storage and transport face challenges due to boil-off losses, which can be mitigated using highly insulating tanks. The LH2CRAFT project is developing a membrane containment system designed for large-scale hydrogen shipping, which is a novel technology for LH_2 and requires additional safety validation. Systematic risk assessments are underway to achieve classification society approval, expected in 2027. The project also integrates a sustainability assessment tool with a materials database to aid in selecting insulation materials. Meanwhile, the SINGLE project is advancing proton ceramic electrochemical reactors for ammonia cracking and hydrogen purification, consolidating multi-stage processes into a single step for decentralized applications. By pursuing a PGM-free approach, SINGLE reduces reliance on costly and scarce ruthenium catalysts, enhancing sustainability and cost efficiency. The HYLICAL project is exploring magneto-caloric hydrogen liquefaction, reviewing over 400 materials with promising magnetic entropy and adiabatic temperature properties, such as light rare earth Laves phases and Holmium. The project has made significant progress in reviewing these materials and identifying promising candidates, which is a crucial step towards developing a demonstrator. This is a highly ambitious goal, as the project needs to go from basic materials research to demonstrating a prototype. Showing support for the project's potential is the EUR 6.8 million in seed funding from industrial partner Engie to project partner Magnotherm[24].

Compression, purification and metering solutions: Depending on the hydrogen production pathway, the gas may require separation from a mixture or additional purification. This can be achieved using various techniques, including Pressure Swing Adsorption (PSA), membrane-based separation, cryogenic separation with partial condensation, electrochemical separation, or combinations of these methods in hybrid systems. Compressors are needed for the delivery of hydrogen, with pressures above 700 bar required for refuelling and up to 100 bar for injection into pipelines.

Compressors are among the components most susceptible to failure at hydrogen refuelling stations (HRS), highlighting the need for research aimed at enhancing reliability, reducing costs, and improving efficiency. Current demonstration projects, COSMHYC DEMO and H2REF-DEMO, are addressing these challenges. COSMHYC DEMO showcases a hybrid system combining a metal hydride and a mechanical compressor, while H2REF-DEMO features a compressor based on a bladder accumulator. Both initiatives build on prior JU-funded projects, including COSMHYC, COSMHYC XL, and H2REF.

24 ENGIE New Ventures invests in MAGNOTHERM, expanding our seed financing round up to 6.8 million Euros

Hydrogen Refuelling Stations: The first HRS demonstration project funded by the CHJU (at the time FCH-JU) was H2moves.eu Scandinavia in 2010-2012[25]. Funding to this area has increased since then, shifting primarily to projects enabling improved HRS performance.

As mentioned earlier, COSMHYC DEMO builds on the scalable, modular hybrid compression technology developed under the COSMHYC and COSMHYC XL projects, combining a metal hydride compressor with a mechanical compressor to potentially reduce energy consumption and CAPEX. DelHyVEHR focuses on developing and demonstrating a high-flow cryogenic transfer pump along with a boil-off gas management system for liquid hydrogen refuelling stations. Meanwhile, RHeaDHy is advancing a high-performance HRS by integrating all necessary components and validating the refuelling protocols from PRHYDE, partnering with Toyota this year to provide a test bench and truck for testing and deployment.

State-of-the-art

Underground Storage: Hydrogen storage can support intermittent renewable energy sources and enable seasonal energy storage, which is critical for a low-carbon energy system. To meet the EU's 2030 and 2050 climate targets, a model-based analysis, the EU requires UHS capacities of 45 TWh by 2030 and 270 TWh by 2050[26]. The current project pipeline in Europe seems to fall far short of these capacities. Internationally, many demonstration projects are at various stages of implementation. In Europe there are various sources of public funding, for instance the Hy2Infra IPCEI mobilises €12.3 billion (€6.9 billion public, €5.4 billion private) across seven member states for developing hydrogen infrastructure, which includes 370 GWh of storage capacity, primarily in salt caverns[27]. European UHS capacities remain modest compared to international ambitions in Australia and the UK.

From a policy and financial perspective, Europe lacks dedicated support mechanisms for UHS, with the UK being an exception. Germany has shown interest in UHS, with the government establishing an EUR 18.9 billion amortisation account to support infrastructure development. However, there is disagreement on the best financing approach, with different studies recommending varying methods such as Contracts for Difference, amortisation methods, and investment grants.

Hydrogen in the NG grid: In Europe, research is focused on safely distributing large quantities of hydrogen through pipelines, including injecting hydrogen into the natural gas grid, constructing dedicated hydrogen pipelines, and repurposing natural gas pipelines for 100% hydrogen transmission and distribution. Research continues to ensure safety, targeting topics like material compatibility with hydrogen and leak detection. European standards, such as EN 12007-5 and EN 1594, are being revised to include provisions for hydrogen compatibility assessment, material requirements, and repurposing natural gas pipelines for hydrogen use. National codes, such as those proposed by DVGW and IGEM, also provide field-tested guidelines. The European Committee for Standardization (CEN) is expected to address the remaining gaps in areas such as gas quality, odorisation, and component performance in the future. However, existing regulations primarily focus on safety concerns, and more work is needed to address climate impact mitigation, including recognising hydrogen as an indirect greenhouse gas and limiting leakages[28]. The EU regulation 2024/1787 on methane emissions in the energy sector may provide a framework for reducing hydrogen leakages[29].

Liquid H2 storage, Liquid H2 carriers, improving existing hydrogen transport means: Hydrogen delivery technologies are advancing rapidly, with various options being explored for large-scale transportation. Liquid Hydrogen (LH_2) is one promising approach, with several projects demonstrating its feasibility. For example, South Korea aims to develop a 10,000 t LH_2 carrier by 2040, while Japan's Suiso Frontier project has successfully transported 75t LH_2 using a double-shell structure with vacuum insulation. Membrane containment systems, such as those developed by Samsung Heavy Industries and GTT with Total Energies, are being explored for large-

25 Historical Analysis of Clean Hydrogen JU Fuel Cell Electric Vehicles, Buses and Refuelling Infrastructure Projects–Clean Hydrogen Partnership

26 RPT-EU_Underground_Hydrogen_Storage_Targets-090424-CLEAN.pdf

27 Hydrogen Europe

28 Integrating Hydrogen Emissions Into the EU Policy Framework

29 Regulation–EU–2024/1787–EN–EUR-Lex

scale LH_2 storage and transportation. Global liquefaction capacity is currently around 450 tonnes per day, with the US hosting over 65% of this capacity. New facilities are being developed, including a 90 t/day plant in South Korea and a 63 t/day plant in China. Most liquefaction plants use the Claude cycle with liquid nitrogen precooling, a 50-year-old technology. While improvements have been made, energy consumption remains high at 10-15 kWh/kg LH_2, far from the theoretical minimum of 3.5 kWh/kg LH_2. Researchers are exploring ways to reduce energy demand, such as integrating with existing LNG infrastructure, optimising design, or using alternative refrigeration cycles like the magneto-caloric effect.

Alternative approaches, such as Liquid Organic Hydrogen Carriers (LOHCs), are also being developed. LOHCs offer advantages in terms of infrastructure compatibility and ambient-temperature transport, with companies like Chiyoda and Hydrogenious Technologies making significant progress. Chiyoda has demonstrated the commercial readiness of its toluene/methylcyclohexane (MCH) system, while Hydrogenious Technologies is developing a benzyltoluene (BT) system with good cycle stability. Other LOHC systems, such as Hynertech's carbazole-based system, are also being explored.

Ammonia-based carriers are another option, with synergies with industrial applications and potential for large-scale production. Ammonia cracking is a well-established industrial technology currently used in applications such as metallurgy and heavy water production,[30] with large-scale facilities operational in countries like Argentina (4,800 tonnes NH3/day capacity)[31] and India (in total 800 tonnes NH3/day)[32]. Companies like AFC Energy have achieved energy efficiencies of 9.5 kWh/kgH2. Europe is active with 23 industrial-scale projects under development for a total capacity of 1.9 million tonnes of H2, according to the Ammonia Energy Association[33]. This is close to half of the 2030 RePowerEU target of 4 million tH2. European projects like ENHANCE and Amplifhy are advancing the development of ammonia import terminals and crackers, with the potential to produce large quantities of hydrogen. The floating ammonia to hydrogen cracker concept, being developed by Höegh Evi and Wärtsilä Gas Solutions, could also play a significant role in the future of hydrogen production[34]. The Asia-Pacific region seems to be shifting from traditional thermal processes to electrified, catalyst-driven systems, as showcased by an all-electric ammonia cracker, achieving 290 kg H_2/day at 11 kWh/kg (81% energy efficiency, 99% conversion), commissioned by Syzygy Plasmonics and Lotte Chemical in Ulsan, South Korea[35].

Road transport of hydrogen is also evolving, with tube trailers still being used for smaller volumes. Composite solutions are replacing steel, increasing payload and reducing costs. Type IV trailers dominate, delivering ~1 t H_2 at 350–500 bar with CAPEX EUR 800–1000/kg-H_2 and mature manufacturing[36 37]. At present, Europe's CALVERA leads with a capacity of 1.3 tH2 at 517 bar[38]. In the U.S., Infinite Composites and ORNL are validating Type V linerless vessels at pressures up to 993 bar, proving high gravimetric efficiency and targeting volumes of 5-325 liters[39]. ORNL used 3D printing technology and a dissolvable liner. Hexagon Composites offer a 540 bar solution for 1.5 t H2 storage, at a cost of USD 900/kg H2[40]. These efforts collectively push toward higher capacity, pressure, and cost reduction.

Compression, purification and metering: Compressors are needed for the delivery of hydrogen, with pressures above 700 bar required for refuelling and up to 100 bar for injection into pipelines. Most compressors used in HRS are mechanical compressors, including diaphragm, piston, and ionic liquid compressors[41]. Mechanical

30 The existing large scale plants mentioned here are both producing hydrogen for heavy water production.
31 P-Brito-2024.pdf
32 Recent Progress on Ammonia Cracking Technologies for Scalable Hydrogen Production
33 Ammonia Cracking is Developing with Pilots Under Construction | Ammonia Energy Association
34 Höegh LNG, Deutsche ReGas to develop floating ammonia cracker
35 Syzygy Plasmonics and Lotte Chemical Unlock Ammonia as a Hydrogen Carrier in Asia, Successfully Complete Trial of Ammonia e-Cracking Unit
36 Bulk Hauling Equipment for CHG
37 Techno-economic Analysis of Conventional and Advanced High-pressure Tube Trailer Configurations for Compressed Hydrogen Gas Transportation and Refueling | Argonne National Laboratory
38 CALVERA HYDROGEN develops the largest ever hydrogen transport tube trailer model for Shell Hydrogen–Calvera Hydrogen
39 Infinite Composites: Type V tanks for space, hydrogen, automotive and more | CompositesWorld
40 Bulk Hauling Equipment for CHG
41 Review on equipment configuration and operation process optimization of hydrogen refueling station–ScienceDirect

compressors tend to be expensive and unreliable. Non-mechanical compressors are at a lower maturity level, but can offer some advantages over mechanical compressors, such as no moving parts (lower chance of failure and maintenance) and lower costs[42]. Non-mechanical compressors include metal hydride, electrochemical, and adsorption compressors, each with its own advantages and drawbacks. Research that explores innovative solutions, including hybrid compressors and disruptive concepts, is therefore needed.

Proton-conducting ceramic electrolysis (PCCEL), as developed by the project WINNER, is a cutting-edge technology for efficient green hydrogen production, operating at intermediate temperatures (400–700°C). Research efforts are currently looking into reducing the operating temperature of PCC cells[43]. Current state-of-the-art cells, often based on yttrium-doped barium zirconate (BZY) and its cerium-doped variants like (BZCYYb) electrolytes[44] exhibit promising current densities but face challenges in achieving consistent reproducibility and large-scale manufacturing.

Hydrogen Refuelling Stations: The deployment of HRS is expanding globally. In 2024, 125 new HRS went into operation worldwide. 42 new HRS were opened in Europe, around 63 in Asia, and 13 in North America. Similar to 2021, 2022, and 2023, South Korea was the country adding the largest number of new stations[45]. The number of HRS in the EU is increasing, although at a different pace in the different Member States; the majority of stations remain concentrated in Germany, followed by France, the Netherlands, Switzerland, and Belgium[46]. The European HRS Availability map (Figure 10), an initiative funded by the Clean Hydrogen JU, offers a portal providing live-status information on most public HRSs in Europe. In June 2025, it reported 184 publicly available hydrogen refuelling stations (HRS). Of these, 170 operate at 70 MPa for fuel cell passenger cars, 52 at 35 MPa for passenger cars, and 109 at 35 MPa for fuel cell buses. According to COM (2025) 260 final[47], by the end of 2024, more than 250 HRS were serving a total of 4,700 cars, 320 vans, 140 lorries, and 320 buses. More than half of these are dispensing 700 bar H2. Similarly, CINEA has managed 56 projects planning to deploy over 150 HRS throughout Europe since 2014, with a total funding of EUR 504 million. 44 out of 174 planned HRS were to be located in France, 24 in the Netherlands, and 23 in Poland. Many of these projects are in varying stages of development, from early construction to partial operation.

The total amount of HRS that closed globally in 2024 is not known. Shell announced the closing of 7 light-duty HRS in California[48], while Germany saw 6 light-duty HRS operated by H2 Mobility closing[49]. The company announced the closing of an additional 22 HRS this year in Germany on the grounds of "network consolidation", as it focuses on heavy-duty vehicles[50].

42 Electrochemical Compression Technologies for High-Pressure Hydrogen: Current Status, Challenges and Perspective | Electrochemical Energy Reviews

43 https://doi.org/10.1038/s41560-023-01350-4

44 https://doi.org/10.1016/j.matt.2023.04.013

45 Press Release 2025–Milestone reached: over 1,000 hydrogen refuelling stations in operation worldwide in 2024–H2Stations.org

46 HRS Availability Map

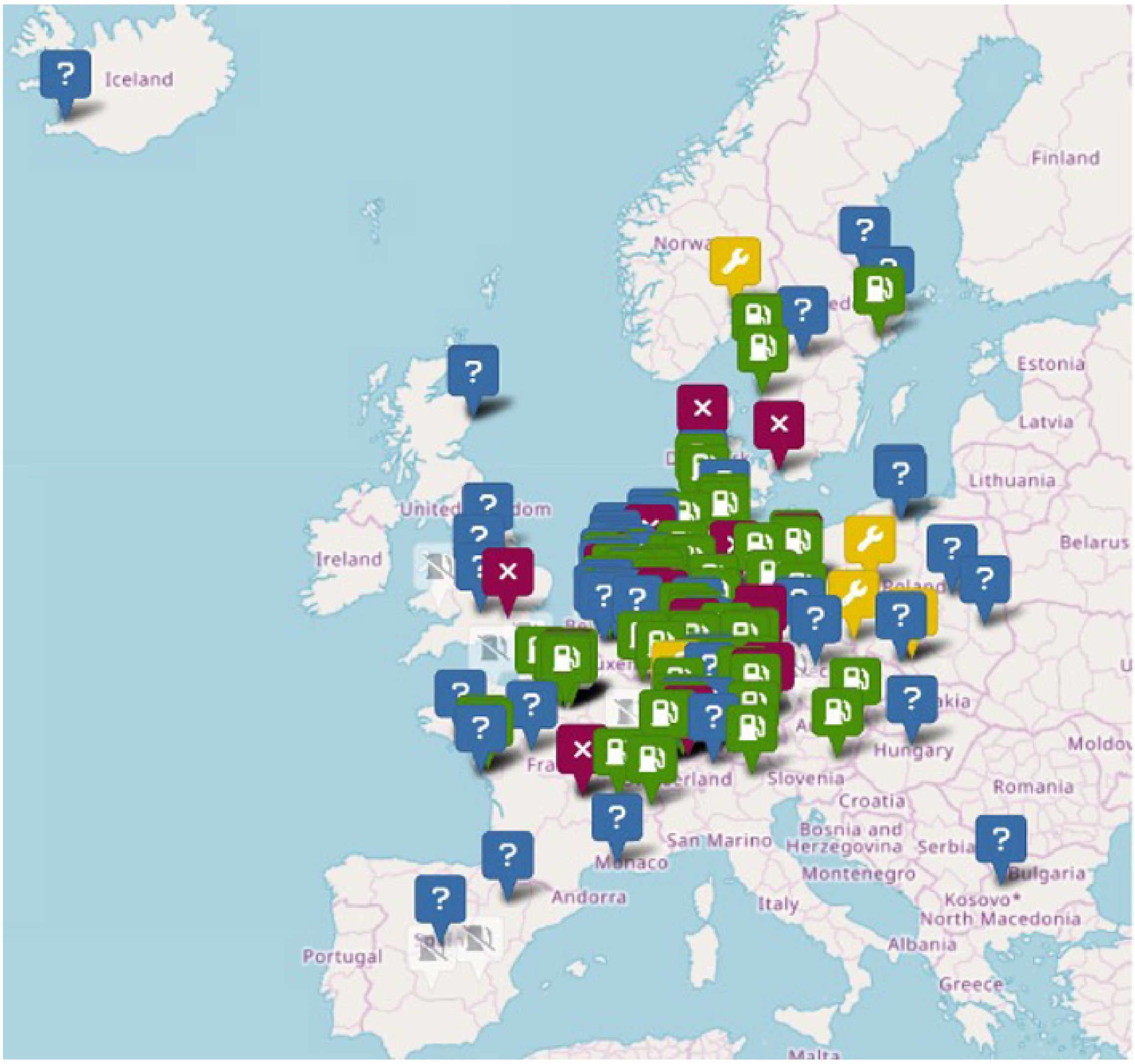
47 com(2025)260_en.pdf

48 Shell permanently closes light-duty hydrogen fueling stations | S&P Global

49 Information on the H2 MOBILITY hydrogen refuelling station network–H2.LIVE

50 Press & Download–H2Mobility

Figure 10: HRS availability map for 700 bar



Liquid hydrogen has been widely used in the space sector, and its use is currently being explored for other heavy-duty mobility applications. In February 2024, the first public liquid HRS pilot for fuel cell trucks was inaugurated in Germany[51]. The first passenger and car ferry running on liquid hydrogen, MF Hydra, has been operating in Norway since 2023. The ferry operator, NORLED, also owns and developed the bunkering system and procedures[52]. ALRIGH2T and GOLIAT (Pillar 3) are addressing LH_2 aircraft refuelling, and Airbus is developing a liquid-hydrogen-powered aircraft, testing the necessary components and protocols (see Pillar 3). Projects addressing and demonstrating liquid hydrogen bunkering, such as DelHyVEHR, are highly relevant and may help advance this technology.

Programme highlights

The Clean Hydrogen JU is putting efforts into improving and advancing innovative technological solutions, and many of the projects under this Pillar are demonstrating significant advances in different areas of research and innovation.

51 Safe, Fast and Simple: Daimler Truck and Linde Set New Standard for Liquid Hydrogen Refueling Technology | A Linde Company

52 POWERPOINT PRESENTASJON

For underground hydrogen storage, projects have generated a lot of knowledge, made accessible by many public deliverables and tools. HYSTORIES and HYUSPRE have significantly advanced the state of the art for porous rock underground storage, while FRHYGE and EUH2STARS can be considered complementary projects, as they are demonstrating the storage of hydrogen in salt caverns and depleted gas fields, respectively.

For H_2 in the natural gas grid, projects can provide the necessary information for future standard updates, enabling the safe use of pipelines as hydrogen transportation. It is worth noting that there are synergies and relevance among projects from this research area and projects from other pillars such as between NHyRA (pillar 5) and OPTHYCS as well as PILGRHYM and SHIMMER.

Regarding the research areas Liquid H_2 storage, Liquid H_2 carriers, and improving existing hydrogen transport means, SRIA targets are being addressed in contrast to previous years, although not met yet, due to the fact that the projects started recently. LH2CRAFT is progressing towards its target of approval from a classification society by performing systematic risk assessments, with a general approval planned for 2027. SINGLE's PGM-free approach represents a significant advantage in terms of costs and sustainability while HYLICAL has reviewed over 400 magnetocaloric materials with potential for hydrogen liquefaction.

With respect to Compression, purification and metering solutions, the start-up developed under the COSMHYC series of projects provides the metal hydride compressor for HYGHER, enabling a longer test cycle of the compressor solution. The decision to conduct an environmental assessment taken within the HYGHER project is a commendable initiative, as it was not a requirement in the original call topic. HQE has already impacted three standards, going beyond the SRIA target for 2030. WINNER achieved remarkable progress at both component level and system integration for such a low-TRL technology. The flexible multi-tube module design enables adaptation to various industrial contexts. The outcomes of the projects will be valuable for the SINGLE project, which targets ammonia cracking. Finally, it should be highlighted that in February 2025, the French company HRS was named a "Key Innovator"[53] by the European Commission's Innovation Radar for its contributions to H2REF-DEMO and RHeaDHy.

For hydrogen refuelling stations, experienced operators who have managed multiple stations over several years have noted that newer stations show higher availability compared to earlier models from the same supplier, indicating that lessons learned from early deployments are being applied to design and operations. Sharing these best practices is essential to ensure that stations from new suppliers and operators also achieve high reliability.

Gap Analysis – Main JRC Recommendations

Underground Storage: Technical challenges remain, such as developing comprehensive geochemical reaction databases and improving multiphase flow modelling capabilities. Pilot-scale testing and demonstration projects are crucial for overcoming these challenges and scaling up to commercial operation. Immediate measures are required to tackle the increasing gap between anticipated hydrogen storage demand and the projects currently in the pipeline.

Although the main obstacles to hydrogen storage development lie in policy and regulatory frameworks, they cannot be addressed by Clean Hydrogen JU alone. Current market structures lack adequate mechanisms to valorise the services that UHS can provide to the energy system. The absence of a dedicated EU hydrogen storage strategy and appropriate financing instruments, creates uncertainty and deters private investment. Complex and lengthy administrative procedures, involving multiple regulatory bodies and assessments, are delaying project development, as experience in Germany has shown[54]. However, the Clean Hydrogen JU could gather information from all European projects and provide input on various topics such as financial schemes for storage operators, developing and making publicly available certification schemes (such as HyPSTER's safety protocols that could be used to train storage operators), as well as improved knowledge transfer by centralising data.

53 HYDROGEN REFUELING SOLUTIONS (HRS)–HRS IS RECOGNIZED 'KEY INNOVATOR' BY THE EUROPEAN COMMISSION–04/02/2025–18H00–Actusnews Wire

54 Frontier_Economics_-_Finanzierungsmechanismus_für_Wasserstoffspeicher_-_FINAL.pdf

Hydrogen in the NG grid: Since the lack of a regulatory framework for hydrogen detection and minimisation of leakages has been identified already by two projects, the Clean Hydrogen JU could try to advocate for the recognition and inclusion of environmental impacts of hydrogen leaks at the regulatory level and in existing standards[55].

Liquid H_2 storage, Liquid H_2 carriers, improving existing hydrogen transport means: For hydrogen distribution at scale, Asian leadership is emerging through coordinated national strategies with substantial government backing. In Europe, innovation is supporting technological diversity, but there may be a lack of competitiveness in terms of TRL and due to funding scale differentials. Emerging technologies with low maturity levels often face significant hurdles. For example, HYLICAL aims to upscale its liquefaction technology by a factor of 100, relying on unproven materials. This approach can lead to scalability issues and uncertainty about meeting long-term goals. While research in these areas can advance scientific knowledge, it may not be enough to overcome the challenges and achieve desired outcomes within a specific timeframe. To ensure the SRIA targets are achievable, it is recommended that the Clean Hydrogen JU recalibrate the objectives for these research areas to better reflect the current project portfolio, available budgets, and TRL levels. A greater emphasis on higher TRL activities that can deliver tangible results should be given. Targeted support for projects that address engineering and scale-up challenges could provide more immediate benefits and practical solutions for hydrogen storage, transport, and liquefaction. Finally, the JU should clarify the market opportunities and potential impact of the technologies under investigation, particularly for ammonia cracking projects like SINGLE and WINNER. Greater coordination between complementary projects, leveraging common partners and shared knowledge, can maximise synergies and avoid duplication of effort.

Compression, purification and metering: Recent funding for hydrogen compressors has primarily focused on bladder accumulator-based and metal hydride–mechanical hybrid solutions, yet testing is incomplete and proven performance remains unverified, posing risks for ongoing projects like HYGHER. Following the completion and review of current projects, consideration should be given to supporting additional lower-TRL compression technologies.

Hydrogen Refuelling Stations: The COSMHYC project series has spanned nearly a decade with incremental TRL advancements, yet technical targets and KPIs remain largely unchanged and misaligned with SRIA objectives, raising concerns about whether current projects are on track to meet 2030 HRS CAPEX and performance goals. Additionally, while LH_2 refuelling is a critical stage with high boil-off rates, no SRIA KPI currently addresses this, highlighting the need for dedicated metrics and alignment between call topics and overarching SRIA targets.

5.3. PILLAR 3: HYDROGEN END-USES: TRANSPORT APPLICATIONS

Pillar 3 focuses on accelerating the uptake of fuel cell and hydrogen (FC) technologies in transport. While FCH JU (the predecessor of Clean Hydrogen JU) made substantial progress in developing, validating, and demonstrating FC passenger cars, buses, and medium/heavy-duty vehicles that are now considered market-ready, further work is required in harder-to-decarbonise sectors. Applications such as heavy-duty trucks, off-road and industrial vehicles, rail, maritime, and aviation still need development and demonstration, drawing on the technical expertise already gained in FCEVs and FCBs.

The 26 ongoing projects within Pillar 3 cover both research projects and demonstration initiatives, and are divided into the following five Research Areas:

- **Aeronautic Applications**: Focuses on the development of liquid hydrogen storage systems and fuel cell technologies for aviation.
- **Building Blocks**: Addresses material design and system optimisation for PEM fuel cell technologies for transport applications.

55 It should be noted that the ISO/TR 15916:2015 on the basic considerations for the safety of hydrogen systems is currently under revision, and that the hydrogen safety topic is also being addressed in Working Group 3 of the CEN JT6 committee.

- **Heavy Duty Vehicles, including Buses/Coaches**: Focuses on the optimisation of the Balance of Plant (BoP) for heavy duty vehicles. Buses and coaches demonstration projects aiming at the further deployment of the hydrogen fuel cell technologies in this segment are also included.
- **Rail Applications**: Focuses on hydrogen storage and refuelling technologies in the rail sector.
- **Waterborne Applications**: Focuses on research and demonstration projects for fluvial and maritime applications, including port activities.

Overview of Research Areas

Aeronautic Applications: This research area is dedicated to optimising component and system architecture design to meet the specific requirements of aviation and builds on the outcomes of completed projects, such as **HEAVEN**, which successfully demonstrated a fuel cell system on a small aircraft, and **FLHYSAFE**, which validated the use of a fuel cell as an emergency power unit through a virtual demonstrator. In 2025, the portfolio includes two projects focused on advancing fuel cell technologies for aeronautics (**BRAVA** and **NIMPHEA**) as well as one project on the development of an integrated liquefied hydrogen storage system for aircraft, **COCOLIH2T** (see project posters in Annex III for more details on the projects).

Building Blocks: Despite the satisfactory performance of commercial PEMC systems, durability remains a bottleneck for the widespread dissemination of FCs in the industrial and transport sector. A challenge is reducing reliance on costly and scarce PGMs to below 0.4 mg/cm², while still ensuring that performance remains stable and effective throughout the entire lifetime of the fuel cell. Ultimately, advancing the understanding of degradation mechanisms and their root causes while achieving satisfactory performance at end-of-life with non-PGM-loaded catalysts is the goal of the funded projects. In this research area, ongoing projects include FURTHER-FC, H2MAC, HIGHLANDER, IMMORTAL, MEAsureD, MORE-Life, PEMTASTIC, RealHyFC, and StasHH projects based on PEM fuel cell technology, along with the project SH2APED that is developing a hydrogen gas storage system (see project posters in Annex III for more details).

Heavy-Duty Vehicles, including Buses/Coaches: Fuel Cell Trucks (FCTs) are widely regarded as one of the most promising pathways to decarbonise heavy-duty freight transport. They are particularly well-suited for long-haul operations and carrying heavy loads, offering connectivity to remote areas where alternatives like battery-electric or catenary trucks face limitations. The primary objective of this research area is to optimise Balance of Plant (BoP) architectures in order to better meet the performance, efficiency, and durability requirements of Heavy-Duty Vehicles (HDVs). Demonstration activities showcasing the improvement of deployment of hydrogen fuel cell heavy-duty vehicles, including buses and coaches, are currently carried out within the JIVE, JIVE 2, H2Haul, REVIVE, and H2Accelerate TRUCKS projects (see project posters in Annex III for more details). A historical analysis report assessing the research and demonstration projects on hydrogen mobility conducted over the last two decades was published by the European Commission Joint Research Centre in close collaboration with the Clean Hydrogen JU[56].

Rail applications: In recent years, Fuel Cell Power Systems (FCPS) have gained interest in railway applications, with pilot projects underway in Europe (Austria, Germany, France, Italy, Poland, and the UK) and globally in Canada, Japan, China, India, Korea, and the USA. However, for large-scale deployment, apart from the need for significant investments, several challenges remain, such as the production, storage, and distribution of clean hydrogen, which requires compression and cooling to reduce boil-off in liquid hydrogen. There is one project in this research area at the moment, i.e., **FCH2RAIL** (see project posters in Annex III for more details).

Waterborne applications: This research area covers both research and demonstration projects for fluvial and maritime applications, including port activities. There are currently 6 projects (SHIPFC, HyShip, FLAGSHIP, RH2IWER, H2Ports, and H2MARINE) focusing on improving access to the market for hydrogen and its derivatives, and fuel cells for waterborne applications (see project posters in Annex III for more details).

56 https://publications.jrc.ec.europa.eu/repository/handle/JRC137101

State-of-the-art

Aeronautic Applications: In 2021, members of IATA (International Air Transport Association) committed to achieving net-zero carbon emissions from their operations in 2050. Their strategy towards net-zero CO_2 emissions envisages the shift to SAF (sustainable aviation fuel) but also the deployment of electric and hydrogen-powered aircrafts[57]. Consequently, the number of manufacturers developing hydrogen-fuelled aircraft prototypes keeps increasing.

Airbus has explored different hydrogen-based propulsion concepts since 2020. In 2025, Airbus announced that fuel cell technology had been selected as the propulsion method for its future aircraft[58]. In 2023, Airbus demonstrated a 1.2 MW hydrogen-propulsion system, and in 2024, end-to-end testing of an integrated fuel cell stack, electric motors, gearboxes, inverters, and heat exchangers was concluded. The power generation system developed by BRAVA project (in which Airbus is a consortium partner) will have a power range of 2.4 MW. In 2025, Airbus presented a new hydrogen aircraft concept powered by four 2-megawatt fuel-cell-based engines. The aircraft will use liquefied hydrogen stored in liquid tanks[59].

ZeroAvia is a British-American hydrogen-electric aircraft developer. Their design for a 20-seat aircraft has a multi-stack LT-PEM fuel cell architecture providing 600 kW of power. For larger powertrains (40 – 80 seats aircraft) HT-PEMFC-based architecture is used, operating at 135-162 °C, and demonstrating power density of 2.5 kW/kg at the cell level and with a prospect of reaching more than 3 kW/kg at the system level in the short term[60]. ZeroAvia is also considering liquid hydrogen as the most suitable fuel storage[61].

The French start-up Beyond Aero completed France's first crewed flight of a hydrogen-electric aircraft in 2024. Powered by an 85-kW fuel cell and battery powertrain (45 kW fuel cell and a 340-bar hydrogen storage), the modified 2-seater aircraft was flown from Gap-Tallard airfield in southern France. The BYA-I prototype will be a light jet featuring a 2.4 MW fuel cell stack and 700 bar tanks[62].

Boeing is supporting the decarbonisation of airports. In 2025, a B-737 passenger aircraft trialled a turnaround at Exeter airport using a hydrogen-powered ground support equipment[63].

The Clean Aviation Joint Undertaking (CAJU) programme includes R&D activities on hydrogen-powered aircrafts in two phases. The first phase, until 2026, is focused on the technology development and demonstration of all relevant hydrogen systems (liquid hydrogen storage on-board, fuel distribution systems, fuel cell-based propulsion drive trains, direct combustion of hydrogen into a gas turbine-based engine). This also involves the development of digital twin platforms and demonstrator facilities. The second phase will focus on the integration and demonstration of hydrogen technologies onboard aircrafts, combined with electric hybridisation[64].

Clean Aviation JU is funding four projects related to fuel cells for aircraft. NEWBORN will generate operational data to support CS-25 aircraft certification to demonstrate widely scalable fuel cell power source technology with a power density of >1.2 kW/kg and stack power density of > 5kW/kg, stack efficiency of approximately 60% (trade with weight), and stack peak (hot spot) operating temperature of 105 °C[65]. HYPoTrade is to design, assemble, and ground-test a set of 500 kW modular FC-battery hybrid electric distributed electric propulsion powertrain, including a cryo-enabled thermal management, emulating operation in a relevant environment[66]. FAME scope is developing a complete high-efficiency full electric propulsion system, based on liquid hydrogen,

57 https://www.iata.org/en/programs/sustainability/flynetzero/

58 ZEROe: our hydrogen-powered aircraft | Airbus

59 https://www.airbus.com/en/newsroom/press-releases/2025-03-airbus-showcases-hydrogen-aircraft-technologies-during-its-2025

60 https://zeroavia.com/

61 https://h2-tech.com/news/2025/06-2025/zeroavia-wins-uk-government-grant-for-development-and-flight-test-of-liquid-h2-fuel-system/

62 https://www.beyond-aero.com/

63 https://h2-tech.com/news/2025/05-2025/uk-s-first-h2-powered-live-aircraft-turnaround-takes-place-at-exeter-airport/

64 https://www.clean-aviation.eu/research-and-innovation/clean-aviation/our-strategic-research-innovation-agenda

65 NEWBORN–NExt generation high poWer fuel cells for airBORNe applications, https://newborn-project.eu/

66 HyPoTraDe–Hydrogen Fuel Cell Electric Power Train Demonstration, https://hypotrade.eu/

for short to medium range aircraft. FAME will develop the sub-systems and integrate them in a MW FC propulsion system ground demonstrator, aiming to scale it up to aircraft level[67]. Finally, the project HEROPS will develop a hydrogen propulsion system for regional aircrafts. The system will only use a fuel cell and liquid hydrogen as a power source, without the need for high-power batteries. HEROPS targets to demonstrate a 1.2 MW propulsion system based on a scalable 600 kW stack module at TRL4. The module and all further sub-systems will be validated up to TRL5. Complemented by simulation and electrical network testing of the overall modularised system, scalability to the 2 – 4 MW power level will be confirmed[68].

The German national project BALIS aims to develop and test a fuel cell powertrain with an output of 1.5 MW (for a 40 to 60-seat regional aircraft) and a range of 1,000 kilometres[69]. BALIS will work on the overall system, namely the complete hardware and the essential infrastructure, the fuel cell system, the hydrogen tanks, the electric motor, and the control technologies. For this purpose, DLR opened a unique test facility in 2024[70].

The project GENESIS, finished in 2023, designed a full electric hybrid (battery and fuel cell) aircraft for 50 passengers. They considered both PEMFC and SOFC options in their design[71]. In addition, Horizon Europe is also funding two projects on SOFC technology for aviation. HYLENA will develop and optimise a hydrogen-powered electrical aircraft propulsion concept based on the integration and combination of SOFC with turbomachinery, to use both the electric and thermal energy for maximisation of propulsive efficiency[72]. FlyECO also aims to integrate gas turbine, SOFC and batteries in a 1MW hydrogen-based propulsion system. Using simulations, the propulsion architecture will be refined to meet commuter/regional aircraft requirements[73].

It is important to note that in addition to BRAVA, Airbus also participates in the projects FAME and HYLENA.

On fuel cell system thermal management, the CAJU project THEMA4ERA aims to demonstrate the dissipation of required additional heat in the order of 20 to 50 kW for systems and 300 to 1,000 kW for power storage and generation in batteries, APU, and fuel cells in a hybrid electric regional aircraft[74]. The Horizon Europe project EXFAN tackles the recuperation of heat from the fuel cells in an aircraft by including a ducted heat exchanger in the nacelle of the propulsion system. It will use the ram jet effect (Meredith effect) to generate thrust from waste heat[75].

Projects developing on-board aircraft hydrogen storage systems for aeronautic applications are running alongside projects on fuel cells. In addition to Clean Hydrogen JU's COCOLIH2T, two CAJU projects are ongoing. H2ELIOS will develop a lightweight liquid hydrogen storage solution for aviation uses. This hydrogen storage system will be seamlessly integrated into an aircraft's primary structure and will be demonstrated on-ground up to TRL 5[76]. The project fLHYing tank is developing a thousand-litre cylindrical vacuum-insulated composite liquid hydrogen storage system with peripherals and instrumentation, which will be tested in-flight in a Pipistrel Nuuva V300 cargo unmanned aerial vehicle[77]. Funded by CINEA, project OVERLEAF, finished in 2025, has developed a quasi-spherical shaped (2m x 2m x 2.3m) modular tank for storage of 105 kg of liquid hydrogen, with a fuel-to-

67 FAME–Fuel cell propulsion system for Aircraft Megawatt Engines, https://cordis.europa.eu/project/id/101140559

68 HEROPS–Hydrogen-Electric Zero Emission Propulsion System, https://aeroreport.de/en/innovation/cleaner-flight-europe-explores-paths-to-climate-neutral-air-travel

69 https://www.dlr.de/en/tt/research-transfer/projects/project-archive/2023/balis

70 https://www.now-gmbh.de/en/news/pressreleases/balis-test-field-goes-into-operation/

71 GENESIS–Gauging the ENvironmEntal Sustainability of electrIc aircraft Systems, https://www.genesis-cleansky.eu/the-project/ and Fuel Cell Hybrid-Electric Aircraft: Design, Operational, and Environmental Impact

72 HYLENA – HYdrogen eLectrical Engine Novel Architecture, Bauhaus Luftfahrt: HYLENA: Carbon neutral aircraft engine architecture for aviation

73 Fly-ECO–Future enabLing technologies for hYdrogen-powered Electrified aero engine for Clean aviation, https://flyeco-european-project.eu/

74 THEMA4HERA–Thermal Management for the Hybrid Electric Regional Aircraft, https://www.clean-aviation.eu/thema4hera

75 exFan–Novel recuperation system to maximize exergy from anergy for fuel cell powered geared electric aircraft propulsion system, https://exfan-project.eu/

76 HELIOS–Large Scale Lightweight Liquid Hydrogen Integral Storage Solutions, see all the new presentations, https://h2elios.eu/home

77 fLHYing Tank–Liquid hydrogen load bearing tank for commuter, https://www.flyingtank.eu/

weight ratio of 0.23 and a 2% boil-off rate in 13.5 hours[78]. Also funded by CINEA, HASTA focuses on overcoming the technical challenges associated with integrating LH_2 tanks into aircraft, particularly the issues related to sloshing within these tanks during flight. Airbus is a consortium partner in HASTA[79].

The CAJU is funding projects on hydrogen direct combustion engines, such as CAVENDISH[80], HYDEA[81], HOPE[82] and TROPHY[83]. Additionally, CAJU funds project on the development of aviation platforms for demonstration of hydrogen-based powertrains, such as HERA aircraft, that will include hybrid-electric propulsion based on batteries or fuel cells as energy sources supported by SAF or hydrogen burning for the thermal source[84].

Horizon Europe is also funding projects on refuelling infrastructure at airports. ALRIGH2T will develop and demonstrate two technologies for liquid hydrogen aircraft refuelling: direct refuelling and tank swapping. For developing direct LH_2 refuelling, ALRIGH2T will define operational protocols for safe and rapid refuelling. Refuelling/defueling tests using an LH_2 transfer pump and an instrumented tank will be carried out in the laboratory and will serve to build a digital twin model. For liquid hydrogen tank swap refuelling ALRIGH2T will work on the supply chain of tank modules and the design of the associated on- and off-site infrastructure. Both concepts will achieve TRL 6 by the end of the project and will be demonstrated at Milan Malpensa and Paris (Orly or Le Bourget), respectively[85]. GOLIAT will demonstrate how high-flow LH_2 handling and refuelling technologies can be developed and used safely and reliably for airport operations[86]. On decarbonisation of airports, the CINEA project TULIPS is demonstrating the use of hydrogen fuel cells in ground power devices and tow tractors capable of moving A380 or B777 aircrafts[87].

Building Blocks: Currently, commercial PEMFC systems for transport and stationary applications deliver satisfactory performance, but there is still a need for further development in terms of durability. The loss of performance in fuel cell systems remains a bottleneck for the widespread dissemination of FCs in the industrial and transport sectors. Ongoing projects are often at a low TRL of 3-5. For comparison, PowerCell offers FC stacks for road applications with capacities ranging from 75 to 125 kW and an operational lifespan of 20,000 hours,[88] while Ballard commercially provides FC modules for HD applications with capacities of 70 to 100 kW and a tested lifetime exceeding 25,000 hours.[89]

A better understanding of degradation mechanisms, their causes, and mitigation strategies is essential for improving the durability of PEMFCs. The effective use of test data, post-mortem images, and available scientific knowledge as training data for AI models, when combined with expert advice, could help uncover underlying principles of degradation in FC components. A continuous challenge is the reduction in the use of expensive and rare materials, primarily platinum group metals (PGMs), to below 0.4 mg/cm^2 for electrocatalysts, while maintaining satisfactory performance up to the end of life (EoL).

In the USA, the Department of Energy (DOE) has an extensive Hydrogen and Fuel Cells Program[90] that focuses, among other objectives, on advancing fuel cell technologies to decrease reliance on fossil fuels and promote clean energy solutions. The program seeks to overcome technical barriers, address safety concerns, and facilitate

78 OVERLEAF–nOVel low-prEssure cRyogenic Liquid hydrogEn storAge For aviation, https://overleaf-project.eu/ and OVL_Technical_brochure_digital-1.pdf

79 HASTA–Hydrogen Aircraft Sloshing Tank Advancement, https://hasta-project.eu/

80 CAVENDISH–Consortium for the AdVent of aero-Engine Demonstration and aircraft Integration Strategy with Hydrogen, https://clean-aviation.eu/cavendish-consortium-for-the-advent-of-aero-engine-demonstration-and-aircraft-integration-strategy

81 HyDEA–Hydrogen Demonstrator for aviation, https://cordis.europa.eu/project/id/101102019

82 HOPE–Hydrogen Optimized multi-fuel Propulsion system for clean and silEnt aircraft, https://hope-eu-project.eu/

83 TROPHY–Technological Research On Propulsion by Hydrogen, https://cordis.europa.eu/project/id/101140638

84 HERA–Hybrid-Electric Regional Architecture, https://project-hera.eu/

85 ALRIGH2T–Airport-Level DemonstRatIon of Ground refuelling of Liquid Hydrogen for AviaTion, https://alrigh2t.eu/refuelling-innovations/#COMPONENTS

86 GOLIAT–Ground Operations of LIquid hydrogen AircrafT, https://cordis.europa.eu/project/id/101138379

87 TULIPS–DemonsTrating lower pollUting soLutions for sustaInable airPorts acrosS Europe, https://tulips-greenairports.eu/

88 https://powercellgroup.com/wp-content/uploads/2022/05/p-stack-v-221.pdf

89 https://www.ballard.com/docs/default-source/spec-sheets/fcmovetm.pdf

90 https://www.hydrogen.energy.gov/home

the widespread adoption of fuel cell technologies across various sectors. It places a strong emphasis on R&D to enhance FC performance and reduce costs. The 2024 Annual Merit Review and Peer Evaluation Report[91] states that the FC technologies sub-program develops FC systems with emphasis on near-term heavy-duty transportation applications that are highly durable, efficient, and low-cost, while meeting application-specific constraints such as dynamic response, resilience, packaging, and heat rejection as well as new materials and components for next-generation FC technologies in diverse applications for power generation and long-duration grid-scale energy storage, emphasising innovative mid-to-long-term approaches that can use FC to co-produce power, heat, and fuel. This sub-program established, among other aspects, the following milestones to be achieved by 2030: 68 % peak-efficient direct hydrogen FC power system for heavy-duty trucks with a durability of 25,000 hours and mass-produced at a cost of USD 80/kW, and demonstrate HD FC manufacturing capacity of 20,000 stacks annually into a single manufacturing system.

In Japan, the New Energy and Industrial Technology Development Organization (NEDO), a semi-governmental organisation under the Japanese Ministry of Economy, Trade and Industry (METI), updated its roadmap for FCs in HDV applications in 2023, primarily focusing on the technological development of a common platform for fuel cells for large trucks and other HDVs with a vision extending to 2050.[92]

Heavy-Duty Vehicles, including Buses/Coaches: **Rail applications:** Hydrogen technology can still compete with Battery Electric Vehicle (BEV) and be deployed in the transportation sector for the decarbonisation of heavy-duty vehicles, not only for the ones delivering the heaviest goods[93] with long-haul application, but also for local passengers' transport by buses or coaches.

From the technology point of view, the truck makers, i.e., Hyundai, Daimler, DAF, MAN, and Scania, are deploying mainly compressed H_2 tanks at 350 bars with capacities between 30 to 40 kg and ranges around 300-500 km. The only exception is that of Daimler-genH_2 trucks that use liquid hydrogen tanks with 80 kg capacity and a range of up to 1000 km. One of the advantages of FCETs is the refuelling speed, which is now at 1 min/7 Kg of H_2 compared to 1 min/kg of H_2 for cars. Current hydrogen consumption is in the order of 9 kg/100 km, while future targets [94] less than 7 kg/100 km.

Fuel cell type is currently based on PEM technology, but some suppliers are taking into consideration also the high temperature SOFC.

For FCETs, Asia leads the deployment with China having 98% of the world share, followed by Europe with 1.7% and lastly North America with 0.3%.

Switzerland, thanks to the agreement with Hyundai for the deployment of 140 Xcient Trucks, leads the European market. As of June 2024, 48 FCETs were in operation at 23 Swiss logistics, distribution, and supermarket supply companies, covering a total driving distance exceeding 10 million km. Nevertheless, at this point, the ambitious plan to grow to 1,600 trucks by 2025 seems to be in danger.

The fuel cell buses market is largely dominated by China, which accounts for over 85% of global deployment[95]. The Zero Emission internal market share is equal to 73%, but is mainly covered by BEVs, while about 7,000 FCEBs contribute to less than 1% of the total Chinese fleet. Deployments of fuel cell bus fleets in other regions such as Europe, South Korea, the United States, and Japan are also taking place, although at a slower pace. Europe as a whole had about 600 fuel cell buses in operation at the end of 2024, and they account for only 3% of the new EU urban buses in 2024[96] (Figure 11).

91 https://www.hydrogen.energy.gov/library/annual-review/2024-annual-merit-review-and-peer-evaluation-report

92 https://www.nedo.go.jp/content/800016621.pdf

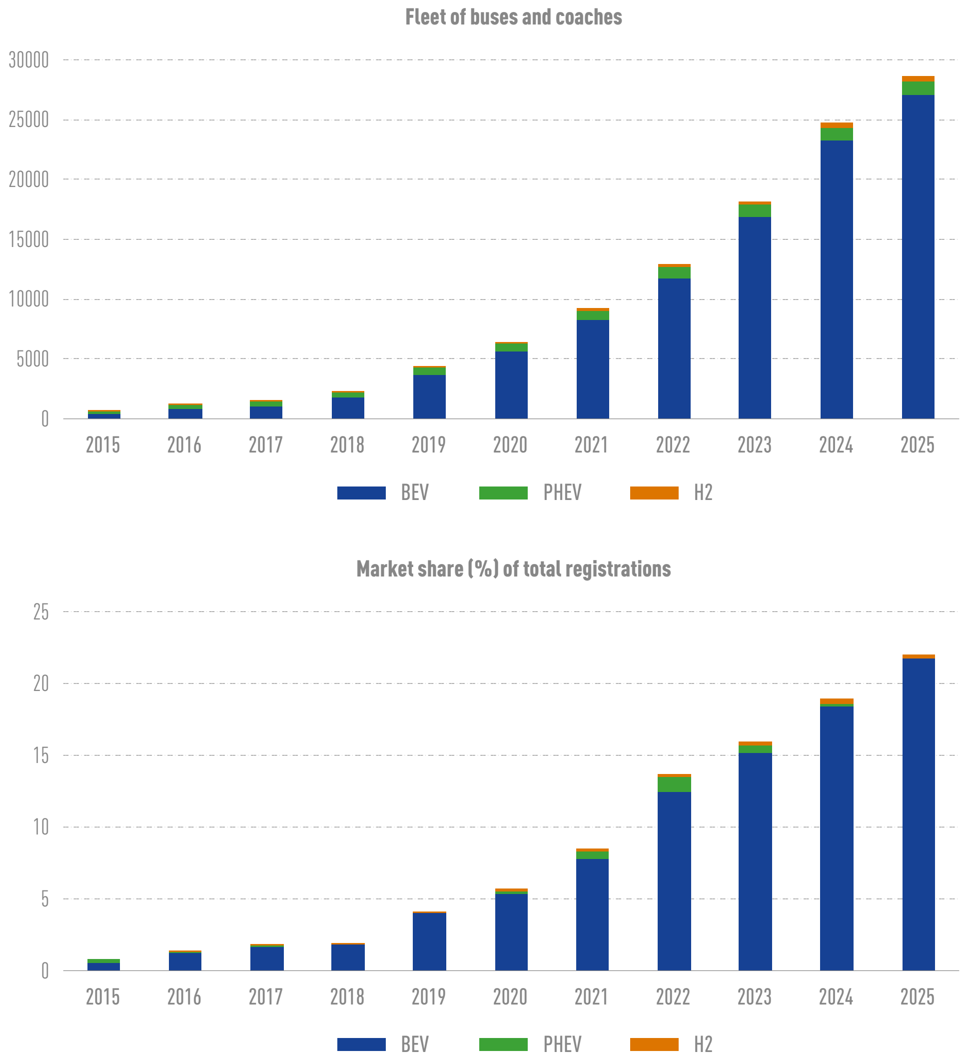
93 Decarbonisation of heavy duty transport: zero emissions heavy goods vehicles, JRC, 2021 https://publications.jrc.ec.europa.eu/repository/handle/JRC125149

94 https://theicct.org/publication/fuel-cell-tractor-trailer-tech-fuel-jul22/

95 https://www.ieafuelcell.com/fileadmin/publications/2023/2023_Deployment_of_Fuel_Cell_Vehicles_and_Hydrogen_Refueling_Station.pdf

96 https://www.transportenvironment.org/articles/half-of-new-eu-city-buses-were-zero-emission-in-2024

Figure 11: Fleet and market share of total registrations of buses and coaches



Source: EAFO, end of year 2024

For the bus fleets, the technology is still dominated by 350 bar hydrogen storage tanks, but some OEMs are considering upgrading to the 700 bar tanks. PEM fuel cell technology is predominant for the energy generator unit. The technical specifications of the buses (fuel cell power capability, storage capacity, range, and hydrogen consumption) have clearly improved worldwide over the last few years, contributing to a reduction in the current price of an FCEB to around 500 K€, a price approaching the diesel bus benchmark of 300 K€.

Rail applications: Despite progress, several key challenges must be overcome for widespread adoption of FCPS to achieve high energy efficiency and lower carbon and greenhouse gas emissions. Additionally, developing a costly hydrogen refuelling infrastructure and integrating energy and thermal management of FCPS with train systems are crucial areas of focus. Safety concerns, especially related to the potential release of hydrogen during operations or accidents, also need significant attention.

Waterborne applications: The number of projects in Europe demonstrating the use of hydrogen and fuel cells in waterborne applications has been growing in recent years. In addition to those demonstration projects, many research projects are working on improving access to the market for hydrogen and its derivatives.

In Germany, the ELEKTRA II project developed a push boat for use in the Berlin-Brandenburg region and between Berlin and Hamburg. The push boat is using bundles of 750 kg H_2 placed on the deck and is powered by a hybrid powertrain consisting of a battery and a 300 kW fuel cell. The CONDOR H2 project, which started in 2023, aims at providing hydrogen storage and fuel cells with a battery pack on a pay-per-use basis, enabling ships to become zero-emission with limited investment for ship owners.

In the Netherlands, the first hydrogen-powered zero-emission inland container vessel, "H_2 Barge 1", has been in service since 2023[97]. The vessel is a retrofitted barge powered by a 900 kW fuel cell system. The hydrogen cargo vessel "ANTOINE", powered by a hybrid powertrain consisting of a 1,100 kWh battery pack and a 320 kW fuel cell, is operating between Delfzijl and Rotterdam to transport salt[98]. The 1,200 kg of hydrogen consumed in a round trip are stored on board at 300 bar[99].

In France, the HYBARGE project developed a hybrid hydrogen barge that operates using only hydrogen for 80% of its navigating time and can sail in all of the European canals. Removable tank racks of 170 kg of hydrogen at 350 bar provide the necessary hydrogen[100].

In Italy, the prototype ship ZEUS is equipped with a 144 kW fuel cell system, a lithium battery system, and a 50 kg metal hydride hydrogen storage. This hybrid powertrain allows the ship to sail for approximately eight hours at a speed of 7.5 knots in zero emission mode, using the fuel cells, or sailing for another four hours at a speed of four knots, using the battery[101].

In Norway, the "HYDRA" double-ended Ro-Pax passenger ferry, which is fuelled with 80 m3 liquid hydrogen and propelled with a 400 kW low temperature PEM fuel cell, is operated by the Norwegian operator Norled[102].

As part of the HORIZON Mission, a consortium with French, Latvian, and Estonian institutions aims at accelerating the transition to fleets of small-scale fisheries (<12 m) equipped with greener and energy-efficient technologies to reduce fuel consumption and emissions, including acoustic noise reduction[103]. The project will implement the design, construction, and operational demonstration of a hybrid hydrogen-electric 12 m fishing vessel that will be deployed in three countries from 2026.

Seven research and demonstration projects are funded by the European Climate Infrastructure and Environment Executive Agency (CINEA) for the period 2023-2027. The H2ydroShuttle project in the Netherlands targets a zero-emission short sea container service powered by multi-megawatt liquid hydrogen fuel cells[104]. The Swap2Zero project is building a 400 passenger, zero emission cruise ship capable of sailing for 30 days using a mix of wind/solar energy, hydrogen, and liquefied methane. Equipped with PEMFC and SOFC, as well as wind-assisted propulsion system covering 50% of energy needs, the ship will reduce greenhouse gas emissions by 80%. Swap2Zero is demonstrating the scalability of high-power fuel cells (2 MW)[105]. The SHIP-AH2OY project aims at developing and demonstrating a zero-emission propulsion technology on board ships combining the use of liquid organic hydrogen carriers (LOHC) and a Solid Oxide FC[106]. The ZEAS project will design, build, and operate a hydrogen-powered passenger ferry ship in the Adriatic Sea[107]. The HyEkoTank project is developing cost-effective technology for retrofitting seagoing and inland waterway vessels with PEM fuel cell systems[108]. The FuelSOME project is developing a multifuel SOFC stack system, capable of operating on ammonia and methanol in addition

97 https://www.portofrotterdam.com/en/news-and-press-releases/future-proof-shipping-first-zero-emission-hydrogen-powered-inland-container
98 https://swzmaritime.nl/news/2023/11/20/first-newbuild-hydrogen-inland-vessel-antonie-performs-trials/
99 https://www.wevaproject.nl/en/
100 https://www.lequipage.eu/hybarge-presentation
101 https://www.rina.org/en/media/news/2022/11/16/zeus-rina-classed-ship
102 https://www.bairdmaritime.com/work-boat-world/passenger-vessel-world/ro-pax/vessel-review-hydra-norled-takes-delivery-of-ferry-designed-to-run-on-liquid-hydrogen/
103 https://h2-tech.com/news/2024/05-2024/genevos-wins-european-commission-funding-for-h-sub-2-sub-fishing-vessel-demonstrator/
104 https://www.advanceh2.com/news/technology/fuel-cells/european-commission-invests-48-billion-in-net-zero-projects-7zi5s6hj4e
105 https://strategic-technologies.europa.eu/be-inspired/step-stories/swap2zero-worlds-first-zero-emission-cruise-ship_en
106 https://shipah2oy.eu/
107 https://projectzeas.eu/
108 https://cordis.europa.eu/project/id/101096981

to hydrogen, for maritime applications[109]. The LIFE21-ENV-DE-LIFE OCEAN project aims to demonstrate the viability of replacing diesel generators used for the internal energy needs of the Sanlorenzo superyacht with a 60 kWe microbial fuel cell system. It will install a prototype clean energy system whereby a methanol reformer produces hydrogen that feeds a PEM fuel cell[110].

The Dutch project SH2IPDRIVE (Sustainable Hydrogen Integrated Propulsion Drives) is conducting research for the safe use in maritime applications of different hydrogen storage technologies (compressed, liquefied, LOHC, and borohydrides). It is also integrating fuel cell systems into different vessels, such as inland ones, both retrofitted and new, short sea vessels, passenger vessels, and a special-purpose ship[111].

The ZEWT Partnership is also funding several projects to bring hydrogen technologies for waterborne applications closer to mass market. The APOLLO project, funded for the period 2023-2025, is demonstrating a marine tri-fuel ammonia-based internal combustion engine, based on 70% ammonia, 29% liquefied natural gas, and 1% marine gas oil. It is planned to have it deployed on the Eidesvik's Viking Energy vessel and operated in the North Sea[112]. The AMMONIA2-4, funded for the period 2022-2026, is demonstrating a two-stroke and a four-stroke dual fuel marine internal combustion engine running on ammonia. The two-stroke engine is a medium-pressure ammonia system that can be retrofitted into any commercial marine engine, while the four-stroke solution is a 10 MW new design engine that will be demonstrated in lab conditions simulating real-life operations in ambient conditions[113]. The SHYPS project, funded for the period 2022-2026, is developing both a storage and fuel cell system fitted into an ISO container, so that it can be adapted to multiple types of vessels[114]. Liquid hydrogen and a supply logistics based on swapping pre-filled containers are planned for its operation.

Fuel cell systems of approx. 6 MW, corresponding to 30-50 times the fuel cell power used in bus applications, are being developed specifically for maritime applications. Fincantieri is constructing the first cruise ship in the world to be powered by a 6 MW advanced fuel cell system and by hydrogen storage onboard for both propulsion and electricity generation, with delivery scheduled for late 2026[115]. Ballard has received an order for a 6.4 MW fuel cell system for deployment on two emission-free vessels[116]. The 6.4 MW fuel cell system will consist of the integration of 32 fuel cells of 200 kW. Feadship is developing the world's first hydrogen fuel cell superyacht, named Project 821[117] consisting of an advanced fuel cell system from the PowerCell Group and liquid hydrogen cryo-storage below deck.

The Innovation Fund, funded by the EU Emissions Trading System and that focuses on highly innovative technologies and flagship projects within Europe that can bring about significant emission reductions, has been funding two maritime demonstration projects: H2ydroShuttle and EO2 Energy Observer 2. The H2ydroShuttle project aims to transform short-sea container shipping with two zero-emission vessels powered by multi-MW liquefied hydrogen fuel cells[118]. The EO2 Energy Observer 2 project aims to build and operate a cargo ship powered by liquid hydrogen that will address the challenges of decarbonising the maritime freight shipping sector[119]. In addition, the 2024 European Hydrogen Bank auction, which is a market-based instrument for funding innovative low-carbon technologies, selected 3 Norwegian projects aiming at the uptake of hydrogen technologies for maritime applications in Norway[120].

109 https://fuelsome.eu/vision/

110 https://webgate.ec.europa.eu/life/publicWebsite/project/LIFE21-ENV-DE-LIFE-OCEAN-101074503/fuel-cell-and-methanol-reforming-system-for-clean-energy-on-board

111 https://sh2ipdrive.com/

112 https://apollo-project.eu/about/

113 https://www.ammonia2-4.eu/the-project

114 https://www.shyps.eu/

115 Fincantieri | Fincantieri and Viking announce the world's first hydrogen-powered cruise ship and sign contracts for two new units

116 Ballard announces order for 6.4 MW to eCap Marine for Samskip vessels–Ballard

117 https://www.feadship.nl/pressroom/feadship-ushers-in-the-fuel-cell-era-with-the-launch-of-118-80-metre-project-821

118 https://ec.europa.eu/assets/cinea/project_fiches/innovation_fund/101191247.pdf

119 https://ec.europa.eu/assets/cinea/project_fiches/innovation_fund/101191276.pdf

120 https://climate.ec.europa.eu/eu-action/eu-funding-climate-action/innovation-fund/calls-proposals/if24-auction_en

Programme highlights

Aeronautic Applications: Activities on H_2-related aircraft technologies within the Clean Aviation JU and Clean Hydrogen JU are aligned with the joint technical roadmap and the respective SRIAs of the two JUs. Projects **BRAVA** and **NIMPHEA** have already passed their halfway point and are showing steady progress towards their objectives. In particular for NIMPHEA, the safety analysis for the HT-MEA use in aeronautical applications has begun with a first intrinsic hazard analysis. Regarding the project on liquified hydrogen storage, COCOLIH2T has released a preliminary safety assessment for liquid hydrogen storage systems in aviation[121], and as part of the project, NLR is establishing a liquid hydrogen test facility in Marknesse (Netherlands) to carry out integration and testing of the COCOLIH2T demonstrators.

Building Blocks: The StasHH project developed testing protocols for heavy-duty fuel cell modules in heavy-duty applications (across road, rail, maritime, and off-road sectors), engaged eight leading vendors in prototype testing, and successfully proposed standardised module sizes and interfaces, including APIs, to the IEC, which were approved. The IMMORTAL project developed second-generation membrane electrode assemblies with reduced platinum content, achieving a power output of 1.2 W/cm². Protocols to enhance zero-emission transport in Europe, focusing on FCs for heavy-duty vehicles, were developed by MORE-Life. Although they created a digital twin for simulating vehicle conditions, dissemination challenges remain due to incomplete collaboration with international standardisation groups. Significant power output with new catalyst technologies was achieved by the HIGHLANDER project. Finally, the SH2APED project enabled the integration of fibre optic sensors into composite vessels for real-time condition monitoring[122], advanced leak-before-burst technology to enhance fire resistance[123], and developed innovative on-tank valves and manifolds for multi-element compressed hydrogen storage systems.

Heavy-Duty Vehicles, including Buses/Coaches: Projects JIVE and JIVE2 have shown increasing dissemination activities. As of February 2025, these projects deployed 242 buses in real-world operations in 16 cities, with another 48 having started operations by the end of June 2025, reaching a total of 290 FC buses, which is a good result compared to the objective of 300. The H2Accelerate Trucks project, which aims to build and operate 150 trucks across nine European countries with over 20 fleet operators for two years, is making good progress in truck design, testing, and hydrogen refuelling network mapping. The REVIVE project reported that H_2 trucks show relatively high availability (~87%), comparable to diesel trucks (~93%), but with significant yearly variability ranging from 15% to 100%. However, their utilisation rates remain lower due to limited HRS accessibility, a shortage of trained drivers, and other unspecified factors. Finally, for H2Haul, not only were the three HRS fully operational at the end of 2024, but also the first VDL truck has been fully commissioned, while IVECO completed the construction of 12 trucks, accumulating over 15,000 km driven in validation trials and successfully delivering five vehicles to deployment countries.

Rail applications: The FCH2RAIL project successfully demonstrated hydrogen storage and refuelling solutions in the rail sector by testing a multi-purpose Fuel Cell Hybrid PowerPack (FCHPP) across seven rail lines in the Iberian Peninsula, completing 10,000 km in hydrogen mode and 6,000 km in electric mode during a 37-day campaign without incidents. The project proved the feasibility of bi-mode rail operations with fuel cell traction, supporting rail decarbonisation with long service autonomy, while also contributing to the development of three upcoming IEC standards, conducting a regulatory gap analysis, and drafting proposals to adapt the European normative framework.

Waterborne applications: Demonstration vessels powered by hydrogen fuel cells are already in operation for European inland navigation, showcasing the feasibility of these technologies and enhancing the visibility of Clean Hydrogen JU projects in this sector. Different hydrogen-powered vessel types within the FLAGSHIP and SHIPFC projects have already received class approval from authorities such as the Central Commission for the Navigation

121 Simonetto, M.; Pascoe, J.-A.; Sharpanskykh, A. Preliminary Safety Assessment of a Liquid Hydrogen Storage System for Commercial Aviation. *Safety* **2025**, *11*, 27. https://doi.org/10.3390/safety11010027

122 Wosniok A. Schukar M Woody P & Kriegsmann, A. (2024). Distributed fiber optic strain sensing for structural health monitoring of 70 MPa hydrogen vessels. In Conference Proceedings-Prepublication (pp. 1-8). https://www.ndt.net/search/docs.php3?id=29745 .

123 V. Molkov, S. Kashkarov, D. Makarov, Breakthrough safety technology of explosion free in fire self-venting (TPRD-less) tanks: The concept and validation of the microleaks-no-burst technology for carbon-carbon and carbon-glass double-composite wall hydrogen storage systems, International Journal of Hydrogen Energy 48, Issue 86, 2023,https://doi.org/10.1016/j.ijhydene.2023.05.148.

of the Rhine (CCNR) and the Norwegian Maritime Authority, establishing an important foundation for broader system homologation and vessel certification by class societies and regulators. An energy assessment of a 1.1 MW diesel-powered vessel on Lake Garda, Italy (RH2IWER projects), confirmed hydrogen fuel cell technologies as the most promising alternative, offering advantages in pollutant reduction, cost, size, and weight. Finally, the visibility of the Clean Hydrogen JU-funded projects has increased with the FLAGSHIP project receiving the "Best Outreach Award" at the EU Hydrogen Week, as well as the H2Ports project organising a demonstration event at the port of Valencia and receiving the "Best innovation project in the renewable gases value chain" award at the Gasnam-Neutral Transport Entrepreneurship and Innovation Awards[124].

Gap Analysis – Main JRC Recommendations

Aeronautics Applications: The current portfolio of projects in this research area is still in the testing and validation phase, making it premature to draw definitive conclusions on their outcomes. Nevertheless, some important knowledge gaps are already visible. For example, BRAVA's two-phase cooling system and fuel cell architecture will require further demonstration in operational environments if proven successful. High-temperature PEM fuel cells appear particularly promising for long-range and high-passenger flights, yet more R&D is needed to improve efficiency and optimise gravimetric performance. Additionally, critical gaps remain in understanding sloshing effects in liquid hydrogen tanks (an issue especially relevant for both waterborne and aeronautic applications) and in developing ground-based LH_2 refuelling systems for airports, where little operational experience exists. The absence of harmonised approaches to safety assessment, permitting, and regulation of hydrogen infrastructure at airports further complicates progress, as does the limited availability of publicly accessible testing facilities for liquid hydrogen components, despite initiatives such as the LH_2 Bread Board facility in Grenoble.

To address these gaps, stronger alignment between Clean Hydrogen JU and Clean Aviation JU will be necessary, particularly when defining future call topics and SRIA targets. Clean Hydrogen JU should focus on advancing and validating key components such as HT-PEMFCs and liquid hydrogen storage systems in laboratory and relevant environments, while Clean Aviation JU can support their demonstration within integrated aircraft configurations and digital twins. A more detailed environmental assessment of liquefied hydrogen use in aviation is also needed to justify the investments required for scaling up these technologies. Finally, experience from ongoing projects should be consolidated and shared, contributing to the development of a handbook for hydrogen equipment approval to ensure compliance with aviation safety standards and to accelerate the certification of hydrogen technologies for aeronautical use.

Building Blocks: The current set of projects in this research area has produced important contributions, particularly in the field of testing protocols. IMMORTAL delivered a final protocol for heavy-duty accelerated stress tests (AST) and load profile tests, which could play a significant role in international standardisation. Similarly, MORE-Life provided AST and SUSD protocols based on short-stack and stack data, which could be relevant for the future IEC TC 105 WG 105 activities. However, broader issues remain. Many test results are unnecessarily classified as confidential, which limits knowledge sharing despite being funded by public money. Moreover, dissemination of digital products such as models and software remains very limited, with only a few projects making them open access. The potential of AI tools for materials discovery and manufacturing optimisation is still underutilised, representing a missed opportunity. From a technical perspective, uncertainties persist regarding the optimal configuration of hydrogen storage systems in heavy-duty vehicles and their behaviour during refuelling, while data communication between vehicle tanks and dispensers remains reliant on basic infrared systems with no experience yet in more advanced hardware and protocols.

To overcome these challenges, stronger integration into international fuel cell standardisation activities is recommended, ensuring that deliverables such as protocols are adopted more broadly. Project consortia should provide clear justifications for confidentiality claims, ideally including embargo periods and standardised templates to encourage open access to test results once restrictions expire. Establishing a central public access database for archiving test data, alongside repositories of open-source models and software, would significantly improve dissemination. Calls for projects should also explore the application of AI in FC development, particularly for the discovery and synthesis of durable, PGM-free materials. Finally, funding should target studies on how

124 https://h2ports.eu/valenciaport-pioneering-port-in-europe-in-the-use-of-hydrogen-awarded-at-the-green-gas-mobility-summit-2023/

different hydrogen storage configurations affect refuelling in HDVs, and support the development of next-generation communication systems between dispensers and vehicle receptacles. Ideally, these communication systems should be trialled in Clean Hydrogen JU demonstration fleets, while contributing to ISO/TC 197 WG24 work ISO DIS 19885-2 for refuelling protocols advanced communication.

Heavy Duty Vehicles, including Buses/Coaches: The deployment of FCTs and FCBs faces several structural challenges that limit their competitiveness against both diesel and BEVs. According to ICCT's Total Cost of Ownership study and the JIVE2 final report[125], the high cost of hydrogen fuel (currently three times higher than diesel) remains the single most critical barrier to economic viability. While FCTs offer advantages such as lower weight, better space utilisation, and faster refuelling, BEVs are advancing rapidly, already achieving 10–20% market share in China compared to less than 2% for FCTs[126]. Market growth for FCTs and FCBs is therefore highly dependent on the availability of hydrogen refuelling infrastructure and green hydrogen supply. Deployment experience from JIVE projects highlights additional barriers, including high costs for component maintenance, depot modifications, and certification requirements for repairs, as well as frequent downtimes linked to peripheral mechanical and electrical components. Operational challenges are also amplified by a lack of training for drivers, depot staff, technicians, and first responders, while retrofitting options in the coach sector face significant legal and certification obstacles, making new vehicle design a more practical path forward. Moreover, the hydrogen mobility supply chain remains underdeveloped, and the high level of customisation in FCBs prevents economies of scale, further delaying cost reductions.

To address these issues, long-term and targeted policy support will be essential. The JRC recommends[127] enhancing financial support mechanisms, such as subsidies or tax incentives, to offset higher operational costs and strengthen the business case for hydrogen vehicles. Developing a robust European supply chain for hydrogen mobility components is equally important, ensuring flexibility, reliability, and availability of spare parts. Standardisation should be advanced, particularly in methods for measuring and reporting fuel cell degradation and operational performance, accompanied by broader data transparency to inform improvements. Finally, infrastructure expansion remains a priority: hydrogen refuelling networks must continue to grow, and integrated "package solutions" combining production, storage, dispensing, and maintenance should be developed to support the roll-out of both FCTs and FCBs across Europe. Together, these measures would significantly improve competitiveness, support scaling, and accelerate the transition to hydrogen-based transport.

Rail applications: Further research is required to address key challenges in hydrogen technologies for the rail sector, including cost reduction, supply chain development, refuelling infrastructure, standardisation and homologation, fleet scalability, and maintenance. Advancements are also needed to achieve higher power and energy capacity, longer lifetimes, improved efficiency, and lower overall costs. In particular, high-capacity hydrogen fast refuelling remains unresolved, with the TIR SAE 2601-5 revision still ongoing. In addition, more large-scale testing under commercial service conditions is needed to validate technologies in real-world environments.

It is recommended to map existing large test facilities capable of handling heavy equipment, high hydrogen flow rates, and large quantities of green hydrogen while safely dissipating loads, to ensure that they are suitable for research and innovation activities for the rail sector. Future call topics should also require the participation of entities that can address the technical and administrative differences across Europe, including gaps in normative frameworks, refuelling protocols, and refuelling curve development.

Waterborne Applications: Hydrogen and fuel cell technologies for waterborne applications still require significant improvements, particularly in reducing costs and enhancing durability, to become competitive with conventional maritime and fluvial solutions. This includes adapting hydrogen and fuel cell components more effectively to the needs of these sectors and developing next-generation systems beyond initial demonstrations. Moreover, national authorities have limited experience in approving hydrogen-powered vessels and permitting hydrogen infrastructure in ports, a situation compounded by the absence of clear regulations and suitable standards. The supply chain for liquid hydrogen in Europe remains weak, and a cost-effective, reliable supply chain for fuel cells

125 https://www.fuelcellbuses.eu/sites/default/files/documents/JIVE2_D4.4_Final_Report_Final_110325.pdf

126 https://theicct.org/publication/ze-mhdv-market-china-2024-mar25/

127 Recommendations are taken from the 2024 JRC report "Historical Analysis of Clean Hydrogen JU Fuel Cell Electric Vehicles, Buses and Refuelling Infrastructure Projects" JRC 137101

is still not fully in place, as production is often limited to small-scale, on-demand manufacturing at high cost, leading to supply shortages and long delivery times.

The FLAGSHIP, RH2IWER, and H2MARINE projects should actively contribute to European and international standardisation activities. For example, FLAGSHIP and RH2IWER are encouraged to share findings with the CEN/TC268/WG5 committee on hydrogen refuelling for inland navigation, under the M/581 standardisation request, while H2MARINE can provide valuable input on fuel cell testing requirements and load curves for marine applications. National authorities that have granted vessel approvals or port permits should exchange knowledge and work toward harmonised practices, supporting the future development of a unified European regulation. To strengthen the sector, the liquid hydrogen supply chain must be further funded and expanded, enabling large-scale marine demonstration projects. Finally, demonstration projects frequently struggle to complete long-duration durability tests within original timelines due to delays in vessel development, permitting, and unforeseen technical challenges. Future projects should include realistic timelines that account for such risks, ensuring that durability assessments are properly carried out, since those are a critical step in validating hydrogen-powered vessels.

5.4. PILLAR 4: HYDROGEN END-USES: CLEAN HEAT AND POWER

Pillar 4 focuses on advancing renewable and flexible heat and power generation systems that can serve diverse end-users, ranging from households to large-scale power plants. While the main emphasis is on technologies operating with 100% hydrogen, SRIA also supports transitional solutions using hydrogen-natural gas mixtures of up to 20% in the gas grid. The supported technology portfolio includes stationary fuel cells, gas turbines, boilers, and burners, all aimed at accelerating decarbonisation and enabling flexible integration of hydrogen into Europe's energy system.

In 2025, Pillar 4 covers 13 active projects, distributed across different research areas. Six projects are focused on Commercial and industrial-sized combined heat and power (CHP) systems, while another six target the development of turbines, boilers, and burners. Additionally, one project addresses next-generation degradation, performance, and diagnostics, ensuring reliability and efficiency in hydrogen-based power systems. Previous projects under the micro-CHP and off-grid/backup/gensets categories concluded before 2024 and are therefore not part of this report.

Overview of Research Areas

Commercial and Industrial Size Systems: Since 2015, the Clean Hydrogen JU has funded ten projects under the Commercial Size Combined Heat and Power (CHP) research area, three of which are ongoing: SO-FREE, E2P2, and AMON. The E2P2 project is developing two 45 kW SOFC systems for Uninterruptible Power Supply (UPS) applications in data centres. The SO-FREE project targets the creation of a 5 kW SOFC-based CHP system capable of operating with multiple fuels. Meanwhile, the AMON project is advancing a fuel cell ammonia system to generate electricity for port applications, aiming for 70% system efficiency and contributing to the decarbonisation of maritime transport.

The Industrial Size CHP research area has supported five projects since 2015, with three included in the 2025 report. The SWITCH project, completed in 2024, developed a reversible SO system with 25 kW (SOFC) and 75 kW (SOEC) capacities for industrial use. The ongoing 24/7 ZEN project is working on a reversible SO system designed to enhance grid stability, while the CLEANER project is developing and demonstrating a >100 kW PEM fuel cell system capable of running on industrial-grade hydrogen. Both projects remain in early stages and are expected to deliver more tangible outcomes in the coming years.

Next generation, Degradation and Performance & Diagnostics: Five projects have been allocated in this research area since 2015. There is currently only one active project, RUBY (see project posters in Annex IV for further details).

Turbines, boilers and burners: This newly established research area focuses on gas turbine and burner technologies that enable the cost-effective repurposing of existing infrastructure for renewable gases and zero-carbon power. These technologies are designed to operate with lower fuel purity requirements, tolerate impurities, and support efficient hydrogen production, with the ultimate goal of achieving 100% hydrogen-ready European gas turbines and burners by 2030, meeting emissions standards while delivering zero-carbon dispatchable power and high-temperature heat. This research area currently includes six projects (FLEX4H2, HELIOS, ACHIEVE, H2AL, HyPowerGT, and HyCoFlex, see project posters in Annex IV for more details), which address the combustion of hydrogen, ammonia, natural gas, or their mixtures in gas turbine combustors and boiler burners.

State-of-the-art

Commercial and Industrial Size Systems: The global stationary fuel cell market is experiencing significant growth, though its trajectory is shaped by regional market dynamics, technological innovation, and regulatory frameworks, leading to varied adoption rates across geographies. While the sector holds substantial promise, it confronts obstacles such as high maintenance expenses, competition from alternative energy solutions, and the necessity for robust policy support to accelerate uptake.

Solid oxide fuel cells are gaining prominence in both the stationary and transportation sectors, offering a pathway for energy system decarbonisation through their capacity to deliver reliable, low-emission power. Meanwhile, the global CHP market has grown by over 25% since 2010, though most systems still depend on fossil fuels, with coal and natural gas accounting for approximately 60% and 30% of inputs, respectively[128]. Asia-Pacific, Europe, and North America dominate CHP adoption, particularly in energy-intensive industries like chemicals, pulp/paper, and food processing, as well as in hospitals, universities, and district heating networks.

Demand for CHP technologies is projected to surge in Asia (notably China and India), South America, and North America, driven by incentives such as the US Inflation Reduction Act of 2022. Key adopters will include industries requiring continuous heat, alongside expanding applications in residential/ commercial buildings, district heating, and public infrastructure. Stationary fuel cells are deployed for backup power, remote electrification, urban power plants, distributed generation, and cogeneration, where waste heat is repurposed for space heating.

Fuel cell manufacturing and adoption vary by region and technology type. The US leads in large-scale stationary systems (MCFC, SOFC, PAFC), while Japan and Europe focus on smaller-scale installations. South Korea similarly emphasises PAFC and MCFC for stationary use. Emerging markets, particularly China, are prioritising FC investments to drive hydrogen economy adoption, including vehicle fleets, refuelling infrastructure, and CHP units as end-use hydrogen applications[129]. These initiatives, highlighted by China's Ministry of Science and Technology, aim to decarbonise industry while boosting hydrogen vehicle markets. As a result, the Chinese market has attracted significant interest from both domestic and international firms, spurring pilot projects and deployment efforts.

Next generation, Degradation and Performance & Diagnostics: Diagnostic and monitoring tools are essential for ensuring the reliable performance and safety of stationary fuel cell (FC) systems, and it is a critical aspect to be considered for the integration of fuel cell systems into real applications. The development of these tools is a cross-cutting priority across multiple pillars, including Pillar 1 and 3, where tools are developed for electrolysers (e.g. REACTT project) or FC mobility applications (realHyFC project).

Turbines, boilers and burners: The global landscape of gas turbines operating on H_2 blends and pure hydrogen is advancing rapidly, driven by decarbonisation initiatives in the energy and industrial sectors. Micro-gas turbines (MGTs), with their compact design, rapid startup capabilities, and ability to adjust to varying loads, are emerging as suitable backup solutions for decentralised future energy systems.

128 CWC's 2nd Global Market Report confirms growing use of cogeneration technologies around the world – COGEN World Coalition

129 *Energies* **2021**, *14*(16), 4963; **https://doi.org/10.3390/en14164963**

Producing green hydrogen via water electrolysis and utilising it in gas turbines has become a critical focus, addressing the rising demand for hydrogen across transportation, heating, and power generation[130]. Recent advancements have shown promising results in 100-kW MGTs operating on hydrogen-blended fuels (varied from 50% to 100%), achieving stable performance and significantly reduced nitrogen oxide (NO_x) emissions. Notably, tests with pure hydrogen demonstrated emissions below 25 ppm of NO_x and entirely eliminated carbon-based greenhouse gases[131].

Across Europe, there are several notable examples of gas turbine prototypes utilising hydrogen as fuel. As part of the HYFLEXPOWER project, 12 MW SGT-400 gas turbine manufactured by Siemens Energy was installed in Smurfit-Kappa paper mill in Saillat-sur-Vienne (France), ultimately powered with 100% H_2[132]. DLR and the company PSC have converted a commercial micro gas turbine to run on hydrogen for the first time[133]. GE Vernova gas turbines have experience operating on fuels with hydrogen content ranging from 5% (by volume) up to 100%[134].

While pure hydrogen combustion remains in demo stage with limited commercial deployment, leading companies like Siemens Energy are already pursuing ambitious plans to develop, jointly with the British SSE utilities, a 600 MW gas turbine capable of operating on 100% hydrogen by 2030. If realised on time, it is set to be the largest hydrogen turbine in the world[135]. Mitsubishi Power announced at the end of 2023 that they will be demonstrating its advanced class gas turbine with 30% blended H_2 Takasago Hydrogen Park[136].

100% H_2 gas turbines are also being pursued in the USA and Japan, with many large and small projects at the whole range of TRL. Baker Hugues has already developed a 17.5 MW NovaLT™16 turbine ready to operate at 100% H_2, however with the need of having selective catalytic reduction treatment for NO_x reduction at the exhaust[137].

This indicates a growing interest from industry and utilities in pursuing this path, which is critical to its success. However, significant technological and operational challenges remain, and projects under this research area are actively addressing them. Nevertheless, additional challenges require attention, as outlined in the gaps and recommendations section.

Programme highlights

The projects within the commercial and industrial size systems research area are expected to deliver impact over a 5 to 10 year horizon. They aim to contribute to standardisation efforts (SO-FREE, E2P2), enhance resilience in regions with limited electrical grid infrastructure (E2P2), support grid balancing services (24/7 ZEN), and facilitate the decarbonisation of maritime (AMON) and digital (E2P2) sectors. Furthermore, these projects support broader sustainability objectives, including zero-emission heating and power solutions, while strengthening competitiveness and market opportunities for participating companies. They also promote energy resilience and enable potential revenue generation through distributed electricity production.

The SWITCH project, which concluded in 2024, successfully tested a large stack module (25 kW FC and ~77 kW EC) at DLR under both SOE and SOFC modes, demonstrating the required operational range and production capacity. The project achieved strong overall performance, and Sweco prepared a Market Deployment Plan outlining a viable strategy for market introduction. SWITCH was also awarded the Energy Globe Award for Italy.

An overview of the electrical efficiency at a system level for PEM and SO CHP systems across the programme is given in Figure 12 and Figure 13. The data from mid-size PEM fuel cell (FC) projects indicate that their electrical efficiency exceeds the 2024 SRIA target (red line), with the majority falling within the previous low and high

130 Rolo, Inês; Costa, Vítor A. F.; Brito, Francisco P., Energies (Basel), 2024

131 Banihabib, Reyhaneh; Assadi, Mohsen, Sustainability, 2022

132 Siemens Energy avvia in Francia la prima turbina a gas al 100% idrogeno rinnovabile–Hydrogen-news.it

133 Retrofit for commercial micro gas turbines successfully tested

134 Hydrogen-Fueled Gas Turbines | GE Vernova

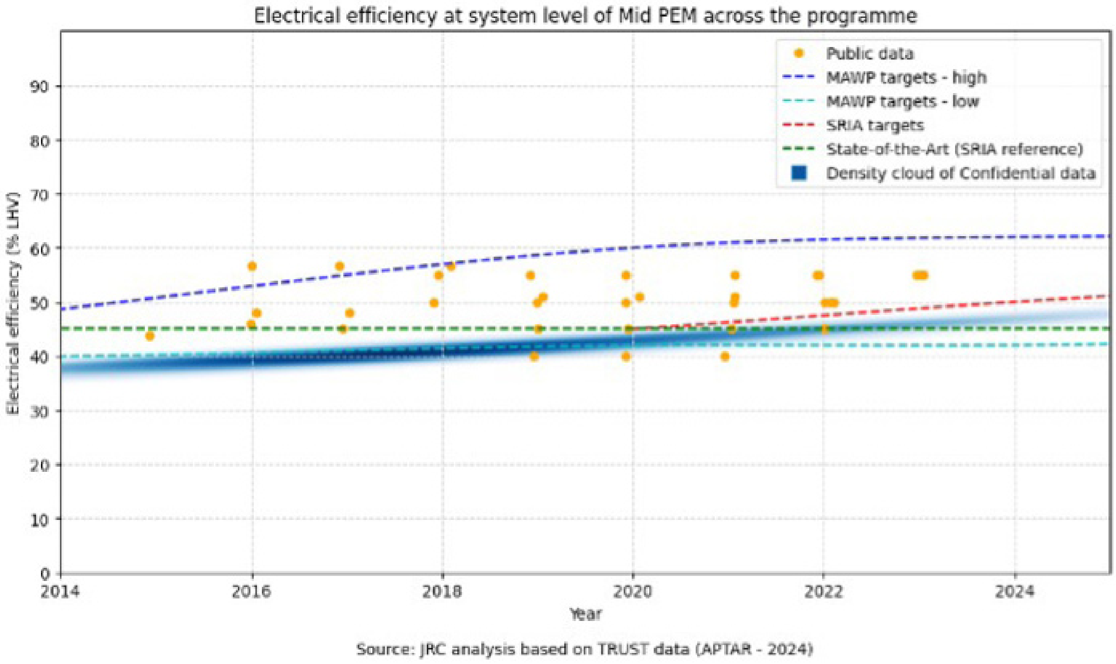
135 Siemens Energy to develop massive 600MW gas turbine capable of running on 100% hydrogen | Hydrogen Insight

136 https://www.mhi.com/news/23113001.html

137 NovaLT™16 Gas Turbine | Baker Hughes

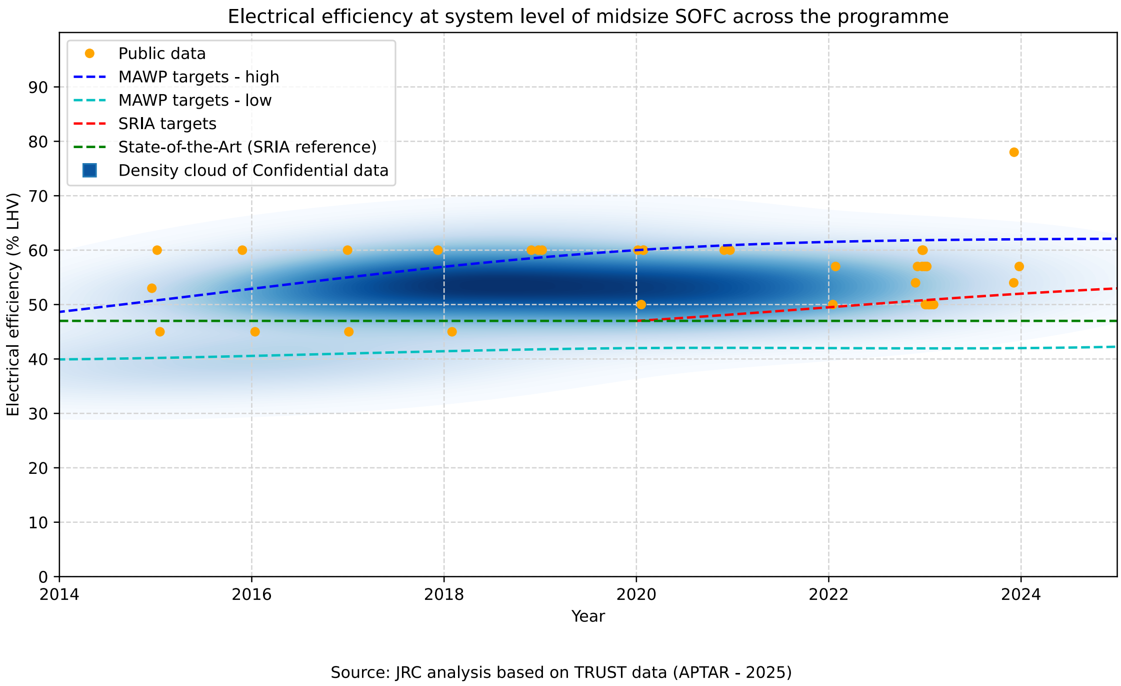
MAWP target ranges. However, confidential data points generally remain below both the 2024 SRIA target and the low MAWP threshold. For SOFCs, no data fall below the low MAWP target, and all projects since 2020 have consistently reported electrical efficiencies surpassing the 2024 SRIA target. A notable exception is the AMON project, which uses ammonia as fuel and reports higher electrical efficiency compared to others.

Figure 12: Electrical efficiency at system level for PEM FC CHP



Source: JRC analysis with data from Clean H2 JU

Figure 13: Electrical efficiency at system level for SOFC CHP



Source: JRC analysis with data from Clean H2 JU

Diagnostic and monitoring tools are crucial for ensuring the reliable performance and safety of stationary FC systems, and their development is essential for successful real-world integration. The RUBY project is in its final year and aims to deliver a comprehensive management tool designed to improve the performance and durability of stationary FC units. This tool will also provide maintenance service forecasts based on the internal health status of the systems and will enable testing of additional procedures, such as predictive maintenance protocols for both PEM and SOFC technologies. It is anticipated that the tool will be ready for engineering validation, final certification, and scalable production, allowing it to be integrated into commercial fuel cell systems. It should be noted here that this research area represents a cross-cutting priority spanning multiple pillars, including Pillar 1 and Pillar 3, where similar tools are being developed for electrolysers (e.g., REACTT project) and fuel cell mobility applications (e.g., realHyFC project).

The six projects within the turbines, boilers, and burners research area collectively aim to accelerate the adoption of hydrogen as a fuel for power generation, tackle operational challenges, and provide practical solutions for industrial decarbonisation. While most projects are still in early stages and require further development to deliver mature products, several notable achievements have already emerged. The H2AL project has completed burner modelling and experimental activities, while also defining safety and technical aspects and establishing crucial collaborations with other projects and stakeholders. The HELIOS project conducted a high-pressure experimental test campaign on a full-scale burner, demonstrating promising performance compared to the baseline combustor operating at 100% hydrogen. Similarly, the FLEX4H2 project has completed the first-generation burner design and testing at high pressures with pure hydrogen. The project has developed modelling capabilities to effectively downselect concepts, a key milestone for progressing to higher TRLs, and has carried out extensive outreach to promote its objectives, hydrogen energy, and the European gas turbine sector more broadly.

Gap Analysis – Main JRC Recommendations

Commercial and Industrial Size Systems: Stationary fuel cell systems based on SO technology for CHP generation still require technological refinement and increased production scale to effectively compete with conventional solutions. The main objectives are to reduce both capital and operational expenditures while enhancing system longevity. The SWITCH project has made significant progress, achieving 1,000 operational hours and demonstrating near higher heating value (HHV) efficiency in SOFC mode, aligning with the 2024 SRIA CAPEX targets under mass production conditions. However, there are still critical challenges to address. These include reducing hydrogen production costs, demonstrating the scalability of the technology for large industrial or commercial applications through megawatt-scale prototyping, and understanding and mitigating system degradation mechanisms. Addressing these challenges is essential for increasing technology readiness and enabling the widespread deployment of solid oxide fuel cells. Additional hurdles reported by various projects, such as supply chain disruptions, extended delivery timelines, and the exit of key partners, highlight vulnerabilities. This underscores the importance of systematic risk assessment during proposal development and the availability of skilled labour for operation and maintenance.

Repurposing existing gas turbines to operate on hydrogen mixtures is emerging as a complementary approach within Pillar 4. Hybrid systems that combine fuel cells with gas and steam turbines can provide adaptable and sustainable power solutions ranging from tens of kilowatts to hundreds of megawatts. Beyond co-generation, tri-generation systems that produce electricity, hydrogen, and heat offer additional value[138].

To enhance the timely execution and effectiveness of new projects, it is vital to draw on the insights and experiences gathered from earlier initiatives. Many Pillar 4 projects dedicate their efforts to developing and testing new systems, but frequently struggle to allocate enough time for collecting valuable operational data. This data is instrumental in evaluating potential, market reach, and environmental implications, often leading to a missed opportunity for utilising knowledge from earlier systems. For instance, initiatives like 24/7 ZEN build on the groundwork established by projects such as SWITCH, which wrapped up in 2024, while also introducing innovative elements. However, this drive for innovation can also present new challenges.

138 Tri-Generation | FuelCell Energy

Recommendations for achieving more effective and practical project outcomes include assessing the viability of current systems for further testing and refinement, focusing funding on projects that enhance existing systems rather than initiating entirely new ones, and encouraging transparency and public sharing of data to maximise its usefulness. Extending field testing is also important for gaining deeper insights into real-world impacts, while incorporating N-1 scenario planning and identifying alternative suppliers within project designs will enhance long-term sustainability through better risk management. These suggestions align with the strategy of 'Better Use of Generated Knowledge,' allowing for the effective application of lessons learned from past experiences. Additionally, fostering data sharing through initiatives similar to the U.S. National Renewable Energy Laboratory (NREL) can strengthen collaboration and facilitate the tracking of technological advancements. The Clean Hydrogen JU could take inspiration from NREL by developing an Open Access Database to support stakeholders in evaluating market opportunities and formulating energy policies.

Lastly, investigating hybrid and tri-generation systems can yield significant advantages in efficiency, cost-effectiveness, sustainability, and energy resilience. Learning from projects like Bio-HyPP and FlexiFuel-SOFC is essential to identifying the right sectors for these systems, ensuring successful implementation.

Next generation, Degradation and Performance & Diagnostics: The RUBY project's tool should undergo testing within commercial fuel cell systems operating in real-world conditions. A thorough analysis is needed to identify areas for further improvement. It is recommended that new projects targeting stationary fuel cell applications implement this tool while current projects should consider utilising it whenever possible. Furthermore, advancements in fuel cell diagnostic applications could be achieved through the integration of AI and machine learning. A retrospective analysis should follow, along with the collection of lessons learned. The RUBY project should establish communication with the Clean Hydrogen JU to discuss the application of the tool in potential commercial and research endeavours, as well as to share any valuable insights. This collaboration could significantly enrich the JU Knowledge Hub.

Turbines, boilers and burners: Recent studies on hydrogen blending in gas turbines (addressing technical, safety, economic, and operational challenges) highlight their potential to support the integration of variable renewable energy into the grid while optimising investments in renewable systems. To advance this field, identifying specific application areas is critical. In aeronautics, for example, assessing the creep life of hydrogen-fuelled aero engines is necessary to address durability and operational safety. At the same time, integrating gas turbines with fuel cells in hybrid systems offers a promising path for higher efficiency and greater flexibility, providing complementary strengths across different energy applications.

Despite the progress, several barriers remain before hydrogen-powered gas turbines can be deployed at scale. These include constraints in the hydrogen supply chain (covering production, storage, transportation, infrastructure for hydrogen blends, and equipment retrofitting) as well as the absence of harmonised safety and performance standards. Material compatibility challenges, such as hydrogen embrittlement in pipelines and turbine components, require dedicated research. In addition, reducing capital and operational costs for H_2-ready turbines will be key to competitiveness. A thorough assessment of environmental impacts, including lifecycle emissions and sustainability considerations, is also needed to support large-scale adoption.

In summary, hydrogen-blended turbines are advancing rapidly, but achieving large-scale deployment of pure hydrogen combustion systems remains a long-term goal, requiring significant technological, infrastructural, and regulatory developments. Global collaboration, harmonised standards, and strong policy support will be essential. For the six active projects under this research area, it is recommended that they leverage completed national and European projects as much as possible to accelerate progress. More tailored and project-specific recommendations will be provided in the 2026 Review as the initiatives move toward higher technology readiness levels.

5.5. PILLAR 5: CROSS-CUTTING ISSUES

While cross-cutting issues are integrated across the programme, a dedicated set of projects in this pillar specifically addresses them, reinforcing Europe's leadership and accelerating mass-market adoption. The research areas on

Safety, Pre-Normative Research and Regulations, Codes and Standards, and Sustainability, LCSA, recycling and eco-design play a central role in ensuring safe, sustainable, and future-proof hydrogen technologies. In parallel, the RA on Education and Public Awareness focuses on preparing a skilled workforce and fostering societal acceptance. To further strengthen global positioning, a new RA on International Cooperation was created in 2025 to support the strategy of building long-term partnerships across the hydrogen supply chain.

Overview of Research Areas

Education and public awareness: The European hydrogen industry is expected to drive economic growth, generate high-value jobs, and employ millions of people across multiple industrial sectors, both directly and indirectly. Realising this potential requires the development of a skilled and educated workforce, alongside fostering social awareness and public trust in hydrogen technologies to ensure efficient and sustainable growth. Within this context, this research area currently includes two projects (HYPOP and H2Academy.EU, see project posters in Annex V for more details).

International Cooperation: As part of the SRIA, the international cooperation strategy has three main objectives: i) strengthening cooperation with industrialised non-EU countries and emerging economies, ii) giving particular priority to partners in the EU's immediate vicinity, including through association to Horizon Europe, and iii) deepening partnerships with Africa, Latin America, and other regions. This RA consists of only one project, **JUST GREEN AFRH2ICA**, which developed a Green Hydrogen Transition Roadmap aimed at aligning African and European hydrogen transition strategies to ensure mutual benefits, environmental and social sustainability, and to avoid exploitative dynamics often referred to as "Africa hydrogen colonisation". Central to this vision was the creation of resilient hydrogen economies, the establishment of innovative R&D ecosystems, and the development of value chains that prioritise independence and long-term continental partnerships. Among its key achievements, the project delivered a **Technology-Policy-Investment Roadmap**, grounded in a comprehensive energy system model of the continent that also integrated social indicators.

Safety, Pre-Normative Research and Regulations, Codes and Standards: As hydrogen technologies transition from the industrial to the public domain, promoting hydrogen safety has long been a priority of the Clean Hydrogen JU Programme. Safety is not only a technical requirement but also a cornerstone for building public trust, which is a critical non-technical enabler for widespread technology deployment. The hydrogen industry has accumulated extensive experience in handling hydrogen safely, but introducing hydrogen-based technologies in new environments requires maintaining the highest safety standards to build trust and ensure broad adoption. Achieving this relies on consistent safety approaches, a robust safety culture, and the establishment of an enabling policy and regulatory framework supported by pre-normative research. This research area contains four projects (e-SHyIPS, ELVHYS, THOTH2 and SHIMMER).

Sustainability, LCSA, recycling and eco-design: The successful deployment of hydrogen-based technologies requires a sustainable, circular approach. This involves reducing environmental impacts, promoting material recovery and recycling, and creating assessment tools to guide decision-making. Within this context, two projects are currently underway (HyPEF and NHYRA), while two others were completed in 2024 (SH2E and eGHOST).

State-of-the-art

Education and public awareness: The widespread adoption of hydrogen technologies, irrespective of application, hinges not only on technological advancements but also on societal acceptance. This acceptance, in turn, is heavily influenced by public awareness and education about hydrogen's benefits, risks, and potential applications. Given that hydrogen technologies are still in the developmental or early deployment stages in many regions, effective education and public outreach are important. Building a knowledge base among stakeholders, ranging from industry professionals to the public, is critical to ensuring safe, informed, and widespread adoption of hydrogen.

Hydrogen education efforts need to span various levels, from technical education for professionals working in hydrogen-related industries to general public outreach aimed at fostering awareness and understanding of hydrogen's role in the energy transition. At the professional level, specialised training programs and academic curricula are essential to ensure that engineers, technicians, and researchers possess the necessary expertise to design, implement, and maintain hydrogen systems. Several universities and research institutions have already integrated hydrogen technologies into their curricula. For instance, in Europe, there are several universities offering master's degree programs related to hydrogen[139]. As hydrogen infrastructure expands internationally, there is a growing demand for a workforce skilled in handling the specific safety, engineering, and operational requirements of hydrogen systems. Educational institutions, therefore, play a critical role in preparing the future workforce.

A recent paper presented a systematic review of the literature on the educational outcomes necessary for developing a hydrogen engineering workforce[140]. The study identifies a significant gap between the current educational programs and the skills, knowledge, and attributes required for the low-emissions hydrogen industry. The review highlights the importance of cross-sector collaboration, involving higher education institutions and industry partners, to co-design relevant curriculum and training programs. Unfortunately, empirical studies capturing practitioner perspectives to inform curriculum design remain scarce. The authors emphasise the need for an approach that includes both technical and social competencies to prepare engineers for the hydrogen sector. They call for further research to define educational outcomes and competencies, ensuring they align with industry expectations.

Globally, a wide range of hydrogen training programs are equipping professionals, policymakers, and students with the skills needed for the rapidly growing hydrogen sector. In the context of the Clean Hydrogen JU programme, projects such as TRAINHY-PROF, KNOWHY, NET-TOOLS, TEACHY, and FCHGO have developed educational and training programs on hydrogen and fuel cell technologies, covering various education levels (formal, vocational), target groups (students, policymakers, technicians), and technological topics (fuel cells, electrolysers, safety, life cycle assessment). These initiatives use diverse teaching methods (traditional, collaborative, hands-on), tools (virtual reality, e-learning), and offer different certifications, aligning with the European Skills Agenda[141]. The current project HyAcademy.EU aims to build and expand on these achievements, guaranteeing their availability and validity beyond the end of the projects.

H2EDGE (Hydrogen Education for a Decarbonized Global Economy) was a major U.S. workforce development initiative, running 2023-2024, led by the Electric Power Research Institute (EPRI) and supported by the Department of Energy, designed to build a skilled labour force for the emerging hydrogen economy[142]. The program collaborated with universities, including Oregon State University, University of Delaware, and University of Houston, as well as industry partners to develop and deliver comprehensive training materials, professional courses, and updated university curricula focused on hydrogen production, delivery, storage, and use. Key accomplishments include the creation of a national university network, the launch of professional training and retraining programs, new and revised university courses, and targeted outreach to Historically Black Colleges and Universities, Minority Serving Institutions, and Underserved Communities to broaden workforce diversity. H2EDGE has also established an industry advisory board. Internationally, the Green Hydrogen Policy Accelerator Training Course, organised by the Green Hydrogen Organisation (GH2) and International Solar Alliance (ISA), brings together policymakers from emerging markets to build expertise in policy, technology, and standards for green hydrogen development[143]. These are just two examples of many efforts from outside the EU.

Beyond formal education, public awareness campaigns play a critical role in shaping societal perceptions of hydrogen. Historically, public engagement with hydrogen has been limited as it has been constrained to mostly industrial applications. Limited understanding can pose a barrier to the successful deployment of hydrogen

139 Clean Hydrogen Partnership, "European Hydrogen Observatory–Training Programmes." Accessed: May 20, 2025. [Online]. Available: https://observatory.clean-hydrogen.europa.eu/learn-about-hydrogen/training-programmes?keys=&field_type_of_training_target_id%5B1000%5D=1000&items_per_page=200

140 R. McHenry, S. Krishnan, and L. Tuck, "Knowledge, skills, and attributes needed for developing a hydrogen engineering workforce: A systematic review of literature on hydrogen engineering education," Int. J. Hydrogen Energy, vol. 72, no. May, pp. 380–387, 2024, doi: 10.1016/j.ijhydene.2024.05.380.

141 European Skills Agenda–European Commission

142 Electric Power Research Institute (EPRI), "H2EDGE," 2025. Accessed: May 20, 2025. [Online]. Available: https://hydrogen.epri.com/en/h2edge.html

143 Green Hydrogen Organisation (GH2), "2024 Handbook of the Green Hydrogen Policy Accelerator Training Course," 2024. [Online]. Available: https://gh2.org/publication/2024-handbook-green-hydrogen-policy-accelerator-training-course

technologies, as public scepticism or fear can influence the adoption of hydrogen-based solutions, particularly in areas such as transportation and energy infrastructure, which inevitably brings the technologies close to the public. To bridge this knowledge gap, several public awareness campaigns have been launched, particularly in countries leading the hydrogen transition. For instance, a hydrogen museum was established in Tokyo (Japan) to provide a hands-on learning experience about hydrogen for all ages[144]. Moreover, the Japanese government planned to leverage Expo 2025 in Osaka as an opportunity to showcase hydrogen technologies and to allow the public to familiarise with them through direct interactions, using, for instance, fuel cell vessels[145]. In Germany, Hyundai partnered with a tech influencer to answer questions from his audience about hydrogen vehicles[146]. At the global level, the *Education & Outreach Working Group*[147] of IPHE (International Partnership for Hydrogen in the Economy) has been active for several years, collecting and sharing information on challenges, opportunities, and initiatives across IPHE members. This Working Group organises events and activities targeting a broad range of stakeholders, from policy makers and government officials at the federal, state, regional, and local levels, as well as stakeholders from academia, industry, non-governmental organisations, associations, and other decision makers. Their outputs range from fact sheets to monitoring funding, programs, and policies in each member country. A particular focus is dedicated to student education, and an Early Career Network[148] is in place. More recently, the IPHE has created the Hydrogen Skills Task Force H2SK[149].

Initiatives aimed at improving understanding of hydrogen technologies, such as technology introduction events and professional seminars, have shown that increased knowledge can enhance public confidence and acceptance of, e.g., hydrogen fuelling stations, despite initial lower levels of awareness among participants in introductory events compared to those in seminars[150].

Public perception of hydrogen technology is shaped by risk awareness and environmental considerations. Studies indicate that while there is a general tendency to favour hydrogen produced from renewable sources, concerns about safety and environmental impacts persist, particularly in regions with lower awareness, such as rural areas in the Philippines.[151] The perception of risk associated with hydrogen energy is complex, as it varies among different stakeholders and is influenced by cultural and ideological contexts. This complexity underscores the importance of targeted public awareness campaigns to address concerns and facilitate acceptance[152].

Odoi-Yorke et al.[153] reviewed the research from 2003-2023 on hydrogen energy acceptance, identifying several key determinants of hydrogen acceptance: limited public awareness, perceived usefulness, safety concerns, cost, and associated health benefits. Additionally, the effectiveness of financial policies, industry support for climate protection, government trust, and strategic communication are pivotal factors in shaping public acceptance. Leading countries in hydrogen research include Japan, China, and Germany, with notable contributions from several more European nations. However, there are significant acceptance gaps in regions such as Africa and South America, which need to be addressed in order to foster global adoption. The body of research indicates a shift toward a deeper understanding of societal perceptions and attitudes, suggesting the necessity for interdisciplinary approaches that integrate technological, social, and environmental perspectives.

In the European Union and the United Kingdom, the acceptance of green hydrogen is shaped by various factors, such as knowledge, information dissemination, trust, communication, cost, safety, environmental and climate

144 https://www.tokyo-suisomiru.jp/language/en/ (Tokyo Hydrogen Museum)

145 https://www.meti.go.jp/shingikai/enecho/shoene_shinene/suiso_seisaku/pdf/20230606_5.pdf (METI, Basic Hydrogen Strategy)

146 https://www.hyundai.com/worldwide/en/brand-journal/sustainable-vision/h2u-alexibexi (H2U x AlexiBexi)

147 E&O Working Group | IPHE

148 Early Career Network | IPHE

149 Hydrogen Skills Task Force | IPHE

150 Hienuki et al., 2019

151 Palanca et al., 2025)

152 C. Parente, F. Teixeira, and J. Cerdeira, “Stakeholders’ perceptions of hydrogen and reflections on energy transition governance,” Energy. Sustain. Soc., vol. 14, no. 1, pp. 1–19, 2024, doi: 10.1186/s13705-023-00429-w

153 F. Odoi-Yorke, E. B. Agyekum, F. L. Rashid, J. E. Davis, and H. Togun, “Trends and determinates of hydrogen energy acceptance, or adoption research: A review of two decades of research,” Sustain. Energy Technol. Assessments, vol. 73, no. September 2024, p. 104159, 2025, doi: 10.1016/j.seta.2024.104159.

issues, experience with the technology, and socio-demographic characteristics[154]. Although the prevailing attitude towards green hydrogen is one of acceptance, many people remain undecided, highlighting the need for targeted efforts to raise awareness, build trust, and promote a better understanding of the advantages and potential of green hydrogen.

The state-of-the-art analysis delivered by project HYPOP[155] presents similar conclusions, revealing a positive yet conditional public attitude towards hydrogen technologies. The study also highlights a general awareness but limited in-depth understanding of these technologies. The analysis covers both scientific literature and original data from the *Awareness of Hydrogen Technologies Survey Report* conducted by Gallup International in EU27 countries.[156] The latter revealed that over 80% of respondents have some level of awareness of hydrogen energy, though familiarity varies by gender and age, with men typically claiming greater knowledge. The research identifies a positive but conditional public attitude toward hydrogen, influenced by environmental concerns and trust in scientific progress, yet hindered by infrastructural and safety apprehensions, as evidenced by the 'Not in my backyard' phenomenon, notably in Germany, Denmark, and Poland. The document underscores the importance of targeted communication strategies to enhance public engagement and acceptance, suggesting that increasing public understanding through educational initiatives could strengthen support for hydrogen.

Looking ahead, both formal and informal education efforts must continue to evolve as hydrogen technologies advance. The rapid development of hydrogen production methods, from traditional steam methane reforming to more sustainable approaches such as electrolysis powered by renewable energy, will require ongoing updates to educational content and training programs. Furthermore, as new applications of hydrogen, such as hydrogen for aviation and maritime transport, emerge, education efforts must adapt to include these novel use cases. In conclusion, hydrogen education and public awareness are integral to the successful transition to a hydrogen-based economy. Education at both the professional and public levels will be crucial in dispelling misconceptions, reducing safety concerns, and fostering acceptance of hydrogen technologies.

International Cooperation: International collaboration is a key cross-cutting theme across all pillars of the hydrogen initiative, with 35 Clean Hydrogen JU projects already involving partnerships with international countries. These collaborations facilitate knowledge sharing on hydrogen economy ecosystems, create mutual benefits and networks, and leverage the EU's technological expertise, policy frameworks, and regulatory experience to amplify collective strengths.

To achieve the European Green Deal ambitions on domestic renewable hydrogen consumption by 2030, imports are expected to play a crucial role, with several African nations well-positioned to supply this demand. However, while some African countries have already developed national hydrogen strategies, technological and deployment efforts remain fragmented. It will be essential for African nations to align their hydrogen roadmaps with their specific contexts and capabilities, set realistic objectives, and move toward a cohesive continental hydrogen strategy.

Safety, Pre-Normative Research and Regulations, Codes and Standards: The research areas of hydrogen safety and pre-normative research supporting regulations, codes, and standards enable and facilitate the deployment of hydrogen solutions.

As the technologies are expected to move from the industrial domain to the public domain, promoting **hydrogen safety** has been, for a long time, a priority of the Clean Hydrogen JU Programme. Hydrogen safety is also closely connected to public trust, a non-technical enabler for technology deployment. Over decades, significant progress has been made in understanding hydrogen behaviour during accidental releases and developing both passive and active safety measures for various environments, thanks to projects such as HYSEA and HYTUNNEL-CS, while initiatives such as HYRESPONSE and HYRESPONDER were focused on safety education and training. Strong attention has also been dedicated in the past to the safety of compressed storage, with the projects HYCOMP, HYPACTOR, and FIRECOMP. The ability to handle liquid hydrogen safely has been hindered by a lack

154 L. Maketo and P. Ashworth, "Social acceptance of green hydrogen in European Union and the United Kingdom: A systematic review," Renew. Sustain. Energy Rev., vol. 218, no. April, p. 115827, 2025, doi: 10.1016/j.rser.2025.115827

155 Jensen et al., 2024

156 Clean Hydrogen Partnership, 2023

of knowledge of its behaviour under accidental conditions. Tangible progress has been achieved in this area by project PRESLHY followed by project ELVHYS. All these projects have been at the forefront of international scientific progress.

The state of the art of hydrogen safety is difficult to summarise as it is heavily context-specific. Nonetheless, some overarching efforts to define the current state exist. The HySafe Research Priorities Workshop 2024 Outcomes Report highlights the current state of hydrogen safety research, with a strong focus on pre-normative research and the identification of RCS gaps[157]. The workshop brought together international experts from academia, industry, and government who assessed and ranked the most pressing research needs for the safe deployment of hydrogen technologies. Key findings indicate that the highest priority areas are advancements of Quantitative Risk Assessment (QRA) methods, and Reliability data acquisition. Other key areas were Mitigation, Sensors and Hazard Prevention and Phenomena Understanding and Modelling. The industry stakeholders in particular indicated RCS as an important topic. The workshop found that accident physics for gas-phase hydrogen is reasonably well understood, with the exception of gas explosion modelling and impinging jets. Cryogenic hydrogen was deemed a more pressing research area, where modelling tools, release behaviour, and Boiling Liquid Expanding Vapour risks were particularly highlighted. Overall, the workshop underscored the need for continued international collaboration and targeted pre-normative research to address outstanding safety challenges and inform future RCS development, ensuring that hydrogen technologies can be deployed safely at scale.

In the United States, the Department of Energy's Hydrogen and Fuel Cell Technologies Office (HFTO) has been instrumental in advancing hydrogen safety research. Through initiatives such as the Hydrogen Safety Panel and various collaborations with national laboratories, the U.S. has made significant advances in establishing safety protocols for hydrogen refuelling stations, storage, and transportation infrastructure[158]. One example is the NFPA 2 Hydrogen Technologies Code, developed by the National Fire Protection Association (NFPA), which provides a set of safety requirements for hydrogen production, storage, and distribution[159]. This code is widely referenced for designing and implementing hydrogen infrastructure, outside of the United States as well. The HFTO multi-year programme plan prioritises five key areas of research, development, and demonstration: hydrogen behaviour and risk research, component validation, materials compatibility, codes and standards harmonisation, and safety resources. Domestic and global harmonisation of standards is highlighted as one of the more important topics.

Japan's Ministry of Economy, Trade, and Industry (METI) has developed a Hydrogen Safety Strategy that focuses on three main pillars: utilising scientific data to establish evidence-based safety standards, streamlining and optimising regulations across the hydrogen supply chain, and promoting international harmonisation with global standards[160]. The strategy also emphasises the importance of risk communication and workforce training to enhance public understanding and acceptance of hydrogen technologies. METI supports these efforts with pre-normative research, including experimental studies on hydrogen hazards and the development of a centralised Hydrogen Safety Portal to share regulatory information and best practices.

While progress has been made, challenges remain in harmonising safety standards on a global scale. Differences in regulatory frameworks, safety protocols, and industry practices across regions present obstacles to the seamless adoption of hydrogen technologies worldwide. To address these challenges, international organizations such as the Hydrogen Council and the International Energy Agency (IEA) are working toward achieving global alignment on safety standards, which is essential for fostering international trade and the widespread deployment of hydrogen systems. In conclusion, hydrogen safety research has advanced significantly in recent years, partly thanks to some influential projects of the Clean Hydrogen JU programme. But the development of comprehensive, harmonised regulations and standards remains an ongoing challenge. As hydrogen technologies continue to scale, it is essential that research and regulatory efforts continue to evolve to address emerging safety concerns.

157 International Association for Hydrogen Safety (HySafe), "Research Priorities Workshop 2024 – Outcomes Report," Hydrog. Saf., vol. 2, no. 1, pp. 1–23, 2024, doi: 10.58895/hysafe.15

158 U.S. Department of Energy, "Hydrogen and Fuel Cell Technologies Office Multi-Year Program Plan," 2024. [Online]. Available: https://www.hydrogen.energy.gov/library/roadmaps-vision/clean-hydrogen-strategy-roadmap.

159 The National Fire Protection Association, "NFPA 2–Hydrogen Technologies Code," 2023.

160 Japan's Ministry of Economy Trade and Industry (METI), "Interim Report for the Hydrogen Safety Strategy Released," 2023. Accessed: May 20, 2025. [Online]. Available: https://www.meti.go.jp/english/press/2023/0313_003.html

The **development of standards** is essential to ensure the safe use of hydrogen, which is characterised by its flammability, potential for deflagrations and detonations, and material compatibility challenges. For several years, a focused effort within the international hydrogen community has been directed towards establishing science-based codes and standards that are informed by rigorous research activities. These efforts aim to enhance the scientific understanding of hydrogen behaviour, to refine risk assessment tools, and address material compatibility and fuel quality issues[161]. The need for targeted pre-normative research in support of harmonised RCS is manifested in several roadmaps in the EU. The European Clean Hydrogen Alliance's Roadmap on Hydrogen Standardisation is a roadmap published in March 2023 covering ongoing hydrogen-related standardisation activities, standardisation gaps, priorities, and needs[162]. It identifies over 400 standardisation topics across the hydrogen value chain, revealing key gaps particularly in industrial applications, mobility (including heavy-duty vehicles, aviation, and maritime), and safety aspects such as material compatibility and leakage prevention. The roadmap highlights the urgent need for pre-normative research to support the development of harmonised regulations, codes, and standards (RCS), with a strong focus on risk-informed safety measures and interoperability.

Another roadmap is the DVGW Standardisation Roadmap for Hydrogen Technologies 2024, which presents a strategic roadmap to accelerate the development and harmonisation of technical rules across the entire hydrogen value chain in Germany[163]. Developed by over 600 experts across 39 working groups and led by key organisations including DVGW, DIN, and DKE, the roadmap covers five major areas: Production, Infrastructure, Application, Quality infrastructure, and Training, certification, and safety. The main conclusion is that while technical standardisation is well advanced in sectors like fuel cell energy systems, road vehicles, and grid-bound infrastructure, significant gaps remain in aviation, shipping, off-shore hydrogen production, and hydrogen derivatives.

Other gap analyses dedicated to the RCS dimensions of the hydrogen supply chains have been produced by several international organisations, namely the intergovernmental International Partnership for Hydrogen in the Economy[164] (IPHE) and the industry-led Hydrogen Council[165]. While these gap analyses are a valuable tool for prioritisations at the policy level, the implementation actions in terms of new or updated standards and technical regulations encounter a series of difficulties. On one side, there is the existence of national overarching laws and administrative rules which do not allow the hydrogen supply chain to be handled as a stand-alone set of technologies. On the other side, is the lack of an established market and the existence of several technology options that make it difficult to standardise without creating obstacles to innovations. The ISO Technical Committee 197 on Hydrogen technologies[166] is a driving force behind internationally recognised standards, with its own gap analysis and foresight methodology. A similar approach is adopted by the ICE TC 105 on Fuel Cells Technologies. In Europe, the standardisation bodies are traditionally mirroring the international development in the classic hydrogen engineering areas, and in some cases lack resources to undertake their own independent efforts. This is particularly evident for the CEN/CENELEC Joint Technical Committee 6 on Hydrogen in energy systems[167], which, since its creation in 2016, has been able to publish only one formal document in 2025; a Vocabulary[168].

For the **regulatory dimension**, the earlier project HYLAW remains the most comprehensive effort identifying legal and administrative obstacles hindering the widespread commercialisation of hydrogen technologies in Europe. Another key initiative is the CERTIFHY project and its follow-ups, which have evaluated the market and regulatory

161 C. San Marchi et al., "Overview of the DOE hydrogen safety, codes and standards program, part 3: Advances in research and development to enhance the scientific basis for hydrogen regulations, codes and standards," Int. J. Hydrogen Energy, vol. 42, no. 11, pp. 7263–7274, 2017, doi: 10.1016/j.ijhydene.2016.07.014.

162 European Clean Hydrogen Alliance, "Roadmap on hydrogen standardisation," 2023. [Online]. Available: https://www.cencenelec.eu/media/CEN-CENELEC/News/Press

163 DIN et al., "Standardization Roadmap Hydrogen Technologies 2024," 2024. [Online]. Available: https://www.din.de/resource/blob/1140546/bfe3e27f3211008924c3c27b7b9efc8c/standardization-roadmap-for-hydrogen-technologies-2024-data.pdf

164 https://www.iphe.net/

165 https://hydrogencouncil.com

166 https://www.iso.org/committee/54560.html

167 https://standards.cencenelec.eu/dyn/www/f?p=305:7:0:25:::FSP_ORG_ID,FSP_LANG_ID:2121095

168 ISO 24078:2025–Hydrogen in energy systems–Vocabulary

prerequisites necessary to design and establish a European framework for renewable and low-carbon hydrogen guarantees of origin, aiming to support market development and regulatory harmonisation across Europe.

As in the case of safety, defining the **state of the art in the RCS area** is challenging due to its application-specific nature. Most RCS are tailored to address a particular subset of applications, and many are not exclusively designed for hydrogen, but rather can be adapted for it. Ensuring compatibility with hydrogen is crucial, nonetheless. To illustrate the current state of the art, two ongoing projects (THOTH2 and e-SHyIPS) have conducted analyses for distinct applications: one focusing on measuring devices in gas infrastructure and the other on maritime passenger transport. These examples provide insight into the advancements and developments in this RA for specific use cases.

The THOTH2 project presents a review of the current state of measuring devices within natural gas (NG) transmission and distribution networks, with a particular focus on hydrogen integration. The project identifies significant gaps in normative standards and suggests the development of new methodologies and protocols for validated testing of metering devices to ensure hydrogen readiness. It highlights the necessity for systematic review and updating of standards, analysis procedures, and field operation protocols, as well as training for field operators on hydrogen's effects. The document underscores the importance of addressing the metrological impacts of hydrogen on various measuring technologies. Furthermore, it discusses the challenges posed by hydrogen's effect on materials and metrological performance.

The e-SHyIPS project provides two comprehensive reviews of the current regulatory and standardisation landscape concerning hydrogen technologies in maritime passenger transport[169]. The first deliverable outlines the framework of existing RCS, highlighting identified gaps in hydrogen-related safety standards and the need for experimental scenarios to address these deficiencies. The report identifies significant gaps in the International Code of Safety for Ships using Gases or other Low-flashpoint Fuels (IGF Code) concerning hydrogen. Through workshops and expert consultations, the project has prioritised these gaps and proposed targeted pre-normative research and standardisation actions, including simulation and laboratory testing. The second deliverable expands on the technical and risk assessment aspects, addressing the lack of specific hydrogen requirements in existing standards.

Sustainability, LCSA, recycling and eco-design: The global community is actively working to enhance the sustainability of various products and technologies, including hydrogen technologies. The EU is at the forefront of developing methodologies and setting legislative targets and requirements. Several EU laws mandate the assessment of sustainability criteria for hydrogen production and use[170]. While the primary focus has been on GHG emissions, additional criteria, such as the "do no significant harm" principle from the Taxonomy regulation, are being progressively introduced. The EU has established the Environmental Footprint method[171] to assess the overall environmental impact of products across 16 categories. Work is also underway on other methodologies, including eco-design guidelines[172]. However, these generic tools need to be adapted for the unique characteristics of hydrogen technologies. Recognising this, the FCH JU has funded projects since 2010 to develop specific guidelines for assessing the environmental impact of hydrogen technologies. The FC-GUIDE and HyGUIDE projects (2010-2011) pioneered an LCA methodology for fuel cells and hydrogen technologies, culminating in the FC-HyGUIDE guidelines. Despite their release in 2011, their adoption across FCH JU projects has been limited and inconsistent. A decade later, these guidelines required updates to reflect technological advancements. The

169 M. Gentilini et al., "D 1.1: SoA of measuring devices installed in NG transmission and distribution networks," 2023. [Online]. Available: https://thoth2.eu/news-and-publications/deliverable-d1-1-soa-of-measuring-devices-installed-in-ng-transmission-and-distribution-networks/; N. Baumann and T. Wannemacher, "D 1.4: State of the art of safety technical framework and updated risk & safety assessment and plan," 2022. [Online]. Available: https://e-shyips.com/file/D1.4_Attachment_0-17.pdf; C. Di Maria et al., "D 1.3: State of the art of safety standardisation framework," 2023. [Online]. Available: https://e-shyips.com/file/D1.3_Attachment_0-15.pdf

170 A. Arrigoni et al., "Life cycle assessments use in hydrogen-related policies: The case for a harmonized methodology addressing multifunctionality," Int. J. Hydrogen Energy, vol. 69, no. April, pp. 1426–1438, 2024, doi: 10.1016/j.ijhydene.2024.04.346

171 European Commission, "Commission Recommendation (EU) 2021/2279 of 15 December 2021 on the use of the Environmental Footprint methods to measure and communicate the life cycle environmental performance of products and organisations," Off. J. Eur. Union, vol. L 471/1, no. December 2021, p. 396, 2021, [Online]. Available: http://eur-lex.europa.eu/legal-content/EN/ALL/?uri=OJ:L:2013:124:TOC

172 U. Eynard et al., Review of the MEErP–Methodology for Ecodesign of Energy-related Products. 2024. doi: 10.2760/24524.

need for harmonised guidelines has also been emphasised in the literature[173]. Although the sustainability of hydrogen technologies is being investigated globally, incomplete definitions of technical parameters hinder comprehensive comparisons of LCA results for similar FCH systems, jeopardising the interpretability and utility of these results for further harmonisation research[174]. Furthermore, not all hydrogen technologies are investigated with the same depth; hydrogen production and road transport applications are the most frequently analysed via LCA. Electrolysis from renewable energy sources, compressed hydrogen, and fuel cells are the most widely considered production methods, storage options, and conversion equipment in existing LCAs[175].

To address these shortcomings, the FCH 2 JU set new priorities in 2020, designing three call topics aimed at developing: updated and more complete Life Cycle Sustainability Assessment (LCSA) guidelines, eco-design guidance, and sustainable solutions for the end-of-life of hydrogen technologies. The three funded projects (SH2E, eGHOST, and BEST4HY) have significantly advanced the understanding of hydrogen technology sustainability and provided tools for its monitoring. Moreover, in 2024, a panel of experts, the European Hydrogen Sustainability and Circularity panel, was formed to support the sustainability and circularity activities of the Clean Hydrogen JU. Once methodologies are established, data and benchmarks are crucial for assessing and improving the impacts of hydrogen technologies. There remains a significant gap in data availability, particularly concerning the materials used in electrolyser and fuel cell stacks, and the production and end-of-life of specific materials, such as iridium, yttria-stabilised zirconia, and the electrolyte polymers[176]. Another critical gap is the quantification of hydrogen losses along the supply chain and their climatic impact[177]. Moreover, existing databases are often in different formats, and modelling assumptions are not always fully reported. While the SH2E guidelines and the LCA Checklist developed by JRC[178] are expected to improve future hydrogen technology LCAs, there is still a need for new data collection. In 2021, the EC recommended using the Environmental Footprint method to develop datasets. Compared to the previous standard methodologies, such as ISO 14040, ISO 14044, and the ILCD Handbook, the Environmental Footprint method provides further specifications necessary to achieve a higher degree of robustness, consistency, reproducibility, and comparability[179]. Technical secretariats from various industries have also begun developing Product Environmental Footprint Category Rules (PEFCRs) to establish specific rules for determining relevant environmental information within product categories. Since no PEFCRs have been developed for hydrogen technologies yet, a new project, HyPEF, was funded to address this. HyPEF aims to develop PEFCRs specifically for FCH products, which will facilitate future benchmarking and ranking of FCH products entering the EU market. Concurrently, a hydrogen node has been created on the European Commission's Life Cycle Data Network for uploading new inventories.

To address the knowledge gap on hydrogen losses and their environmental impact, several projects have been funded, primarily in the EU and USA[180]. In the EU, the NHyRA project (funded by the Clean Hydrogen JU) aims to create a comprehensive inventory of hydrogen releases from the value chain and develop methodologies for measurement and calculation. This will provide a complete picture of release scenarios and formulate recommendations for standards and technical specifications to support decision-makers in mitigating hydrogen releases. Under the Horizon Europe framework, the HyDRA and HyWAY projects have also been funded. HYDRA comprehensively assesses the potential risks and impacts of a large-scale hydrogen-based economy, including safety and climatic risks, and aims to develop guidelines, mitigation actions, and a remote-control monitoring

173 A. Valente, D. Iribarren, and J. Dufour, "Life cycle assessment of hydrogen energy systems: a review of methodological choices," Int. J. Life Cycle Assess., vol. 22, p. 346, 2017

174 G. Puig-samper, E. Bargiacchi, D. Iribarren, and J. Dufour, "Life-cycle assessment of hydrogen systems: A systematic review and meta-regression analysis," J. Clean. Prod., vol. 470, no. December 2023, p. 143330, 2024, doi: 10.1016/j.jclepro.2024.143330

175 D. I. Rinawati, A. R. Keeley, S. Takeda, and M. Shunsuke, "Life-cycle assessment of hydrogen utilization in power generation: A systematic review of technological and methodological choices," Front. Sustain., vol. 3, 2022, doi: 10.3389/frsus.2022.920876

176 V. Santucci, U. Eynard, A. Valente, and F. Mathieux, Developing life cycle inventory datasets for the hydrogen value chain. 2024. doi: 10.2760/426933.

177 A. Arrigoni and L. Bravo Diaz, "Hydrogen emissions from a hydrogen economy and their potential global warming impact," Publications Office of the European Union, Luxembourg (Luxembourg), 2022. doi: 10.2760/065589 (online).

178 V. Santucci, U. Eynard, A. Arrigoni, E. Weidner, and F. Mathieux, "LCA Checklist: a tool to improve the communication of the environmental sustainability of the Clean Hydrogen Joint Undertaking projects–v.1," 2024.

179 European Commission, "Commission Recommendation (EU) 2021/2279 of 15 December 2021 on the use of the Environmental Footprint methods to measure and communicate the life cycle environmental performance of products and organisations," Off. J. Eur. Union, vol. L 471/1, no. December 2021, p. 396, 2021, [Online]. Available: http://eur-lex.europa.eu/legal-content/EN/ALL/?uri=OJ:L:2013:124:TOC

180 U.S. Department of Energy, "Hydrogen Emissions and Environmental Impacts Workshop. 2024 Workshop Summary Report," 2024

tool for detecting and quantifying hydrogen leakages. HyWAY will focus on developing novel emission modelling and installation-level emission measurement, and quantifying the global warming potential of hydrogen and its effective radiative forcing. These three projects have recently commenced, so concrete recommendations for policies and regulations are still forthcoming. Nevertheless, discussions on whether to include the indirect global warming effect of hydrogen emissions are ongoing in various forums, including the ISO working group developing a methodology for assessing the carbon footprint of hydrogen.

Research is also focusing on the end-of-life impacts and circularity of hydrogen technologies, particularly for recovering precious materials like Platinum Group Metals. Reusing components and recycling materials are crucial for reducing supply chain risks and the environmental impact associated with mining and transportation. A recent study found that recycling materials from end-of-life electrolysers and fuel cells can reduce GHG emissions by 16%[181]. Currently, recycling of electrolysers and fuel cells is limited due to the small volumes of these relatively new technologies and their complex compositions[182]. While some recycling strategies are still in early stages, others are quite mature. For instance, established technologies for recovering valuable PGMs are already in industrial use for extracting these metals from vehicle catalytic converters. Among the prominent PGM recovery methods, hydrometallurgy involves leaching PGMs from the Membrane Electrode Assembly using an acid (hydrochloric acid) and an oxidant (hydrogen peroxide or nitric acid), followed by recovery through various extraction and separation steps involving organic solvents or ion exchange membranes. This method has shown high-quality platinum recovery yields ranging from 64% to 99% from PEMFCs[183]. Another approach, pyro-hydrometallurgy, first incinerates the membrane before proceeding with hydrometallurgy. This method boasts even higher PGM yields of 96% to 100% and eliminates the need for mechanical pre-treatment. However, a drawback is the release of fluorocarbon gases, which can contribute to ozone depletion, global warming, and human health issues. It's worth noting that platinum quality definitions can vary, often linked to purity, particle size, or morphology, all of which influence catalytic performance. Beyond PGM recovery, several emerging recycling techniques are also concentrating on ionomer recovery and minimising fluorine emissions. Acid dissolution, for example, liquefies the ionomer and PGMs in concentrated sulfuric acid at elevated temperatures, with subsequent component separation through extraction. While platinum yields (65–100%) are comparable to hydrometallurgy, the harsh conditions of acid dissolution can compromise the quality of the recovered catalysts and membranes[184]. Alternatively, solvent dissolution utilises an alcohol-water mixture at elevated temperatures to delaminate the ionomer from other MEA components, achieving yields of 63% to 99%[185]. While laboratory studies have demonstrated impressive iridium recovery rates of 98%[186], industrial end-of-life recovery has so far only reached 40% to 50%[187]. Unfortunately, data on the recycling of other electrolyser components, such as titanium, carbon paper, and graphite, remain scarce[188].

Programme highlights

Thanks to the Education and public awareness research area, the programme has effectively created educational materials for diverse stakeholders through various projects. Notable projects include HYRESPONDER, aimed

181 T. Uekert, H. M. Wikoff, and A. Badgett, "Electrolyzer and Fuel Cell Recycling for a Circular Hydrogen Economy," Adv. Sustain. Syst., vol. 8, no. 4, pp. 1–11, 2024, doi: 10.1002/adsu.202300449.

182 A. Valente, D. Iribarren, and J. Dufour, "End of life of fuel cells and hydrogen products: From technologies to strategies," Int. J. Hydrogen Energy, vol. 44, no. 38, pp. 20965–20977, 2019, doi: 10.1016/j.ijhydene.2019.01.110.

183 T. Uekert, H. M. Wikoff, and A. Badgett, "Electrolyzer and Fuel Cell Recycling for a Circular Hydrogen Economy," Adv. Sustain. Syst., vol. 8, no. 4, pp. 1–11, 2024, doi: 10.1002/adsu.202300449

184 T. Uekert, H. M. Wikoff, and A. Badgett, "Electrolyzer and Fuel Cell Recycling for a Circular Hydrogen Economy," Adv. Sustain. Syst., vol. 8, no. 4, pp. 1–11, 2024, doi: 10.1002/adsu.202300449.

185 M. Robert, F. Dubelley, A. Paul, L. Svecova, and C. Bas, "Investigation of Membrane–Electrode Separation Processes for the Recycling of Ionomer Membranes in End-of-Life PEM Fuel Cells," Energy & Fuels, vol. 39, no. 5, pp. 2758–2771, Feb. 2025, doi: 10.1021/acs.energyfuels.4c04930

186 M. Carmo et al., "PEM water electrolysis: Innovative approaches towards catalyst separation, recovery and recycling," Int. J. Hydrogen Energy, vol. 44, no. 7, pp. 3450–3455, 2019, doi: 10.1016/j.ijhydene.2018.12.030

187 C. Minke, M. Suermann, B. Bensmann, and R. Hanke-Rauschenbach, "Is iridium demand a potential bottleneck in the realization of large-scale PEM water electrolysis?," Int. J. Hydrogen Energy, vol. 46, no. 46, pp. 23581–23590, 2021, doi: 10.1016/j.ijhydene.2021.04.174

188 T. Uekert, H. M. Wikoff, and A. Badgett, "Electrolyzer and Fuel Cell Recycling for a Circular Hydrogen Economy," Adv. Sustain. Syst., vol. 8, no. 4, pp. 1–11, 2024, doi: 10.1002/adsu.202300449.

at first responders, and NET-TOOLS, which developed an e-learning platform. The new project, HyAcademy.eu, seeks to build on past results to reach a wider audience and produce additional educational content. Previous initiatives have examined public awareness, with the HyPOP project adopting a comprehensive approach to these issues, promising benefits for the entire programme. The HYPOP project analysis indicates a generally positive but conditional public attitude toward hydrogen technologies. Finally, the Clean Hydrogen JU has also focused on increasing awareness among government stakeholders through annual programme review days and a stakeholders' forum.

Regarding International Cooperation, the JUST GREEN AFRH2ICA project has developed tools to foster partnerships between the EU and the African Union and support future investments. Its objectives align well with the EU's strategic vision for international collaboration, particularly with Africa as part of the EU Global Gateway initiative. The project's outcomes are crucial for the Hydrogen Valley initiative, advocating for localised, context-driven strategies rather than generic models, to ensure effectiveness.

The Safety, Pre-Normative Research, and Standards research area is characterised by extensive collaboration among projects, driven by their pre-competitive nature. Coordinated at the programme level by the RCS Strategy Coordination Group and the European Hydrogen Safety Panel, these collaborations aim to address urgent policy gaps, such as hydrogen transport issues. Recent advancements in understanding liquid hydrogen behaviour promise to broaden its applications, moving beyond the limited use by a few industrial operators. All projects in this area engage with standardisation bodies to ensure that their research findings are integrated into the standardisation process effectively.

Finally, key highlights in sustainability advancements for hydrogen technologies include the development of the first hydrogen-specific life cycle sustainability assessment (LCSA) guidelines, which address the unique aspects of hydrogen systems when evaluating environmental impacts, and the creation of hydrogen-specific eco-design guidelines to facilitate future standardisation and promote circularity. Additionally, the first hydrogen-specific Product Environmental Footprint category rules (PEFCRs) were established to align life-cycle assessments and benchmarking of fuel cell and hydrogen products with policy objectives. Progress has also been made in recovering and recycling critical materials such as platinum group metals, rare earth elements, and ionomers, as well as in understanding potential hydrogen losses across the value chain to better assess the climate implications of a hydrogen economy. Initiatives, like SH2E and eGHOST, have contributed to standardisation, with LCSA guidelines providing a foundation for embedding sustainability principles into standards and the eGHOST European Roadmap guiding the future standardisation of eco-design.

Gap analysis – Main JRC Recommendations

Education and public awareness: The acceleration of the hydrogen economy within the EU depends not only on domestic production but also on imports from other countries, making awareness and acceptance of hydrogen technologies in exporting nations crucial. To date, studies on awareness and acceptance have been largely limited to European countries, leaving a gap in understanding how hydrogen technologies are perceived in key supplier regions. Additionally, educational initiatives face challenges of continuity, as previous projects have shown that outdated or poorly maintained materials quickly lose value, negatively affecting learning outcomes.

To address these gaps, awareness and communication activities should be established in non-European countries expected to supply hydrogen to the EU. Furthermore, a strategy for continuous educational and training efforts is recommended, with the Clean Hydrogen JU taking the lead in its development and implementation. Relying solely on individual funded projects is insufficient, as they cannot guarantee the sustained availability and up-to-date quality of educational offerings necessary to support a growing hydrogen economy.

International Cooperation: The JUST GREEN AFRH2ICA project has generated valuable data and insights on the potential for green hydrogen production, providing a strong foundation for engaging policymakers and aligning regulatory frameworks to boost renewable energy and green hydrogen initiatives. To effectively leverage these outcomes, it will be essential to actively engage pan-African and regional decision-makers, particularly within the broader context of political events focused on Africa's energy transition. However, the project faced challenges in collecting reliable data for its modelling efforts, as African and European partners applied differing methodologies, highlighting the need for in-person training events in Africa to harmonise approaches and ensure alignment.

Safety considerations must also be integrated into green hydrogen roadmaps, given the potential hazards of hydrogen, ammonia, and methanol, especially in African countries where regulatory frameworks are still evolving. The project has produced high-quality content for online training, which should be further promoted and regularly updated to maximise its impact (a shortcoming noted in several Clean Hydrogen JU Education RA projects). Additionally, establishing international standards from the outset is critical to support the growth of the green hydrogen market and facilitate investment, ensuring sustainable and safe deployment across the continent.

Safety, Pre-Normative Research and Regulations, Codes and Standards: Hydrogen safety is a cross-cutting issue that must be addressed both in isolation for in-depth knowledge development and within the context of actual hydrogen technology applications. Sharing lessons learned (ranging from incidents to risk analysis and management) is critical to maintaining risks at acceptable levels and supporting permitting processes. Efficient dissemination of these lessons among actors would enhance safety practices and facilitate smoother approval procedures. Additionally, safety, pre-normative research, and regulations, codes, and standards are inherently multi-faceted topics, making it difficult for the Clean Hydrogen JU alone to address all gaps. Other institutes have highlighted needs in areas such as quantitative risk assessment methods, reliability data, aviation, shipping, offshore hydrogen production, and hydrogen derivatives, indicating significant opportunities for collaboration. The time required to obtain operational permits for deployment projects is also hampered by the lack of common safety design methodologies and harmonised permitting principles across Europe, causing costly delays.

Re-starting and strengthening inter-project experience sharing on hydrogen safety is recommended, not only regarding incidents and near-misses, but also lessons learned in permitting and safety design processes. This includes exploring inter-project collaborations across RA topics and reinforcing the role of the newly formed European Hydrogen Safety Panel (EHSP) to act as a knowledge gateway with the international scientific community. Developing robust quantitative risk assessment methods and gathering reliability/failure data is also essential, particularly for large-scale sites subject to the Seveso III directive, and should leverage knowledge from Clean Hydrogen JU projects. Moreover, follow-up on standardisation processes is needed to ensure pre-normative research results are embedded into evolving standards, despite the typical delay between project completion and standard updates. The JU Governing Board should explore funding mechanisms enabling experts to participate in standardisation working groups, potentially using existing European Commission tools such as EISMEA[189].

Finally, to strengthen the bi-directional exchange between standardisation bodies and the Clean Hydrogen JU, a formal liaison mechanism should be considered. This would allow the JU to respond to emerging data needs that arise during the standard development process and ensure that pre-normative research can support the creation of updated and relevant standards.

Sustainability, LCSA, recycling and eco-design: Gaps in the sustainability of hydrogen technologies reveal several critical areas that require attention. Despite the development of methodologies to assess and reduce environmental impacts, there is a notable deficiency in the collection of primary high-quality data from projects regarding the environmental performance of their technologies. This data is essential to properly evaluate the sustainability of hydrogen technologies. Furthermore, there is a lack of benchmarks to compare the environmental performance of different hydrogen solutions, making it difficult to assess progress across JU-funded projects or to guide sustainability-related program activities. Assessing the environmental and social impacts of complex hydrogen ecosystems, particularly projects spanning multiple steps of the value chain, remains a challenge. In addition, potential impacts from accidents along the hydrogen supply chain, such as those arising during hydrogen transportation via ammonia, have not been thoroughly investigated.

To address these gaps, integrating sustainability considerations into the preparation of the annual and multi-annual work programs is recommended. The European Hydrogen Sustainability and Circularity Panel should play a central role in identifying current gaps in sustainability assessments and in suggesting activities that

189 https://eismea.ec.europa.eu/index_en

could enhance overall sustainability performance. This input should directly inform the selection of annual call topics. Additionally, a sustainability monitoring structure should be established, enabling systematic evaluation of sustainability activities across projects, including those outside this specific Research Area. Projects should provide high-quality primary Life Cycle Assessment (LCA) data, coordinated with the JRC and stored in the "Hydrogen" node of the Life Cycle Data Network, to support comprehensive environmental assessments.

The establishment of environmental impact benchmarks is also critical. The Panel or a dedicated call could define benchmarks for the environmental performance of different hydrogen technologies, and once the current state-of-the-art is understood, specific sustainability targets (e.g., reductions in global warming impact, water consumption) could be set. These benchmarks and targets will facilitate tracking progress toward EU sustainability objectives. Finally, guidelines should be developed for assessing and monitoring the environmental and social impacts of hydrogen valleys, which are complex hydrogen ecosystems.

Gaps and recommendations related to this research area are also given in Pillar 8 on Strategic Research Challenges, in particular with respect to reducing PGMs and PFAS.

5.6. PILLAR 6: HYDROGEN VALLEYS

Hydrogen Valleys, first conceptualised in 2018 by the Clean Hydrogen Partnership, have since become a cornerstone of Europe's clean hydrogen strategy, with the Clean Hydrogen JU leading their deployment[190]. These valleys are integrated hydrogen ecosystems defined within a specific geography, ranging from local or regional hubs such as industrial clusters, ports, or airports, to larger national or cross-border regions such as hydrogen corridors. They establish a common hydrogen supply infrastructure that serves multiple sectors, including mobility, industry, and energy end uses. By design, Hydrogen Valleys encompass the full hydrogen value chain, from production and storage to distribution and offtake, enabling large-scale demonstrations of hydrogen technologies in real-world conditions while fostering synergies across sectors.

Overview of Research Areas

The objectives of Pillar 6 centre on developing comprehensive regional green systems that integrate the full hydrogen value chain while enhancing efficiency, resilience, and sustainability. Its scope extends to market creation, regulation and standards development, knowledge management, and the assessment of environmental and socio-economic impacts. The research areas include **Large Scale Valleys**, which focus on integrating renewables, demonstrating hydrogen's potential for significant GHG emissions reduction, and covering the complete value chain (four projects are included in this RA, see project posters in Annex VI for more details). In parallel, **Small Scale Valleys** emphasise smaller-scale hydrogen production and applications to foster local hydrogen economies and promote innovation, with nine projects included in this RA (see project posters in Annex VI for more details). Collectively, these objectives and research areas aim to accelerate the development and demonstration of a hydrogen economy, strengthening Europe's industrial competitiveness, generating job opportunities, driving economic growth, and contributing meaningfully to climate change mitigation.

State-of-the-art

The European hydrogen valley landscape is rapidly evolving, with 98 projects currently registered on the Mission Innovation Hydrogen Valley Platform[191]. Of these, 71 projects are European, with 10 under construction and 4 fully operational. Building on earlier experiences such as the 2015 BIG HIT project, the Clean Hydrogen JU has actively supported the demonstration of hydrogen valleys since 2019, funding 14 of these European valleys, though most remain in early stages. Beyond direct project funding, the JU has taken steps to strengthen the development pipeline. Its dedicated Project Development Assistance (PDA) initiative has provided technical,

190 On 24 June 2024, the European Commission published a European roadmap for hydrogen valleys to support stakeholders in their development while identifying key barriers: https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/13875-REPowering-the-EU-with-Hydrogen-Valleys-roadmap-_en

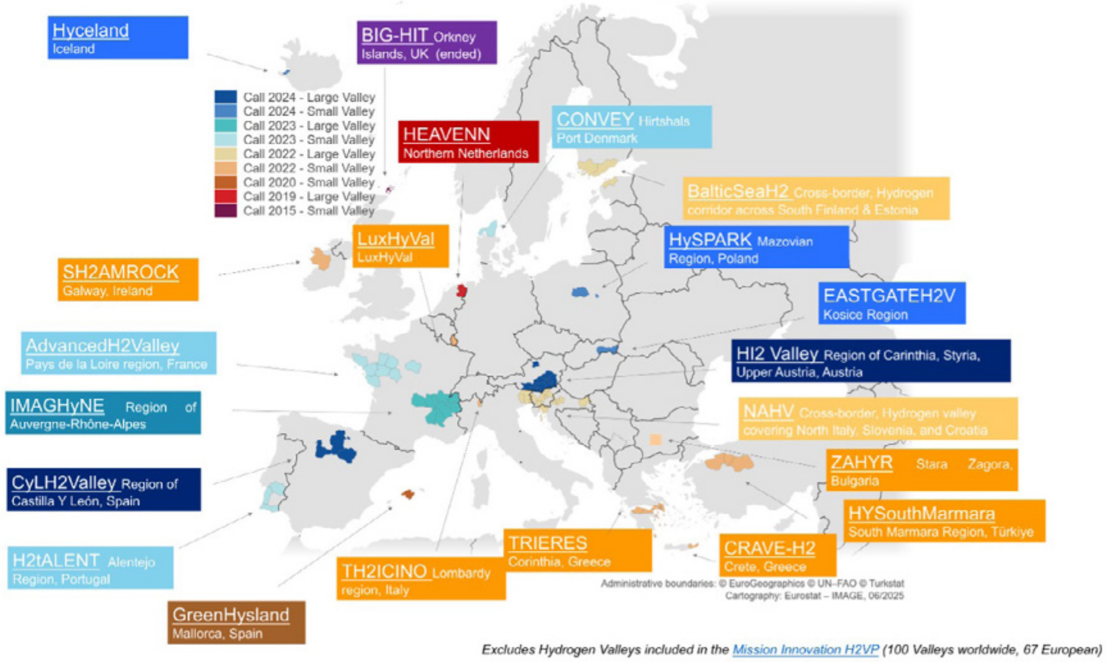
191 https://h2v.eu/ (accessed April 2025)

financial, and legal support, with PDA II concluding in March 2024 after assisting 14 regions (a final report has been published[192]). By 2025, 21 valleys are expected to be deployed in the EU (Figure 14).

An analysis of the value chain stages involved shows that storage is the least addressed stage among JU-funded valleys, with five not including it in their planning; a divergence from the European average, where distribution is typically the least developed stage. In terms of applications, mobility is a key target across all JU valleys, underlining hydrogen's strong potential to decarbonise transport. The energy and industrial sectors are also well represented, reflecting European trends that highlight hydrogen's role in cutting greenhouse gas emissions.

A closer look at European hydrogen valley projects highlights a wide variety of approaches and technologies aimed at decarbonisation end uses. For instance, some valleys are advancing applications in steel production, chemical manufacturing, or glass production, while others explore stationary fuel cells for energy distribution. This diversity underscores hydrogen's versatility as an energy carrier and its central role in enabling the transition to a low-carbon economy. Moreover, the deployment of electrolysers within hydrogen valleys offers additional benefits such as grid stabilisation and new revenue streams. By leveraging surplus renewable electricity to produce hydrogen, electrolysers can mitigate renewable energy variability and help balance the grid. Their operational flexibility further allows them to adjust consumption to shifting grid demand, enhancing both economic value and system resilience as hydrogen valleys continue to expand and innovate.

Figure 14: Map of deployed valleys funded by the Clean Hydrogen Partnership expected by 2025



Source: Clean Hydrogen Joint Undertaking

Programme highlights

Since no significant differences have been observed between the two research areas, they are presented together in this section. Among the highlights, **HEAVENN** stands out as the most advanced large-scale valley project. Launched in 2020, it has faced challenges and delays linked to global events that slowed the hydrogen industry. Nonetheless, several small off-takers are already operational. Remaining challenges concern the integration of larger off-takers: the delay in the hydrogen backbone infrastructure, which should be connected to the valley,

192 https://www.clean-hydrogen.europa.eu/media/publications/final-report-project-development-assistance-regions-ii-cohesion-countries-outermost-regions-and_en

created uncertainty regarding the hydrogen supply. On the small-scale side, **GREEN HYSLAND** is the most advanced project, aiming to establish a hydrogen ecosystem on Mallorca island to cut carbon emissions and foster sustainable energy. The project has faced technical and permitting issues that required deviations from its original plan and timeline[193]. Despite these hurdles, progress has been achieved, and the project still holds strong potential to deliver on its objectives, including boosting innovation, opening new market opportunities, and tackling environmental challenges.

Gap analysis – Main JRC Recommendations

The absence of a harmonised framework covering standards, regulations, and funding schemes is one of the most significant gaps in the development of hydrogen valleys at the moment. Such a framework is essential to ensure consistency, safety, and environmental integrity while avoiding inefficiencies or overlapping initiatives. Given that hydrogen valleys are highly context-dependent (shaped by geography, production methods, and end-use applications), tailored actions are needed. However, without harmonisation, it becomes difficult to formulate effective policies, allocate resources efficiently, or assess progress across different valleys.

Another key gap lies in the absence of pillar-specific KPIs. These would enable more nuanced evaluation of projects, tracking performance across production, storage, distribution, and end-use, and providing clear evidence to guide investment and policy decisions. Without KPIs, project performance is harder to benchmark, best practices are difficult to identify, and monitoring progress remains fragmented.

Beyond these systemic issues, more research is needed to address the integration of hydrogen valleys with existing energy systems. Hydrogen valleys can play a vital role in decarbonisation and grid stability, but integration is technically and economically complex. Key research areas include grid interconnection, system flexibility, and the role of hydrogen as a storage medium to complement variable renewable energy. At the same time, the social and environmental dimensions of hydrogen valleys need greater focus. While valleys can create new jobs and strengthen regional economies, they may also disrupt existing industries and communities if not managed inclusively. Holistic approaches are required to ensure that hydrogen valley development balances economic growth with community needs, social equity, and environmental sustainability.

Finally, collaboration and knowledge-sharing remain insufficient. Developing hydrogen valleys requires coordinated efforts between industry, academia, governments, and civil society, but existing platforms and networks are not yet fully equipped to enable such cross-stakeholder dialogue at scale. Stronger partnerships, including international collaborations and structured exchanges of best practices, are needed to pool expertise and resources.

Overall, harmonising funding and permitting processes across member states, developing a standardised framework for environmental and social impact assessments, and establishing KPIs to track progress (such as the percentage of hydrogen distributed to active off-takers within a valley) are recommended.

5.7. PILLAR 7: SUPPLY CHAIN

Pillar 7, as defined in the SRIA, focuses on strengthening the hydrogen technology supply chain, which has been recently identified by the European Commission as a strategic value chain for Europe. This Pillar remains a relatively new area of focus and is structured around three research areas: manufacturing for stationary applications, manufacturing for transport applications, and critical raw materials, with benchmarking activities underway to guide future strategic actions.

193 https://greenhysland.eu

Overview of Research Areas

While only one dedicated project under this Pillar directly addresses supply chain issues, more than 20 projects across different pillars (both ongoing and completed) have integrated supply chain aspects into their work. These include cost reduction strategies for mass manufacturing through advanced production methods, the development of novel materials and design solutions, performance improvements for fuel cell stacks, and efforts to reduce the reliance on critical raw materials.

State-of-the-art

Achieving the targeted increase in hydrogen production will require significant growth in qualified supply chain companies, spanning raw material processing (such as electro-catalysts), component manufacturing, and system integration, while also considering broader value chain elements like job creation, economic value, and industry competitiveness. However, recent global challenges, such as COVID-related disruptions and unstable geopolitics, have strained supply chains, causing restricted availability, volatile prices, and long delivery times. Several Clean Hydrogen JU-funded projects developing prototypes and demo installations have reported supply chain issues and insufficient budgets as key reasons for delays. Shortages of raw and processed materials, as well as difficulties sourcing specific components, have been highlighted as particularly problematic. To address these challenges, broader European initiatives such as the Critical Raw Materials Act and the Net-Zero Industrial Act are already targeting the enhancement of raw material supply and manufacturing resilience for European industries.

Programme highlights

European companies and research organisations currently hold leadership positions across many segments of the hydrogen supply chain, providing Europe with a competitive edge over other global players such as Japan, South Korea, the USA, and, more recently, China. Preserving this leadership will require continuous investment in research and innovation to address existing gaps, mitigate vulnerabilities, and ensure competitiveness on a global scale. To this end, the Clean Hydrogen JU has conducted an update of the 2019 EU supply/value chain study for hydrogen and fuel cell technologies, which identifies current weaknesses and proposes targeted solutions[194]. A summary report was published in October 2024[195]. Complementary information on suppliers of fuel cell systems, components, and related service providers is also available through the European Hydrogen Observatory (EHO), offering further insights into Europe's evolving supply chain landscape[196].

The 2025 Programme Review of Pillar 7 focuses on the AMPS project (Automated Mass Production of SOC Stacks) launched in 2023 to advance automated processes for large-scale cell manufacturing. The project aims to integrate recycling and reuse of cell waste materials while embedding inline quality control measures, targeting industrial-scale production to lower costs and increase competitiveness both within Europe and against global suppliers. Key achievements to date include the selection of a full automated stack assembly station design concept, successful lab-scale demonstrations of automated stack component handling, and the development of a digital twin of the production facility with component tracking. Furthermore, the project contributes to regulation, legislation, and safety frameworks by conducting cradle-to-gate life cycle assessments (LCA), ensuring that scalability also aligns with environmental and sustainability objectives.

Gap analysis – Main JRC Recommendations

Although Pillar 7 currently includes only a single dedicated project, supply chain challenges are a recurring issue across nearly all hydrogen R&I activities. Addressing these challenges requires a holistic strategy to reinforce the hydrogen technology value chain, in line with SRIA objectives. While the study on the EU hydrogen and fuel cell

194 Value added of the hydrogen and fuel cell sector in Europe, FCH 2 JU, 2019.

195 https://www.clean-hydrogen.europa.eu/media/publications/study-sustainable-supply-chain-and-industrialisation-hydrogen-technologies_en

196 https://observatory.clean-hydrogen.europa.eu/directory

supply/value chain, mapping existing vulnerabilities and proposing corrective measures[197], is forward-looking, it could be complemented by a retrospective analysis focused on lessons learned from past and ongoing projects that faced material shortages, component delays, or procurement difficulties. A useful step forward could be the organisation of a dedicated workshop, coordinated by the JU with JRC support, involving project coordinators, European OEMs, and supply chain specialists to exchange practical experiences and recommendations.

Such a workshop would aim to identify recurring bottlenecks, explore mitigation strategies grounded in real-world cases, and ultimately produce guidelines for managing supply chain risks in ongoing and future initiatives. In addition, conducting a structured "post-mortem" review of completed large demonstration projects (via interviews and targeted surveys) could provide further insights to refine these guidelines. The outcomes could also inform the design of new JU calls, for instance, by requiring applicants to demonstrate the existence of multiple European suppliers for key materials, components, and services. Embedding such requirements early in project proposals would not only reduce risks of disruption but also stimulate the development of a more resilient and competitive European hydrogen supply chain.

5.8. PILLAR 8: STRATEGIC RESEARCH CHALLENGES

The hydrogen sector is heavily dependent on materials that are either classified as critical (i.e., essential for advancing technology but vulnerable to supply shortages) or hazardous if released into the environment. These materials are required across the full hydrogen value chain: from CRMs such as iridium and platinum for electrolysers and fuel cells. Although progress has been made in recent years, the overall demand for these materials remains substantial, and the projected scale-up of hydrogen technologies will only amplify the pressure to reduce reliance on them. This creates a strong need for research focused on improving the durability and performance of hydrogen technologies, enabling reductions in CRM usage, fostering the development of alternative materials, and ultimately lowering total costs of ownership.

Overview of Research Areas

Pillar 8 is designed to sustain a steady flow of early-stage scientific knowledge, something that conventional three-year research projects may struggle to deliver consistently. Past roadmaps have highlighted three critical research challenges: (i) lowering dependence on critical materials such as PGMs or on unsustainable substances like PFAS in electrolysers and fuel cells; (ii) advancing novel materials and processes for hydrogen storage; and (iii) deepening the understanding of performance and durability mechanisms in electrolysers and fuel cells. To address these priorities, three projects have been funded in this pillar (SUSTAINCELL, ECOHYDRO, and ELECTROLIFE), each targeting one of the identified challenges.

State-of-the-art

A comprehensive list of critical raw materials used in electrolysers and fuel cells is available in Carrara et al.[198]. Efforts to reduce the use of CRMs have been ongoing for decades. For example, the platinum load in fuel cells has decreased from 1.0 g kW^{-1} in the 1990s to 0.3 g kW^{-1} today[199]. Despite these advances, the demand for these materials remains high, and the anticipated expansion of hydrogen technologies has intensified the need to minimise their usage. Research is therefore needed to enhance understanding of the performance and durability mechanisms of hydrogen technologies to reduce the use of CRMs, develop innovative materials, and reduce the TCO.

The key challenge for fuel cells and electrolysers lies in their reliance on platinum group metals (PGMs) for low-temperature devices and rare earth elements (REEs) for high-temperature devices. Both PGMs and REEs

197 () Value added of the hydrogen and fuel cell sector in Europe, FCH 2 JU, 2019.

198 S. Carrara et al., "Supply chain analysis and material demand forecast in strategic technologies and sectors in the EU–A foresight study, JRC Science for Policy Report," 2023. doi: 10.2760/334074

199 S. Zhang, X. He, Y. Ding, Z. Shi, and B. Wu, "Supply and demand of platinum group metals and strategies for sustainable management," Renew. Sustain. Energy Rev., vol. 204, no. August, p. 114821, 2024, doi: 10.1016/j.rser.2024.114821

are classified as CRMs by the EU due to their limited European production, concentrated global supply chains, economic importance in various technologies, and limited substitutability. In the realm of fuel cells, platinum catalysts facilitate the reaction between hydrogen and oxygen. The oxygen reduction reaction (ORR) at the cathode is crucial for determining energy conversion efficiency, and Pt-based nano-catalysts are the preferred choice for commercial applications. The current state of the art for platinum loading in PEM fuel cells is 0.3 g kW^{-1}, suggesting that the SRIA targets for 2030 (0.3 g kW^{-1} at high TRL and <0.25 g kW^{-1} at low TRL) may be more ambitious. It is important to note that the SRIA target is specific to a particular application (heavy-duty vehicles), and the required power density and durability for this application will influence the platinum loading. Alongside reduction strategies, substituting platinum with base metals presents another viable option. Transition metals, such as iron (Fe) and cobalt (Co), along with nitrogen co-doped carbon catalysts, show promise due to their catalytic activity and stability in acidic electrolytes. However, their application has been limited by rapid degradation under practical conditions[200].

Regarding low-temperature electrolysers, PGM-based catalysts and support materials are necessary to withstand high electrochemical potential and oxidising environments on the anode side. On the cathode side, platinum nanoparticles on high surface area carbon support are typically used to catalyse the hydrogen evolution reaction (HER) in acidic media, with loadings of 0.33-0.5 g kW^{-1} of platinum. On the anode side, a mix of unsupported IrO_2 and RuO_2 is commonly used in commercial PEMEL stacks to catalyse the oxygen evolution reaction (OER) in acidic media, with iridium loadings of 0.67-0.75 g kW^{-1}[201]. The current PGM loading in PEM electrolysers is approximately 1-1.25 g kW^{-1}, with SRIA targets of 0.25 g kW^{-1} for 2030. Molybdenum disulphide (MoS_2) and transition-metal phosphides are promising substitutes for acidic HER but are currently outperformed by Pt, particularly in terms of durability. No real substitute exists at the moment for iridium in acidic OER. Thus, nano-structuring and particle size reduction to the single-atom level are viable strategies to minimise PGM use in catalyst materials. Under alkaline conditions, transition metal-based compounds demonstrate high stability and activity, offering viable alternatives to PGMs. Ni-based catalysts, such as NiMo, have shown excellent performance among PGM-free materials in alkaline HER, exhibiting >1000 h stability[202].

In the context of high-temperature electrolysers, specifically solid oxide technology, PGMs are not used, but rare earth metals like yttrium, lanthanum, and scandium are essential, along with other critical raw materials like nickel and zirconium. Rare earth metals face two potential bottlenecks: (i) production is highly dominated by China (60%), and (ii) there is a limited annual supply (e.g., scandium total global supply is 10 tonnes, which could support only 0.5 GW SOEC deployment annually). Therefore, the Yttria-stabilised-Zirconia (YSZ) membrane needs modification to reduce or eliminate scandium content. Alternatively, membranes such as gadolinium-doped cerium oxide could be used, but this would shift the issue from scandium to gadolinium and cerium[203].

A summary of substitution solutions for fuel cells and electrolysers with indication about TRL, and performance compared to state of the art is reported in Ierides et al.[204]. While significant progress has been made in reducing reliance on CRMs in hydrogen technologies, transitioning to CRM-free materials is a complex and prolonged process that demands intensified research efforts. The focus has largely been on technical strategies for reducing or substituting CRMs, but expanding the scope to include circular economy strategies, such as repairing, reusing, and recycling, is essential. Given the growing demand for CRMs across various green technologies, it is crucial to avoid substituting these materials with others that may themselves become critical, such as nickel (Ni) and manganese (Mn). This highlights the need for strategic material selection that addresses both supply security and environmental sustainability. A comprehensive evaluation of the impacts of material substitution

200 S. Zhang, X. He, Y. Ding, Z. Shi, and B. Wu, "Supply and demand of platinum group metals and strategies for sustainable management," Renew. Sustain. Energy Rev., vol. 204, no. August, p. 114821, 2024, doi: 10.1016/j.rser.2024.114821

201 S. Kiemel, T. Smolinka, F. Lehner, J. Full, A. Sauer, and R. Miehe, "Critical materials for water electrolysers at the example of the energy transition in Germany," Int. J. Energy Res., vol. 45, no. 7, pp. 9914–9935, 2021, doi: 10.1002/er.6487.

202 L. M. Salonen, D. Y. Petrovykh, and Y. V Kolen, "Materials Today Sustainability Sustainable catalysts for water electrolysis: Selected strategies for reduction and replacement of platinum-group metals," Mater. Today Sustain., vol. 11–12, p. 100060, 2021, doi: 10.1016/j.mtsust.2021.100060

203 E. Eikeng, A. Makhsoos, and B. G. Pollet, "Critical and strategic raw materials for electrolysers, fuel cells, metal hydrides and hydrogen separation technologies," Int. J. Hydrogen Energy, vol. 71, no. February, pp. 433–464, 2024, doi: 10.1016/j.ijhydene.2024.05.096.

204 M. Ierides, L. Nohl, P. Alves Dias, M. Nohl, D. Blagoeva, and N. Magnani, "Substitution and reduction of critical and strategic raw materials in clean energy technologies. An overview of solutions using advanced materials," 2025. doi: 10.2760/1465999

or reduction should consider both perspectives. Life cycle assessments (LCAs) are vital in this context, as they help ensure that changes do not inadvertently increase environmental impacts while addressing supply security concerns.

To support this transition, policy measures could include banning the export of CRM-containing waste outside the EU, establishing individual recycling targets for CRMs, and ensuring that eco-design standards for all fuel cell and hydrogen technologies mandate dismantlability[205]. Enhanced recycling and reprocessing of CRMs can complement efforts to reduce CRM content in devices, maintaining device performance while advancing sustainability goals. Ultimately, increased recycling and careful material management will be essential for achieving a sustainable and environmentally friendly economy, with balanced attention to both supply security and ecological considerations.

As regards materials that are potentially toxic if released to the environment, hydrogen technologies heavily rely on chemicals belonging to the family of per- and polyfluoroalkyl substances (PFAS). In the hydrogen value chain, fluoropolymers are used to manufacture proton exchange membranes in PEM electrolysers and fuel cells, as binder materials in the electrodes, both anode and cathode, and as a component of the gas diffusion layers (GDLs). Moreover, fluoropolymers are used for gaskets and sealings in most electrolyser and fuel cell types, and in parts of the transport and distribution system in valves. Hydrogen Europe[206] estimated that fluorinated components represent approximately 10% in mass of a fuel cell stack, with sealing materials being the major contributor (approx. 90%). Sealing materials are made of fluoropolymers (FKM and PTFE) or fluorine rubber made of fluorinated elastomers. In PEM technologies, polytetrafluoroethylene (PTFE) is typically used as reinforcement for the ionomer membrane, which consists of this highly hydrophobic PTFE backbone and hydrophilic side chains each terminated with a sulfonic acid group (− SO_3H), and as hydrophobic agent in the GDL. The major risks for the release of toxic chemicals are during the manufacturing of the polymers, since the building blocks and solvents are fluids. The use phase is expected to pose a lower risk as the fluoropolymers are thermally stable during operating conditions. At the end-of-life, the GDLs and sealings are likely burnt in special facilities that capture fluorine-containing compounds from the off-gas by reaction with calcium hydroxide, resulting in calcium fluoride, which is used again as a raw material for the production of fluorine-containing material. As for the membrane and electrodes (which are physically bound to the membrane, thus cannot be separated from each other), there are two ways to recycle. Today, the most common technique is to ash the catalyst-coated membrane (or even the entire MEA, including GDLs and possibly sealing), dissolve the residue in acid, and use this as a base for recycling of the noble metals. Upon this process, the same happens as described above, the fluorine-containing polymers burn and release hydrofluoric acid (HF), which is captured. An alternative process that is currently under evaluation is to dissolve the ionomer from the unit, which is likely to be achieved by using conventional solvents. The ionomer is transferred into the liquid phase and can be separated from the electrocatalyst and reinforcement. The aim of this process is to try and recycle the ionomer. Such an ionomer is also a highly expensive and valuable material, so the development of recycling processes can be commercially attractive.

Research has been undertaken to reduce the amount of PFAS in PEM technologies and to find alternatives. The thickness of the membrane has reduced significantly in the past 20 years, from 175 µm to 100 µm thick[207]. Fluorine-free membranes have been developed in the past years[208],[209], but although they reach good performances, their durability is often poor. As regards sealants, elastomers without fluorine already exist but suffer from dimensional stability. Important R&D efforts are still needed in order to find viable solutions to replace PFAS in hydrogen technologies. In addition to the projects funded under this pillar, further research is being carried out on this topic. For instance, the CNF Membrane project[210] funded under the European Innovation Council aims to

205 M. Axt, B. Baldassarre, and J. Kirchherr, "Towards greater circularity in the hydrogen technology value chain," Ecol. Econ., vol. 236, no. April, p. 108679, 2025, doi: 10.1016/j.ecolecon.2025.108679.

206 Hydrogen Europe, "Hydrogen Europe Position Paper on PFAS," 2023.

207 Hydrogen Europe, "Hydrogen Europe Position Paper on PFAS," 2023.

208 M. Di Virgilio, A. B. Peressut, V. Arosio, A. Arrigoni, S. Latorrata, and G. Dotelli, "Functional and Environmental Performances of Novel Electrolytic Membranes for PEM Fuel Cells: A Lab-Scale Case Study," Clean Technol., pp. 74–93, 2023.

209 N. Esmaeili, E. M. A. Gray, and C. J. Webb, "Non-Fluorinated Polymer Composite Proton Exchange Membranes for Fuel Cell Applications – A Review," ChemPhysChem, vol. 20, no. 16, pp. 2016–2053, 2019, doi: 10.1002/cphc.201900191.

210 https://cordis.europa.eu/project/id/101161627

develop a more efficient, bio-based, ion-selective membrane using natural cellulose for electrochemical energy devices, such as PEM fuel cells.

Enhancing the understanding of the performance and durability mechanisms of electrolysers and fuel cells is also needed. Degradation stems from chemical, mechanical, and physical phenomena. To extend the lifespan and efficiency of electrolysers, there is an importance of tailored materials and robust design strategies. In low-temperature systems, issues include catalyst instability from corrosion and dissolution, and membrane degradation from reactive intermediates. High-temperature systems face catalyst deactivation from sintering and poisoning, along with the mechanical instability of ceramic electrolytes due to thermal and mechanical stress. These degradation mechanisms are often accelerated by operational factors such as load fluctuations and on/off cycles. While traditional technologies are more mature, research is still needed to fully understand all degradation mechanisms and to define standardised test protocols for durability. Future research will focus on developing advanced protective coatings and membranes tailored to specific stressors, and emphasising self-healing materials and robust catalyst designs to enhance durability.

In the context of hydrogen infrastructure, advancing materials and processes for hydrogen storage is a key challenge that must be addressed. Currently, the industrial standard for hydrogen tanks relies on carbon/epoxy composites, which have several significant drawbacks. These materials are inherently brittle, exhibiting low impact resistance, and are also difficult to recycle. Additionally, their manufacturing process requires post-curing, which leads to prolonged production cycle times and higher energy consumption[211]. Research is underway to improve the properties of tanks, in particular to improve safety, durability, environmental sustainability, and cost.

Programme highlights

The three projects under Pillar 8 stand out from similar research activities in other pillars due to their lower TRL levels and extended duration, focusing primarily on addressing fundamental research challenges rather than producing concrete prototypes or systems. Their scope is inherently transversal, encompassing multiple hydrogen technologies rather than a single application, and their multi-faceted approach further differentiates them from other projects. This broad, cross-technology perspective allows the knowledge and lessons generated by Pillar 8 projects to be shared and applied across various pillars, amplifying their overall impact. Key technical achievements include advancements in the development of CRM-free or CRM-lean catalysts and progress in creating PFAS-free or PFAS-lean ionomers.

Gap analysis – Main JRC Recommendations

The projects funded under this pillar are generally aligned with the scope and objectives of the research areas, demonstrating progress in line with expectations, although they are still in their early stages. As the projects advance, potential gaps and critical issues may arise that require closer attention. Preliminary analysis highlights several key areas needing further focus, including the quantification of CRMs throughout the hydrogen value chain, assessment of PFAS emissions during hydrogen production and use, the environmental implications of substituting critical or toxic materials through life cycle assessments, and the development of a comprehensive reuse and recycling roadmap to promote circularity in hydrogen technologies.

To address these gaps, conducting a thorough quantitative assessment of CRM usage across the entire hydrogen supply chain, from production and transportation to storage and end-use applications, is recommended. Harmonised CRM targets should be established for all hydrogen technologies, incorporating durability metrics to ensure meaningful reductions. Additionally, experimental campaigns should be designed to monitor and mitigate PFAS emissions, while durability testing and LCAs must be integrated into any material substitution strategies to avoid unintended environmental or social impacts.

Leveraging existing research infrastructure and collaborative platforms, such as the Open Innovation Test Bed, the Central European Research Infrastructure Consortium, and the JRC Open Access Scheme, should be

211 A. Magliano, C. Perez Carrera, C. M. Pappalardo, D. Guida, and V. P. Berardi, "A Comprehensive Literature Review on Hydrogen Tanks: Storage, Safety, and Structural Integrity," Appl. Sci., vol. 14, no. 20, pp. 1–38, 2024, doi: 10.3390/app14209348.

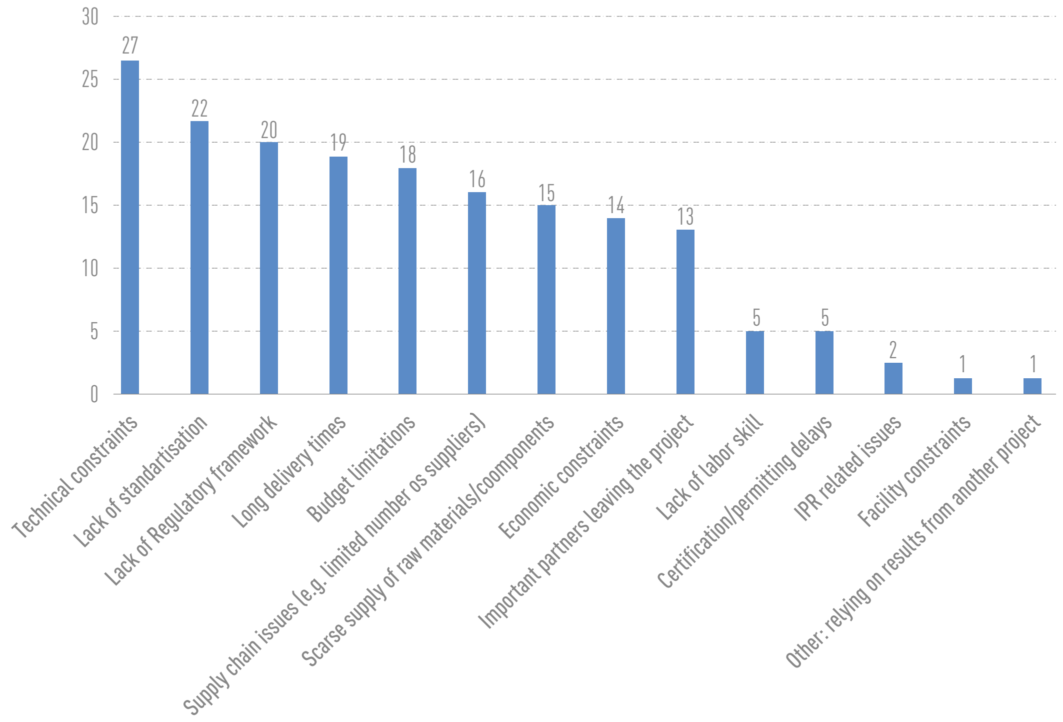
emphasised in order to facilitate knowledge sharing and accelerate the development of sustainable hydrogen technologies. Finally, a dedicated project should be funded to create a comprehensive reuse and recycling roadmap for hydrogen technologies, potentially establishing an institution to coordinate circular economy practices and ensure long-term sustainability across the sector.

VI. GENERAL JRC RECOMMENDATIONS

Following the Annual Programme Technical Assessment, JRC has formulated a set of strategic recommendations, intended to serve as a comprehensive reference framework for assessing and guiding programme implementation, with a strong emphasis on project performance metrics. The analysis identifies both areas of strength and aspects requiring improvement, aiming to enhance the effectiveness, impact, and efficiency of current projects while providing a roadmap for future initiatives. Moreover, the assessment highlights potential gaps that could inform the design of forthcoming funding calls under the Clean Hydrogen JU.

Overall, most projects face significant challenges in meeting their ambitious targets, largely due to constraints in timelines and budgets. The most frequently reported obstacles include technical limitations (noted by 27 projects), insufficient standardisation (22 projects), and gaps in the regulatory framework (20 projects) (see Figure 15). Technical challenges encompass overly ambitious performance targets, difficulties in component interchangeability, inconsistencies in test comparability across different scales, reliance on non-standard commercial components, and the need for redesigns due to the innovative nature of project activities.

Figure 15: Challenges and bottlenecks reported by projects



Source: JRC analysis with data from the Clean Hydrogen JU

Additional recurring challenges include delays in delivery, budget limitations, supply chain disruptions, and material shortages. Economic pressures, such as elevated hydrogen and electricity costs, combined with the departure of key partners, further exacerbate project delays. Less frequently cited issues comprise shortages of skilled personnel and hurdles in certification or permitting (affecting five projects each), while facility limitations and intellectual property rights constraints were rare.

General recommendations

Effective collaboration and knowledge sharing are essential for advancing hydrogen technologies, particularly through comprehensive data management.

Operational and Experimental Data: Data from both operational processes of demonstration projects and testing of systems should be consistently delivered to the Knowledge Hub. This data is vital for developing comprehensive datasets that facilitate long-term technology deployment. Incorporating this requirement into grant agreements or relevant amendments is recommended.

Materials Properties Data: Compiling and making accessible the extensive information on materials properties from various projects is crucial to facilitate innovation.

Lessons Learned: Insights and lessons learned from past demonstration projects should be systematically captured through surveys and workshops. This valuable knowledge can support new entrants and should be organised and shared via the Knowledge Hub. This can help address challenges related to standardisation and supply chain resilience.

Avoid duplications: Database records should reference open-access publications and archives, ensuring that complete, publicly accessible information is maintained until at least the end of Horizon Europe's successor program.

Sustainability and circularity: The Clean Hydrogen JU has made significant efforts in developing guidelines for assessing and enhancing the sustainability and circularity of hydrogen technologies. In line with promoting 'Open data policy', to further advance this work, there is a need for more high-quality data from projects on the environmental performance of these technologies, as well as benchmarks for comparative purposes. Data should be stored on the "Hydrogen" node of the Life Cycle Data Network.[212]

Open access publications: Despite the mandatory requirement, some projects are not complying with open access publishing guidelines. To ensure better adherence, projects should be strongly encouraged to make their publications open access, given that they are funded by public money. The JU should also enhance monitoring of this practice.

Wider use of AI tools by projects: Promote the expanded and intelligent use of open-access AI tools to enhance current R&D efforts, as well as to support design and engineering efforts. The JU could facilitate the creation and maintenance of dedicated datasets for training machine learning methods, particularly in the field of material discovery and synthesis routes for catalysts, electrodes, and membranes. A new, dedicated project could be established with this as its scope.

Promoting wider use of the developed diagnostic tools: In alignment with the goal of "better use of the generated knowledge," diagnostic tools developed by JU projects (such as REACTT and RUBY) should be utilised by ongoing and future projects, whenever feasible, to i) predict and improve the degradation behaviour of developed systems/stacks, and ii) further improve the tools themselves.

Pillar-specific recommendations

Pillar 1

Standardisation of designs and testing: Establish a unified European framework for water electrolyser design, supply chain, and testing to reduce fragmentation and enable cross-project compatibility. This would support the emergence of a European supply chain. The JU should partner with the European hydrogen industry to develop standardised platforms for each electrolyser type, modelled on the automotive industry's approach to common design platforms.

212 https://eplca.jrc.ec.europa.eu/uploads/Poster-Data-Network-a4.pdf

Update on the harmonised testing protocols: Several stakeholders (academia and industry) reached out to JRC and asked about possible updates of the protocols. There should be a common format organised by the JU (e.g. a workshop) to get collective feedback from the stakeholders in a condensed form. JRC would participate and steer the meeting's discussion.

Promote harmonised degradation monitoring: Require projects to use EU harmonised test methods for this purpose. Promote the use of a standardised tool for stack degradation monitoring to enable real-time monitoring and data sharing.

Develop Economic Toolboxes for Stakeholders: Simplify GO Certification for Operators. User-friendly toolboxes and guidelines should be created for economic operators (e.g., SMEs, startups) to navigate GO certification. This can be done through engaging with Hydrogen Europe.

Pillar 2

Establishing realistic KPIs: Pillar 2 includes several overly ambitious KPIs that are misaligned with the low TRL of most technologies and the limited available budget. To address this, the KPIs, if revised, should be aligned with both the current technology status and available resources. It seems counterproductive to define KPIs that will likely not be met and will most probably be assessed as a failure of the Programme in future reviews.

Establishing the right balance in the project selection criteria–innovation vs. continuation and incremental improvement: In Pillar 2, innovative projects are seemingly being prioritised over those focused on incremental improvements that are also needed to advance a technology. The Clean Hydrogen JU should adjust the project selection criteria to balance innovation with short-term viability by giving more weight to projects at higher TRLs that can demonstrate tangible results to better achieve the SRIA targets. This recommendation aligns with Pillar 4's specific recommendations, which emphasise that progress in demonstration projects depends heavily on leveraging results and insights from earlier projects, as well as the effective use of knowledge generated by prior work, rather than on novel elements that could delay or complicate their successful completion.

More focused strategy: The broad range of technological options in Pillar 2 has resulted in the limited budget being spread across many approaches. A more focused strategy, prioritising a narrower set of key topics, would have been more effective.

Pillar 3

Demonstration projects: A number of demonstration projects suffer from significant delays and challenges, often due to unforeseen issues in relation to permitting, safety requirements, operational requirements, changes in technology providers and/or demonstration sites. This is a recurring issue, and a number of demonstration projects need to be extended in order to achieve sufficient demonstration time. A comprehensive risk assessment should be performed as part of the project proposals, and mitigation measures should be drawn up from the risk assessment. Redundancy in mitigation measures may even be requested for identified critical risks that may impede the feasibility and/or implementation of the project.

Regulatory and standardisation gaps: Many demonstration projects collect field data from their operation and generate lessons learned. Those are mainly used internally within the project to improve their own prototype/activities/processes. Lessons learned from demonstration projects, based on field data from operation, should be shared with the relevant entities in the field, including regulatory authorities and standardisation bodies, and be used to fill regulatory and standardisation gaps.

Harmonised permitting processes: The national authorities that grant approval of hydrogen fuel cell vessels and/or permits for hydrogen infrastructure in ports as part of Clean Hydrogen JU projects should share their experience and work together in a uniform way of assessing those applications, paving the way to harmonised practices/standards, and ultimately the development of a single European regulation. This may be implemented through the organisation of a workshop with participation of representatives of the national authorities that grant the approval of hydrogen fuel cell vessels and/or permits for hydrogen infrastructure in ports. Common challenges and potential solutions would be discussed at the workshop, and a report on recommended/best practices would subsequently be issued.

Pillar 4

Enhance Exploitability of Project Outcomes: Future JU initiatives could focus on dedicated projects designed to maximise the impact of completed projects, rather than solely pursuing new scientific achievements. This approach could involve generating more data from installed demonstration systems to address unresolved issues, as well as leveraging lessons learned from past projects. This is in line with the 'Foster collaboration and knowledge sharing' general recommendation.

Building upon previous projects: This approach involves leveraging the achievements of past projects to develop new innovations. Examples include HyCoFlex, which builds on the HYFLEXPOWER project, and SWITCH, which advances the CH2P project to demonstrate its scalability for large-scale Hydrogen Refueling Stations (HRS).

Proof-of-concept projects: Future projects could leverage existing TRL 5-7 products to develop proof-of-concept demonstrations, evaluating feasibility and associated risks when applying a specific technology to a targeted application. Such projects could reveal critical details that simulations or models might miss. They can also help address compliance, safety, or regulatory requirements early, easing the path to commercialisation.

Pillar 5

The Pillar 5 recommendations have identified several ongoing and approved projects with a PNR/RCS dimension that have the potential to contribute to standards development. Nevertheless, these projects will need to invest additional effort to actively participate in standardisation. To mitigate the challenges associated with standards development, such as reaching the end of a project, funding constraints, and changing company priorities, the Clean Hydrogen JU could consider establishing a dedicated support mechanism, possibly in collaboration with the JRC, to facilitate the involvement of these projects in standardisation activities. For instance, large-scale deployment projects like H2ME and JIVE gather field data and generate lessons learned to refine their own processes. They also identify numerous regulatory gaps. The collected data and experiences should be used to improve the existing standards and complete them, as well as support the development of new IEC/ISO/CEN/CENELEC standards. This will assure a wider and more balanced European representation at the level of working groups/sub-committees.

Data-driven, on-demand research for standardisation: During the early stages of standard development, unforeseen data gaps may arise. The Clean Hydrogen JU could address these gaps through its funding mechanisms. Establishing a formal liaison to strengthen two-way communication of strategies and progress between standardisation bodies and the JU would also be valuable, ensuring alignment and mutual support in addressing evolving needs.

Development of a pan-European approach to project permits: Lack of quantitative risk assessment (QRA) methods and reliability/failure data need to be addressed, especially for large-scale sites, e.g., covered by the Seveso III directive. Addressing these gaps through the development of such methods, leveraging knowledge from Clean Hydrogen JU-funded projects and similar initiatives—would represent a strategic step toward harmonising risk evaluation practices, that could be an important step in assisting the development of a pan-European approach to project permits.

The **European Hydrogen Sustainability and Circularity Panel** should be involved in the annual and multi-annual work program preparation to identify current gaps in sustainability assessments that could improve sustainability performance.

Pillar 6

The Hydrogen Valleys are still in their early stages of development, with most projects, except for pioneering initiatives like GREEN HYSLAND and HEAVENN, requiring guidance and support to drive their growth and increase maturity. The achievements and recommendations emerging from these frontrunner projects should be leveraged to inform and guide the development of other projects within the pillar, ensuring that valuable lessons learned and best practices are disseminated and built upon. To facilitate more effective project analysis and evaluation, the definition of pillar-specific KPIs is essential. These KPIs should enable the tracking of critical metrics, such as the number of end-use cases and their corresponding hydrogen utilisation rates, providing a clearer understanding of project performance and progress towards stated objectives.

Moreover, the complex interplay of multiple stakeholders and their interdependencies within Hydrogen Valleys necessitates the development of contingency plans to mitigate potential delays or setbacks. The involvement of a large number of actors, each with their own interests and priorities, increases the risk of companies dropping out or experiencing difficulties, which can have a ripple effect throughout the entire project. To address this challenge, additional de-risking supporting mechanisms could help establish a more stable and resilient framework, enabling projects to better navigate potential obstacles.

Ultimately, the success of Hydrogen Valleys will depend on the ability to facilitate collaboration and coordination among various stakeholders, including Member States, industry partners, and other relevant actors. By fostering closer cooperation and alignment with local authorities, for example, facilitated by the PDA or the Hydrogen Mechanism, it may be possible to speed up the necessary permits, secure additional funding, and leverage existing resources and expertise, ultimately driving the growth and development of Hydrogen Valleys and realising their full potential to demonstrate the feasibility of an interconnected hydrogen economy. It would be good to encourage projects to have local authorities involved from the start of the project.

Pillar 7

Harnessing the lessons learned to improve supply chain strength: Supply chain issues are a persistent concern across many projects, with multiple aspects being tackled by various projects across different pillars. Therefore, to strengthen the overall hydrogen technology supply chain, as outlined in the SRIA, a more comprehensive approach is needed. This should involve identifying supply chain challenges not only from active projects but also from completed ones, which could offer valuable insights and lessons. To achieve this, the JU, with support from the JRC, could host a dedicated workshop. This event would invite representatives from projects that mentioned supply chain issues as a cause for delay. The primary objective of this workshop could be to develop guidelines for ongoing projects to manage supply chain issues effectively.

Furthermore, the workshop could help identify requirements for new projects, which could then be integrated into future Clean Hydrogen JU calls. One potential requirement could be demonstrating the availability of more than one European supplier for critical materials, components, and services already in the project proposal.

Pillar 8

Conduct a quantitative assessment of CRMs and PFAS materials usage and losses across the entire hydrogen value chain, to identify areas for reduction and substitution, and develop harmonised targets for all hydrogen technologies incorporating durability.

Develop a reuse and recycling roadmap relevant to hydrogen technologies, which is crucial for reducing waste, conserving critical resources, and promoting a circular economy.

VII. EUROPEAN HYDROGEN SECTOR OVERVIEW

(This section has been prepared solely by the Clean Hydrogen Partnership. The information and views set out in this section are those of the authors and do not necessarily reflect the official opinion of this report's co-author, the Joint Research Centre (JRC).)

The European Hydrogen Observatory (EHO) [213] is one of the initiatives of the Clean Hydrogen JU, designed to provide a comprehensive overview of technology and market statistics, socio-economic indicators, policies and regulations, as well as financial support measures across the hydrogen sector. Its primary role is to enable systematic monitoring of hydrogen technology deployment, policy implementation, research outputs, and academic activity. As an open-access platform covering the EU-27, EFTA countries, and the UK, the EHO serves policymakers, industry stakeholders, and the wider public as the main entry point to European hydrogen data. Initially launched in 2018 as the Fuel Cells and Hydrogen Observatory and relaunched under its current name and branding in September 2023, the platform has since experienced a steady growth in visitors, reflecting its recognition as a trusted and authoritative information source. The EHO is continuously updated and expanded with new datasets and key insights, ensuring its relevance for stakeholders across the European hydrogen value chain.

In 2024, hydrogen production capacity[214] reached approximately 11.2 million tonnes, remaining almost unchanged compared to 2023, with an average capacity utilisation of 70% based on estimated consumption levels. Germany, the Netherlands, Poland, France, and Italy together accounted for 57% of this capacity, highlighting their central role in Europe's hydrogen landscape. The conventional production method (reforming, partial oxidation, gasification, and by-product production from refining and petrochemical operations) continued to dominate, representing 95.4% of the total. By-product electrolysis, mainly from chlorine and sodium chlorate production, contributed 3.6%, while reforming with carbon capture and Power-to-Hydrogen each accounted for only 0.5% of the total production capacity in 2024. The total hydrogen demand was estimated at 7.9 Mt, marking a slight decline compared to 2023. Refineries accounted for the largest share, consuming around 4.5 Mt or 58% of the total, while the ammonia industry followed with approximately 2 Mt, representing 25%. Combined, these two sectors were responsible for more than 83% of overall hydrogen consumption. In 2024, European manufacturers deployed approximately 142 MW of water electrolysers, representing a sharp 118% increase compared to 2023. PEM technologies dominated these deployments, accounting for 66% of the total, or 93.2 MW, while AEL technologies contributed around 24%, equivalent to 34.2 MW. The remaining 14.6 MW came from projects where the specific electrolyser technology was not disclosed.

The average levelised cost[215] of hydrogen production via SMR in Europe was about 3.3 EUR/kg, while when excluding marginal costs (CAPEX amortisation and fixed expenses), the LCOH was slightly lower at around 3.1 EUR/kg. Incorporating carbon capture increased SMR production costs to an average of 4.1 EUR/kg. For electrolysis using grid electricity, costs ranged widely from 4.1 to 16.1 EUR/kg, with an average of 7.4 EUR/kg and a median of 7.1 EUR/kg. Electrolysis directly connected to renewable energy sources was somewhat more competitive, with costs between 4.3 and 10.5 EUR/kg, averaging 6.7 EUR/kg and a median of 6.4 EUR/kg. However, these renewable-based systems are constrained by the limited capacity factor of the connected renewable source, despite avoiding grid-related charges and taxes.

213 https://observatory.clean-hydrogen.europa.eu/homepage

214 https://observatory.clean-hydrogen.europa.eu/hydrogen-landscape/production-trade-and-cost/hydrogen-production

215 https://observatory.clean-hydrogen.europa.eu/hydrogen-landscape/production-trade-and-cost/cost-hydrogen-production

Although the European hydrogen market remains largely captive, with most production dedicated to on-site consumption, hydrogen trade[216] is already taking place across the continent via pipelines and trucks, and is expected to grow significantly with the emergence of the clean hydrogen market and the EU's ambition to import 10 million tonnes of renewable hydrogen by 2030. In 2024, hydrogen flows between European countries reached 18,206 tonnes, of which the Netherlands was the largest importer, accounting for 57% (10,344 tonnes), followed by France (12%), Austria (4%), Belgium (4%), and Portugal (3%), together making up nearly 81% of imports. On the export side, Belgium dominated with 61% (11,133 tonnes), followed by Germany (12%), the Netherlands (10%), Spain (5%), and Slovakia (4%), together representing almost 91% of exports. The single largest flow in 2024 was Belgium's export to the Netherlands, representing 56% of all hydrogen traded in Europe.

Regarding hydrogen production and consumption projects[217], as of May 2025, 131 operational water electrolysis projects accounted for 556 MWel of production capacity, while an additional 84 projects under construction are set to add 2,662 MWel by 2028[218]. Germany, France, and the UK lead with 62, 26, and 16 projects, respectively. On the consumption side, the mobility sector has the largest number of projects (88), but the steel (34%) and refining (32%) sectors are expected to dominate in volume, jointly consuming around two-thirds of the 362 kilotons of clean hydrogen anticipated once all under-construction projects come online.

Regarding electrolyser costs[219], the total CAPEX for AEL in Europe was 2310 EUR/kW (323 EUR/kW for the stack, 693 EUR/kW for the BoP, 693 EUR/kW for other utilities, and 601 EUR/kW for other CAPEX) while the OPEX was 46 EUR/kW/year excluding electricity costs. For PEM electrolysis, CAPEX in Europe was 2503 EUR/kW (563 EUR/kW for the stack, 647 EUR/kW for BoP, 693 EUR/kW for other utilities, and 601 EUR/kW for other CAPEX) while OPEX amounted to 50 EUR/kW/year excluding electricity costs.

By the end of 2025, Europe's total water electrolyser manufacturing[220] capacity is projected to reach 14.4 GW per year, with 10.6 GW/year already operational as of May 2025 and an additional 3.8 GW/year planned. For 2026, projects under construction or with a final investment decision are expected to raise the total capacity to 15.2 GW/year. Looking at the current and planned water electrolyser manufacturing capacity by technology type until the end of 2025, alkaline electrolysers are expected to account for 39% (5.58 GW/year), while PEM technologies will continue to dominate with 52% (7.52 GW/year). By 2026, assuming all planned expansions are realised, PEM technologies will represent 49% of operational capacity (7.52 GW/year), followed by alkaline with 41% (6.18 GW/year), while SO and AEM will account for 7% (1.01 GW/year) and 3% (0.53 GW/year), respectively.

Since 2020, activity in the European FCEV market has shown signs of stabilisation[221]. Registrations rose from 962 in 2020 to 1,549 in 2022 (+61%), then dropped to 1,026 in 2023 (-34%) before recovering slightly to 1,202 in 2024 (+17%). This trend is mirrored in the total fleet, which continued to expand but at a slower pace, from 5,459 vehicles in 2022 to 6,509 in 2024 (+19%). Germany led in 2024 with the highest registrations (532) and fleet size (2,227), followed by France with 529 registrations and a fleet of 1,301. Passenger cars remain the dominant category, having driven growth until 2022 before seeing declines in recent years, while the deployment of FCEV buses (613) and trucks (364) has steadily increased, marking a diversification of the fleet.

Regarding HRS[222], between 2015 and 2020, the number of HRS[223] expanded rapidly, reaching 153, but growth slowed thereafter, with 186 operational stations by mid-2025. Germany hosts the largest share with 72 stations, followed by France (30) and the Netherlands (23). Most stations are equipped with 700 bar dispensers for cars, while around two-thirds also feature 350 bar dispensers suitable for heavy-duty vehicles, cars, or both.

216 https://observatory.clean-hydrogen.europa.eu/hydrogen-landscape/production-trade-and-cost/hydrogen-trade

217 https://observatory.clean-hydrogen.europa.eu/hydrogen-landscape/projects-and-valleys/hydrogen-production-and-consumption-projects

218 This data-stream provides an overview of hydrogen production and consumption projects in Europe that are either operational or under construction, covering electrolysis facilities with a minimum capacity of 0.5 MWel and other clean hydrogen production sites above 9,000 tonnes per year.

219 https://observatory.clean-hydrogen.europa.eu/hydrogen-landscape/production-trade-and-cost/electrolyser-cost

220 https://observatory.clean-hydrogen.europa.eu/hydrogen-landscape/technology-manufacturing/electrolyser-manufacturing-capacity

221 https://observatory.clean-hydrogen.europa.eu/hydrogen-landscape/end-use/hydrogen-fuel-cell-electric-vehicles

222 https://observatory.clean-hydrogen.europa.eu/hydrogen-landscape/distribution-and-storage/hydrogen-refuelling-stations

223 This data-stream tracks publicly accessible and operational hydrogen refuelling stations (HRS) in Europe, detailing their locations and dispenser types (700 bar for cars, 350 bar for cars and/or heavy-duty vehicles).

Finally, the latest insights into European and national policies, legislations, strategies, and codes and standards that impact the deployment of hydrogen technologies and infrastructures are provided[224]. The EHO database tracks 32 EU policies and legislations directly or indirectly shaping hydrogen technology development and deployment, with three new additions in 2024: the Advanced Materials for Industrial Leadership Strategy, the adopted Electricity Market Design Reform, and the Revised Industrial Emissions Directive. This expansion underscores the increasing regulatory focus on the hydrogen sector, with policies influencing the entire value chain from production to transport, storage, distribution, and end-use. Key developments also include the final adoption of the Hydrogen and Decarbonised Gas Market Package, the Net Zero Industry Act, the Critical Raw Materials Act, the Energy Performance of Buildings Directive, and updated CO_2 emission standards for new heavy-duty vehicles.

At the national level, as of May 2024, 21 out of 32 European countries have published hydrogen strategies, while three are in draft form. Lithuania has now published its first hydrogen strategy, and Romania has progressed from no strategy to a draft stage compared to July 2023. Several national strategies incorporate quantitative indicators, particularly electrolyser capacity, as a central target for scaling renewable hydrogen production. Germany maintains the most ambitious target at 10 GW by 2030, followed by France with 6.5 GW, alongside other metrics such as hydrogen refuelling stations, fuel cell electric vehicles, and renewable hydrogen uptake in industry or injection into the transmission grid.

In parallel, progress has been made in the development of European codes and standards supporting hydrogen technologies and infrastructures, with 16 standards revised or introduced in 2024 (six of which are already included in the EHO database). These updates span different stages of the hydrogen value chain, with 10 standards addressing distribution and storage, seven targeting end-use applications, and one focused on cross-cutting areas. Notably, no standards on production were revised or adopted during this period. The newly developed standards cover areas such as hydrogen fuel cell technologies, road vehicles, hydrogen refuelling stations, and plastic pipes, fittings, and valves for gas transport, thus contributing to improved safety, interoperability, and reliability across hydrogen applications.

224 https://observatory.clean-hydrogen.europa.eu/hydrogen-landscape/policies-and-standards

VIII.RECENT STUDIES ON HYDROGEN TECHNOLOGIES

Several initiatives complement the project funding activities managed by the Programme Office, including recent studies aligned with the programme's objectives. These studies, conducted between the second half of 2024 and September 2025, provide valuable insights into recent developments in the hydrogen sector and were either commissioned by the Clean Hydrogen JU or carried out by international organisations.

The "**Study on sustainable supply chain and industrialisation of hydrogen technologies**" was published in October 2024[225]. The report highlights the critical role of the hydrogen supply chain in achieving a net-zero economy, examining EU hydrogen strategies and regulations in comparison with other global regions. It emphasises that a robust, efficient, and independent supply chain is essential for Europe's energy security, resilience, and decarbonisation efforts, while also preventing past mistakes, such as dependence on Chinese solar PV components, and maintaining competitiveness against regions actively investing in hydrogen technologies. The analysis compares CAPEX and OPEX in hydrogen production, noting that while CAPEX is crucial for individual installations, OPEX dominates in dual energy setups, highlighting the multifaceted considerations required when evaluating hydrogen investments. European hydrogen technology development faces challenges due to relatively limited financial and regulatory support compared with the US, China, and Japan, where initiatives like the US IRA, China's prioritisation of hydrogen production, and Japan's R&D focus provide stronger backing. The report includes detailed descriptions and SWOT analyses for key components of the EU supply chain, assessing current and future competitiveness, circularity, and sustainability, and offers recommendations to address vulnerabilities and mitigate disruptions. Insights from an Advisory Board of European industrial and research experts contributed to a comprehensive overview, revealing that the European hydrogen supply chain still shows immaturity in several areas, posing challenges for maintaining global leadership.

The "**Technical Assistance to Generate Synergies with Member States and Regions**", which ran from January 2023 until June 2024, was published in November 2024[226]. It successfully supported the Clean Hydrogen Partnership in finalising 10 Memoranda of Cooperation (MoCs) with National and Regional Managing Authorities (MAs). An initial framework was developed through a comprehensive assessment of policy and funding initiatives, identifying gaps and opportunities for synergies between national or local hydrogen strategies and the Clean Hydrogen Partnership's SRIA. The MoCs were developed through continuous engagement between the selected MAs and the JU, outlining the support services the Partnership will provide to advance hydrogen technology deployment in their regions. Cooperation areas were identified based on a preliminary analysis of existing national and regional hydrogen strategies and the specific needs and gaps of each MA. Three MoCs were officially signed during the Hydrogen Valleys Days ceremony on June 17 2024 in Brussels, while six more have been finalised and were signed during the European Hydrogen Week, from the 18th to the 22nd of November 2024[227]. These agreements establish structured work streams and collaboration frameworks, ensuring targeted support to accelerate the uptake of hydrogen technologies at both regional and national levels.

The "**European Hydrogen Sustainability and Circularity Panel (EHSCP)**" was published in April 2025[228]. The report provides a comprehensive overview of EHSCP[229] activities during its first year of operation, from February

225 https://www.clean-hydrogen.europa.eu/media/publications/study-sustainable-supply-chain-and-industrialisation-hydrogen-technologies_en

226 https://www.clean-hydrogen.europa.eu/media/publications/final-study-technical-assistance-generate-synergies-member-states-and-regions_en

227 https://www.clean-hydrogen.europa.eu/media/news/amplifying-efforts-lead-europes-hydrogen-revolution-2024-11-27_en

228 https://www.clean-hydrogen.europa.eu/media/publications/final-report-european-hydrogen-sustainability-and-circularity-panel-ehscp_en

229 Established to align hydrogen deployment with the EU's climate neutrality and circular economy objectives.

2024 to February 2025, highlighting its role in embedding sustainability and circularity principles across the Clean Hydrogen JU and the wider hydrogen sector. The panel assessed 356 Clean Hydrogen JU-funded projects covering production, storage, distribution, end-uses, and cross-cutting activities, developing methodological approaches to evaluate sustainability performance and formulating strategic recommendations. The findings indicate that while economic indicators such as CAPEX, OPEX, and LCOH are widely considered, environmental, circularity, and social aspects remain inconsistently addressed. Circularity metrics (material criticality, recyclability, and resource efficiency) are often overlooked, and social dimensions such as labour conditions and public acceptance are largely absent. To address these gaps, the panel recommends reinforcing data collection and reporting through standardised methodologies, templates, and digital tools; building project-level capacity via guidance, benchmarking, and training; and embedding sustainability and circularity criteria in funding calls while fostering collaboration with institutions such as the JRC. Additionally, communication and stakeholder engagement through workshops, policy dialogues, and recognition mechanisms are emphasised to promote best practices.

In addition to the above studies, it is also important to mention activities of the Clean Hydrogen JU complementing its other activities and the reporting of the developments in the (European) hydrogen sector:

1. Workshop "**Towards RCS for cryogenic and LH2 transferring operations and facilities**" by international experts from ELVHYS consortium and international Regulations, Codes and Standards committees that took place on the 5th of June 2025. A thorough overview was presented on the national and international regulatory and standardisation activities for hydrogen technologies with a focus on cryogenic and liquid hydrogen applications.
2. Webinar "**Hydrogen Sustainability and Circularity**" which took place on the 8th of May 2025. The discussion was focused on clean hydrogen production and its role in decarbonising transport, particularly on storage, resource efficiency, and circularity. Complementing this, experts presented insights on hydrogen life cycle analysis (LCA) and eco-design from the SH2E and eGHOST projects, with additional contributions from the Joint Research Centre (JRC) addressing hydrogen sustainability.
3. Workshop "**Advancing Water Electrolysis with Cutting-Edge Catalysts, Electrodes, and Sustainable Solutions**" which took place on the 29th of January 2025, delving into critical areas such as catalyst and electrode development for water electrolysis and sustainability as a cornerstone for electrolyser advancement.

On the international stage, the International Energy Agency (IEA) published its annual "**Global Hydrogen Review 2025**"[230] tracking international developments in hydrogen production and demand, as well as progress in critical areas such as infrastructure development, trade, policy, regulation, investments, and innovation. This year's report evaluates progress achieved so far and highlights the challenges that lie ahead, offering a comprehensive assessment of the level of hydrogen adoption that may be reached by 2030. A dedicated chapter focuses on Southeast Asia, examining the region's near-term potential for producing and deploying low-emission hydrogen, as well as hydrogen-derived fuels and products. As discussed in the report, the hydrogen sector is expanding despite ongoing challenges such as project cancellations and structural barriers. Global demand reached nearly 100 million tonnes in 2024, a 2% increase compared to 2023, consistent with overall energy demand growth. However, the uptake of low-emission hydrogen continues to lag behind expectations, constrained by high costs, uncertain demand, regulatory hurdles, and limited infrastructure. Although the pipeline of low-emission projects has contracted, prospects for substantial growth by 2030 remain. China continues to dominate electrolyser deployment and manufacturing, though international market access faces obstacles. Meanwhile, policy efforts to stimulate demand are advancing, and Southeast Asia is positioning itself as a rising hydrogen market.

Focusing more on deployment, the Hydrogen Council released its "**Global Hydrogen Compass 2025**"[231], highlighting that the first wave of mature projects is coming online with a committed investment in clean hydrogen projects surpassing $110 billion across 510 projects. As shown, of the 6 million tonnes per year of committed clean hydrogen capacity worldwide, around 1 is already in operation. Taking into account project delays and attrition risks, the current pipeline could deliver between 9 and 14 million tonnes per year of capacity by 2030, contingent on securing sufficient offtake agreements. China currently leads global electrolysis deployment, holding over half of the committed renewable hydrogen capacity, while North America is ahead in low-carbon hydrogen. The

230 https://www.iea.org/reports/global-hydrogen-review-2025

231 https://hydrogencouncil.com/wp-content/uploads/2025/09/Hydrogen-Council-Global-Hydrogen-Compass-2025_Final.pdf

most recent operational capacity growth has taken place in China, where output has expanded sixfold since 2022. Looking toward 2030, around 8 million tonnes per year of demand could emerge across the EU, US, Japan, and Korea if current policies are implemented and enforced, while approximately 2 million tonnes per year of Chinese FEED+ projects are expected to meet rising domestic needs.

Finally, IRENA published in November 2024 the "**A quality infrastructure roadmap for green hydrogen**"[232], exploring the importance of QI services and discussing how they play a key role in the successful global production and use of green hydrogen. Moreover, in their "**Analysis of the potential for green hydrogen and related commodities trade**" published in July 2025[233], the techno-economic potential for the trading of green hydrogen using a cost-optimisation approach is explored.

232 https://www.irena.org/Publications/2024/Nov/A-Quality-Infrastructure-Roadmap-for-green-hydrogen

233 https://www.irena.org/Publications/2025/Jun/Analysis-of-the-potential-for-green-hydrogen-and-related-commodities-trade

IX. CONCLUSIONS AND NEXT STEPS

The Clean Hydrogen JU plays a key role in advancing the EU's climate neutrality objective by driving research, innovation, and deployment of hydrogen technologies across the full value chain. It provides the framework to accelerate the transition from fossil fuels to sustainable energy carriers, ensuring that hydrogen contributes effectively to decarbonisation, energy security, and industrial competitiveness. By mobilising European industry and research organisations, the JU fosters collaboration and innovation that not only aim at reducing greenhouse gas emissions but also at strengthening Europe's position in the global hydrogen landscape.

Since its establishment, the Clean Hydrogen JU and its predecessors (the FCH JU and FCH2 JU) have significantly advanced progress in hydrogen production, storage, distribution, and end-use applications, complemented by cross-cutting initiatives that integrate these elements. Demonstration projects such as Hydrogen Valleys exemplify this systemic approach, creating regional clusters where hydrogen is produced, stored, distributed, and utilised across multiple sectors, including mobility, industry, and heating. In parallel, JU-funded projects have improved the performance and cost-effectiveness of electrolysers and fuel cells, scaled up refuelling infrastructure for road and maritime transport, and explored innovative storage technologies. Importantly, transversal projects addressing safety, standards, and skills development ensure that these technologies are deployed within a supportive ecosystem. While notable progress has been made, a number of gaps remain.

Pillar 1 has placed Europe at the forefront of electrolyser development, which remains the cornerstone of clean hydrogen production. Considerable progress has been made in enhancing the performance and durability of Alkaline, Proton Exchange Membrane, and Solid Oxide electrolysers, while emerging technologies such as Anion Exchange Membrane and Proton Conducting Ceramic electrolysers are progressing through early validation stages. Nevertheless, challenges persist in reaching the durability, efficiency, and cost targets required for widespread market adoption. Solar-to-hydrogen technologies, though conceptually promising, still fall short of efficiency thresholds at plant scale. Across all production technologies, reliance on scarce and critical raw materials remains a structural vulnerability. Future initiatives should focus on standardisation of electrolyser design and testing, harmonised methods for degradation monitoring, and the development of user-friendly economic and certification tools to facilitate the entry of smaller operators into the market.

Under Pillar 2, progress in storage, transport, compression, and hydrogen carriers reflects the diversity of potential pathways for hydrogen distribution. The Clean Hydrogen JU has funded a wide range of projects, from compressed and liquid hydrogen solutions to chemical carriers, covering both large-scale and decentralised systems. However, a number of the key performance indicators have proven overly ambitious in relation to the maturity of the technologies and the scale of the available funding. A recalibration of KPIs is needed to ensure they remain realistic and measurable, as well as a more strategic concentration of resources on the most promising solutions. Future calls should also carefully balance support for breakthrough innovations with incremental improvements, as both are essential for ensuring that technologies progress reliably towards commercial deployment.

Transport applications supported under Pillar 3 continue to represent one of the most visible areas of hydrogen deployment. Passenger cars and buses are already market-ready thanks to sustained investment under the predecessor FCH JU, but decarbonising harder-to-abate modes of transport (heavy trucks, maritime shipping, aviation, and rail) is ongoing. Demonstration projects in these areas are advancing but frequently encounter delays, often linked to permitting bottlenecks, safety considerations, or changes in industrial partners. Field data and operational lessons from demonstrations are not yet sufficiently channelled into regulatory and standardisation processes, slowing down the creation of enabling frameworks. Establishing mechanisms to ensure that knowledge is shared with regulatory and standardisation bodies would accelerate harmonisation and unlock faster market uptake.

In the stationary power and heat sector, addressed under Pillar 4, the JU has supported projects advancing 100% hydrogen technologies, such as turbines, boilers, burners, and stationary fuel cells, as well as transitional solutions with blended fuels. These technologies are crucial for integrating renewable hydrogen into Europe's power and heat systems. While strong technical progress has been achieved, there is a recurring risk that results from completed projects not being sufficiently exploited, leading to missed opportunities for scaling and replication. A more deliberate strategy to build upon existing outcomes, rather than pursuing novelty alone, would increase efficiency. Proof-of-concept demonstrations leveraging existing commercial products could also bridge the gap between R&D and deployment by testing feasibility and compliance in real operating environments. This would not only accelerate market readiness but also provide early insight into regulatory and safety challenges.

Pillar 5 has made the importance of cross-cutting issues such as safety, standards, sustainability, education, and public awareness clear. The projects under this pillar contribute to building the enabling framework that ensures hydrogen technologies are not only technically viable but also safe, sustainable, and socially accepted. The creation of the European Hydrogen Sustainability and Circularity Panel has added a strategic dimension to sustainability integration, aligning the programme with EU climate and circular economy policies more closely. However, the pathway from project-level outputs to standards development remains underdeveloped. A dedicated support mechanism would help projects translate results into regulatory and standardisation contributions.

The Hydrogen Valleys supported under Pillar 6 have become flagship projects, demonstrating integrated hydrogen ecosystems at the regional level. Pioneering initiatives such as HEAVENN and GREEN HYSLAND illustrate the potential of these ecosystems to combine production, distribution, and end-use across multiple sectors. Yet, most valleys remain in early stages, facing challenges of scale, complexity, and stakeholder coordination. The risk of delays is amplified by the interdependencies between numerous actors, underlining the need for de-risking measures, contingency planning, and stronger KPI frameworks tailored to the unique characteristics of hydrogen valleys. Facilitating closer alignment with regional and local authorities would accelerate permitting and unlock co-funding opportunities.

Strengthening the hydrogen supply chain, the objective of Pillar 7, has proven both timely and urgent. Recent global disruptions have exposed vulnerabilities in raw material availability, component supply, and logistics, highlighting the importance of developing a resilient and competitive European supply chain. A more structured and comprehensive approach is needed, including systematic post-mortem analyses of completed projects and dedicated workshops to exchange experience among project partners, OEMs, and supply chain experts. Requirements to demonstrate the availability of multiple European suppliers for critical materials and components could be integrated into future project calls, reducing dependence on single sources and strengthening resilience.

Finally, Pillar 8 has ensured that early-stage, low-TRL research continues to feed the innovation pipeline. Projects under this pillar address fundamental questions on critical raw material reduction, sustainable alternatives to substances such as PFAS, and the development of advanced materials for storage, electrolysis, and fuel cells. By focusing on long-term challenges, these projects provide the scientific foundation for the next generation of hydrogen technologies. However, the need remains for systematic quantification of CRM and PFAS use across the hydrogen value chain, coupled with harmonised durability targets and comprehensive LCAs to evaluate substitution strategies.

Overall, management of the accumulated knowledge and data is becoming critical. The Hydrogen Knowledge Hub will improve the data collection interface and visualisation of data. It will collect and manage the knowledge produced by the Clean Hydrogen JU programme and its projects by coordinating access to non-confidential information for stakeholders, the scientific community, and society in general. The Knowledge Hub must be open to the whole hydrogen value chain in Europe, collecting data from R&I projects and large demonstrations, including European, regional, and local projects, and act as a single data repository for hydrogen applications.

In summary, the Clean Hydrogen JU has been instrumental in positioning hydrogen as a cornerstone of Europe's decarbonisation strategy, advancing technologies from laboratory to demonstration scale, and fostering integrated ecosystems such as Hydrogen Valleys. Yet, to meet the EU's climate neutrality targets and remain globally competitive, further progress is needed in closing performance gaps, reducing costs, ensuring supply chain resilience, and embedding sustainability and circularity across the value chain. By implementing the recommended actions, the JU can not only deliver on its KPIs but also create the conditions for a truly sustainable and resilient hydrogen economy in Europe.

Clean Hydrogen Partnership

ANNEX: PROJECTS REVIEW & POSTERS

X. PILLAR 1: HYDROGEN PRODUCTION

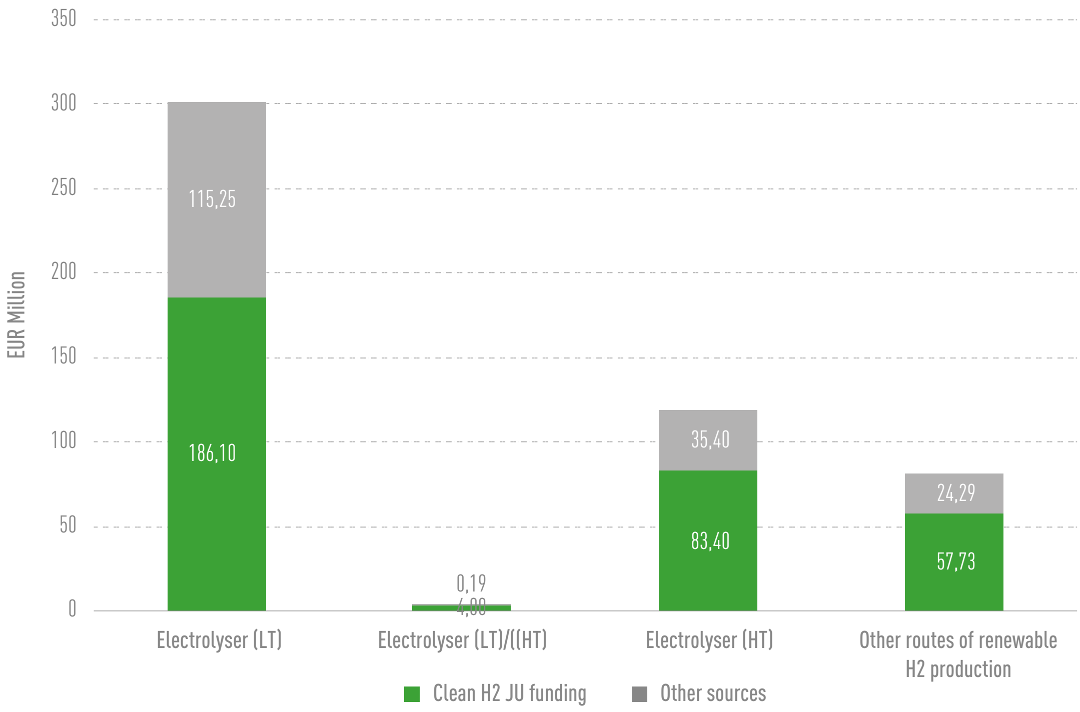
OBJECTIVES: The main technology funded under this Pillar is electrolysis. Higher-TRL technologies such as Alkaline Electrolysers (AEL), Proton Exchange Membrane Electrolysers (PEMEL) and Solid Oxide Electrolysers (SOEL) are supported, along with newer lower-TRL technologies Anion Exchange Membrane Electrolysers (AEMEL) and Proton Conducting Ceramic Electrolysers (PCCEL). The alternative hydrogen production technology funded under this Pillar is thermo-chemical cycles with concentrated solar energy and photoelectrochemical water splitting.

Pillar 1 includes the following three Research Areas and the respective ongoing projects:

- Low temperature electrolysis, including AEL (Djewels, ENDURE, EPHYRA, EXSOTHyC, PEACE, REDHy, SEAL-HYDROGEN, and X-SEED projects), PEMEL (REFHYNE, ADVANCEPEM, and HOPE projects) and AEMEL (AEMELIA, HERAQCLES, HYPRAEL, and HYScale projects);
- High-temperature electrolysis, including SOEL (MultiPLHY, PROMETEO, REACTT, HyP3D, Hy-SPIRE, NOAH2, OUTFOX, PilotSOEL, and PressHyous projects) and PCCEL (PROTOSTACK project);
- Other routes of renewable hydrogen production, including biomass gasification (HYIELD project) and solar-to-hydrogen (STH) (HYSELECT and PH2OTOGEN projects).

OPERATIONAL BUDGET: The Clean Hydrogen JU supported 88 projects relevant to this pillar between 2008 and 2024, with a total Clean Hydrogen JU contribution of EUR 331.2 million and a contribution from partners of EUR 175.1 million. The distribution of funding over the three research areas considered in this pillar is shown in Figure 16.

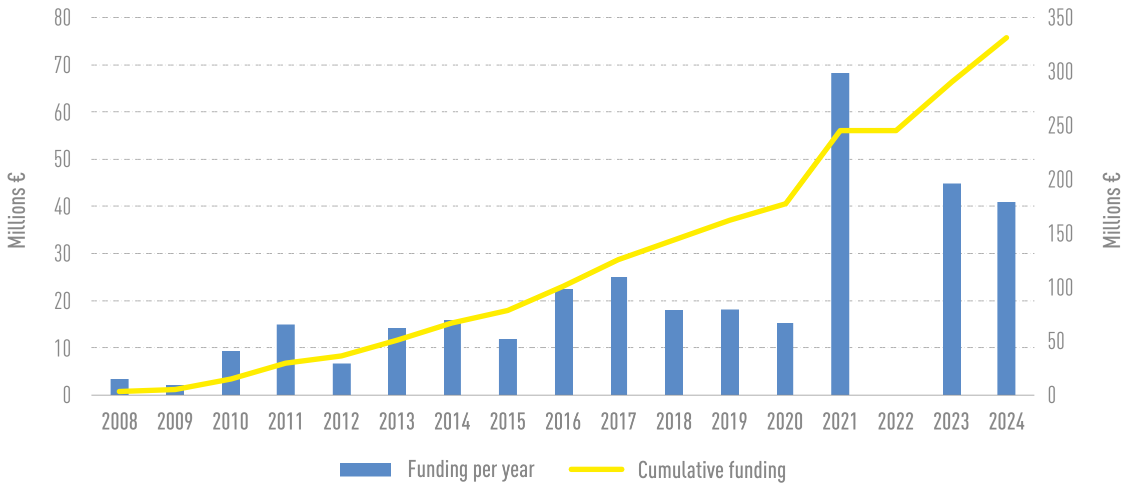
Figure 16: Funding for pillar 1 projects from 2008 to 2024



Source: Clean Hydrogen JU.

In the last two years (2023 and 2024), funding allocations under this Pillar have seen a notable increase, as illustrated below in Figure 17. Projects focusing on low-temperature (LT) electrolysers have clearly been prioritised, receiving the majority of resources compared to those targeting high-temperature (HT) electrolysers. Despite the well-documented potential of HT electrolysers to achieve higher overall system efficiencies by leveraging available heat, the share of funding directed towards these technologies remains disproportionately low. This imbalance is particularly evident when contrasted not only with LT electrolysers but also with alternative renewable hydrogen production pathways. Given the strategic importance of HT electrolysers for enabling efficient large-scale hydrogen production and integration into industrial processes, future funding discussions and topic prioritisation should place greater emphasis on their development, ensuring that their potential benefits are adequately realised.

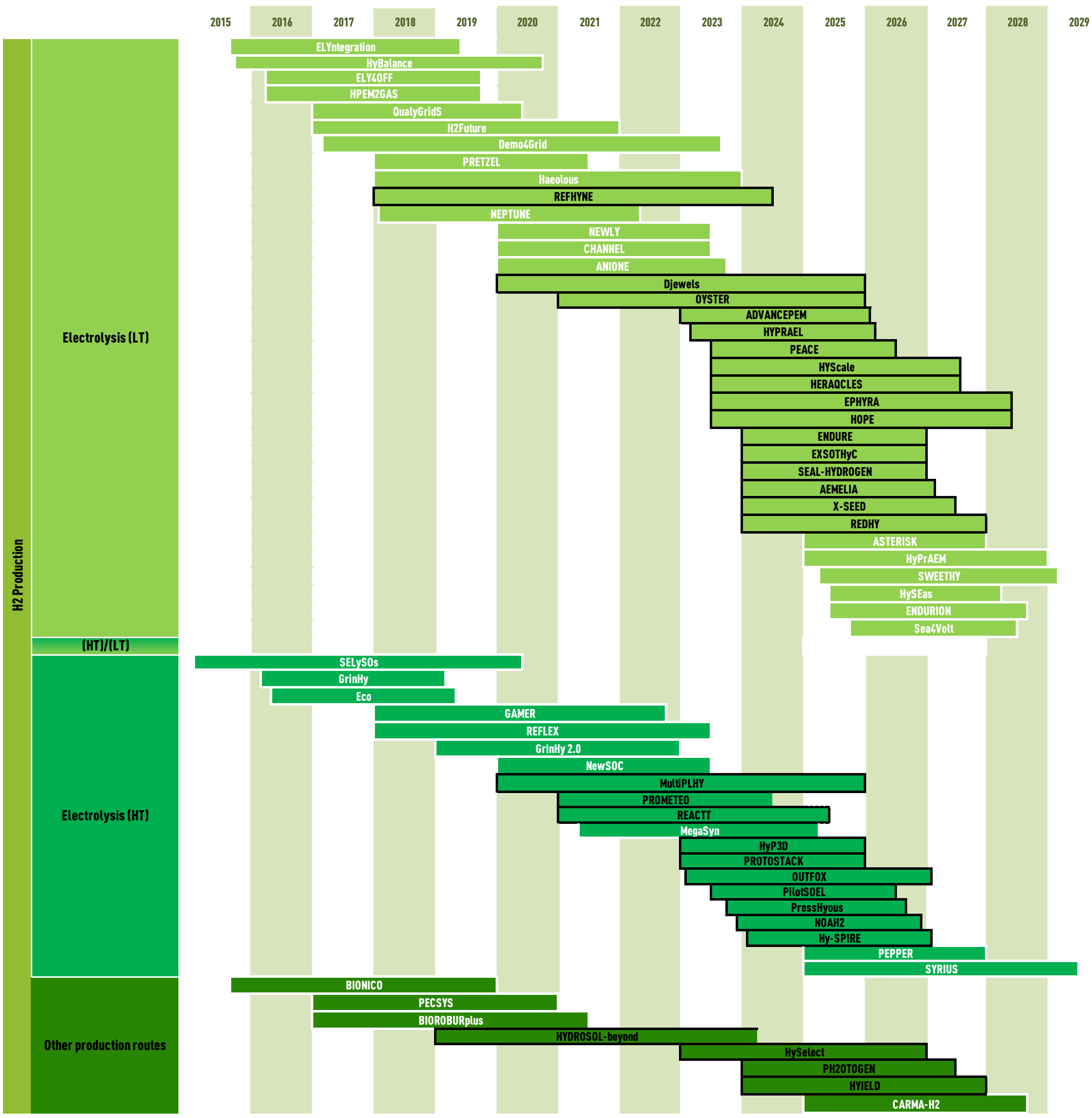
Figure 17: Funding (per year in green/left axis and cumulative in grey/right axis) for Pillar 1 projects from 2008 to 2024



Source: Clean Hydrogen JU.

PILLAR IN BRIEF: The 30 Pillar 1 projects reviewed in the document are listed and highlighted in black in Figure 18.

Figure 18: Project timelines of Pillar 1 – Hydrogen Production



Source: Clean Hydrogen JU.

Participation in these projects is dominated by beneficiaries from France, Germany, and Italy, which together account for the highest number of involvements, followed closely by the Netherlands and Spain. Beyond these, participation declines gradually, with smaller Member States, such as Luxembourg, Poland, and Latvia, contributing to only a single project each (Figure 19). The collaboration network (Figure 20) offers additional insights into cross-border cooperation, highlighting three distinct regional clusters: one centred around Germany, France, and Belgium (purple cluster), another grouping Italy, the Netherlands, and Greece (green cluster), and a third comprising Spain, Poland, and Denmark (red cluster). A fourth, lighter blue cluster involves mainly Baltic and Nordic countries such as Estonia, Finland, and Latvia. Together, these clusters illustrate both strong regional alignment and active international cooperation across Europe.

Figure 19: Pillar 1: Project participation by EU country

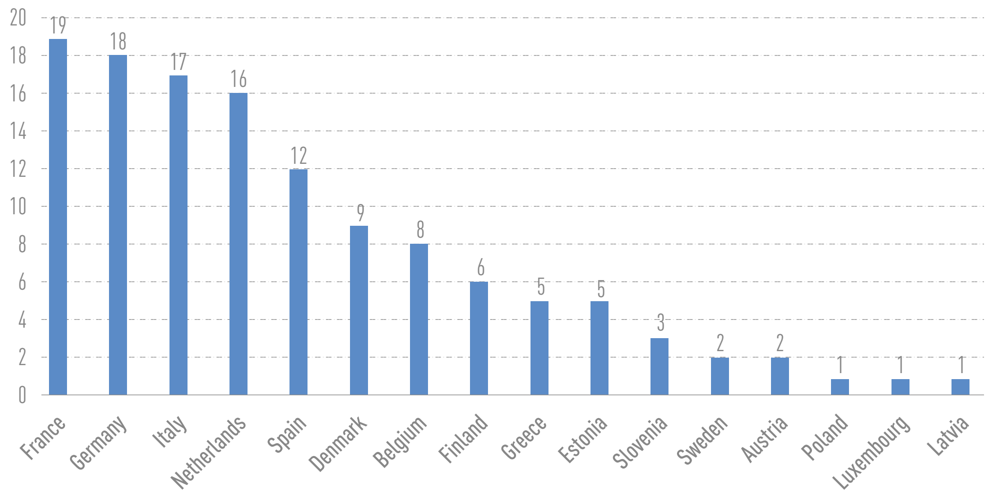
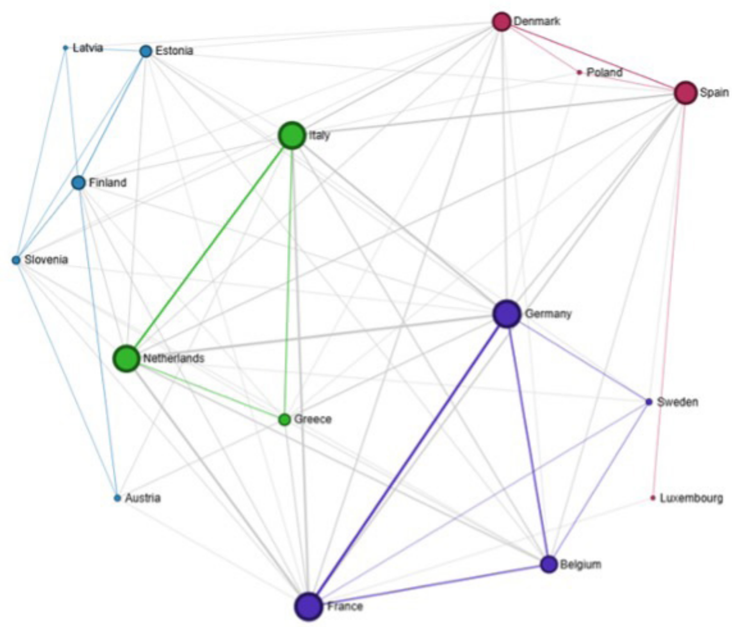


Figure 20: Pillar 1: Collaboration network of EU countries



The distribution of participation across organisation types shows a fairly balanced representation between academia (including higher education institutions and research institutes) and the private sector, including SMEs (Figure 21). From 2018 to 2024, private companies participated in 27 projects, closely followed by research institutions (26 projects) and SMEs (23 projects), while higher education institutions contributed to 19 projects. Public bodies and other entities remain marginal participants, each involved in only one project. Leading research organisations such as CEA, DTU, DLR, SINTEF, EPFL, CNR, ENEA, and VTT, together with private sector partners, form a highly interconnected research and demonstration network (Figure 22). Within this network, CEA leads with eight projects, followed by DLR and SINTEF with six each. The collaboration landscape is characterised by three major clusters (Figure 22): a dense group of public research organisations centred on CEA, CNRS, and DLR (purple cluster), an industry-oriented cluster built around VTT and its partners (blue cluster), and a public–private collaboration network anchored by SINTEF (green cluster). Finally, the number of scientific publications disseminating results increased to 10 in 2023 and 8 in 2024 across 14 projects and 9 projects, respectively (Figure 23). Half of the publications were peer-reviewed.

Figure 21: Pillar 1: Participation by organisation type across years

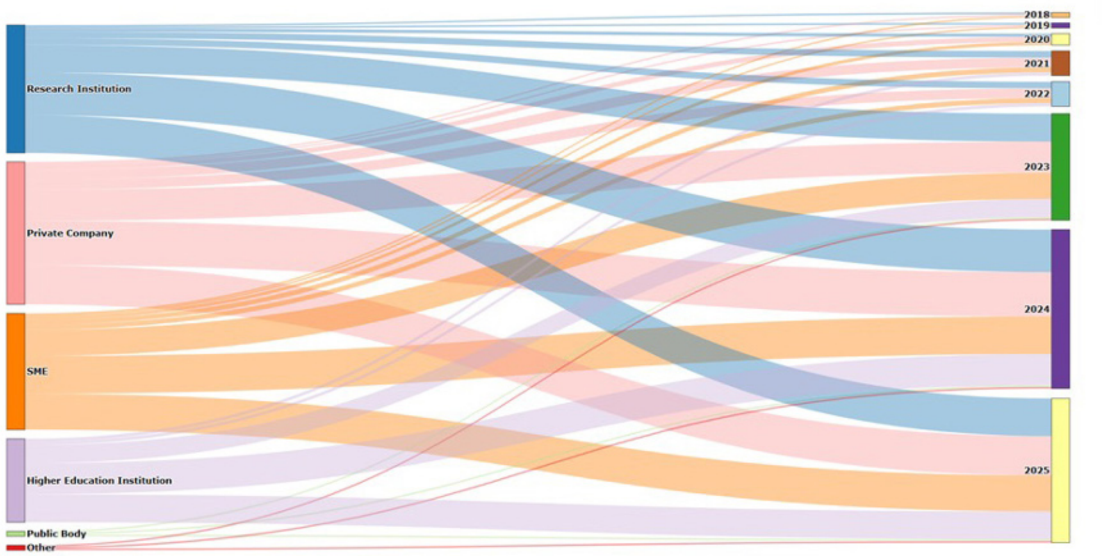


Figure 22: Pillar 1: Collaboration network of top participating institutions

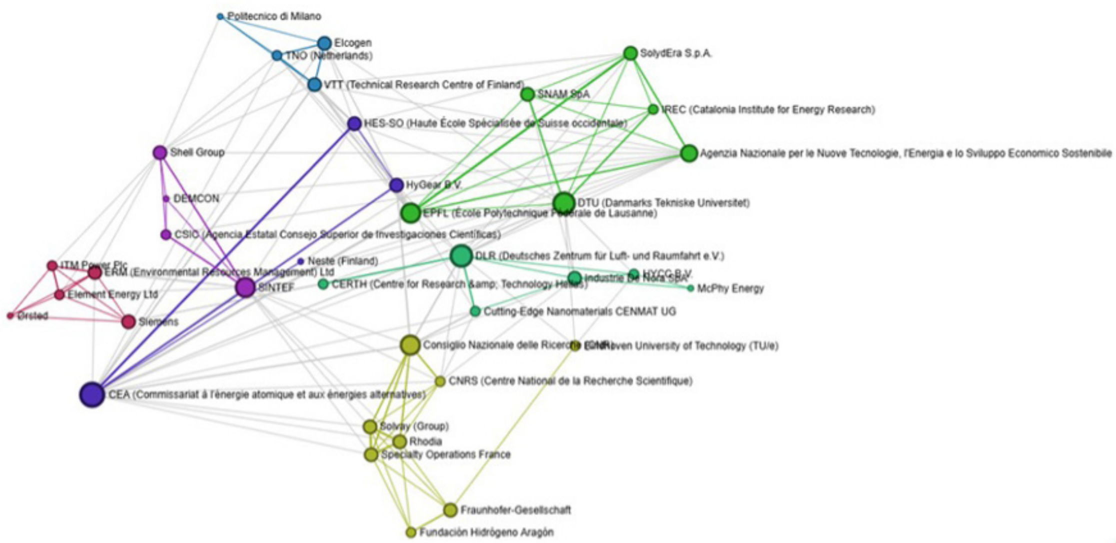
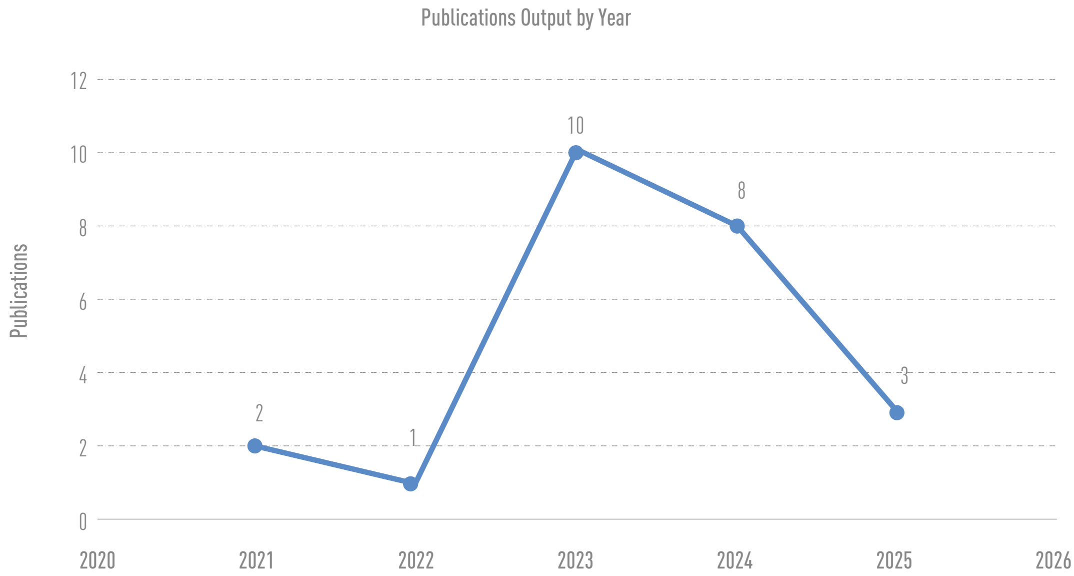
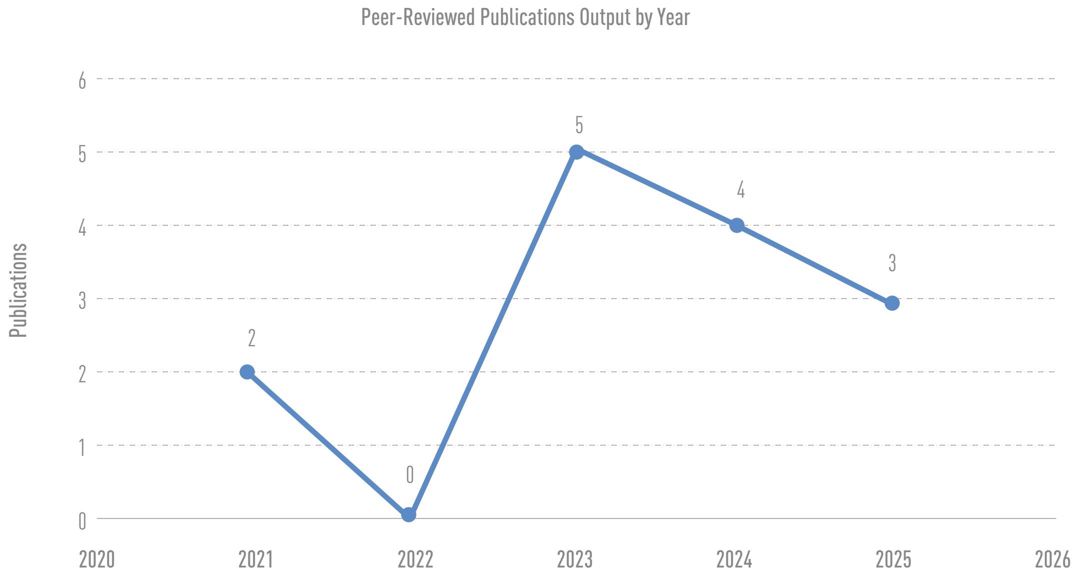


Figure 23: Pillar 1: Number of publications per year





PROJECTS FACTSHEETS

ADVANCEPEM

ADVANCED HIGH PRESSURE AND COST-EFFECTIVE PEM WATER ELECTROLYSIS TECHNOLOGY

Project ID	101101318
PRR 2025	Pillar 1 - H_2 Production
Call Topic	HORIZON-JTI-CLEANH$_2$-2022-01-03
Project Total Costs	1 631 066.56
Clean H_2 JU Max. Contribution	1 607 330.00
Project Period	01-02-2023 - 31-01-2027
Coordinator Beneficiary	CONSIGLIO NAZIONALE DELLE RICERCHE, IT
Beneficiaries	RHODIA OPERATIONS, SPECIALTY OPERATIONS FRANCE, HSSMI TRADING LIMITED, OORT ENERGY LTD, RWE GENERATION SE, IRD FUEL CELLS A/S, Rhodia Laboratoire du Futur, SOLVAY SPECIALTY POLYMERS ITALY SPA, RWE POWER AKTIENGESELLSCHAFT

https://advancepem.eu/

PROJECT AND GENERAL OBJECTIVES

Direct production of highly pressurised hydrogen from electrolytic water splitting can allow significant amounts of energy to be saved compared with down-stream gas compression. ADVANCEPEM aims to develop a set of breakthrough solutions at materials, stack and system levels to increase hydrogen pressure and current density, while keeping the nominal energy consumption at < 50 kWh/kg H_2. Reinforced Aquivion® polymer membranes that have enhanced conductivity, a high glass transition temperature and increased crystallinity, and are able to withstand high differential pressure, have been developed for this application. To mitigate hydrogen permeation to the anode and related safety issues, efficient recombination catalysts are integrated in both the membrane and the anode structure. The new technology has been validated by demonstrating a high-pressure electrolyser of 50 kW nominal capacity in an industrial environment. The consortium comprises an electrolyser manufacturer, a membrane and catalyst supplier, a membrane electrode assembly developer and an end-user for demonstrating the system.

NON-QUANTITATIVE OBJECTIVES

- Develop a novel polymer electrolyte membrane (PEM) electrolyser able to produce hydrogen at very high pressure thus reducing the post-compression energy consumption.
- Develop a cost-effective technology allowing to achieve large-scale application of PEM electrolysers.
- Achieve a significant reduction of capital costs by minimising use of critical raw materials, developing cheap coated bipolar plates and operating the electrolyser at a high production rate while assuring high efficiency and safe operation.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

- Development of functional components and stack with the following initial results:
  - (i) Thin (90 µm) Aquivion membranes containing radical scavengers showing conductivities of about 200 mS cm-1.
  - (ii) IR-free O_2 and H_2 evolution overpotentials 120 mV cumulative vs. thermoneutral potential at 5 A cm-2 with PGM loading 1.2 mg cm-2 with an IrRu-oxide solid solution anode and Pt/C cathode catalyst.
  - (iii) Performance of 5 A cm-2 at 1.83 V/cell, 90 °C, with a total PGM loading per MEA 1.2 mg cm-2 combining Aquivion membrane/ionomer and advanced PGM catalysts.
- Design for the validation of the PEM electrolyser.

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- Definition of the most important technical, health, safety and environmental standards, technical parameters and boundary conditions with regard to installation, commissioning and testing of the new developed technology.
- Set up of the project website and identity.
- Publication of a paper on an international open access journal.
- The Data Management plan and the Communication, Dissemination and Exploitation plan were submitted and delivered.

FUTURE STEPS AND PLANS

- Development of the life cycle analysis process.
- Development of the most promising reinforced membrane based on large-scale manufacturing potential.
- Scale-up to larger batches of the oxygen evolution reaction (OER) and hydrogen evolution reaction (HER) catalysts and recombination catalyst for membrane electrode assembly (MEA) manufacturing.
- Production of large area MEAs for the stack.
- Procurement of components.
- Kick off meeting for construction site.
- Delivery of the ADVANCEPEM demonstrator.
- Trials operation phase.
- Continuation of dissemination activities.

PROJECT TARGETS

Target source	Parameter	Unit	Target	Achieved to date by the project	Target achieved?	SoA result achieved to date (by others)	Year for reported SoA result
Project's own objectives	CAPEX referred to input power	€/kW	500			900	2020
	CAPEX referred to capacity	€/(kg/d)	1 000			2 100	
	Hydrogen output pressure	bar	200	30		30	
	Hot idle ramp time	sec	1				
	Cold start ramp time	sec	10			30	
	Electricity consumption @ nominal capacity	kWh/kg	50	48.6 (at cell level)		55	
	Low Electrode Overpotentials	mV vs. Etn @ 5 A cm-2	200	120	✓	N/A	N/A
	Cell performance	V@ 5 A cm-2	1.85	1.83		2.2	2020
	Degradation	%/1 000 h	0.25	0.1		0.19	
	Nominal Current Density	A/cm^2	5	5		2.2	
	Cell/Stack operating temperature	°C	90	90		90	2021
	Membrane conductivity	mS cm-1	200	> 200		200	2024

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AEMELIA

ANIONIC EXCHANGE MEMBRANE WATER ELECTROLYSIS FOR HIGHLY EFFICIENCY SUSTAINABLE, AND CLEAN HYDROGEN PRODUCTION

Project ID	101137912
PRR 2025	Pillar 1 - H_2 Production
Call Topic	HORIZON-JTI-CLEANH$_2$-2023-01-01
Project Total Costs	2 764 927.00
Clean H_2 JU Max. Contribution	2 764 926.75
Project Period	01-01-2024 - 28-02-2027
Coordinator Beneficiary	COMMISSARIAT A L ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES, FR
Beneficiaries	SPECIALTY OPERATIONS FRANCE, MATGENIX, CLAIND SRL, SINTEF AS, Rhodia Laboratoire du Futur, FUNDACION TECNALIA RESEARCH and INNOVATION, SOLVAY SPECIALTY POLYMERS ITALY SPA, CONSIGLIO NAZIONALE DELLE RICERCHE, IMPERIAL COLLEGE OF SCIENCE TECHNOLOGY AND MEDICINE, CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS

https://aemelia.eu/

PROJECT AND GENERAL OBJECTIVES

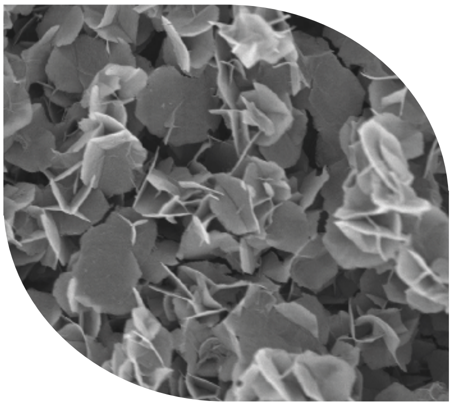
AEMELIA accepts the challenge to design and prototype an anion-exchange membrane electrolysis (AEMEL) method that meets and surpasses Hydrogen Europe's 2030 targets for performance, durability, safety and cost. For example, AEMELIA targets:

- A current-density of 1.5 A cm-2 at low voltage (1.72 V).
- An energy-efficiency of 46.2 kWh/kg or 86% of maximum theoretical efficiency, to increase H_2 production while decreasing energy consumption, compared with CLAIND's actual product (1.76 V (47.1 kWh/kg) at 0.5 A/cm^2 in 0.2 M KOH at 42°C and 10 bar).
- A levelised cost of hydrogen of 2.5 €/kg H_2 (17% lower than the 2030 target).
- A degradation rate enabling a 10-year lifetime.
- A capital expenditure which is expected to reach 2030 targets by upscaling.

NON-QUANTITATIVE OBJECTIVES

AEMELIA intends to bring new technology for anion-exchange membrane WE based on the following:

- An innovative route for electrode preparations without ionomer.
- Implementation of recombination catalyst and electrodes without any platinum group metals in the stack.
- Increased cell efficiency through use of pulsed supply current due to small time periods for oxygen bubble release.
- Design of optimal membrane backbone and side chain to sustain high hydroxide conductive, despite high operating temperature (t> 60°C), through a machine learning approach.
- Machine learning investigation of low environmental impact solvent use to dissolve polymer for preparing ionomer dispersion solution.



PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

- Development of a data-driven methodology to support membrane optimisation using deep learning.
- Analysis of SYSENQO's Beion membrane showing high hydroxide conductivity (236 mS/cm at 50 °C), but its use is limited due to fluorination.
- Investigation of Ni_2P as the first non-PGM recombination catalyst, targeting promising activity for oxygen reduction reaction (ORR) and hydrogen evolution reaction (HER).
- Development of ionomer-free electrodes, using NiMo and NiFeB coatings with thermal treatments showing enhanced activity.
- Investigation of $NiMoS_x$ catalysts for HER, targeting overpotential reduction.
- Preliminary cell testing highlighting temperature-dependent performance differences among membranes, with Fumatech and Piperlon excelling under different conditions.
- Optimised stack design through computational fluid dynamics.
- Development of an environmental assessment method.

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Co-funded by the European Union

FUTURE STEPS AND PLANS

Ionomer-free electrodes:

- Adhesion improvement of physical vapor deposition (PVD) based anode.
- Testing of PVD based cathode and electrodeposited anode at single cell level.
- Testing of electrode prepared with chemically activated porous transport layer (PTL) fibers at single cell level.
- Establishing cell performance and ageing tests.

Classical route of electrodes preparation avoiding fluorinated ionomer, such as Nafion:

- Testing of molybdenum sulfide-based cathode catalyst with an alternative to Nafion.
- Thermal treatment of NiFeO allowing electron conductivity enhancement of the OER catalyst.

The development on polymers should allow to down select a fluorine-free polymer able to sustain high hydroxide conductivity at 80°C. This polymer should be soluble in eco-friendly solvent. To find out this compound, the machine learning already in use needs to be fed with more data, that may come from the literature.

Beside the stack design and the importance of the position of the manifold, the flow design's influence will be investigated. A final design of the full stack will be fixed by the end of 2025, in order to start the manufacturing.

PROJECT TARGETS

Target source	Parameter	Unit	Target	Achieved to date by the project	Target achieved?
Project's own objectives	Safe and sustainable: Fluorine-free ionomers and membranes prepared with green and safe solvents via a cost-effective process.	-	No fluorine polymer and safe solvent for the ionomer dissolution.		
	Development and testing of CRM-free electrodes and PGM-free RC for AEMEL cells and stacks.	g/kW	0	0 mg/cm² on the electrodes, 0 mg/cm² for the recombination catalyst (need more additional development)	
	High performance, long lifetime, and safe components, and stack.	% @ 1.5 A/cm²	84.5	67% @ 1.2 A/cm²	
	TEA shows low-cost hydrogen towards.	€/kg	3	-	
	To ensure market entry by 2031 and ~750MW capacity by 2036 (Number of companies willing to test AEMELIA development).	Number	6	-	

CARMA-H2

CARBON-NEGATIVE PRESSURIZED HYDROGEN PRODUCTION FROM WASTE USING AN ENERGY EFFICIENT PROTONIC MEMBRANE REFORMER

CARMA · H2

Project ID	101137756
PRR 2025	Pillar 1 - H_2 Production
Call Topic	HORIZON-JTI-CLEANH$_2$-2023-01-05
Project Total Costs	12 818 293.75
Clean H_2 JU Max. Contribution	9 954 418.76
Project Period	01-10-2024 - 30-09-2028
Coordinator Beneficiary	ASOCIACION DE LA INDUSTRIA NAVARRA, ES
Beneficiaries	HAFFMANS BV, NAVARRA DE INFRAESTRUCTURAS LOCALES SOCIEDAD ANONIMA (NILSA), HERA HOLDING HABITAT, ECOLOGIA Y RESTAURACION AMBIENTAL S.L., SNAM S.P.A., SINTEF AS, FONDAZIONE ICONS, UNION ENGINEERING AS, SERVICIOS DE LA COMARCA DE PAMPLONA SA, COORSTEK MEMBRANE SCIENCES AS, SHELL GLOBAL SOLUTIONS INTERNATIONAL BV, AGENCIA ESTATAL CONSEJO SUPERIOR DE INVESTIGACIONES CIENTIFICAS

https://carma-h2.eu/

PROJECT AND GENERAL OBJECTIVES

CARMA-H2 aims to develop and demonstrate an innovative modular reactor at the Arazuri wastewater treatment plant in Navarra, Spain. The project integrates multiple technologies to transform biogas from organic waste into pressurised hydrogen (500 kg/day) and CO_2 (over 4 000 kg/day) with great energy efficiency.

At the core of CARMA-H2 is the Protonic Membrane Reformer (bioPMR), a breakthrough technology that enables direct separation of high-purity hydrogen and capture-ready CO_2 in a single, continuous step. The bioPMR will be deployed alongside three key sub-systems: a biogas pre-treatment unit, a CO_2 liquefaction system, and the existing waste-to-biogas plant at Arazuri. This fully integrated setup ensures a streamlined and highly efficient production process.

To optimise performance and scalability, CARMA-H2 will develop a digital twin, leveraging advanced computational models and control systems to enhance real-time monitoring and process efficiency.

A life cycle assessment will evaluate the CARMA-H2's environmental impact, considering waste streams, biogas sources, and energy inputs. Additionally, CARMA-H2 will assess critical raw material (CRM) usage, ensuring compliance with sustainability and regulatory standards. By combining cutting-edge hydrogen production, circular economy principles, and digital innovation, CARMA-H2 paves the way for decentralised, cost-effective hydrogen generation, supporting Europe's clean energy transition.

NON-QUANTITATIVE OBJECTIVES

CARMA-H2 is more than a technological project—it is a step toward a sustainable hydrogen ecosystem, through:

- Fostering strong collaboration with industry stakeholders and regulatory bodies in the biogas, hydrogen, and CO_2 sectors, ensuring alignment with market needs and evolving policies.
- Creating synergies with European research initiatives, particularly EURAMET's EMPIR program and the European Partnership on Metrology, to enhance hydrogen quality assurance.
- Implementing Guarantees of Origin (GOs) in Spain, to certify the renewable nature of its hydrogen and reinforcing its credibility.
- Engaging directly with end-users across mobility, industry, and energy.
- Exploring real-world hydrogen applications, ranging from urban transport and logistics to metallurgy and power generation.
- Strengthening a circular approach, minimising emissions and maximising resource efficiency by CO_2 utilisation in the agri-food and beverage sectors.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

- Start of design and construction of auxiliary facilities at the Arazuri wastewater treatment plant in Navarra, setting the stage for the installation of the innovative bioPMR.
- Analysis of renewable electricity usage to optimise energy costs and ensure a sustainable power supply for the demonstration phase.
- Ongoing efforts to enhance manufacturing capacity, with new equipment being installed at CTMS's pilot fabrication line to support the production of bioPMR components.
- Launch of CARMA-H2's communication strategy, focusing on engaging multiple audiences through the website and social media.

FUTURE STEPS AND PLANS

- Optimising each stage of the process to maximise efficiency and performance.
- Conducting a comprehensive safety assessment of all sub-systems, ensuring that every component meets the highest standards before full-scale implementation.
- Enhancing the waste-to-biogas conversion process, refining it to achieve higher efficiency and an ideal composition for seamless integration with the bioPMR unit.
- Improving the hydrogen production system by recycling gaseous streams, thereby increasing yield while simultaneously enhancing the value of the CO_2 captured through an upgraded liquefaction unit.
- Technical evaluations including testing the catalytic performance of the Protonic Membrane Reformer under real biogas conditions, alongside verifying the reliability of individual engineering units before full-scale deployment. These steps are crucial to ensuring the robustness and long-term viability of CARMA-H2's innovative technology.

PROJECT TARGETS

Target source	Parameter	Unit	Target	Target achieved?	SoA result achieved to date (by others)	Year for reported SoA result
Project's own objectives	System energy use	kWh/kg	59		64	2020
	System CAPEX	€/(kg/d)	900/2 000		1 250	2020
	System OPEX	€/kg	1.3		1.35	2020

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DJEWELS

DELFZIJL JOINT DEVELOPMENT OF GREEN WATER ELECTROLYSIS AT LARGE SCALE

Project ID	826089
PRR 2025	Pillar 1 - H_2 Production
Call Topic	FCH-02-1-2018
Project Total Costs	41 967 250.00
Clean H_2 JU Max. Contribution	10 999 999.00
Project Period	01-01-2020 - 31-12-2025
Coordinator Beneficiary	HYCC B.V., NL
Beneficiaries	MCPHY ENERGY ITALIA SOCIETA A RESPONSABILITA LIMITATA, BIOMETHANOL CHEMIE NEDERLAND B.V., MCPHY ENERGY DEUTSCHLAND GMBH, INDUSTRIE DE NORA SPA-IDN, HINICIO, MCPHY ENERGY, NOBIAN INDUSTRIAL CHEMICALS BV, NV NEDERLANDSE GASUNIE

http://www.djewels.eu

PROJECT AND GENERAL OBJECTIVES

Djewels demonstrates the operational readiness of 20 MW electrolyser for the production of green hydrogen and fuels in real-life industrial and commercial conditions. It will bring the technology from TRL 7 to TRL 8 and lay the foundation for the next scale-up step; 100 MW on the same site. Djewels will enable the development of the next generation of pressurised alkaline electrolysers, by developing more cost efficient, better performing, high current density electrodes, and is preparing the serial manufacturing of the stack and scale-up of the plant components' balance.

NON-QUANTITATIVE OBJECTIVES

Project development phase:

- Perform the engineering activities for setting up the water electrolysis system.
- Ensure safety performance: (i) completed design; (ii) completed hazard and operability analysis.
- Establish a business case for hydrogen for producing green hydrogen and develop a business plan for large scale upscaling towards 2030.

Operations:

- Evaluate technical and business model performance with regard to predictions through monitoring of system operation.
- Define the optimal operation conditions of the new high density electrode package.
- Demonstrate the reduced footprint of high-pressure alkaline electrolysis versus low pressure systems.
- Demonstrate feasibility of high-pressure alkaline electrolysis to undertake primary grid balancing services.
- Formulate and disseminate project results.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

Technical:

- Finalisation of Djewels basic engineering.
- Technology demonstration of 1 MW stack completed.
- Testing of advanced high current density electrodes on 1 MW stack completed.

Permits:

- Irrevocable environmental permit issued.
- Irrevocable water permit issued.

Financing:

- Wadden fonds subsidy for project development stage approved.
- Tailormade subsidy of 80 M Euros approved by the Dutch state.

Project management:

- Project execution and engineering plan for execution activities has been completed.

FUTURE STEPS AND PLANS

- Finalisation of project contractual agreements in entire supply chain.
- Subsequent move to project execution.
- Start of operations; Q4 2027.

PROJECT TARGETS

Target source	Parameter	Unit	Target	Target achieved?
Project's own objectives	System nominal capacity	MW	20	
	Efficiency degradation @ rated power and considering 8 000 hours operations / year	% increase in energy consumption every year	1.5	
	Energy consumption	kWh/kg	< 52.8	
	CAPEX @ rated power including ancillary equipment and commissioning	M/(t/d)	5.5	
	Flexibility with a degradation <2% year	% of nominal power	3-110	
	Hot start from min to max power	%/secs	20 (ramp up) 100 (ramp down)	

ENDURE

ALKALINE ELECTROLYSERS WITH ENHANCED DURABILITY

Project ID	101137925
PRR 2025	Pillar 1 - H_2 Production
Call Topic	HORIZON-JTI-CLEANH$_2$-2023-01-03
Project Total Costs	2 492 868.75
Clean H_2 JU Max. Contribution	2 492 868.75
Project Period	01-01-2024 - 31-12-2026
Coordinator Beneficiary	STARGATE HYDROGEN SOLUTIONS OU, EE
Beneficiaries	FUNDACION PARA EL DESARROLLO DE LAS NUEVAS TECNOLOGIAS DEL HIDROGENO EN ARAGON, PERMASCAND AB, ZENTRUM FUR SONNENENERGIE- UND WASSERSTOFF-FORSCHUNG BADEN-WURTTEMBERG, UNIVERSITE CATHOLIQUE DE LOUVAIN, FRAUNHOFER GESELLSCHAFT ZUR FORDERUNG DER ANGEWANDTEN FORSCHUNG EV

https://endureh2.com/

PROJECT AND GENERAL OBJECTIVES

The main objective of the ENDURE is to bring the performance and durability of alkaline electrolysers to a new level. More specifically, to drastically decrease the degradation rate and increase the efficiency of alkaline cells and stacks through the development of hierarchically structured flow-engineered monolithic porous transport electrodes, via design/material improvements on stack level, and accelerated testing procedures. If the electrolyser degradation rate could be reduced, it would result in two-fold benefits:

- Lower operating expenditures through lower energy consumption over electrolysers' lifetime.
- Lower capital expenditures through a lower level of oversizing of the balance-of-plant components needed.

Both would positively affect the levelised cost of hydrogen (LCOH).

NON-QUANTITATIVE OBJECTIVES

ENDURE aims to make alkaline electrolysers more durable by drastically reducing the degradation rate of alkaline electrolysis cells and stacks, in order to:

- Reduce carbon emissions and mitigate climate change by enabling the widespread adoption of hydrogen as a clean and sustainable fuel source.
- Reduce the cost of hydrogen production, making it a more competitive fuel source and driving the growth of the renewable energy sector.
- Contribute to the development of a more sustainable and resilient energy system that can balance intermittent renewable energy sources with the need for a stable and continuous energy supply.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

WP1:

- An adopted report for ENDURE on harmonised test protocols provided.
- Baseline stack developed and shipped to FHa for testing.
- EIS measurement device purchased by FHa.
- Adaptations of FHa´s test rig to accommodate the baseline stack and the EIS device.

WP2:

- Via screen printing and doctor blade coated Ni foams have been characterised with X-ray tomography and tested for flow sensitivity.
- Development of a synthesis route for nickel-molybdenum coated electrodes.
- Electrochemical characterisation nickel-molybdenum electrodes showed very high HER and high OER activity.

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WP3:

- Porous material can be effectively simulated.
- Model results show good agreements with experiments.
- First three commercial diaphragm samples characterised for MacMullin number.
- Segmented PTFE gasket approach investigated.

WP4:

- Collection of degradation phenomena and stressors in cooperation with all consortium partners.

WP5:

- The consortium's Dissemination and Communication Strategy is fully defined.
- The consortium's communication tools are fully defined.
- The project website and LinkedIn page were constructed, launched and are running.
- The ENDURE exploitation plan was completed, including both joint exploitation and each partner's individual plans.

WP6:

- Kick-off meeting was held on January 9, 2024.
- Regular consortium meetings held bi-weekly.
- SharePoint folder has been set up.
- A General Assembly meeting was held on September 25, 2024.
- Risks were assessed in M9.

FUTURE STEPS AND PLANS

- Baseline stack is ready and will be delivered to FHA for testing.
- Ongoing testing in WP2 and WP4.
- Work on computer simulations in WP3; sourcing novel gasket materials and starting to build the Prototype Stack.
- General Assembly in Rotterdam.

PROJECT TARGETS

Target source	Parameter	Unit	Target	Target achieved?
Project's own objectives	Baseline degradation profile of a 10-kW electrolysis stack using pre-commercial electrodes at high current density (WP1)	Hours of operation, A/cm² current density	≥500 hours at 1 A/cm² for a prototype stack of ≥5 cells with ≥1 000 cm² electrode footprint	
	Hierarchically structured flow-engineered monolithic porous transport electrodes (PTE) with optimised bubble removal capacity (WP2)	kWh/kg, A/cm², V/cell, temperature (°C), hours	47 kWh/kg at 1 A/cm² and 80°C for 100 hours ≥1.25 A/cm² at ≤1.95V/cell	
	Developing high-performance and PGM-free catalyst coating for the HER and OER (WP2)	mV, A/cm², hours	HER < 150 mV, OER < 250 mV at ±1 A/cm² after 100 hours of electrode testing	
	Upscaling of porous transport electrodes (PTE)	cm²	≥1 000 while maintaining electrochemical performance	
	Low-cost high-performance 10-kW stack prototype	€/kW, cm²	CAPEX target of 150 €/kW for a prototype stack of ≥5 cells with ≥1 000 cm² electrode footprint	
	Testing and validation of innovative stack components (WP4)	kWh/kg, A/cm², number of cells	48 kWh/kg at 1 A/cm² for a laboratory stack of ≥10 cells with ≥100 cm² electrode footprint	
	Degradation profile of a low-cost high-performance 10-kW stack	%/1 000h, hours, cm²	0.1%/1 000h over ≥500 hours for a CRM-free prototype stack of ≥5 cells with ≥1 000 cm² electrode footprint	

EPHYRA

ESTABLISHING EUROPEAN PRODUCTION OF HYDROGEN FROM RENEWABLE ENERGY AND INTEGRATION INTO AN INDUSTRIAL ENVIRONMENT

Project ID	101112220
PRR 2025	Pillar 1 - H_2 Production
Call Topic	HORIZON-JTI-CLEANH$_2$-2022-01-08
Project Total Costs	24 705 752.39
Clean H_2 JU Max. Contribution	17 757 002.50
Project Period	01-06-2023 - 31-05-2028
Coordinator Beneficiary	MOTOR OIL (HELLAS) DIILISTIRIA KORINTHOU A.E., EL
Beneficiaries	ENVIROMETRICS TECHNIKOI SYMVOULOI ETAIREIA PERIORISMENIS EFTHYNIS, INSTITUTO TECNOLOGICO DE ARAGON, SOLUFORCE B.V., STICHTING NEW ENERGY COALITION, ENVIROMETRICS TECHNIKOI SYMVOULOI ANONYMI ETAIREIA, ENERTIME SA, SIEMENS PROCESS SYSTEMS ENGINEERING LIMITED, ETHNIKO KENTRO EREVNAS KAI TECHNOLOGIKIS ANAPTYXIS, RINA CONSULTING SPA, DEUTSCHES ZENTRUM FUR LUFT - UND RAUMFAHRT EV

https://ephyraproject.eu/

PROJECT AND GENERAL OBJECTIVES

EPHYRA will demonstrate the integration of a first-of-its-kind renewable hydrogen production facility at an industrial scale in South-eastern Europe by employing an improved electrolysis technology, at a 30 MW scale. The large-scale electrolysis will be integrated with industrial operations within Motor Oil Hellas's Corinth Refinery, one of the top refineries in Europe and the largest privately-owned industrial complex in Greece. It will be operated for at least two years under commercial conditions and will supply renewable hydrogen to the refinery's processes and external end-users.

The industrially integrated renewable hydrogen production will be developed around a circular economy, industrial symbiotic approach, as the electrolyser will be coupled with (i) renewable electricity production, (ii) an innovative waste heat harvesting technology, (iii) water use environmental optimisation, (iv) valorisation of produced oxygen in current Motor Oil Hellas's refinery operations, (v) a digital twin and (vi) a dedicated energy management system. EPHYRA will contribute to all electrolysis technology key performance indicators as detailed in the Clean Hydrogen Partnership strategic research and innovation agenda objectives. Therefore, EPHYRA will demonstrate the technology's reliability for green hydrogen production at the lowest possible cost thus enabling the EU renewable hydrogen economy, industry decarbonisation and uptake of zero-emission fuels.

NON-QUANTITATIVE OBJECTIVES

- Develop a detailed technology and integration concept for an enhanced electrolysis system.
- Optimise synergies among H_2 production, utilisation, complementary supply, and the valorisation of waste streams (waste heat, oxygen, water), within a circular economy framework.
- Develop a digital twin, controls and automation of the H_2 plant and its (symbiotic) environment.
- Set up and operate the integrated H_2 production plant and complementary supply and valorisation streams (local circular H_2 economy), including standardisation and safety aspects.
- Assess the techno-economic, environmental and societal sustainability of the H_2 production plant and the local circular H_2 economy.
- Achieve sustainable impact by stakeholder engagement, social acceptance and industrial replication (incl. business modelling and development).

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

- Major milestones such as electrolyser procurement, technical validation, and integration planning have successfully been completed.
- A tender process for the procurement of the electrolyser has been launched.
- A comprehensive evaluation of the suggested solutions was conducted, which concluded with METACON AB as the selected vendor.
- A purchase order has subsequently been placed and a solar Power Purchase Agreement (PPA) has been secured.
- A feasibility study has been conducted for integrating an Organic Rankine Cycle (ORC) system with the most cost-efficient scenario identified involving installing ORC in other refinery units rather than directly with the electrolyser by ENERTIME and MOH in providing data for evaluation.
- An economic feasibility of utilising oxygen in the refinery claus unit and a desktop study for the use of oxygen in the FCC unit were also performed. The findings of these studies are critical in guiding investment decisions and ensuring the project's alignment with the overall business strategy.
- Significant activities on digital twin design include the development of a mathematical model of the electrolyser-separator block in gPROMS, the realisation of two configurations of the electrolyser-separator block and the integrated system model, while sensitivity analysis was performed on the steady-state model to identify key performance variables affecting system performance.
- Additional models for optimisation of hydrogen production system configuration to minimise cost, the ORC for waste heat management, as well as renewable energy supply are under development.
- A comprehensive market assessment for large-scale renewable hydrogen production,

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especially in refineries, has been conducted where the significant replication potential in industries such as steel and chemicals was identified. The assessment also emphasised integrating green hydrogen into existing operations for decarbonisation.

- A comprehensive suite of communication and dissemination tools was developed to enhance project outreach and engagement.
- A dedicated project website was launched, serving as a central hub for project-related information and updates.
- Standardised document templates were created to ensure consistency and professionalism in project communications. A LinkedIn project account was established to facilitate networking with industry professionals and policymakers.

FUTURE STEPS AND PLANS

- Completion of the FEED study for the electrolyser, followed by detailed engineering for the integrated industrial green hydrogen production unit in order to precisely define all the technical specifications of the system as well as its operational requirements.
- Conduction of environmental study for the permitting process, as well as the necessary safety studies (HAZID, HAZOP etc) culminating in the final version of the draft safety plan.
- The GO/NO-GO decision is expected in tandem with the selection of the EPC contractor, followed by site preparation and the beginning of the construction phase, leading to the equipment's arrival.
- Conduction of basic and detailed engineering and procurement for the ORC system.
- Refinement of the models developed for the digital twin and the simulation of the auxiliary functions and the energy management system will proceed as planned.
- Further work towards techno-economic, environmental and societal sustainability of the project includes the development of a techno-economic framework and sustainability assessment and a preliminary business plan to assess the project's theoretical feasibility and long-term sustainability.

PROJECT TARGETS

Target source	Parameter	Unit	Target	Target achieved?
Project's own objectives	O_2 production - Base Case	tons/year	19 322	
	Operating hours per year - Base Case	hours/year	3 945	
	O_2 production - Full Load	tons/year	39 184	
	CO_2 savings for project duration - Base Case	ktons/year	52.6	
	Availability - Full Load	%	91	
	H_2 production - Full Load	tons/year	4 898	
	H_2 production - Base Case	tons/year	2 415	
	CO_2 savings for project duration - Full Load	ktons/year	108.1	
	LCOH targeted - Full Load	€/kg H_2	2.6	
	LCOH targeted - Base Case	€/kg H_2	3.3	
	Availability - Base Case	%	45	
	Operating hours per year - Full Load	hours/year	8 000	
	Degradation	%/1 000h	≤0.11	
	Use of critical raw materials as catalysts	mg/W	< 0.6	
	Hot idle ramp time	sec	≤30	
	Cold start ramp time	sec	≤900	
	CAPEX	€/kW	≤ 480 ±10%	
	Current density	A/cm²	> 0.6	
	O&M cost	€/(kg/d)/y	≤ 43±10%	
	Electricity consumption @ nominal capacity	kWh/kg	≤49	

EXSOTHYC

EXSOLUTION-BASED NANOPARTICLES FOR LOWEST COST GREEN HYDROGEN VIA ELECTROLYSIS

Project ID	101137604
PRR 2025	Pillar 1 - H_2 Production
Call Topic	HORIZON-JTI-CLEANH$_2$-2023-01-01
Project Total Costs	2 495 480.00
Clean H_2 JU Max. Contribution	2 495 480.00
Project Period	01-01-2024 - 31-12-2026
Coordinator Beneficiary	STARGATE HYDROGEN SOLUTIONS OU, EE
Beneficiaries	AGFA GEVAERT NV, TECHNISCHE UNIVERSITEIT EINDHOVEN, FRAUNHOFER GESELLSCHAFT ZUR FORDERUNG DER ANGEWANDTEN FORSCHUNG EV, THE UNIVERSITY COURT OF THE UNIVERSITY OF ST ANDREWS

https://exsothyc.com/

PROJECT AND GENERAL OBJECTIVES

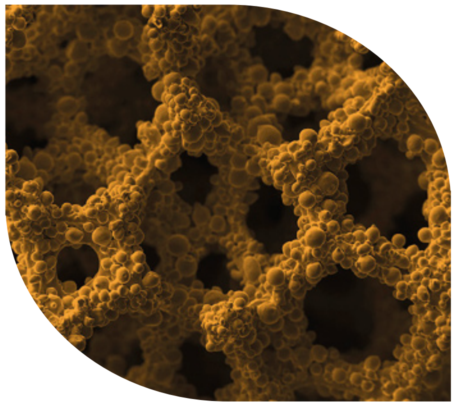
The main objective of the EXSOTHyC is to develop and validate a next generation alkaline electrolyser short-stack prototype with a novel cell design containing disruptive sub-components and breakthrough materials to fulfil the future needs of GW-sized storage of renewable energy.

NON-QUANTITATIVE OBJECTIVES

EXSOTHyC aims to contribute to scientific advances across and within different disciplines like material science, membrane science and engineering, and electrochemistry. EXSOTHyC aims to enhance EU industrial leadership for hydrogen systems and components by creating new materials, catalysts, and production methods that can be applied to other areas of renewable energy and clean technology, thus contributing to standards, the wider adoption of green hydrogen thanks to lower prices, and the growth of the renewable energy sector. EXSOTHyC aims help achieve the Green Deal goals, sustainable energy, energy security, no CO_2 emissions, cleaner air, and a lower environmental impact due to not using platinum group metals and the creation of more green jobs.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

- Obtained overpotential values of 537 mV for oxygen evolution reaction (OER) and 520 mV for hydrogen evolution reaction (HER) at a current density of 10 mA/cm^2 (1 500 rpm, 1 M KOH, 25 °C) for Co, Fe doped $LaAlO_3$ (LACFO) that was reduced at 700 °C.
- For a 0.05% Pt impregnated LACFO sample the overpotential for HER shifted into the 200 mV range. Overpotentials of 213 mV (423 mV @ 100 mA/cm^2) for OER and 163 mV (423 mV @ 100 mA/cm^2) for HER were observed at a current density of 10 mA/cm^2 in 30% KOH at 25°C.
- Novel coated diaphragms have been developed. A trade-off was observed between stability and resistance for all materials. Electrolyser testing with the novel diaphragms showed that the hydrogen-in-oxygen (HTO) can successfully be decreased compared to the reference (down to -50% at 300 mA/cm²) but at the expense of efficiency; further membrane optimisation is required.
- Catalyst coated diaphragms (CCDs) have managed to achieve 0.33 V lower cell potential at 76 °C in 30 wt.% KOH using 2.85 cm^2 large electrodes in comparison to a benchmark with Zirfon 500 and Ni felt.
- Three modified Zirfon PERL UTP 500 membranes (Zirfon B, C, D).



FUTURE STEPS AND PLANS

- Analysis of the LCTNF powder (particle size distribution, SEM/EDX, XRD).
- Optimisation of the ink composition and coating process (CCS).
- Optimisation of the sintering process and conditions (DSE).
- Further electrochemical testing.
- Resolving deposition and binding issues between perovskite oxide catalyst layer and Ni foam, to improve the performance of the structure.

- Further stabilisation of membranes based on polymer B and C.
- Further optimisation in terms of area specific resistance of membranes based on polymer B and C.
- In-situ electrolyser testing of optimised membranes.
- A manuscript for a scientific publication will be developed on the shunt currents.
- Development of reverse current model.
- Experimental work with reference electrode and distribution of relaxation times analysis.
- Testing of next best-performing solutions from the WPs in single-cell configuration.

PROJECT TARGETS

Target source	Parameter	Unit	Target	Target achieved?
Project's own objectives	Development of novel perovskite powders with exsolved nanoparticles highly active-catalyst for the hydrogen and oxygen evolution reaction.	mV	OER < 250 at 10 mA/cm^2, HER < 100 at 10 mA/cm^2	
	Development of DSE (porous substrate coated with the novel catalyst) and CCS for AEL application exhibiting long-term stability and high electrochemical activity.	mV	HER <100 at 0.5 A/cm^2, OER < 250 at 0.5 A/cm^2	
	Diaphragm with reduced HTO (Hydrogen-to-Oxygen) demonstrated.	%	HTO = 0.4 at 50 mA/cm^2	
	Development of catalyst coated diaphragms (CCD) suitable for highly alkaline water electrolysis that lowers the cell potential compared to conventional Zirfon UTP diaphragms without increasing the hydrogen in oxygen content through gas crossover.	V	Cell potential decrease ≥ 0.3 vs. CCS	
	Development and use of a proposed accelerated stress test protocol, mimicking reverse currents during flexible operation combined with advanced cell characterisation.	% per cycle	Degradation rate < 0.0033 (cell level), < 0.0016 (electrode level)	
	Upscaling the prototype sub-components into stack level to be able to fabricate an alkaline electrolysis prototype stack.	cm^2	1 000 per cell (stack active area)	
	Technology validated in a relevant environment – short stack prototype testing.	kWh/kg	< 48 at 1 A/cm^2 (electricity consumption)	

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HERAQCLES

NEW MANUFACTURING APPROACHES FOR HYDROGEN ELECTROLYSERS TO PROVIDE RELIABLE AEM TECHNOLOGY BASED SOLUTIONS WHILE ACHIEVING QUALITY, CIRCULARITY, LOW LCOH, HIGH EFFICIENCY AND SCALABILITY

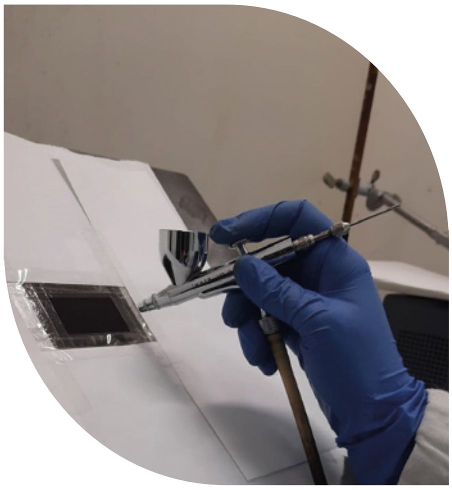
Project ID	101111784
PRR 2025	Pillar 1 - H_2 Production
Call Topic	HORIZON-JTI-CLEANH$_2$-2022-01-04
Project Total Costs	2 342 385.00
Clean H_2 JU Max. Contribution	1 999 622.50
Project Period	01-06-2023 - 31-05-2027
Coordinator Beneficiary	SCHAEFFLER TECHNOLOGIES AG and CO. KG, DE
Beneficiaries	HyGear Fuel Cell Systems B.V., JOHN COCKERILL HYDROGEN BELGIUM, EXENTIS TECHNOLOGY GMBH, HYGEAR OPERATIONS BV, HYGEAR HYDROGEN PLANT BV, HYGEAR TECHNOLOGY AND SERVICES BV, MONOLITHOS KATALITES KE ANAKIKLOSI ETAIREIA PERIORISMENIS EVTHINIS, MANUFACTURE FRANCAISE DES PNEUMATIQUES MICHELIN, HYGEAR FUEL CELL SYSTEMS BV, HYGEAR BV, VLAAMSE INSTELLING VOOR TECHNOLOGISCH ONDERZOEK N.V., CONSIGLIO NAZIONALE DELLE RICERCHE

https://www.schaeffler.com/en/technology-innovation/culture-of-innovation/funded-projects/

PROJECT AND GENERAL OBJECTIVES

HERAQCLES has the following project aims:

- Development of automated manufacturing processes for anion-exchange membrane (AEM) water electrolysers and validate a proof-of-concept 25 kW system operating at 30-50 bar with a hydrogen production rate of about 12.5 kg H_2/d (manufacturing readiness level 5) with detailed design and cost calculation for a 100 MW electrolysis plant.
- Marked increase in operating current density (1A/cm^2 nominal at 1.8 V/cell and 2 A/cm^2 at 2.2 V) while keeping energy consumption < 48 kWh/kg at 1 A/cm^2 with a stack efficiency of 80% in respect of higher heating value (~70% in respect to lower heating value). This will bring an efficiency improvement of at least 2-4 % in respect of the lower heating value compared with the present state-of-the-art in the field of liquid alkaline electrolysers while enabling operation at much higher current density.
- Reduction in capital cost in large scale production (100 MW production volume) to less than 0.6 € million/(tonnes/day H_2). This corresponds to 300 €/kW for a production volume of 100 MW. The development of an automated manufacturing process for a novel stack architecture, the use of non-critical raw materials (cheap Ni-based electrocatalysts, hydrocarbon membranes, and cost-effective Ni-coated stainless-steel bipolar plates), the minimisation of materials use, a simplified balance of plant for differential pressure operation, and the increased current density (according to the Faradays law) will bring a perspective.
- Validation of the durability under steady and intermittent duty cycles conditions in time studies of at least 2 000 hours cumulative (1 000 hours of steady-state and 1 000 hours of cycled operation) with targeted degradation rate lower than 5-7 mV/h at a fixed current density of 1 A/cm^2 corresponding to about 0.2-0.4 %/1 000 h.



- System lifetime of 10 years operation without stack replacement and of 20 years with a single stack replacement (cut-off voltage: 2.4 V).
- Significant reduction in the levelised cost of hydrogen to less than 2-3/kg H_2 with 0.6 € million/(tonnes/day H_2) in capital expenditure and operation and maintenance costs of less than € 20/(kg/day))/year assuming a € 40 /MWh renewable electricity cost and 4 000 h/year of uptime.
- Market competitiveness for green hydrogen targeting a cost of 2-3 €/kg H_2 (theoretically corresponding to about 50-75 €/MWh).

NON-QUANTITATIVE OBJECTIVES

HERAQCLES aims to address new manufacturing approaches for AEM electrolysers to provide reliable AEM technology-based solutions, directly fulfilling targets for the large-scale deployment of cheap green hydrogen. Thus, the project will contribute to the EU policy in terms of limiting the environmental impact of current hydrogen technology applications, minimising materials usage, avoiding critical raw materials, improving the cost-effectiveness of clean hydrogen solutions and reinforcing the EU's scientific and industrial ecosystem.

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HERACLES

FUTURE STEPS AND PLANS

- Testing of Loop 1.
- Stack defining parameters for loop 2 stack.

PROJECT TARGETS

Target source	Parameter	Unit	Target	Achieved to date by the project	Target achieved?
Project's own objectives	Voltage	V	1.8V/cell @ 1A/cm² current density	1.8V/cell at 1A/cm² achieved at single cell level by partner CNR-ITAE.	
	Hydrogen costs	€/kg	2-3		
	Electricity consumption @ nominal capacity	kWh/kg	48 kWh/kg@1A/cm²	48 kWh/kg@1A/cm² achieved for the first period at single cell level by partner CNR-ITAE.	
	CAPEX	€/(kg/d)	600	N/A	
	CAPEX	€/kW	300		
	O&M cost	€/(kg/d)/y	20		
	Degradation	%/1 000h	0.4	Prototype tested for at least 2 000 hours cumulative (steady state/dynamic) with targeted degradation rate at 5-7 µV/h at a current density of 1 A/cm² (0.2 to 0.4 %/ 1 000 h).	
	Current density	A/cm²	1	MEA performance of 1.82 V/cell at 1 A cm-2 and 50°C and 2.2 V at 3.6 A cm-2 was achieved at CNR-ITAE in the presence of a noble metal loading of 0 mg cm-2.	
	Use of critical raw materials as catalyst	mg/W		achieved for the first period at single cell level at partner CNR-ITAE.	

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HOPE

HYDROGEN OFFSHORE PRODUCTION FOR EUROPE

Project ID	101111899
PRR 2025	Pillar 1 - H_2 Production
Call Topic	HORIZON-JTI-CLEANH$_2$-2022-01-10
Project Total Costs	40 287 430.00
Clean H_2 JU Max. Contribution	20 000 000.00
Project Period	01-06-2023 - 31-05-2028
Coordinator Beneficiary	LHYFE, FR
Beneficiaries	STROHM BV, DWR ECO GMBH, FRAMES ENERGY SYSTEMS BV, ERM FRANCE, CNET CENTRE FOR NEW ENERGY TECHNOLOGIES SA, PROVINCIALE ONTWIKKELINGSMAATSCHAPPIJ WEST-VLAANDEREN, ALFA LAVAL COPENHAGEN A/S, COMMISSARIAT A L ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES

https://hope-h2.eu/

PROJECT AND GENERAL OBJECTIVES

HOPE aims to pave the way for the deployment of large-scale offshore production of renewable hydrogen. It involves developing, building and operating the first 10 MW production unit in the North Sea, off the coast of Belgium, by 2026.

The aim is to demonstrate the technical and economic viability of this offshore project, and of pipeline transport for supplying onshore customers. This unprecedentedly large-scale project (10 MW) will be able to produce up to four tonnes a day of green hydrogen at sea, which will be exported to shore through a composite pipeline, and then compressed and delivered to customers for use in industry and the transport sector. HOPE is the first offshore project of this size in the world to begin actual implementation, with the production unit and export and distribution infrastructure due to come on stream in mid-2026.

The production site will be powered by electricity supplied under power purchase agreement contracts that guarantee its renewable origin. The water used for electrolysis will be pumped from the North Sea, desalinated and purified.

The production site will comprise three units: (i) production and compression (at medium pressure) at sea; (ii) export by composite pipeline; and (iii) compression (at high pressure), storage and distribution onshore.

NON-QUANTITATIVE OBJECTIVES

HOPE will make it possible to improve the technological solutions for the production of renewable hydrogen offshore and its export onshore, helping to reduce the investment risks for much larger-scale projects in the years to come and paving the way for the production of massive quantities of renewable hydrogen in Europe.

The grant awarded by the European Commission will be used to finance the design phases, the supply of equipment and the construction work, as well as research, development and innovation work focusing mainly on optimising technological solutions and the operation of this type of infrastructure.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

HOPE's main key innovations under development are:

- Recycled offshore barge: The structure housing the production unit will be a second-hand jack-up barge, demonstrating that it is possible to transform infrastructure previously used for oil and gas and give it a second life for the production of renewable energy, while helping to reduce costs and lead times.
- 10 MW polymer electrolyte membrane electrolyser: This highly compact electrolyser will be the first of its size to be installed offshore.
- Seawater treatment system: This low-energy system which is compact, economical and able to use the heat emitted by the electrolyser, will be used for the first time to produce green hydrogen from seawater purified by evaporation.
- Underwater flexible hydrogen pipeline for hydrogen export: The hydrogen will be exported ashore via a flexible thermoplastic composite pipeline of over 1 km long, which will transport hydrogen produced at sea after being given the technical certification for this specific use.
- Completion of three permit submissions. One of them (H_2 pipeline) has been assessed and amendment is ongoing; routing review to cope with local constraints and associated QRA.
- Completion of basic engineering.
- Initiation of consultation phase.

FUTURE STEPS AND PLANS

- Completion of permit process.
- Procurement LLIFID to be submitted.
- Securing CHCI subsidy (from Belgium).

PROJECT TARGETS

Target source	Parameter	Unit	Target	Achieved to date by the project	Target achieved?	SoA result achieved to date (by others)	Year for reported SoA result
Project's own objectives	PEM Electrolyser electricity consumption @ nominal capacity	kWh/kg	52	54		49	2025
	Degradation	%/1 000h	0.15			0.19	2022
	Cold start ramp time	sec	10	70		30	2022

HYIELD

A NOVEL MULTI-STAGE STEAM GASIFICATION AND SYNGAS PURIFICATION DEMONSTRATION PLANT FOR WASTE TO HYDROGEN CONVERSION

Project ID	101137792
PRR 2025	Pillar 1 - H_2 Production
Call Topic	HORIZON-JTI-CLEANH$_2$-2023-01-05
Project Total Costs	15 512 377.50
Clean H_2 JU Max. Contribution	9 999 964.63
Project Period	01-01-2024 - 31-12-2027
Coordinator Beneficiary	MAGTEL OPERACIONES SL, ES
Beneficiaries	HYDROGEN ONSITE SL, MINCATEC ENERGY SAS, AQUAMBIENTE CIRCULAR ECONOMY SOLUTIONS SL, ARISTENG SARL, CEMEX ESPANA OPERACIONES SL, WASTE TO ENERGY ADVANCED SOLUTIONS SL, SYNHELION SA, HYDROGEN ONSITE, SL, CARTAGO VENTURES SL, SINTEF AS, FUNDACIO EURECAT, ARCELORMITTAL BREMEN GMBH, LA FARGA LACAMBRA SA, CETAQUA, CENTRO TECNOLOGICO DEL AGUA, FUNDACION PRIVADA, ENAGAS SA, AGENCIA ESTATAL CONSEJO SUPERIOR DE INVESTIGACIONES CIENTIFICAS

https://hyield.eu/

PROJECT AND GENERAL OBJECTIVES

The overall objective of HYIELD is to open a new low-cost pathway for clean hydrogen production and waste management to accelerate Europe's progress towards zero-carbon and zero landfill goals. HYIELD aims to build Europe's first large-scale waste-to-hydrogen demonstration plant that will produce over 400 tonnes of green hydrogen during the project. The ambition is to develop a robust and efficient solution that will pave the way for commercial scale-up and replication across Europe, enabling the closure of landfills and production of relevant volumes of low-cost green hydrogen that can help decarbonise sectors such as shipping and heavy industry.

The demonstration plant will utilise WtEnergy Advanced Solutions' CleanTech gasification technology and H_2Site membrane separation reactor and it will be implemented at a CEMEX cement factory in Spain, where the green hydrogen will be utilised in cement production.

NON-QUANTITATIVE OBJECTIVES

- Design a multi-stage gasification, gas cleaning and gas separation process for a beyond state-of-the-art waste to hydrogen plant.
- Gain deeper knowledge of organic waste gasification reactions to identify opportunities to optimise H_2 yield.
- Develop new digital tools and models for optimising performance of waste to hydrogen plants.
- Unlock energy potential in new organic waste feedstock for the waste to hydrogen applications.
- Increase knowledge of planning and regulatory requirements for the implementation of waste-to-hydrogen plants.
- Develop and test a novel water-gas shift membrane reactor at industrial scale.
- Develop and test a novel metal hydride hydrogen storage unit at industrial scale.
- Validate the integrated waste-to-hydrogen plant at near industrial scale and in real-world setting.
- Validate clean hydrogen quality certification and clean hydrogen guarantees of origin for waste-to-hydrogen technologies.
- Benchmark the waste-to-hydrogen solution developed against other clean H_2 pathways.
- Develop a regional scale-up plan for after the project.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

The kick-off meeting, held on the 18th January 2024 in the HQ of WtEnergy Advanced Solutions located in Barcelona and was attended by all partners, along with project and financial officers from the Clean Hydrogen Partnership.

FUTURE STEPS AND PLANS

Work is commencing to define the demonstrator specification and parameters, prepare the site (including permit issuing), develop models and digital tools, and start the communication campaign, among other activities. The second general assembly is planned at the demonstration site in Spain.

PROJECT TARGETS

Target source	Parameter	Unit	Target	Target achieved?	SoA result achieved to date (by others)	Year for reported SoA result
Project's own objectives	System carbon yield	kg H_2/kg C	0.32		0.15	2020
	System CAPEX	€/(kg/d)	2 736		1 806	2020
	System OPEX	€/kg	0.328		0.013	2020
	Conversion efficiency	%	>50		40-50	2020
	Operational hours	hours	>4 000		N/A	N/A
	LCOH at target production	€/kg	< 3		1.8-3.4 (USD/kg)	2020
	Reactor size	MW	≥3		N/A	N/A
	Yearly Hydrogen Production	t/year	≥180		N/A	N/A

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HYP3D

HYDROGEN PRODUCTION IN PRESSURIZED 3D-PRINTED SOLID OXIDE ELECTROLYSIS STACKS

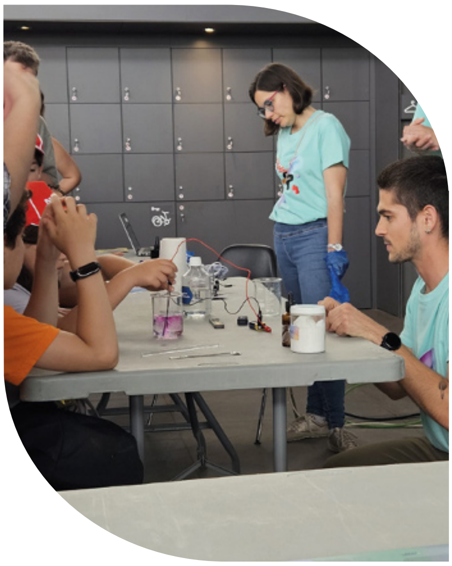
Project ID	101101274
PRR 2025	Pillar 1 - H_2 Production
Call Topic	HORIZON-JTI-CLEANH$_2$-2022-01-01
Project Total Costs	2 543 398.75
Clean H_2 JU Max. Contribution	2 543 398.75
Project Period	01-01-2023 - 31-12-2025
Coordinator Beneficiary	FUNDACIO INSTITUT DE RECERCA DE L'ENERGIA DE CATALUNYA, ES
Beneficiaries	VAC TRON SA, SNAM S.P.A., H_2B2 ELECTROLYSIS TECHNOLOGIES SL, SAS 3DCERAM SINTO, BARCELONA SUPERCOMPUTING CENTER CENTRO NACIONAL DE SUPERCOMPUTACION, POLITECNICO DI TORINO, DANMARKS TEKNISKE UNIVERSITET

https://hyp3d.eu/

PROJECT AND GENERAL OBJECTIVES

The main goal of the HyP3D project is to deliver a new generation of ultra compact high pressure stand-alone solid oxide electrolyser cell (SOEC) stacks able to convert electricity into compressed hydrogen for power-to-gas (P2G) and hydrogen refuelling station (HRS) applications.

HyP3D manufacturing technology represents a breakthrough compared with traditional ceramics SOEC processing due to a significant reduction in the time to market (from years to months), the use of raw material (76% reduction) and the required initial investment (42% reduction from conventional cell manufacturing plants, from the first MW) while introducing great flexibility and scalability of the production lines.



NON-QUANTITATIVE OBJECTIVES

- Develop disruptive electrolyte-supported Solid Oxide Electrolysis Cells based on 3D-printed 3YSZ and 8YSZ with non-flat geometry.
- Design high-pressure sealing based on 3D-printed self-tightening joints and optimised glass sealants with enhanced adhesion by surface modification.
- Fabricate ultra-compact and lightweight kW-range stacks based on 3D-printed HyP3D cells, cost-effective flat coated interconnects and surface-modified sealants.
- Build up a neural network-based digital twin of the HyP3D stack able to run in high performance computing environments.
- Design simple SOEL systems based on standalone HyP3D stacks for the particular applications of H_2 injection in the gas grid and on-site generation for hydrogen refuelling stations.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

- The cell design design has been optimised, taking into account both printing and post-printing processes. The first generation of designed cells feature large active area corrugated membranes (45 cm^2 of projected and 72 cm^2 of real one) with embedded functionalities (gas channels) that allow the use of flat thin (200 μm) interconnects at stack level with foreseen advantages in terms of power densities.
- Large area cells 3D-printing processes (pastes formulation, printing and post-printing) were successfully optimised. 3YSZ 3D-printed cells were produced with good reproducibility, free of cracks and deformation.
- 3YSZ 3D-printed cells were successfully tested at SRU and sub-stack (three cells) level at atmospheric pressure, with performance in line with the literature considering the thickness of the electrolyte and its ionic conductivity; OCV of 0.8 V/cells in SOEC mode, injected current of 25 A corresponding to 0.55 A/cm^2 and 35 W/cell.
- One stack (18 cells) was successfully built and tested in SOEC mode at atmospheric pressure with the following recorded performances: 330 W, corresponding to: 508 W/L, 274 W/kg, 290 mA/cm^2, 3.65 kg/kW.
- Commercial glass-ceramic sealants were successfully modified in order to increase their viscosity at operating temperatures with a refractory behaviour and enhance their resistance to differential pressures and

shear stresses generated during operations in real conditions for HyP3D stacks.

- Laser-milling of metallic interconnects and 3D printed YSZ was developed in order to increase the surface roughness of the metals in the sealing regions. Through increasing the interlocking effect and the resistance to shear stresses a roughness of 5.7 um and 4.9 um was reached respectively for Crofer22APU and YSZ. The developed joints demonstrated excellent compatibility between the interfaced materials with sound and continuous interfaces and good infiltration of the glass-ceramics inside the tracks of the milled materials.
- Interlocking sealing concept was successfully tested at room temperature and under high differential pressures. The joint laser-milled-Crofer22APU/modified glass-ceramic/laser-milled-YSZ demonstrated leakages rates below the detection limit at room temperature with 4 bar applied pressure.
- Compressive sealing concepts for high pressure were also developed by introducing 3D-structures on YSZ thanks to 3D-printing. The developed non-flat sealing geometries are suitable to be coupled with compressive mica-based sealants. The introduction of notches on YSZ improved the gas tightness with respect to the flat geometries up to 5 times at high pressures (5 bar).
  - » HyP3D 3YSZ cells have been demonstrated to withstand up to 1.5 bar of unbalanced pressure across the membrane.
- Protective coatings deposition via EPD (Electrophoretic Deposition) was developed, and the sintering treatment was optimised. The resulting coatings exhibit suitable thicknesses (>10 μm) and satisfactory densification (>80%).
- Initial simplified thermo-mechanical and fluid-dynamic simulations were successfully performed on both cell and SRU models.

FUTURE STEPS AND PLANS

- Increase the level of complexity of the simulations including further elements in the assembly; current collection Ni and Ag foams. By carrying out fluid dynamic simulations of 30 cells hyP3D stack.
- Building and testing HyP3D short stack (five cells) at high pressure.

PROJECT TARGETS

Target source	Parameter	Unit	Target	Achieved to date by the project	Target achieved?
Project's own objectives	Pressure	bar	5	Ambient pressure for SRU and short stacks. HYP3D cells demonstrated to be able to resist up to 1.5 bars of unbalanced pressure across the membrane. The high pressure sealing concepts demonstrated to be able to operate at high pressures (4-5 bars).	
	Power per stack	kW	2.14	0.85 kW by (3 cells sub-stack)	
	Injected current density	A/cm²	-0.9 at 1.3V	-0.55 at 1.4V	
	Use of critical raw materials	kg/kW	0.9	2.2	
	Footprint	kW/L	3.4	0.6	
	Degradation	%/1 000h	1	5	
	Electrical consumption nominal capacity	kWh/kg	38	37.7	✓
	Cold start ramp time	hours	8	3	

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HYPRAEL

ADVANCED ALKALINE ELECTROLYSIS TECHNOLOGY FOR PRESSURISED H_2 PRODUCTION WITH POTENTIAL FOR NEAR-ZERO ENERGY LOSS

Project ID	101101452
PRR 2025	Pillar 1 - H_2 Production
Call Topic	HORIZON-JTI-CLEANH$_2$-2022-01-03
Project Total Costs	3 134 235.00
Clean H_2 JU Max. Contribution	2 653 915.00
Project Period	01-03-2023 - 28-02-2026
Coordinator Beneficiary	FUNDACION PARA EL DESARROLLO DE LAS NUEVAS TECNOLOGIAS DEL HIDROGENO EN ARAGON, ES
Beneficiaries	RHODIA OPERATIONS, SPECIALTY OPERATIONS FRANCE, VECO BV, GREEN HYDROGEN SYSTEMS A/S, Rhodia Laboratoire du Futur, AGFA GEVAERT NV, SOLVAY SPECIALTY POLYMERS ITALY SPA, FRAUNHOFER GESELLSCHAFT ZUR FORDERUNG DER ANGEWANDTEN FORSCHUNG EV

http://hyprael.eu/

PROJECT AND GENERAL OBJECTIVES

HYPRAEL's goal is to develop and validate the next generation of alkaline electrolysis (AEL) for highly pressurised H_2 production (at least 80 bar). In addition, an immense increase in energy efficiency will be made possible by raising the temperature to at least 120 °C. HYPRAEL will achieve these goals and move beyond the state-of-the-art by performing research covering areas from design and advanced assessment of electrocatalysts and polymers to the engineering and process intensification of an innovative cell design in four phases: (i) materials development for pressurised electrolysis with an elevated temperature; (ii) material screening for applicability in pressurised electrolysers (both phases will be performed at lab scale and in a single cell with an area of 10 cm^2, 1-30 bar, 80-120 °C;(iii) scale up of the most promising materials from phase 1 and 2; and (iv) scale up of developed materials and their integration into an advanced stack.

The validation of the components scaled up in phase 3 will be performed in the existing test bench of FHa designed in the frame of the Grid integrated multi megawatt high pressure alkaline electrolysers for energy applications project (Elyntegration) at 60 bar, 120 °C,6-15 kW (pilot scale), whereas the demonstration at the target pressure of above 80 bar, at a minimum temperature of 120 °C and in a cell stack of at least 50 kW capacity will be develop by Green Hydrogen Systems in a new test bench. In addition, the HYPRAEL concept will focus on developing an energy efficient high-pressure electrolyser while addressing the circularity principle of the EU objectives for a carbon neutral economy.

NON-QUANTITATIVE OBJECTIVES

- Contributing to climate neutrality by producing green hydrogen with zero CO_2 emissions and utilising renewable energy, thereby supporting climate change mitigation.
- Advancing industry, innovation, and infrastructure by fostering technological advancements in electrolysis and promoting the development of a sustainable hydrogen infrastructure.
- Enhancing access to affordable and clean energy by providing a renewable energy source and reducing operating costs through high-pressure hydrogen production, eliminating the need for additional compression.
- Promoting responsible consumption and production by optimising resource utilisation, improving efficiency, and minimising environmental impact.
- Strengthening international cooperation by encouraging global partnerships for the development and deployment of green hydrogen technology.

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PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

- Development and testing of long-term stable substrates and Raney Ni-based catalysts for hydrogen and oxygen evolution in high-temperature, pressurised electrolysis.
- Focus on achieving stability in 120°C, 40 wt.% KOH.
- Design of a new test infrastructure to accommodate these extreme conditions, as durability data for materials and sensors under such conditions is limited.
- Insight achieved into the behaviour of the Ni-based catalyst layers on Ni substrates concerning temperature, coating thickness, and substrate form factors through uniform testing.
- Adaption of the IFAM's 3EA test infrastructure in Dresden to measure at temperatures above 100°C, preventing electrolyte contamination from Si or Fe.
- Observation of a slight degradation, which can be attributed to the highly concentrated KOH solution (40 wt%). Even at 80°C, the higher concentration has a negative impact. It is worth mentioning that the catalyst system can be used as a bifunctional system for hydrogen evolution reaction and oxygen evolution reactions.
- Successful coating of AGFA separators using atmospheric plasma spraying, to improve durability under high-temperature, high-pressure electrolysis. The current separators used in state-of-the-art alkaline electrolysers are not designed for increased temperature and pressure. The optimisation strategies focused on pore structure, hydrophilicity enhancement and the thermal stability. Polymers of different families with enhanced stability have been screened for the required temperature and KOH concentration.
- Optimisation of Zirfon membrane through a method developed to reduce gas crossover caused by higher pressure.
- Upgrade of FHA's pilot-scale test bench, with component and control logic selected to meet high-pressure, high-temperature demands.

FUTURE STEPS AND PLANS

- Development of materials for pressurised electrolysis at elevated temperature.
- Screening of materials for applicability in pressurised electrolysers.
- Scale up of developed materials and integration into an advanced stack.
- Validation at relevant environment and scale.

PROJECT TARGETS

Target source	Parameter	Unit	Target	Target achieved?
Project's own objectives	Temperature	°C	120	
	LCOH	€/kg	≤3	
	Pressure	bar	80	
	Energy efficiency	%	improvement 2-4%LHV	
	Long-term stable and highly active materials improving stack durability for harsh environment conditions	%/1 000h	Stack degradation meeting the target of maximum 0.1 %/1 000 h efficiency loss at 1 A/cm^2.	

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HYSCALE

HYSCALE – ECONOMIC GREEN HYDROGEN PRODUCTION AT SCALE VIA A NOVEL, CRITICAL RAW MATERIAL FREE, HIGHLY EFFICIENT AND LOW-CAPEX ADVANCED ALKALINE MEMBRANE WATER ELECTROLYSIS TECHNOLOGY

Project ID	101112055
PRR 2025	Pillar 1 - H_2 Production
Call Topic	HORIZON-JTI-CLEANH$_2$-2022-01-05
Project Total Costs	5 295 799.25
Clean H_2 JU Max. Contribution	5 295 799.25
Project Period	01-06-2023 - 31-05-2027
Coordinator Beneficiary	CUTTING-EDGE NANOMATERIALS CENMAT UG HAFTUNGSBESCHRANKT, DE
Beneficiaries	HyGear Fuel Cell Systems B.V., HYGEAR OPERATIONS BV, HYGEAR HYDROGEN PLANT BV, META, HYGEAR TECHNOLOGY AND SERVICES BV, HYGEAR FUEL CELL SYSTEMS BV, HYGEAR BV, META GROUP SRL, UNIVERZA V LJUBLJANI, BEKAERT NV, DIMOSIA EPICHEIRISI ILEKTRISMOU ANONYMI ETAIREIA, CONSIGLIO NAZIONALE DELLE RICERCHE, DEUTSCHES ZENTRUM FUR LUFT - UND RAUMFAHRT EV, COMMISSARIAT A L ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES

https://www.hyscale.eu/

PROJECT AND GENERAL OBJECTIVES

HYScale aims to upscale an advanced alkaline membrane water electrolysis technology to produce economic green hydrogen at significantly higher current densities than state-of-the-art electrolysers. The technology is free of critical raw materials, fluorinated membranes and ionomers. Unique materials and design allow for cost-effective upscaling.

HYScale focuses on optimising material synthesis – especially membranes, ionomers, electrodes and transport layers – in line with Europe's circular economy plan. A 100 kW stack with an active surface area of 400 cm² will be developed, capable of high-dynamic-range operation at 2 A/cm² at 1.85–2 V and 60°C, producing hydrogen at 15 bar. The final goal is a functional electrolyser system with a capital expenditure target of € 400 kW, validated at technology readiness level 5 in an industrially relevant environment, accelerating technology development and promoting sustainability in Europe.

NON-QUANTITATIVE OBJECTIVES

- Cross-sector collaboration: Forge a dynamic, multidisciplinary ecosystem linking academia, SMEs, and industry to drive innovation and accelerate technology adoption.
- Bridging research and market: Seamless transition from lab-scale breakthroughs to industrial implementation by integrating cutting-edge materials and scalable design strategies.
- Sustainability and circularity: Embrace Europe's circular economy principles by developing a critical raw material–free, eco-friendly technology that promotes long-term sustainability.
- System safety and reliability: Enhance the overall robustness and durability of the electrolyser system through optimised component design, rigorous testing, and strategic safety measures.
- Stakeholder engagement and knowledge transfer: Foster effective communication and dissemination of insights to ensure regulatory alignment, market readiness, and broad societal impact.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

Key achievements include:

- Upscaled materials production: enhancement of the synthesis and reproducibility of critical components—such as the AionFLX membrane and ionomer—with improved strategies to reduce hydrogen crossover and ensure safety.
- Large-area cell development: development of a 400 cm² single cell that not only matches the performance of small-scale cells at lower current densities but also excels at higher current densities, confirming its scalability.
- Durability and efficiency: extended continuous tests have shown faradaic efficiencies exceeding 98% and robust performance over prolonged operation, validating the design's long-term reliability.
- Component optimisation: development of advanced catalyst-coated substrates and improved porous transport layers, reducing catalyst loadings and production time while enhancing mass transport and adhesion.
- System integration and scalability: progress toward a fully integrated 100 kW stack is underway, with ongoing discussions on balance-of-plant design and system-level validation that will elevate the technology to TRL 5.

FUTURE STEPS AND PLANS

- Finalise the upscaling and assembly of the 100 kW electrolyser stack, ensuring all components work harmoniously under realistic operating conditions.
- Conduct comprehensive long-term and dynamic grid-condition tests to validate durability, efficiency, and safety at high current densities.
- Further optimise manufacturing processes, scaling up membrane and catalyst production, to achieve the target CAPEX of 400 €/kW and lower operating expenses.
- Deepen the assessment of the levelised cost of hydrogen and develop robust strategies for market deployment.
- Strengthen collaboration with industrial partners and end-users, ensuring smooth knowledge transfer and regulatory alignment for a successful market launch.

PROJECT TARGETS

Target source	Parameter	Unit	Target	Achieved to date by the project	Target achieved?	SoA result achieved to date (by others)	Year for reported SoA result
Project's own objectives	Active surface area	cm²	400	-		65.5	2021
	System size	kW	100	-		2.4	2021
	Stack performance	A/cm @ 2V/cell	2	-		0.47	2020
	Degradation rate	µV/h	5	5	✓	N/A	N/A
	Single cell performance	A/cm² @2V	2	2		0.7	2024

HYSELECT

EFFICIENT WATER SPLITTING VIA A FLEXIBLE SOLAR-POWERED HYBRID THERMOCHEMICAL-SULPHUR DIOXIDE DEPOLARIZED ELECTROLYSIS CYCLE

Project ID	101101498
PRR 2025	Pillar 1 - H_2 Production
Call Topic	HORIZON-JTI-CLEANH$_2$-2022-01-06
Project Total Costs	3 982 105.00
Clean H_2 JU Max. Contribution	3 982 104.50
Project Period	01-01-2023 - 31-12-2026
Coordinator Beneficiary	DEUTSCHES ZENTRUM FUR LUFT - UND RAUMFAHRT EV, DE
Beneficiaries	GRILLO-WERKE AG, FEN RESEARCH GMBH, HELIOHEAT GMBH, AALTO KORKEAKOULUSAATIO SR, ETHNIKO KENTRO EREVNAS KAI TECHNOLOGIKIS ANAPTYXIS, AGENZIA NAZIONALE PER LE NUOVE TECNOLOGIE, L'ENERGIA E LO SVILUPPO ECONOMICO SOSTENIBILE

https://hyselect.eu/

PROJECT AND GENERAL OBJECTIVES

HySelect proposes a solution to boost the efficiency of solar thermal water splitting by introducing two innovative core devices for the steps of the hybrid sulphur cycle (HYS): (i) a sulphuric acid splitting decomposition/sulphur-trioxide-splitting (SAD-STS) reactor that is spatially decoupled from the solar receiver and is allothermally heated using solid particles and (ii) a sulphur-dioxide-depolarised electrolyser (SDE) that does not use platinum group metals.

The ambition of HySelect is to close the technical gaps and provide the missing links in the overall, complete HYS cycle technology concept, for a realistic overall evaluation of the technology and its scale-up. The innovations to be implemented will lead to highly efficient, long-term and cost-competitive concentrated-solar-technology-driven hydrogen production.

HySelect will:

- Demonstrate the production of hydrogen by splitting water using concentrated solar technologies (CST) with an attractive efficiency and cost, through the hybrid sulphur cycle (HyS).
- Introduce, develop and operate, under real conditions, a complete H_2 production chain focusing on the SAD-STS reactor and an SDE.
- Develop and qualify non-critical materials and catalysts, for integration into plant scale prototype units for both the acid splitting reactor and the SDE unit.
- Combine experimental work with component modelling and overall process simulation culminating in a demonstration integrating HySelect's key units of a solar particle receiver, a hot particles storage system, a splitting reactor and an electrolyser into a pilot plant.
- Establish the HySelect targeted efficiency and costs through testing in a large-scale solar tower, driven with smart operation and control strategies.
- Carry out an overall process evaluation to assess the technical and economic prospects of the HySelect technology, directly linked to the know-how and developments of the sulphuric acid and water electrolysers industries.

NON-QUANTITATIVE OBJECTIVES

- Successful pilot-scale HYS technology demonstration.
- Implementation of sulphuric acid decomposition and SDE devices under industry-compatible and industry-scalable conditions.
- New approach for transferring heat from a solar receiver to endothermic catalytic reactions.
- New catalytic ways to perform SO_3 splitting.
- New sulphur dioxide depolarised electrolysers.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

- Design of flow chart of the HySelect demonstration plant with process simulation results and the main design of all relevant technology blocks is in place.
- Selection of best-performing catalytic formulations for sulphuric acid splitting (SAS), focusing on the technology blocks.
- Design of a modular pilot scale SAS Reactor.
- Investigation of the interface of the SAS reactor with the harvesting of the solar power.
- Commissioning of the solar centrifugal particle receiver.
- Demonstration of an optimised SDE cell and short stack for 50 hours, driving the design of the pilot scale electrolyser.
- Identification and assessment of technical solutions for achieving the target heat recovery. A series of heat exchangers and columns are chosen as the best commercially available technique. A critical element here is the projected cost of all the equipment; an intensive market-search based estimation identifies the essential equipment.

FUTURE STEPS AND PLANS

- Finalisation of the key elements.
- Purchasing, assembly and integration of the technology blocks.
- Conducting experimental campaigns.

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PROJECT TARGETS

Target source	Parameter	Unit	Target	Target achieved?
Project's own objectives	Development of structured SO_3 splitting catalysts with high activity and long-term stability.	%	Loss of activity <10% for at least 3 000 h on stream exposure equivalent via accelerated tests.	
	Development, construction and qualification of optimised SDE stack demonstrating stack costs reduction potential of 2-3 times vs. known analogues without use of platinum group metals.	hours	Operation of at least 100 hours.	
	Scaled-up process plant layouts and techno-economic analysis (TEA) demonstrating an optimised scenario.	€/kg	Hydrogen production cost <5 €/kg.	
	Scaled-up process plant layouts and techno-economic analysis (TEA) demonstrating an optimised scenario.	€k/(kg/day)	Reduction of CAPEX starting from 15.19 in 2024 (design year) to 7.41 k€/kg/day by 2030.	
	Demonstration of on-sun and off sun solar tower testing campaigns with particle receiver prototype.	°C	Temperature drop in hot storage tank < 100 °C for 16 hours.	
	Open access publications in scientific journals.	-	>20	
	Efficient prototype heat exchanger for gas streams SO_2, SO_3, O_2, H_2O.	-	Design and construction	
	Experimental demonstration of HyS process scheme with key units (particle receiver, storage, splitting reactor, electrolyser) integrated into a pilot plant.	%	Average daily solar-to-fuel energy conversion efficiency of > 10 % based on higher heating value (HHV) and direct normal irradiance (DNI).	
	Experimental demonstration of HyS process scheme with key units (particle receiver, storage, splitting reactor, electrolyser) integrated into a pilot plant.	kg/day/m^2 receiver area	Average hydrogen production rates higher than 2.16 kg/day/m^2 receiver area.	
	Scaled-up process plant layouts and techno-economic analysis (TEA) demonstrating an optimised scenario.	€/kg	Reduction of OPEX from 0.59 in 2024 (design year) to 0.30 €/kg by 2030.	
	Demonstration of on-sun and off sun solar tower testing campaigns with particle receiver prototype.	°C	Deliver particles of temperature 900 – 1 000.	
	Gas separation system providing clean SO_2 to the SDE.	-	Design and construction.	
	Presentations at international conferences.	-	> 20	
	Upgrade and improved design of the existing particles-heated, high-efficiency lab-scale prototype sulphuric acid splitting reactor.	hours	Test operation for at least 100 hours.	
	A particles-heated prototype reactor for sulphuric acid splitting.	-	Design and construction.	
	Development of structured SO_3 splitting catalysts with high activity and long-term stability.	%	SO_3 conversion 75 of corresponding thermodynamic value.	✓
	SDE cell and short stack (5 cells) design incorporating Au catalytic materials to eliminate or minimise SO_2 carry-over from anode to cathode.	hours	Demonstration of operation <50h.	✓

HY-SPIRE

HYDROGEN PRODUCTION BY INNOVATIVE SOLID OXIDE CELL FOR FLEXIBLE OPERATION AT INTERMEDIATE TEMPERATURE

Project ID	101137866
PRR 2025	Pillar 1 - H_2 Production
Call Topic	HORIZON-JTI-CLEANH$_2$-2023-01-02
Project Total Costs	2 999 523.00
Clean H_2 JU Max. Contribution	2 999 523.00
Project Period	01-02-2024 - 31-01-2027
Coordinator Beneficiary	INSTYTUT ENERGETYKI, PL
Beneficiaries	SOLYDERA SPA, FUNDACIO INSTITUT DE RECERCA DE L'ENERGIA DE CATALUNYA, FONDAZIONE BRUNO KESSLER, ECOLE POLYTECHNIQUE FEDERALE DE LAUSANNE, DEUTSCHES ZENTRUM FUR LUFT - UND RAUMFAHRT EV, DANMARKS TEKNISKE UNIVERSITET

https://hy-spire.eu/

PROJECT AND GENERAL OBJECTIVES

Hy-SPIRE aims to boost the potential of oxide-based electrolysers (SOEL) by lowering the operating temperature below 700°C, and increasing its flexibility in order to fit with renewable energy source generation profiles. Hy-SPIRE will develop novel cells with low degradation equal to or lower than 0.75% per 1 000 hours, operation at high current densities of 1.2 A/cm^2 and the ability to operate dynamically with fast ramping. Hy-SPIRE will aim to:

- Develop oxygen ion- and proton-conducting cells (O-SOE and P-SOE) on ceramic and metallic supports, therefore analysing a broad range of technological possibilities.
- Develop new cells and stacks beyond the state-of-the-art technology in terms of designs, performance and operation.
- Conduct techno-economic analysis, supported by life cycle assessments to evaluate the project innovations and market potential.
- Define barriers and research directions to achieve SRIA objectives, such as reduction of hydrogen production cost to 3 €/kg by 2030, reduction of CAPEX 520 €/(kg/kW) and OPEX 45 €/(kg/kW).
- Design cells and stacks technologies for large-scale production, tailored for coupling with renewable energy sources and other industry sectors.

NON-QUANTITATIVE OBJECTIVES

- Optimisation of the design and materials of cells in order to allow flexible operation with reduced startup time, rapid cycling and faster stop.
- Application of thin electrolytes which substantially reduce the content of critical raw materials (CRM) in stack repeating units (SRU) paving a way for compact stack design.
- Establishing compact design of solid oxide electrolyser stacks with reduced volume which will be able to operate dynamically and easier to thermally manage.
- Establishing stacks with reduced operating temperature and reduced footprint which will ease the integration of SOEL with renewables and industrial process.
- Demonstration of the scalability of ultra high-temperature sintering which will shorten the fabrication time (by reducing thermal treatments from several hours to minutes) and the energy cost of the fabrication of the electrochemically active components of SOELs.
- Adaptation of existing and newly developed testing protocols for electrolysers which operate at the elevated temperature (i.e., SUSTAINCELL, NewSOC, FCTESQA, SOCTESQA, and the harmonised testing protocols for EU (EU harmonised testing protocols for high-temperature steam electrolysis, 2023)).

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

- Development and adaptation of testing protocols for oxygen-ion conducting solid oxide electrolysers (O-SOE) and proton-conducting solid oxide electrolysers (P-SOE). These protocols build upon and refine existing methodologies from key initiatives such as SUSTAINCELL, NewSOC, FCTESQA, and SOCTESQA, as well as the harmonised EU testing protocols for high-temperature steam electrolysis (2023).
- Establishment of standardised evaluation procedures, enabling reliable performance assessment, durability testing, and benchmarking of O-SOE and P-SOE technologies.

FUTURE STEPS AND PLANS

The developed testing protocols for single-cell Solid Oxide Electrolysers (SOE) with oxygen-ion conducting electrolytes (O-SOE) and proton-conducting electrolytes (P-SOE).

PROJECT TARGETS

Target source	Parameter	Unit	Target	Target achieved?
Project's own objectives	Degradation rate	%/1 000 h	0.75	
	Current density	A/cm²	1.2	
	Thickness of the electrolyte	um	1-2	
	Hot idle ramp time	sec	240	
	Cold start ramp time	hours	6	

MULTIPLHY

MULTIMEGAWATT HIGH-TEMPERATURE ELECTROLYSER TO GENERATE GREEN HYDROGEN FOR PRODUCTION OF HIGH-QUALITY BIOFUELS

Project ID	875123
PRR 2025	Pillar 1 - H_2 Production
Call Topic	FCH-02-2-2019
Project Total Costs	9 751 722.51
Clean H_2 JU Max. Contribution	6 993 725.39
Project Period	01-01-2020 - 31-12-2025
Coordinator Beneficiary	COMMISSARIAT A L ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES, FR
Beneficiaries	NESTE ENGINEERING SOLUTIONS BV, NESTE NETHERLANDS BV, ENGIE ENERGIE SERVICES, NESTE ENGINEERING SOLUTIONS OY, PAUL WURTH SA, SUNFIRE GMBH, NESTE OYJ, ENGIE

http://www.multiplhy-project.eu

PROJECT AND GENERAL OBJECTIVES

MultiPLHY will demonstrate the technological and industrial leadership of the EU in solid oxide electrolyser cell (SOEC) technology with its rated electrical connection of ~3.5 MW, electrical rated nominal power of ~2.6 MWel and a hydrogen production rate of more than 670 Nm3/h. MULTIPLHY's electrical efficiency, 85 % with regard to lower heating value, will be at least 20 % higher than efficiencies of low temperature electrolysers, enabling the reduction of operational costs and the reduction of the connected load at the refinery and hence the impact on the local power grid.

MultiPLHY aims to install and integrate the world's first high-temperature electrolyser (HTE) system on a multi-MW scale at a renewable product refinery located in Rotterdam, in the Netherlands. The project's central element is the manufacturing and demonstration of a multi-MW high-temperature electrolyser and its operation in a renewable product refinery. As a result, MultiPLHY promotes the SOEC based HTE from technological readiness level 7 to 8.

NON-QUANTITATIVE OBJECTIVES

- Scale up technology to the multi-MW level by optimising efficiencies, increasing availability, improving operations and improving stack durability.
- Reduce capital cost and operation and maintenance expenditure by developing a design-to-cost strategy and refining the cost analysis.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

- The high-temperature electrolyser (HTE) and hydrogen process unit (HPU) manufacturing, commissioning and factory acceptance test (FAT) have been successfully achieved. The site was prepared (civil works, piping, mechanical, electrical, automation, instrumentation and IT). Mechanical completion of the system installation has been achieved. Commissioning of the installed equipment has taken place. The HTE is fully operational, the HPU has been operated individually and successful coupling between the HPU and HTE has been achieved.
- The design of the HTE and HPU focused on achieving high efficiency. The H_2 output was confirmed during testing of the Gen 2.1.0 module. During FAT, a quality criterion was set for an electrical consumption below 42 kWh/kgH_2. The twelve modules passed this criterion, which is an important milestone towards the final objective of 84 % LHV efficiency. The final assessment of both the efficiency and LCOH will be performed during the demonstration period.
- A service and maintenance concept has been defined. The tests performed on the Gen 2.1.0 module and HPU already contribute to a better knowledge of their reliability. The real availability will be monitored during the operation phase. Ahead of this phase, NESTE operators have been trained to operate the unit and to intervene in case of maintenance/incident. In addition, in order to minimise the downtime, spare components have been ordered and stored close to the unit for replacement as soon as possible, if needed.
- Sunfire stacks and CEA stacks have been successfully tested first in the 2-to-5 kWDC range, then, following upscaling efforts, in the 10-to-20 kWDC range. A total of more than 42 000 hours of operation was accumulated, placing MULTIPLHY at the forefront of projects in terms of durability testing, and at the scale of large stacks. ASR degradations below 15 mOhm cm²/kh, and even as low as 11 mOhm cm²/kh for some test sequences, have been measured on the latest Sunfire generation of stack.
- The operation strategy applied to both stacks, consisting of degradation compensating by an increase of the temperature resulted in stack operation without production loss.
- Reduction of capital cost and of operation and maintenance expenditures.

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- A design-to-cost strategy has been developed and the cost analysis will be refined taking into account operational data that can only be completed when the integration with the refinery is done.
- Techno-economic evaluations have been performed, providing methodology and reference values for several scenarios. Selected use cases of the steam electrolysis technology related to the production of hydrogen in biofuels refinery have been proposed and the techno-economic specifications of the SOEC system designed for industrial application have been determined. The results obtained so far show that the bigger the plant: (i) the higher the impact of electricity prices and efficiency and CAPEX total integration cost, and (ii) the lower the impact of CAPEX Stack. Lastly, in all scenarios high full load hours and lower discount rates are beneficial. Based on the aforementioned results, recommendations for future projects can be formulated.
- Attempts have been undertaken to have MultiPLHY's hydrogen certified that has proven to be a complicated and expensive process. For that reason, the certification of the hydrogen's origin was deemed neither relevant nor feasible.
- Three options for sourcing of renewable power have been described. Guarantee of origin (GO) purchase and contractualisation was found to be the only feasible option. However, the regulatory context and the RE supply options evaluated are not favourable. Due to the fact that in the end the origin of hydrogen produced in MultiPLHY will not be certified, it is not relevant to purchase renewable electricity.

PROJECT TARGETS

Target source	Parameter	Unit	Target	Target achieved?	SoA result achieved to date (by others)	Year for reported SoA result
Project's own objectives	Demonstration duration	hours	as long as possible over year 2025		longest operation reported at system level is also by Sunfire > 15 000 h (Grinhy sequence of projects)	2023
	Downtime	%	2		98%	N/A
	H_2 production loss	% / 1 000 h	1.2	✓	1.9	2017

NOAH$_2$

NOVEL SOE ARCHITECTURES FOR HYDROGEN PRODUCTION

Project ID	101137600
PRR 2025	Pillar 1 - H_2 Production
Call Topic	HORIZON-JTI-CLEANH$_2$-2023-01-02
Project Total Costs	2 656 024.00
Clean H_2 JU Max. Contribution	2 655 084.00
Project Period	01-01-2024 - 31-12-2026
Coordinator Beneficiary	DANMARKS TEKNISKE UNIVERSITET, DK
Beneficiaries	LIBERTY POWDER METALS, GENVIA, SINTEF AS, HAUTE ECOLE SPECIALISEE DE SUISSE OCCIDENTALE, COMMISSARIAT A L ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES, IDRYMA TECHNOLOGIAS KAI EREVNAS

https://noah2.dtu.dk/

PROJECT AND GENERAL OBJECTIVES

The overall goal of the NOAH$_2$ project is to provide a robust, cost-competitive, flexible, and durable stack concept for hydrogen production at intermediate temperatures through innovative electrode, cell, and stack designs. NOAH$_2$ will boost the electrolysis performance of solid oxide cells and stacks significantly beyond state-of-the-art through a combination of optimised structures and highly active materials, with a focus on reducing critical raw materials (CRM) and manufacturability using well-established large-scale routes for solid oxide technology. The NOAH$_2$ stack architecture relies on a metal based monolithic concept with infiltrated electrodes.

NOAH$_2$ will outline a path towards commercialisation, provide a sustainability classification with emphasis on substituting CRMs and an assessment of commercialisation potential compared to state-of-the-art SOEL, PEM, and alkaline electrolysers, and identify potential industrial players for high-volume manufacture.

Specific technical objectives for NOAH$_2$ are to:

- Reduce the costs of SOEL stacks by 50 % compared with that of state-of-the-art through (i) use of metallic instead of ceramic supporting components, (ii) integration of support layer/interconnect functionalities into a single layer, and (iii) reduction of the stack volume with at least 20 % by developing a metal based monolithic structure.
- Increase the hydrogen production rate (current density) by 20 % compared with that of the state-of-the-art, reaching 1.2 A/cm^2, through innovative electrode materials and structuring with infiltration of materials of superior electro catalytic activity at temperatures below 700 °C.
- Demonstrate commercially viable durability with degradation rates below ~0.75%/1 000 hours at the stack level.
- Reach SOEL operation in less than six hours from cold state and less than 240 seconds from hot state to enable fast dynamic operating modes, facilitated by the compact, metal based monolithic stack architecture and highly active electrodes.

NON-QUANTITATIVE OBJECTIVES

NOAH will:

- Outline a path towards commercialisation in terms of projecting costs for large scale manufacture towards MW and GW scales, reaching the 2030 targets of capital expenditure ~ 520 €/(kg/day) and operational expenditure (OPEX) ~ 45 €/(kg/day)/year.
- Provide a sustainability classification (life cycle analysis) with an emphasis on replacing critical raw materials.
- Provide an assessment of commercialisation potential compared with those of state-of-the-art SOEL, polymer electrolyte membrane, and alkaline electrolysers.
- Identify and engage with potential industrial players for high-volume manufacturing and further up-take of the project results.

PROJECT TARGETS

Target source	Parameter	Unit	Target	Target achieved?	SoA result achieved to date (by others)	Year for reported SoA result
Project's own objectives	Cell Current Density	A/cm^2	1.2		1	N/A
	Stack durability	%/1 000 h	<0.75		0.75	N/A
	Stack production costs	%	50		2 737 €/kWel - 1 210 €/kWel	2020
	Reach time to SOEL operation	hours from cold state	6		>6	N/A

OUTFOX

OPTIMIZED UP-SCALED TECHNOLOGY FOR NEXT-GENERATION SOLID OXIDE ELECTROLYSIS

Project ID	101101439
PRR 2025	Pillar 1 - H_2 Production
Call Topic	HORIZON-JTI-CLEANH$_2$-2022-01-09
Project Total Costs	2 925 824.50
Clean H_2 JU Max. Contribution	2 925 824.00
Project Period	01-02-2023 - 31-01-2027
Coordinator Beneficiary	NEDERLANDSE ORGANISATIE VOOR TOEGEPAST NATUURWETENSCHAPPELIJK ONDERZOEK TNO, NL
Beneficiaries	LINQ CONSULTING AND MANAGEMENT LTD, TEKNOLOGIAN TUTKIMUSKESKUS VTT OY, CONVION OY, ELCOGEN OY, AKTSIASELTS ELCOGEN, FONDAZIONE POLITECNICO DI MILANO, SHELL GLOBAL SOLUTIONS INTERNATIONAL BV, POLITECNICO DI MILANO

http://outfoxproject.com

PROJECT AND GENERAL OBJECTIVES

The main objective of OUTFOX is to remove scale as a limiting factor in the deployment of oxide-based electrolysers (SOEL) technologies while proving their potential to become the preferred option for green hydrogen production. By combining experimental results up to the 80 kW scale with the identification of optimal cell, stack and system designs, OUTFOX will prepare SOEL for industrial scale systems of 100 MW with a levelised cost of hydrogen as low as 2.7 €/kg H_2 and applicability to mass manufacturing lines.

NON-QUANTITATIVE OBJECTIVES

OUTFOX will lead to the realisation of ground-breaking large geometric area electrolysis cells, a novel stack and module architecture and new approaches for reproducible, high-volume manufacturing. OUTFOX aims to overcome the current economic and technological SOEL roadblocks, and push Europe into the forefront of the green hydrogen technological landscape.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

Cell development:

- Reference cells for short stack and first batch 80 kW demonstration have been manufactured successfully; over 1 000 cells have been manufactured and delivered.
- OUTFOX is developing two types of scaled-up cells: (i) industrial cells with a cell area ≥300 cm^2 by ELCOAS, (ii) next generation cells with a cell area up to 900 cm^2. Industrial scaled-up cells have been developed and manufactured and have been electrochemically tested at the beginning of 2025. Next generation cells have been developed and manufactured. A current density of 1.15 A/cm^2 has been achieved at thermonetural voltage at 750 °C. The cell has been operated at minimum 0.85 A/cm^2 for more than 2 000 hours.

Stack development:

- Three reference short stacks (with 15 cells) have been manufactured. Stack 1 and 2 have cells with 400 micron thickness, while stack 3 has cells with 300 micron thickness.
- The reference stacks have been tested electrochemically under 0.5 and 0.85 A/cm^2. Each test involved a durability test under predetermined nominal operation up to 2 000 hours.

System development and module scale-up:

- A modelling tool based on computational fluid dynamics has been developed to explore aspects of SOEC stack scaling by design, considering various constraints relating to the physics of flow distribution, thermomechanics, and current density.
- The conceptual design of a larger system module using scaled-up stack is in progress. The design of 80 kW module has been updated.

Techno-economic analysis, circularity, roadmap to pilot:

- A plant/system model has been developed successfully for techno-economic and scale-up analysis. The developed system model is able to capture the plant's modularity, from the stacks to the full-sized plant, with expected capacities up to hundreds of MWel and GWel.
- Techno-economic analysis has been initiated.

FUTURE STEPS AND PLANS

- Validation of electrochemical performance of industrially scaled-up cell as single repeating unit.
- Determining an optimal cell size for near-future large-scale SOEL.
- Optimising industrial manufacturing process for scaled-up cells.
- Delivering stacks for 80 kW (first phase testing campaign).
- Installing and validating an 80 kW system in a relevant environment.

PROJECT TARGETS

Target source	Parameter	Unit	Target	Target achieved?
Project's own objectives	Current density	A/cm^2	0.85	in progress
	Levelised Cost of Hydrogen	€/kg	2.7	
	Module size	kW	400	
	Footprint	m^2/MW	< 150	
	Cell area	cm^2	300 - 900	✓

PEACE

PRESSURIZED EFFICIENT ALKALINE ELECTROLYSER (PEACE)

Project ID	101101343
PRR 2025	Pillar 1 - H_2 Production
Call Topic	HORIZON-JTI-CLEANH$_2$-2022-01-03
Project Total Costs	2 504 965.00
Clean H_2 JU Max. Contribution	2 504 964.75
Project Period	01-06-2023 - 31-05-2026
Coordinator Beneficiary	DEUTSCHES ZENTRUM FUR LUFT - UND RAUMFAHRT EV, DE
Beneficiaries	MATERIALS MATES ITALIA SRL, HYCC B.V., BRANDENBURGISCHE TECHNISCHE UNIVERSITAT COTTBUS-SENFTENBERG, GRANT GARANT SRO, TECHNISCHE UNIVERSITEIT EINDHOVEN, DANMARKS TEKNISKE UNIVERSITET

http://www.h2peace.eu/

PROJECT AND GENERAL OBJECTIVES

PEACE aims to develop a high-pressure alkaline electrolysis (AEL) technology to substantially reduce hydrogen production costs, enhancing the competitiveness of the hydrogen economy. A new concept of hydrogen production with two-stage pressurisation will be developed and demonstrated on an AEL system of more than 50 kW capable of operating at pressures exceeding 50 bar. The integration of advanced components, innovative design, and optimised operation strategies will be explored through modelling and experimental testing, ultimately aiming to demonstrate a system with impressive efficiency characteristics.

The PEACE-produced hydrogen will be already compressed, representing a significant advantage for its subsequent use in downstream processes operating with compressed hydrogen – reducing a significant share of CAPEX and OPEX of an electrolysis system for the chemical sector. PEACE places a strong emphasis on sustainability and circularity aspects – a life cycle assessment of the PEACE technology will be conducted to quantify its environmental impacts.

NON-QUANTITATIVE OBJECTIVES

The main goal of PEACE is to reduce the levelised cost of hydrogen for green H_2 production, through:

- High-efficiency stack development by incorporating advanced and qualified components that are free of precious metals.
- Implementation of an innovative two-stage pressurisation concept to decrease the compression costs for downstream integration.
- Balance of plants and auxiliary optimisation and qualification with a focus on the high-pressure operation.
- Technology demonstration by constructing and operating a newly developed pressurised and high-efficiency stack of > 50kW.
- Effective integration of the PEACE technology with downstream chemical plants to directly use the PEACE-produced hydrogen.
- Reduction of the capital cost of the system by increasing stack efficiency, reducing compression need and optimising the plant's balance.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

- The combination of advanced cell components based on non-precious materials has shown performances of at least 1.8 V to 1.95 V @ 1 A/cm^2.
- The qualifications of non-precious components are expected to reduce the costs for the structural parts of the stack and the exclusion of fluorinated plastic from the list of materials.
- The simulation scenarios have been established for the up-stream and down-stream integration and operation optimisation considering a combination of solar and wind power supplied, and two possible downstream processes: ammonia or methanol production.
- Implementation of a solid Data Management Plan based on FAIR data policy.
- Project communication strategy towards multiple audiences underway based on PEACE website (https://www.h2peace.eu/), and PEACE LinkedIn and X profiles.
- Dissemination and Exploitation Plan and quarterly issuance of PEACE Newsletter.

FUTURE STEPS AND PLANS

- Qualification of various cell- and stack components under pressurised conditions.
- Assembling of the PEACE AEL stack demonstrator with the best-performing components.
- Demonstrator enrichment with dual-stage pressurisation concept.
- Demonstrator in operation; evaluation of function, performance and characteristics simulations
- In depth analysis of sustainability and circularity aspects.

PROJECT TARGETS

Target source	Parameter	Unit	Target	Target achieved?	SoA result achieved to date (by others)	Year for reported SoA result
Project's own objectives	Max current density	A/cm^2	1.45		0.6	2020
	Overall system efficiency	%	68-72		66.7	2020
	Nominal current density	A/cm^2	1		0.6	2020
	Minimal load	% of nominal load	14		30%	2021
	Voltage efficiency (LHV)	%	62-75		55 - 62	2021
	Minimum pressurisation level	bar	50		30	2023
	Cell voltage	V	1.65-2		1.9 - 2.3	2018 - 2019
	Use of critical materials	mg/W			0.6	2020
	Specific energy use, sys	kWh/kg	49		50-59	2020
	Minimum stack size	kW	50			
	LCOH	€/kg	3		5	2020

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PH$_2$OTOGEN

ACCELERATION OF PHOTOCATALYTIC GREEN HYDROGEN PRODUCTION TO MARKET READINESS THROUGH VALUE-ADDED OXIDATION PRODUCTS

Project ID	101137889
PRR 2025	Pillar 1 - H_2 Production
Call Topic	HORIZON-JTI-CLEANH$_2$-2023-01-04
Project Total Costs	2 498 813.75
Clean H_2 JU Max. Contribution	2 498 813.25
Project Period	01-01-2024 - 30-06-2027
Coordinator Beneficiary	TOYOTA MOTOR EUROPE NV, BE
Beneficiaries	SOLARONIX SA, HELMHOLTZ-ZENTRUM BERLIN FUR MATERIALIEN UND ENERGIE GMBH, STICHTING NEDERLANDSE WETENSCHAPPELIJK ONDERZOEK INSTITUTEN, LGI SUSTAINABLE INNOVATION, ECOLE POLYTECHNIQUE FEDERALE DE LAUSANNE, COMMISSARIAT A L ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES, FRIEDRICH-ALEXANDER-UNIVERSITAET ERLANGEN-NUERNBERG

https://ph2otogen.eu/

PROJECT AND GENERAL OBJECTIVES

PH$_2$OTOGEN aims to generate solar hydrogen through a photocatalytic reaction. While most research on photocatalytic hydrogen generation focuses on the splitting of water to form hydrogen and oxygen, PH$_2$OTOGEN aims to couple hydrogen generation with the oxidation of an organic molecule, such as glycerol oxidation to 1,3-dihydroxyacetone (DHA), instead of oxygen formation. Some of the advantages are:

- Avoidance of the concomitant production of hydrogen and oxygen, which can result in a formation of an explosive mixture.
- Since hydrogen (gas) and DHA (oil) are in different states, they can be separated without the need for specially engineered membranes.
- The value of DHA is around 50 times higher than glycerol as a starting material, unlocking other possible revenue stream and accelerating the market-introduction of green hydrogen.

PH$_2$OTOGEN will develop two types of efficient light-absorbing semiconductor materials: (i) a hydrogen evolving particle, and (ii) an oxidising particle.

Through efficiency and stability testing of candidate materials on laboratory scale and advanced analysis, PH$_2$OTOGEN will provide insights into degradation mechanisms and identify countermeasures to solve these issues. The particles will be deposited on a novel transparent, conductive, porous support to allow electronic (electrons and holes) transfer between the two particle types. The synthesis of most promising materials will be scaled up and tested outdoors in a 500 cm^2 device, with a target of 5% solar to hydrogen efficiency. The technical studies, performance data and lifecycle and technoeconomic assessment will be used to select the most promising materials for scale-up and to build a business case. The technology readiness level (TRL) is expected to increase from 2-3 to 5.

NON-QUANTITATIVE OBJECTIVES

- Development of novel semiconductors and co-catalysts for hydrogen evolution and glycerol oxidation.
- Building and outdoor testing of a scalable demonstrator capable of concomitant hydrogen evolution and glycerol oxidation.
- Lifecycle, technoeconomic and market analysis of the materials and device to establish a business case.
- Advanced material analysis to elucidate degradation mechanisms and develop countermeasures.
- Engagement with research communities (through publications, conference presentations, social media and webinars) and the general public (through social media and outreach events).

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

In the first year, PH$_2$OTOGEN focused on benchmarking semiconductor and co-catalyst materials for hydrogen evolution (HEP) and oxidation (OP) reactions using half-cell testing.

Key outcomes:

- **HEP Progress:**

  Organic semiconductors showed promising photocurrents (onset at 0.8 V), outperforming WSe^2. MoSx co-catalysts were developed and validated to boost hydrogen evolution.

- **OP Progress:**

  $BiVO_4$ (via SILAR method) and an organic semiconductor were top candidates.

  $BiVO_4$ demonstrated excellent long-term stability and has been tested under accelerated solar stress.

  MnOx was the most effective co-catalyst for glycerol oxidation.

- **Device Development:**

  A version 1 tandem device using best-performing OP and HEP is being designed for early testing. A novel transparent porous conducting support based on FTO-coated quartz felt has been scaled and improved with regard to conductivity and stability. A 0D model has been developed to simulate hydrogen production efficiency and to guide device design.

- **Sustainability and Market Impact:** Techno-economic analysis and life time assessment inventories have been completed. Glycerol supply has been identified as limiting factor for potential integration into hydrogen and green chemical sectors.
- **Communication and Outreach:** LinkedIn engagement reached 289 followers and two newsletters were released; dissemination targets are on track.

FUTURE STEPS AND PLANS

- Testing of promising HEP and OP in a tandem configuration.
- Development of techniques to deposit HEP and OP onto the TPCS.
- Setting up reparation activities for reactor building and small-scale testing, coupled with modelling studies to optimise the reaction design to be realised in 2026.
- Preliminary assessment of the environment impact and reactor cost.
- Continuation of dissemination and communication activities with conference participation and publications.

PROJECT TARGETS

Target source	Parameter	Unit	Target	Achieved to date by the project	Target achieved?	SoA result achieved to date (by others)	Year for reported SoA result
Project's own objectives	Develop stable and efficient tandem system	%, cm^2	Average of >5% solar-to-hydrogen (750 mmol m-2 h-1) over 500 hours with oxidation reaction forming a value-added product (> 70% purity) Size: 5 - 10 cm^2	-	⚙	H_2 production rate: 20.35 mmol·m−2·h−1	2025
	Lifecycle assessment (LCA) and technoeconomic analysis (TEA) studies to establish competitive advantage	-	LCA and TEA ready for use by partners.	Materials and process inventory prepared for TEA and LCA		TEA done for photoelectrochemical system - demonstrated to be highly competitive, LCA study done of H_2 production coupled with hydrogenation reaction	2024
	Develop stable and efficient oxidising particle (OP)	%	Activity for oxidation (tentative target: >4 mA cm-2 at 0.6 V) that matches 5% solar-to-hydrogen under sacrificial conditions over 500 hours	Photocurrent of 2.5 mA cm-2 at 0.6 V		Photocurrent of 2 mA cm-2 at 0.6 V	2024
	Demonstration device with power density 25 kWh / m2	kWh / m^2, cm^2, %	Cumulative H_2 production: 25 kWh / m2 (over 500 hours) Performance: Average of >5% solar-to-hydrogen over 500 hours with oxidation reaction forming a value-added product (>70% purity) Size: 500 cm^2	-		0.4% STH, 1 m2 (for overall water splitting)	2018
	Develop stable and efficient hydrogen evolving particle (HEP)	%	Activity equivalent to >5% solar to hydrogen efficiency (tentative target > 4 mA cm-2 at 0.6 V) under sacrificial conditions over 500 hours	2.1 mA cm-2		<0.3 mA cm-2 at 0.6 V	2022
	Modelling to define flow rates with quantitative agreement with results	-	Qualitative agreement of the model with experimental results	0D model complete which indicates sensitivity to different parameters including ionic conductivity		N/A	N/A

Clean Hydrogen Partnership
Co-funded by the European Union

PILOTSOEL

ADVANCED PROCESSES ENABLING LOW COST AND HIGH PERFORMING LARGE SCALE SOLID OXIDE ELECTROLYSER PRODUCTION

Project ID	101112026
PRR 2025	Pillar 1 - H_2 Production
Call Topic	HORIZON-JTI-CLEANH$_2$-2022-01-04
Project Total Costs	2 000 000.00
Clean H_2 JU Max. Contribution	2 000 000.00
Project Period	01-06-2023 - 31-05-2026
Coordinator Beneficiary	DANMARKS TEKNISKE UNIVERSITET, DK
Beneficiaries	SIA NACO TECHNOLOGIES, ELCOGEN OY, BENEQ OY, AKTSIASELTS ELCOGEN, UNIVERZA V LJUBLJANI

https://pilotsoel.dtu.dk/

PROJECT AND GENERAL OBJECTIVES

PilotSOEL will focus on innovative upscalable and low-cost solid oxide electrolysis (SOEL) component manufacturing processes, with reduced use of critical raw materials and increased waste recycling in the cell production processes, as well as and increased degree of automation in the stack assembly to reduce manufacturing cost.

PilotSOEL will develop a novel environmentally friendly water-based tape-casting process with a reduced number of process steps for half-cell production. Innovative thin protective barrier layers deposited by atomic layer deposition and physical vapour deposition, together with microstructural cell optimisation, will reduce the cell resistance, thus improving the cell performance and durability at high current operation.

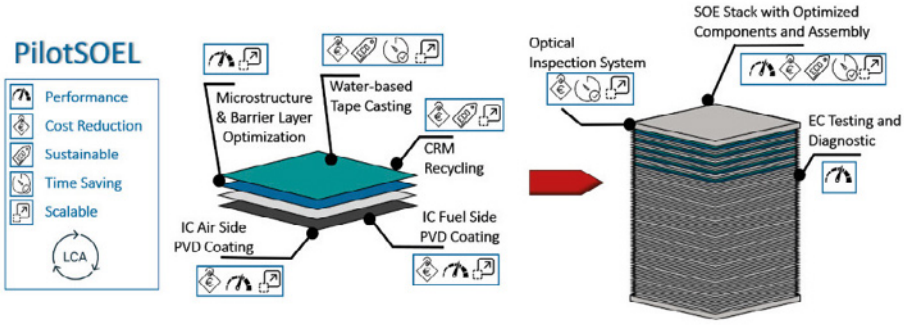
The dense and thin coating made by physical vapour deposition will improve the oxidisation resistance of the interconnector, allowing the use of cheaper alloys, and ensuring a long stack lifetime. A life-cycle assessment and a techno-economic analysis will be performed to benchmark the developed processes in PilotSOEL with the state-of-the-art SOEL production processes. PilotSOEL aims to improve the SOEL processing manufacturing readiness level (MRL) from MRL 4 to at least MRL 5 by the end of the project.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

- A review of the list of coating candidates for the air and fuel sides of interconnector plates has been undertaken.
- Design of Optical Inspection System (OIS) for stack assembly automation and quality assurance has been finalised.

FUTURE STEPS AND PLANS

PilotSOEL will continue working on optimising the manufacture routes for SOEL cell, characterising the manufactured cells and stacks, SOEL inter-connector coating and stack assembly with improved optical inspection systems.



PROJECT TARGETS

Target source	Parameter	Unit	Target	Target achieved?
Project's own objectives	Stack assembly	kW	20	
	Waste material recycle	%	Up to 100% recycle of waste tapes and comparable mechanical and electrochemical performance of the cell	
	Cells produced by water based tape casting process	Number of cells	30	
	Stack assembly defect recognition	%	> 95% accuracy in defect recognition by optical inspection system	
	Interconnector coating degradation	mOhm. cm^2	5 (after 3 000 hours)	✓

PRESSHYOUS

PRESSURIZED HYDROGEN PRODUCED BY HIGH TEMPERATURE STEAM ELECTROLYSIS

Project ID	101101337
PRR 2025	Pillar 1 - H_2 Production
Call Topic	HORIZON-JTI-CLEANH$_2$-2022-01-01
Project Total Costs	2 499 426.00
Clean H_2 JU Max. Contribution	2 499 426.00
Project Period	01-09-2023 - 31-08-2026
Coordinator Beneficiary	COMMISSARIAT A L ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES, FR
Beneficiaries	HyGear Fuel Cell Systems B.V., GENVIA, HYGEAR OPERATIONS BV, HYGEAR HYDROGEN PLANT BV, TEKNOLOGIAN TUTKIMUSKESKUS VTT OY, HYGEAR TECHNOLOGY AND SERVICES BV, AKTSIASELTS ELCOGEN, HYGEAR FUEL CELL SYSTEMS BV, HYGEAR BV, HAUTE ECOLE SPECIALISEE DE SUISSE OCCIDENTALE, ECOLE POLYTECHNIQUE FEDERALE DE LAUSANNE, NEDERLANDSE ORGANISATIE VOOR TOEGEPAST NATUURWETENSCHAPPELIJK ONDERZOEK TNO

PROJECT AND GENERAL OBJECTIVES

PressHyous aims to deliver relevant scientific insights on solid oxide electrolysis (SOEL) hydrogen production under pressure and to therefore foster rapid industrial empowerment, through the following goals:

- A validated lab-scale 30 bar/20 kWe stack in a pressurised vessel.
- A 10 bar pressurised stack operated without needing a pressure vessel.

NON-QUANTITATIVE OBJECTIVES

PressHyous aims to optimise individual components in large-scale HP SOEL systems using modelling tools. Currently, SOEL-stacks operate at atmospheric pressure, but pressurised operation has only been shown on a limited scale. PressHyous aims to develop a pressurised SOEL system capable of operating up to 30 bar using a pressure vessel, demonstrating its functionality at a 20 kWe scale. This will positively impact downstream equipment sizing and costs, and reduce energy consumption for compression. PressHyous will also allow for the reduction of the number of compression stages, reducing energy consumption for compression. The lack of specification for H_2 delivery conditions renders life cycle assessment results hardly comparable. A life cycle assessment of a pressurised H_2 production process based on PressHyous concepts will help identify major environmental aspects and analyse the environmental benefits of energy system integration throughout the project's use cases.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

- Definition of use cases with advisory board.
- System modelling and hazard identification to assess the feasibility of configurations in relation to the selected case studies and provide feedback for the development of stacks and system.
- Design and manufacture of two new generation cells for operation in electrolysis mode up to 30 bar.
- Operation of pressurised-stack up to 7 bars, reaching 1.5 A/cm² at the thermoneutral voltage and 750°C.
- Design of an integrated lab-scale device comprising a SOEL stack and a pressure vessel (up to 30 bar) at the scale of 20 kWe (eq. 13.5 kg H_2/day), and selection of balance of plant (e.g. vessels, stack, compression system, heat exchangers, etc.).
- Implementation of techno-economic analysis and life-cycle analysis and first analyses conducted on the selected case studies.

FUTURE STEPS AND PLANS

- Improvement of cells and other stack components for H_2 production under pressure to be continued (including interconnects, sealings, interconnect protective coatings, stack clamping system etc.).
- Finalised design, assembly, installation and validation of the long-term operation of a lab-scale device comprising a SOEL stack and a pressure vessel (up to 30 bar) at the scale of 20 kWe (eq. 13.5 kg H_2/day).
- Investigation of a promising pressurised stack concept without pressure vessel relieving the cost of plant balance.
- Lifetime of cells and stacks (without pressure vessel) to be estimated up to 30 bars.
- Supply of model-based insights for H_2 production for up to five identified use cases, on expectable performances of both stack concepts (with or without pressurised vessel) towards large scale developments, in strong link with techno-economic analysis (TEA) and life-cycle analysis (LCA).
- TEA and LCA of use cases showing the applicability and the benefits of the developed technologies and its two stack concepts versus alkaline electrolysers (AEL) and proton exchange membrane electrolysers (PEMEL) operating under pressure. This will demonstrate the viability of pressurised high temperature steam electrolysis technology for industrial use, and further increase the confidence in SOEL as a technology capable of decarbonising hard-to-abate industries.

PROJECT TARGETS

Target source	Parameter	Unit	Target	Achieved to date by the project	Target achieved?
Project's own objectives	Current density	A/cm²	-1	-1	✓
	Pressure	bar	5 - 30	7	⚙
	Lifetime	%/kh	1	-	
	H_2 production cost	€/kg	3	-	

PROMETEO

HYDROGEN PRODUCTION BY MEANS OF SOLAR HEAT AND POWER IN HIGH TEMPERATURE SOLID OXIDE ELECTROLYSERS

Project ID	101007194
PRR 2025	Pillar 1 - H_2 Production
Call Topic	FCH-02-2-2020
Project Total Costs	2 765 206.25
Clean H_2 JU Max. Contribution	2 499 531.25
Project Period	01-01-2021 - 30-06-2024
Coordinator Beneficiary	AGENZIA NAZIONALE PER LE NUOVE TECNOLOGIE, L'ENERGIA E LO SVILUPPO ECONOMICO SOSTENIBILE, IT
Beneficiaries	ANGUITA FOTOVOLTAICO SL, GREEN CAPITAL POWER SL, CAPITAL ENERGY SERVICES SLU, SNAM S.P.A., STAMICARBON B.V., NEXTCHEM TECH SPA, SOLYDERA SA, Fundacion IMDEA Energia, FONDAZIONE BRUNO KESSLER, ECOLE POLYTECHNIQUE FEDERALE DE LAUSANNE

https://prometeo-project.eu

PROJECT AND GENERAL OBJECTIVES

PROMETEO aims to produce hydrogen from renewable heat and power sources using solid oxide electrolysis (SOE) in areas with low electricity prices associated with photovoltaics or wind. A 25 kWe SOE prototype (approximately 15 kg/day of H_2 production) will be developed and validated in a real production environment, combined with intermittent sources; non-programmable renewable electricity and high-temperature solar heat with thermal energy storage (TES). Partial-load operation, transients and hot stand-by periods will be studied.

NON-QUANTITATIVE OBJECTIVES

Demonstrate the capability to transfer the technology from component developers to system integrators and end-users.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

- Definition of end-user cases.
- Setting up preliminary process flow diagrams.
- Identification and laboratory-validation of TES system.
- Development of process modelling tools.

FUTURE STEPS AND PLANS

- Experimental determination of the performance map for the SOE stack and the plant balance on laboratory-scale.
- Finalisation of process flow diagrams for the 25 kWe pilot plant under different operation modes.
- Design and construction of integrated pilot plant (25 kWe).
- Shipping of pilot plant to project site.
- Analysis of case studies on multi-MW scale based on finalised process flow diagrams for the pilot plant (25 kWe).

PROJECT TARGETS

Target source	Parameter	Unit	Target	Target achieved?
Project's own objectives	Demonstrate the production of hydrogen by operation of >1 000 hours: Hours of experimental validation runs of the prototype.	hours	1 000	
	Obtain Solar-to-Hydrogen energy conversion efficiency from global solar radiation to H_2 energy (LHV basis).	%	10	

PROTOSTACK

TUBULAR PROTON CONDUCTING CERAMIC STACKS FOR PRESSURIZED HYDROGEN PRODUCTION

Project ID	101101504
PRR 2025	Pillar 1 - H_2 Production
Call Topic	HORIZON-JTI-CLEANH$_2$-2022-01-02
Project Total Costs	2 497 013.75
Clean H_2 JU Max. Contribution	2 497 013.75
Project Period	01-01-2023 - 31-12-2025
Coordinator Beneficiary	SINTEF AS, NO
Beneficiaries	DEMCON HIGH-TECH SYSTEMS EINDHOVEN B.V., DEMCON LIFE SCIENCES and HEALTHEINDHOVEN B.V., DEMCON HIGH-TECH SYSTEMS ENSCHEDE BV, ATENA SCARL - DISTRETTO ALTA TECNOLOGIA ENERGIA AMBIENTE, COORSTEK MEMBRANE SCIENCES AS, SHELL GLOBAL SOLUTIONS INTERNATIONAL BV, UNIVERSITA DEGLI STUDI DI NAPOLI PARTHENOPE, AGENZIA NAZIONALE PER LE NUOVE TECNOLOGIE, L'ENERGIA E LO SVILUPPO ECONOMICO SOSTENIBILE, AGENCIA ESTATAL CONSEJO SUPERIOR DE INVESTIGACIONES CIENTIFICAS

https://protostack.eu/

PROJECT AND GENERAL OBJECTIVES

PROTOSTACK will create a radically new, compact and modular proton-conducting ceramic electrolyte (PCCEL) stack design with integrated hot-box for operation and delivery of hydrogen up to 30 bar. The stack will be demonstrated at 5 kW and provide a pathway for further scale-up to systems of hundreds of kW. These achievements will be an important proof of technological feasibility that will attest to the advancement of PCCEL technology from technology readiness level 2 to 4.

NON-QUANTITATIVE OBJECTIVES

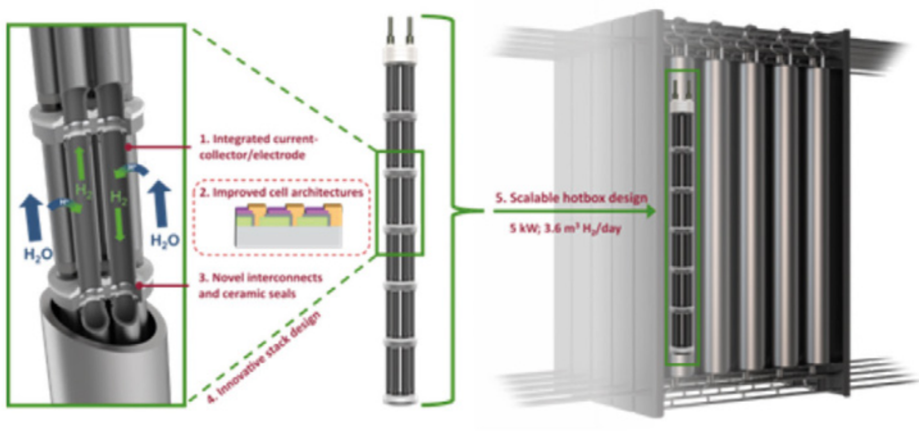
The overall consortium will engage in wide communication and dissemination activities to ensure maximum impact of the PROTOSTACK's outcomes and the industry partners have high ambition for business exploitation and commercialisation of the PROTOSTACK technology.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

- Final designs of the hot-box and stack concept have been completed.
- Production of stack components is underway.
- Validation of key cell and stack components in terms of functionality, scalable manufacturing and stability, as well as the production of the first short-stack with the new stack design for validation of the stack concept.
- Organisation of an autumn school in Valencia with more than 100 participants - mostly graduate students.

FUTURE STEPS AND PLANS

- Continued validation and optimisation of cell and stack components, and dedicated programs for stack production and testing, with emphasis on durability and performance benchmarking under varying operating conditions and delivery pressure.
- Construction and integration of the new hot-box.
- Updated system balance of plant and safety assessment.
- Detailed techno-economic and life-cycle analysis of the technology employed for specific integration scenarios and use-cases for the technology.



Stack concept and overview of key innovations in PROTOSTACK

Clean Hydrogen Partnership

Co-funded by the European Union

REACTT

RELIABLE ADVANCED DIAGNOSTICS AND CONTROL TOOLS FOR INCREASED LIFETIME OF SOLID OXIDE CELL TECHNOLOGY

Project ID	101007175
PRR 2025	Pillar 1 - H_2 Production
Call Topic	FCH-02-3-2020
Project Total Costs	2 712 322.50
Clean H_2 JU Max. Contribution	2 712 322.50
Project Period	01-01-2021 - 31-05-2025
Coordinator Beneficiary	INSTITUT JOZEF STEFAN, SI
Beneficiaries	TEKNOLOGIAN TUTKIMUSKESKUS VTT OY, BITRON SPA, SOLYDERA SA, HAUTE ECOLE SPECIALISEE DE SUISSE OCCIDENTALE, UNIVERSITA DEGLI STUDI DI SALERNO, AVL LIST GMBH, ECOLE POLYTECHNIQUE FEDERALE DE LAUSANNE, AGENZIA NAZIONALE PER LE NUOVE TECNOLOGIE, L'ENERGIA E LO SVILUPPO ECONOMICO SOSTENIBILE, COMMISSARIAT A L ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES

http://www.reactt-project.eu

PROJECT AND GENERAL OBJECTIVES

REACTT will realise a monitoring, diagnostic, prognostic, and control (MDPC) tool for reversible solid oxide cell (rSOC) stacks and systems to increase stack lifetime by 5 %; reach a production loss rate of 1.2 %/1 000 h; increase availability by 3 %, targeting overall availability of 98 %, and reduce operation and maintenance costs by 10 %. The additional cost of the MDPC tool will not exceed 3 % of the overall system manufacturing costs.

NON-QUANTITATIVE OBJECTIVES

- Education/training. Inclusion of the topic of solid oxide cell technologies in MSc and PhD study programmes.
- Public awareness. The web page and the dissemination material are the first step towards raising public awareness.
- Safety. Fault detection, isolation and mitigation in solid oxide electrolyser cells (SOECs) / solid oxide fuel cells (SOFCs) preclude process disruption and potential hazards.
- Regulations and standards. The formulation of a new work item proposal is to be submitted to Technical Committee 105 of the International Electrotechnical Commission.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

- Second release of the updated MDPC board with enhanced communication functionalities concerning the local system controller and the excitation unit. The platform is low-cost, yet with high computational performance, thanks to the carefully selected components and optimised hardware and software design.
- The upgraded excitation module for stack perturbation with conventional sinusoidal and non-conventional discrete random binary signal has been integrated with the MDPC board.
- An extensive experimental campaign has been conducted on two SOEC 70-cell stack boxes. Valuable and comprehensive datasets under carefully selected degradation scenarios have been acquired.
- A framework of the model-based approaches has been settled for feature extraction. It entails two types of approaches: (i) the passive approach utilising conventional signals and the simplified lumped models of the stack and system and (ii) the active approach that requires additional perturbation of the stack to get the complete fingerprint of the stack dynamics in terms of the electrochemical impedance spectra (EIS). EIS spectra are further deconvoluted and interpreted by using equivalent circuit models.
- A real-time optimisation (RTO) strategy for operating solid-oxide electrolyser (SOE) systems at optimal efficiency has been proposed. The RTO problem is formulated as a constrained nonlinear optimisation problem and, at this stage, constraint adaptation with input filtering has been selected as RTO solution approach. First simulation results were obtained on a simulated SOEC system. The proposed RTO scheme effectively pushes the system to higher levels of efficiency and maintains the system there despite perturbations by tracking active constraints.

FUTURE STEPS AND PLANS

The main activities will be focused on the final integration of the MDPC tool and its validation on the three 70-cell SOEC stacks and a 25/cell r-SOC stack.

PROJECT TARGETS

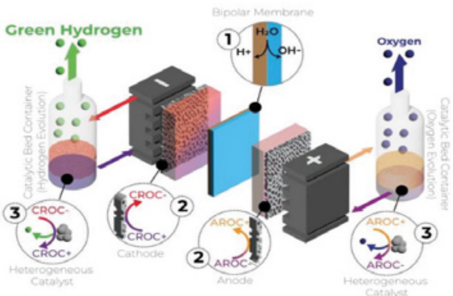
Target source	Parameter	Unit	Target	Achieved to date by the project	Target achieved?	SoA result achieved to date (by others)	Year for reported SoA result
Project's own objectives	Q&M cost	€/(kg/d)/y	120	The experimental campaign has not been completed so no statement can be made about where SolydEra would stand when benefiting from the technology developed.		Based on a recent inventory, no statement can be made about where competitors stand at the moment in their quality and maintenance costs.	2023
	Electrical Consumption at Rated Capacity	kWh/kg	39	34.8, achieved for the stack does not include consumption of the BoP.		40-45	2022

REDHY

REDOX-MEDIATED ECONOMIC, CRITICAL RAW MATERIAL FREE, LOW CAPEX AND HIGHLY EFFICIENT GREEN HYDROGEN PRODUCTION TECHNOLOGY

Project ID	101137893
PRR 2025	Pillar 1 - H_2 Production
Call Topic	HORIZON-JTI-CLEANH$_2$-2023-01-01
Project Total Costs	2 998 988.75
Clean H_2 JU Max. Contribution	2 990 238.75
Project Period	01-01-2024 - 31-12-2027
Coordinator Beneficiary	DEUTSCHES ZENTRUM FUR LUFT - UND RAUMFAHRT EV, DE
Beneficiaries	CUTTING-EDGE NANOMATERIALS CENMAT UG HAFTUNGSBESCHRANKT, INDUSTRIE DE NORA SPA-IDN, UNIRESEARCH BV, UNIVERSITAT POLITECNICA DE VALENCIA, CONSIGLIO NAZIONALE DELLE RICERCHE, CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS

https://redhy.eu/



PROJECT AND GENERAL OBJECTIVES

REDHy aims to surpass the drawbacks of state-of-the-art electrolysers and become a pivotal technology in the hydrogen economy. The REDHy approach is highly adaptable, enduring, environmentally friendly, intrinsically secure, and cost-efficient, enabling the production of economically viable green hydrogen at considerably higher current densities than state-of-the-art electrolysers. REDHy is entirely free of critical raw materials and does not require fluorinated membranes or ionomers, while maintaining the potential to fulfil a substantial portion of the 2024 key performance indicators. A five-cell stack with an active surface area exceeding 100 cm^2 and a nominal power of 1.5 kW will be developed, capable of managing a vast dynamic range of operational capacities with economically viable and stable stack components. These endeavours will guarantee lasting and efficient performance at elevated current densities (1.5 A*cm-2 at Ecell 1.8 V/cell) at low temperatures (60 °C) and suitable hydrogen output pressures (15 bar). REDHy's ultimate objective is to create a prototype, validate it in a laboratory setting for 1 200 hours at a maximum degradation of 0.1%/1 000 hours and achieve technology readiness level 4.

NON-QUANTITATIVE OBJECTIVES

- Develop highly efficient and durable materials free of critical raw and fluorine materials for the REDHy technology to a large area short stack (five cells) with an active surface area of >100cm^2 per cell and a nominal power of >1.5 kW with adequate manufacturing quality.
- Validate the stack's efficiency and robustness when the electrical grid is fed by a large proportion of renewable energy sources or the system is directly interfaced with renewable energy sources.
- Eliminate the use of and the need for critical raw materials and fluorinated membranes and ionomers at stack level.
- Demonstrate optimisation strategies for the porous electrodes to enhance their mass transport characteristics and enhance energy efficiency.
- Demonstrate a reduced energy consumption of 48 kWh*kg-1 H_2 or less by implementing highly reversible, stable redox mediators with enhanced kinetics.
- Demonstrate a drastic reduction in interface resistances across all cell components leading to energy efficiencies > 82%.
- Demonstrate the decoupling of oxygen and hydrogen production and enabling the REDHy system to operate at a minimum 5% of partial load operation (nominal load 1.5 A/cm^2) without exceeding 0.4 % of H_2 concentration in O_2.
- Demonstrate that REDHy technology is capable of performing efficient and direct seawater electrolysis.
- Integrate the short stack in a prototype full system.
- Demonstrate the operation of the REDHy electrolyser at 1.5A*cm-2 with electricity consumption of 48 kWh*kg-1 over at least 1 200 hours of operation with a degradation of 0.1 % /1 000 hours.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

- Initiating theoretical calculations and synthesis of redox mediators.
- Initiating membranes and ionomers for bipolar membranes.
- Initiating quantification of electron transfer kinetics, modelling of the electrode, 3D printing technology and selection of electrode material.
- Initiating development of heterogeneous catalysts and first single cell tests.
- Initiating design of the 5-cell stack.
- Initiating data collection for life cycle analysis.
- Initiating the newsletter, creating and updating the website and social media and planning a workshop.

PROJECT TARGETS

Target source	Parameter	Unit	Target	Target achieved?	SoA result achieved to date (by others)	Year for reported SoA result
Project's own objectives	Partial load	%	5		N/A	N/A
	H_2 conc. in O_2	%	0.4			
	Short stack	Number of cells	5			
	Active area	cm²	100			
	Critical raw material free catalyst	mg/W	0		PEMWE: 2.5 / AWE: 0.6	2020
	Nominal power	kW	1.5		N/A	N/A
	Energy consumption	kWh/kg(H_2)	48		PEMWE: 55 / AWE: 50	2020
	Energy efficiencies	%	82		N/A	N/A
	Current density	A/cm²	1.5		PEMWE: 2.2 / AWE: 0.6	2020
	Hours of operation (system)	hours	1 200		N/A	N/A
	Degradation	%/1 000 h	0.1		PEMWE: 0.19 / AWE: 0.12	2020

REFHYNE

CLEAN REFINERY HYDROGEN FOR EUROPE

Project ID	779579
PRR 2025	Pillar 1 - H_2 Production
Call Topic	FCH-02-5-2017
Project Total Costs	19 758 743.71
Clean H_2 JU Max. Contribution	9 998 043.50
Project Period	01-01-2018 - 30-06-2024
Coordinator Beneficiary	SINTEF AS, NO
Beneficiaries	ERM FRANCE, SHELL ENERGY EUROPE LIMITED, SHELL DEUTSCHLAND GMBH, ENVIRONMENTAL RESOURCES MANAGEMENT LIMITED, SPHERA SOLUTIONS GMBH, ITM POWER (TRADING) LIMITED, ELEMENT ENERGY LIMITED, STIFTELSEN SINTEF

http://www.refhyne.eu

PROJECT AND GENERAL OBJECTIVES

The overall objective of REFHYNE is to deploy and operate a 10 MW PEM electrolyser in a power-to-refinery setting. REFHYNE will validate the business model for using large-scale electrolytic hydrogen as an input to refineries, perform technical, financial and greenhouse gas analyses, and create an evidence base for the policy and regulatory changes needed to underpin the required development of this market.

NON-QUANTITATIVE OBJECTIVES

Further contributions from REFHYNE:

- REFHYNE emphasised collaboration between industry partners, bridging knowledge gaps and fostering a cross-functional team. This involved sharing learnings related to regulations, codes, standards, and technical challenges.
- REFHYNE served as a flagship initiative for decarbonising the industrial sector, demonstrating the potential of green hydrogen to reduce carbon emissions in refineries.
- Through strategic communication, workshops, and events, REFHYNE aimed to raise awareness and encourage the adoption of green hydrogen technologies across various industries.
- Establishing a pathway for future projects: REFHYNE was designed to pave the way for future large scale electrolyser projects, by providing valuable operational data, and lessons learned.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

REFHYNE is a first-of-a-kind project at the forefront of the effort to supply green refinery hydrogen for Europe. REFHYNE has installed and operated a 10MW PEM electrolyser at Shell Energy and Chemicals Park Rheinland. The final phase of REFHYNE, the successful operation of this ITM produced system, has been established including the gathering of operational data and the dissemination of emerging project results. REFHYNE has held several roundtables and workshops with stakeholders across the hydrogen value chain to demonstrate the business case and share project results.

FUTURE STEPS AND PLANS

The system is in full operation, and the electrolyser produces green hydrogen for the refinery operations. Based on the results and success of REFHYNE, Shell with partners have taken FID to realise a 100 MW PEM electrolyser from ITM Power at the same location. It is expected to be in operation from 2027.

PROJECT TARGETS

Target source	Parameter	Unit	Target	Achieved to date by the project	Target achieved?	SoA result achieved to date (by others)	Year for reported SoA result
Project's own objectives	Electricity consumption	kWh/kg	52	45.7 - 53.3	✓	55	2020
	Hot idle ramp time H_2 production (stacks)	sec	1	1		2	2020
	CAPEX	€/(kg/d)	2 000	-	⚙	2 100	2020
	Degradation rate	%/1 000h	0.15	<0.15		0.19	2020

SEAL-HYDROGEN

STABLE AND EFFICIENT ALKALINE WATER ELECTROLYZERS WITH ZERO CRITICAL RAW MATERIALS FOR PURE HYDROGEN PRODUCTION

Project ID	101137915
PRR 2025	Pillar 1 - H_2 Production
Call Topic	HORIZON-JTI-CLEANH$_2$-2023-01-01
Project Total Costs	3 000 048.75
Clean H_2 JU Max. Contribution	3 000 000.00
Project Period	01-01-2024 - 31-12-2026
Coordinator Beneficiary	UNIVERSITAT DE VALENCIA, ES
Beneficiaries	MATTECO TEAM SL, SIEMENS ENERGY GLOBAL GMBH and CO. KG, HORIBA FRANCE SAS, FORSCHUNGSZENTRUM JULICH GMBH

https://seal-hydrogen.eu/

PROJECT AND GENERAL OBJECTIVES

SEAL-HYDROGEN is an ambitious 36-month project aiming to develop laboratory-validated and scalable technology to boost the next generation of efficient, cost-effective, and durable electrolysers. SEAL-HYDROGEN proposes a multidisciplinary approach to develop an efficient and highly durable alkaline water electrolysis (AWE) stack (six cells) able to compete at the highest level with classic anion-exchange membrane (AEM) and polymer electrolyte membrane (PEM) electrolysers. A reliable method based on Raman spectroscopy, will be developed for the precise determination of electrode stability, offering appropriate quality control of great interest, both in research and industry.

NON-QUANTITATIVE OBJECTIVES

Key innovations include:

- Cost-effective layered double hydroxide (LDH) catalysts free of critical raw materials for the oxygen evolution reaction.
- Thermo-mechanical stable catalyst-support-ionomer electrodes.
- Advanced separator-electrode assemblies.
- Cutting-edge in-operando Raman spectroscopy for catalyst activity and stability testing.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

- Kick off Meeting held in Valencia, Spain, 1-2nd February 2024.
- Synthesis of various binary and ternary LDHs with different transition metals achieved. Chemical and morphological characterisation is ongoing and electrochemical tests will follow.
- Upscaling of NiFe LDH to Kg scale.
- Preparation of a large surface area electrode for testing.
- Definition of specifications for a new Raman cell to be developed.
- Study of the dissolution of NiFe LDHs through SFC coupled to ICP-MS, showing promising preliminary results on Matteco LDH stability.
- Construction of the stack test station initiated. Design finalised, holding specifications on Ni substrate properties for the constructed stack.

FUTURE STEPS AND PLANS

- Initial selection of active platinum group metal-free catalysts based on LDHs for the oxygen evolution reaction.
- Webpage, social media profiles and leaflets put in place and shared among stakeholders in various European events.
- Consortium engagement and deliverables up to date (next consortium meeting in Lille, France).
- In-operando Raman cell designed and being evaluated.
- Electrochemical tests of reference catalysts under realistic conditions for alkaline water electrolysis performed.

PROJECT TARGETS

Target source	Parameter	Unit	Target	Target achieved?
Project's own objectives	Interface resistance	-	1.9 V at 0.8 A/cm², 48 kWh/Kg	
	Electricity consumption in stacks	kWh/Kg	1.9 V at 0.8 A/cm², 48 kWh/Kg	
	Partial load operation	%	5	
	CRM	mg/W Pt	<0.3 mg/W	
	Stability - Current	A/cm²	1	

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X-SEED

EXPERIMENTAL SUPERCRITICAL ELECTROLYSER DEVELOPMENT

Project ID	101137701
PRR 2025	Pillar 1 - H_2 Production
Call Topic	HORIZON-JTI-CLEANH$_2$-2023-01-01
Project Total Costs	2 989 495.00
Clean H_2 JU Max. Contribution	2 989 495.00
Project Period	01-01-2024 - 30-06-2027
Coordinator Beneficiary	ACONDICIONAMIENTO TARRASENSE ASSOCIACION, ES
Beneficiaries	SNAM S.P.A., PARTICULAR MATERIALS SRL, INDUSTRIE DE NORA SPA-IDN, DANMARKS TEKNISKE UNIVERSITET

https://www.xseedproject.eu/

PROJECT AND GENERAL OBJECTIVES

X-SEED aims to develop an innovative electrolyser that does not use an alkaline membrane and that works in supercritical water conditions (SCWC, >374 oC; >220 bar) generating high-quality H_2 at pressures over 200 bar. Novel catalysts and electrodes are designed, synthesised, and characterised to ensure high levels of efficiency. Multiscale modeling and cell design ensure laminar fluid flows, allowing H_2 and O_2 separation without a membrane. X-SEED validates results at the laboratory scale (technology readiness level 4) for a single cell and a five-cell stack achieving high energy efficiency (42 kWh/kg H_2), current density (> 3 A/cm^2), and robustness (degradation rate 1%/1 000h). X-SEED also integrates circularity and sustainability assessments in decision-making, limiting the use of critical raw materials (CRM) (use of less than 0.3 mg/W) and using waste water both for catalyst production and as a possible electrolyte for the supercritical electrolyser.

NON-QUANTITATIVE OBJECTIVES

- Maximise the efficiency, sustainability and stability of the innovative nanostructured catalysts and electrodes for anode and cathode based on earth abundant materials.
- Improve the efficiency, cost, and durability of the electrolyser by developing an innovative electrolysis cell and short stack, that do not use an electrolysis membrane, based on use in supercritical water conditions (SPWC).
- Gather evidence of the sustainability and circularity benefits of SPWC electrolyser over current solutions (proton-exchange membrane electrolysis (PEMEL), alkaline water electrolysis (AWEL)) by assessing the economic (life cycle costing), environmental (life cycle assessment) and social (social life-cycle assessment) impacts.
- Demonstrate the improvement of the sustainability and cost competitiveness of the SPWC electrolyser in comparison with PEMEL and AWEL technology.
- Contribution to scientific advances and creation of social awareness and acceptance of green H_2 economy.
- Ensuring exploitation of materials, components, and technologies developed in X-SEED project.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

- Definition of SPWC electrolyser framework: state of art of catalyst and electrodes, survey of industrial wastewater to be used as source of catalyst and electrolyte, survey of industrial thermal waste appropriate for operation of SPWC electrolyser (no IR / no Horizons Results Platform).
- SPWC cell and stack design through 2D and multiphysics simulation.
- Synthesis of first batch of nanostructured catalyst stable at SPWC. Catalyst are based on perovskites, metal oxides and transition metal decorated nanoparticles structures.

FUTURE STEPS AND PLANS

- Selection of waste water suitable for catalyst synthesis via hydrothermal supercritical processes.
- Selection of electrolyte to use at SPWC electrolyser.
- Selection of waste thermal energy form industries suitable to operate the SPWC.
- Electrochemical and physic-chemical characterisation of catalyst and synthesis of improved catalysts.
- Electrode design and development based on high stability materials and synthesised catalysts.
- Start the design and preparation of test bench to operate and evaluate SPWC electrolysis cell.

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PROJECT TARGETS

Target source	Parameter	Unit	Target	Target achieved?	SoA result achieved to date (by others)	Year for reported SoA result
Project's own objectives	Production capacity (Synthesis of catalysts using up-scalable processes -supercritical hydrothermal and electrospinning)	kg/h	1		tn per day is possible for different manufacturing techniques and types of catalyst (not achieved in the article but indicated as a basis for the technoeconomic analysis done in the study) CHFS process: 130 g/h	2018; 2016; 2017; 2011;
	Metals (Ni, Co, Cu, etc.) for the catalyst used coming from wastewater (e.g. mining, galvanic, etc.) using Continuous Hydrothermal Flow Synthesis process	% of metals from wastewater	50		N/A	N/A
	Catalysts with high surface area	m2/g	>10		> 100 m2/g	2020
	Catalyst and electrodes with high electrolytic efficiency. For HER and for OER	mVη10 @ NTP	< 100 for HER < 150 for OER		90 for HER 150 for OER	2021
	High stability catalyst and electrodes (in the electrochemical, thermal, and chemical aging tests).	%/1 000h	< 0.8		N/A	N/A
	Cell and stack electrolyser works at current density	A/cm² @ 1.8 V at SPWC	3		35 A/cm² 3 A/cm² at 2.5V	2023; 2022
	Validate at laboratory scale a short stack supercritical electrolyser integrated by 5 cells of 25 cm²	kW	0.5		for SPWC electrolyser only single cell has been tested	N/A
	Validate electricity consumption at nominal capacity	kWh/kg of H_2	42		47-66 for PEML and AWEL 35 -50 for SOEL at stack level	2020
	Produce H_2 at P	bar	> 200		30 (PEMEL, AWEL) test at 300 bar are realised for SPWC	2020; 2022; 2022
	Separation of products (O_2 and H_2) ensuring that outflows are outside the flammability limits of mixtures at operating temperatures and pressures	% of H_2 @ O_2 gas stream	< 4		N/A	N/A
	Degradation rate, demonstrated by aging stress tests at SPWC cell and stack level	%/1 000h	< 1		N/A	N/A
	High operational flexibility: load range and fast start up and cold down	% sec	5-100 600		load range is 5 to 120 % for PEMEL, 15 to 110% for AWEL or 30 to 125 % for SOEL and the start up and cold down time ranges from <60 seconds for PEMEL to >10 h for SOEL	2020
	Able to operate with direct electrolysis of wastewater	-	yes		N/A	N/A
	Potential cost production of below 3 €/kg H_2.	€/kg	3		Supercritical electrolysis has production cost about 7.5 \$/kg H_2. With CAPEX, cost of electricity, etc. optimized, is expected to achieve 3.10 \$/kg H_2 while AWEL and PEMEL are expected to produce H_2 at 4.0 - 4.5 \$/kg H_2	2021
	1 LCA containing circularity + 1 s-LCA + 1 LCC of the X-SEED electrolyser	Number of studies	3		N/A	N/A
	Reduction of electricity consumption in comparison to AWEL and PEMEL, considering electrolysers powered by electrical grid	% of $kgCO_2$ eq reduction respect AWEL and PEMEL	20		Carbon footprint is influenced by carbon footprint of electricity used; it varies from 25 $KgCO_2$/kg H_2 (for AWEL and SOEL) to 20 $KgCO_2$/kg H_2 for SOEC, considering grid electricity Germany 2018 (0.47 tn CO_2/MWh)	2020
	Non-use Pt, Ru, decrease use of CRM	mg/W	<0.3		0 m g of CRM/W	2021
	Feedback received from experts through one workshop or participatory activity, as part of the social assessment	Number of feedback	>15		N/A	N/A
	Recovery > 50 % of internal heat and demonstrate the feasibility of meeting over 30% of the system's heat demand by utilising industrial waste heat	% of heat recovered	50			
	Contributions in peer reviewed open access articles and conference	Number	22			
	Patents	Number	2			
	Expand the use of renewable H_2 technology among existing and potential end users	Number	5			
	External interactions through social media, workshops, and disclosure articles	Number	5 000			
	Synthesise and study of different classes of catalysts (perovskites, metal oxides and transition metal decorated nanoparticles)	Types of catalyst	3	✓		

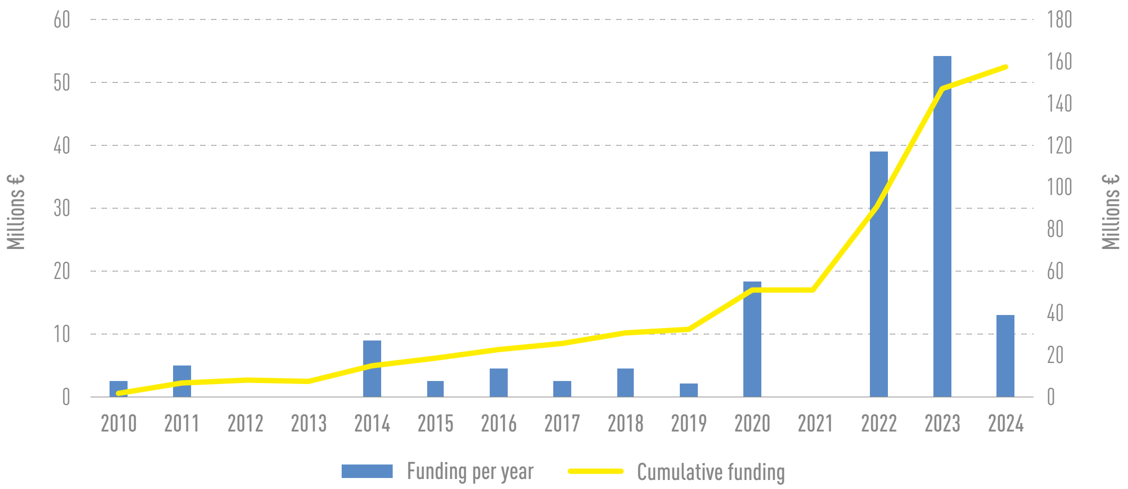
XI. PILLAR 2: HYDROGEN STORAGE AND DISTRIBUTION

OBJECTIVES: Pillar 2 is subdivided into the following Research Areas:

- **Underground storage:** feasibility, risks, and impact of H_2 underground storage.
- **Hydrogen in the natural gas grid**: transport of hydrogen over long distances, repurposing of natural gas pipelines.
- **Liquid hydrogen carriers:** improvement of the round-trip efficiency of conversion and system cost for LH_2, organic hydrogen carriers (LOHCs), ammonia, and other CO2-neutral carriers.
- **Liquid hydrogen storage**: developing concepts for liquid hydrogen storage tanks
- **Improving existing hydrogen transport means:** road transport, hydrogen terminals, and shipping.
- **Compression, purification, and metering solutions**: development of auxiliary equipment.
- **Hydrogen refuelling stations**: reduce cost and energy consumption, improve reliability and availability.

OPERATIONAL BUDGET: Interest in Pillar 2 topics has grown steadily in recent years, reaching a peak in 2023 with the launch of 11 new projects. This momentum has been strongly influenced by the EU Hydrogen Strategy and the REPowerEU Plan, which have accelerated activities in hydrogen technologies and cross-border trade. Recent initiatives have focused particularly on underground storage solutions and hydrogen transport infrastructure, reflecting the need to strengthen Europe's distribution backbone. As illustrated in Figure 24, cumulative funding for Pillar 2 projects has now reached EUR 160 million, underlining the strategic importance of this area within the Clean Hydrogen JU programme.

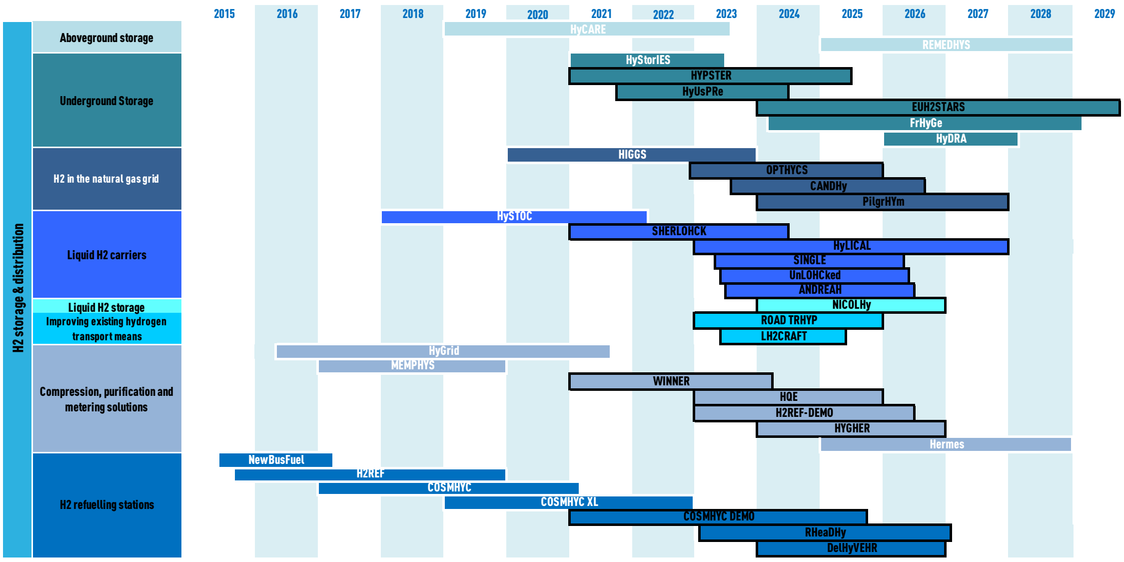
Figure 24: Funding (per year in blue/left axis and cumulative in grey/right axis) for Pillar 2 projects from 2008 to 2024



Source: Clean Hydrogen Joint Undertaking

PILLAR IN BRIEF: Pillar 2 experienced a sharp rise in activity in 2023 with 11 new projects, before declining to 5 new projects in 2024 (Figure 25).

Figure 25: Project timelines of Pillar 2 – Hydrogen Storage and Distribution



Source: Clean Hydrogen Joint Undertaking

France leads participation with 15 projects, followed by Spain and Germany with 12 each, Italy with 10, and the Netherlands with 8 (Figure 26). The collaboration network (Figure 27) highlights the central role of France and Germany, which act as hubs through strong bilateral cooperation and links with Sweden and Denmark, forming a western and northern European cluster (purple). Spain, the Netherlands, and Romania form a distinct southern and eastern European cluster (green), while Italy plays a bridging role, connecting this group with a red cluster that includes Belgium, Slovenia, and Greece. A peripheral but coherent light blue cluster brings together eastern European countries, Poland, Hungary, Austria, Slovakia, and Czech Republic, which remain more loosely connected to the central hubs.

Figure 28 shows that research institutions (19 projects), private companies (17), SMEs (16), and higher education institutions (16) are the most active participants in Pillar 2, while public bodies and other entities are minimally involved with just one project each. Adding a temporal perspective, Figure 29 indicates that most private companies and SME participation occurred in 2023, whereas research institutions and universities are more evenly represented across 2021, 2023, and 2024, pointing to a recent rise in industry-led engagement. Figure 30 ranks 36 organisations with at least two projects, led by ENGIE (5 projects) and followed by Shell Group, SINTEF, and Tecnalia (4 each), reflecting a diverse mix of energy companies, research institutes, universities, and technology centres across Europe. The collaboration network (Figure 31) highlights several clusters: i) a central purple cluster anchored by ENGIE, ZBT, and DLR with dense industrial and applied research links, ii) a large green cluster around SNAM, Shell, and RAG Austria representing infrastructure-oriented public-private ties, and iii) a yellow-brown cluster centred on CEA, CNRS, and CSIC, underlining strong collaboration among major national research institutions.

Figure 26: Pillar 2: Project participation by EU country

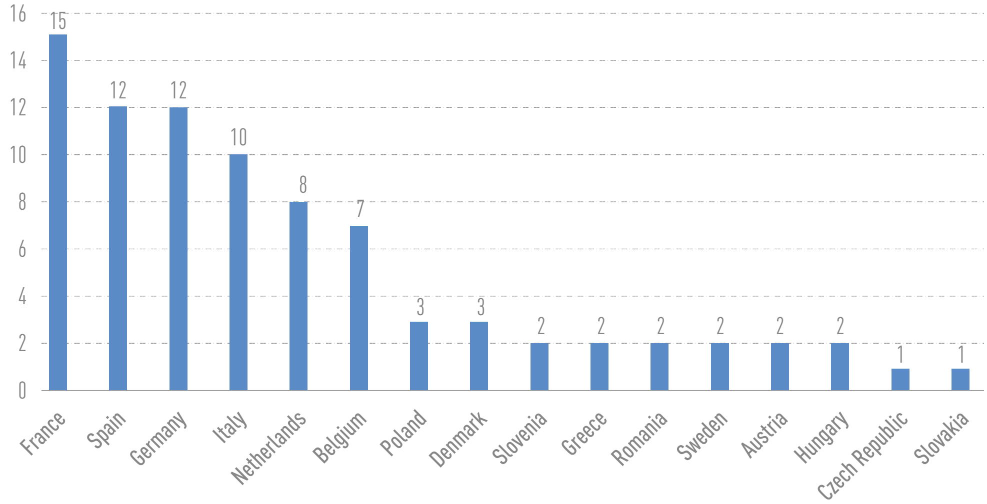


Figure 27: Pillar 2: Collaboration network of EU countries

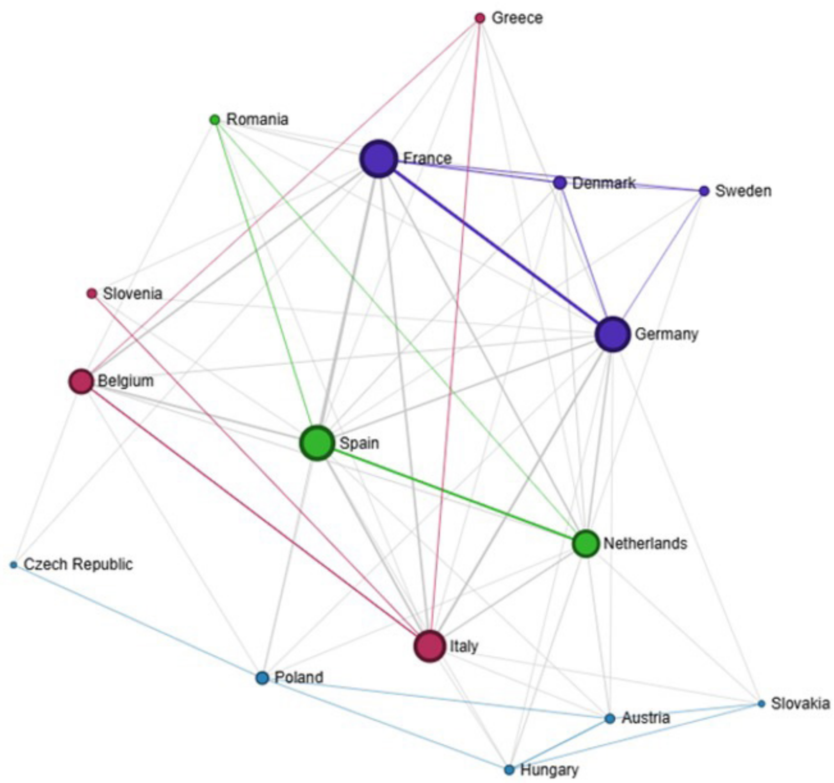


Figure 28: Pillar 2: Breakdown of projects by participating entity type

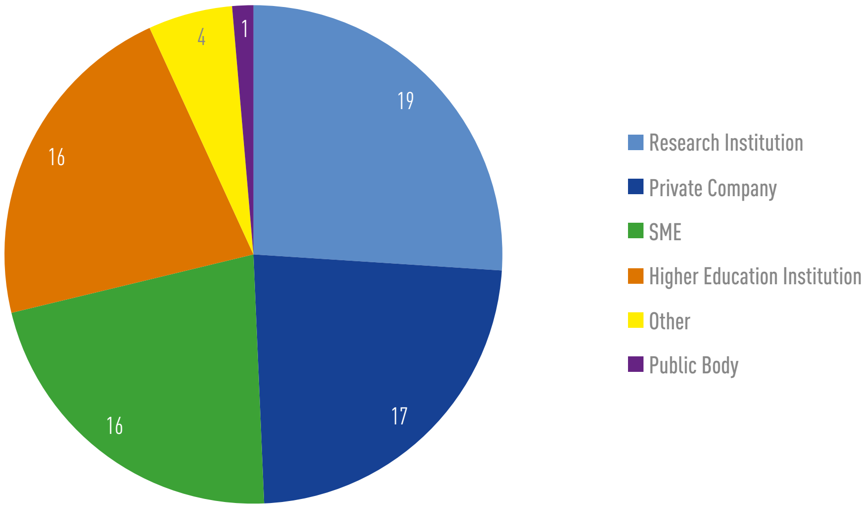


Figure 29: Pillar 2: Participation by organisation type across years

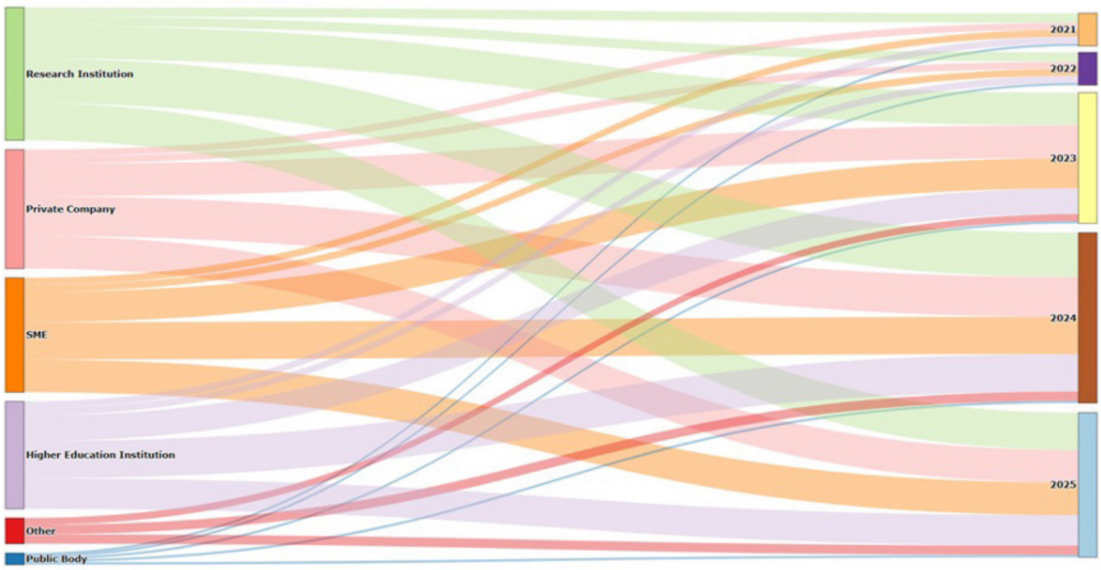


Figure 30: **Pillar 2: Institution ranking by number of projects**

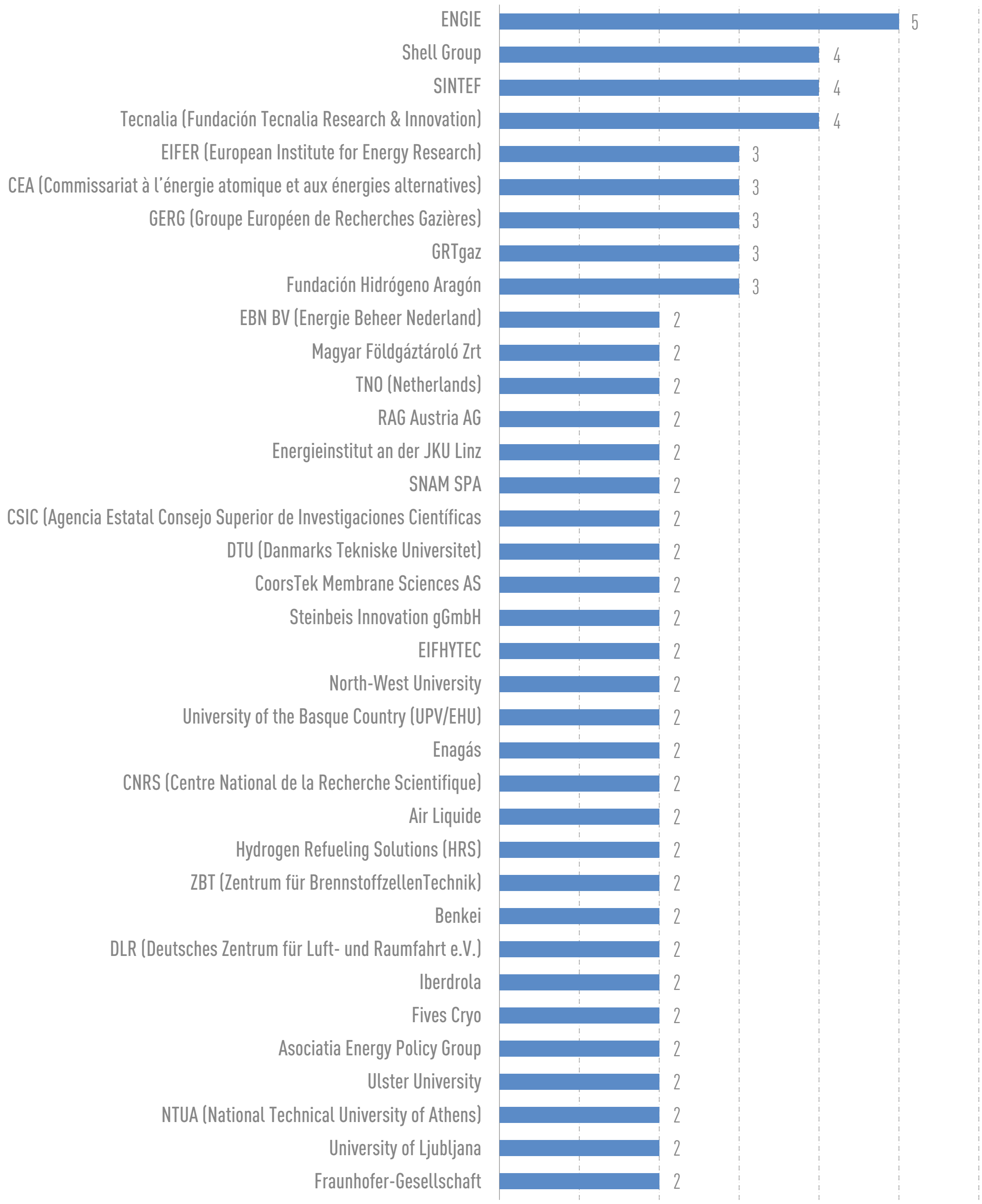
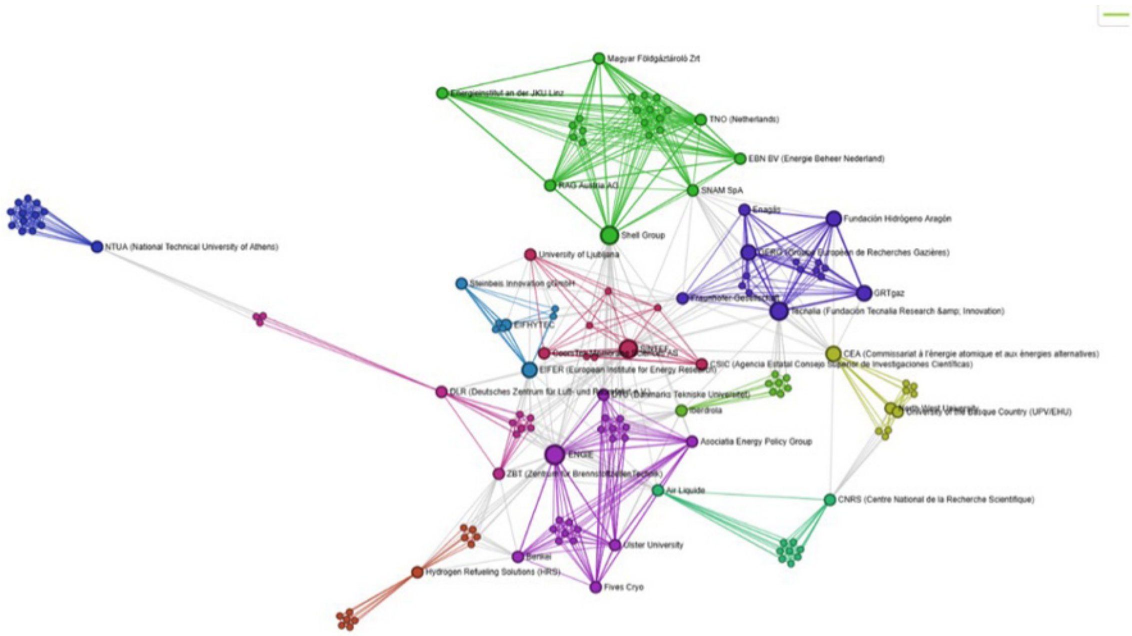


Figure 31: **Pillar 2: Collaboration network of top participating institutions**



PROJECTS FACTSHEETS

ANDREAH

AMMONIA BASED MEMBRANE REACTOR FOR GREEN HYDROGEN PRODUCTION

Project ID	101112118
PRR 2025	Pillar 2 – H_2 storage and distribution
Call topic	HORIZON-JTI-CLEANH$_2$-2022-02-04
Project total cost	EUR 2 980 361.25
Clean H_2 JU max. contribution	EUR 2 980 361.25
Project period	01-07-2023 - 30-06-2027
Coordinator Beneficiary	FUNDACION TECNALIA RESEARCH and INNOVATION, ES
Beneficiaries	VTTI BV, 1 CUBE BV, UMICORE DENMARK APS, IBERDROLA CLIENTES SOCIEDAD ANONIMA, KIC INNOENERGY SE, RINA CONSULTING SPA, TECHNISCHE UNIVERSITEIT EINDHOVEN, CONSIGLIO NAZIONALE DELLE RICERCHE

https://www.andreahproject.eu/

PROJECT AND GENERAL OBJECTIVES

The ANDREAH HORIZON EUROPE project aims to effect a quantum leap in the development of advanced ammonia decomposition technologies to produce ultra-pure hydrogen (>99.998%) by developing an innovative system based on a catalytic membrane reactor for the cracking of Ammonia. The system will be based on the design, construction and testing of an advance ammonia cracker for ultra-pure hydrogen production (10 kg H_2/day) based on a catalytic membrane reactor in order to intensify the process of hydrogen production through the integration of cracking and purification. The advance cracker will include:

- An innovative, environmentally friendly structured catalyst with fewer critical materials, capable of operating at much lower temperatures than the state-of-the-art process.
- Innovative membranes for selective separation of hydrogen during the production process.

ANDREAH will also involve developing novel sorbents for polishing the hydrogen recovered by the membranes. In addition, the design and optimisation of all subcomponents for the balance of plant will be included, with particular attention to optimising thermal integration.

NON-QUANTITATIVE OBJECTIVES

- Designing and setting up a broad and complete network of value chains with world-class universities, research centres and industrial partners to develop the key building blocks for ammonia cracking.
- Developing a full life-cycle assessment, life-cycle costing and health and safety analysis of ANDREAH.
- Developing a set of flexible, cost-effective and environmentally friendly technologies that can be easily tailored for the decomposition of ammonia into green hydrogen for different applications, such as energy and transport.
- Paving the way for the future exploitation of ANDREAH's key results by laying the foundations for new business opportunities in developing advanced catalysts and membranes. These will be integrated into membrane reactors to significantly intensify processes, enabling distributed hydrogen generation from ammonia as a long-term storage medium.
- Promoting the dissemination and communication of ANDREAH's results and expanding its impact.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

Main achievements in 2024 are in line with the planned activities:

- Market and stakeholder analysis.
- Kinetic modelling of catalyst and modelling of membrane.
- Development of the first and second generation of catalyst.
- Demonstration that a 1 wt% Ru based catalyst exhibits performances higher than the project target.
- First-generation structured catalysts developed on open-cell foams and 3D-printed periodic open-cellular structures.
- Development of three different families of sorbents.
- Development of a first-generation carbon membrane selective to hydrogen in a mixture of hydrogen, nitrogen, and ammonia.
- Preliminary integrated analysis of the new technologies based on sustainability pillars and circularity analysis – preliminary LCA, LCC, S-LCA analysis.
- Update of Dissemination, Exploitation and Communication Plan by mid-2024.

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FUTURE STEPS AND PLANS

- Preliminary business model and exploitation strategy.
- Ammonia cracking modelling and sorbent modelling.
- Development of a second-generation structured catalyst on open-cell foams and 3D-printed periodic open-cellular structures.
- Development of a second generation carbon membrane.
- Development of sorbents and the sorbent kinetics sorption modelling.
- Development of ANDREAH's health and safety requirements.
- Review of the Dissemination, Exploitation and Communication Strategy.

PROJECT TARGETS

Target source	Parameter	Unit	Target	Target achieved?	SoA result achieved to date (by others)	Year for reported SoA result
Project's own objectives	OPEX of the ammonia cracking system	k€/year	209.5		282.42	2020
	Decentralised cost of H_2 production	€/kg	4.27		5.51	2020
	CAPEX of the ammonia cracking system	k€	211.74		384.72	2020
	Amount of Ru in the catalyst for low-temperature (<500C) cracking	wt%	<1		2 - 8	2021
	Amount of Pd per membrane	g	<0.1		2.6	2023

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CANDHy

COMPATIBILITY ASSESSMENT OF NON-STEEL METALLIC DISTRIBUTION GAS GRID MATERIALS WITH HYDROGEN

Project ID	101111893
PRR 2025	Pillar 2 – H_2 storage and distribution
Call topic	HORIZON-JTI-CLEANH$_2$-2022-02-01
Project total cost	EUR 2 607 481.25
Clean H_2 JU max. contribution	EUR 2 607 481.00
Project period	01-09-2023 - 31-08-2026
Coordinator Beneficiary	FUNDACION PARA EL DESARROLLO DE LAS NUEVAS TECNOLOGIAS DEL HIDROGENO EN ARAGON, ES
Beneficiaries	SUMNISTROS INDUSTRIALES DIVERSOS SA, GRTGAZ, REDEXIS GAS SERVICIOS SL, REDEXIS SA, GERG LE GROUPE EUROPEEN DE RECHERCHES GAZIERES, RINA CONSULTING - CENTRO SVILUPPO MATERIALI SPA, UNIVERSITA' DEGLI STUDI DI BERGAMO, FUNDACION TECNALIA RESEARCH and INNOVATION

http://candhy.eu/

PROJECT AND GENERAL OBJECTIVES

- Performing a comprehensive review of the state of the art in European gas distribution grids, standards and testing codes for material compatibility with hydrogen, and hydrogen embrittlement mechanisms. The collected information will support the development of testing protocols to determine the properties of material classes studied in CANDHy under relevant operating conditions.
- Designing, developing and performing an experimental campaign to test the most relevant non-steel metallic materials found in CANDHy under different hydrogen levels in order to assess their tolerance towards this gas at operating conditions applicable for the distribution grid.
- Documenting and analysing the effect of hydrogen gas on the non-steel metallic materials tested in the aforementioned experimental campaign.
- Developing models for the prediction of hydrogen embrittlement mechanisms.
- Proposing guidelines, procedures and areas of development to support future standardisation of the testing and qualification of materials in the distribution network in the presence of hydrogen and natural gas blends.
- Developing a technical database on the hydrogen compatibility of metals as a tool to aid in the selection of materials for use in hydrogen gas distribution.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

- A thorough review of the state-of-the-art of grid materials has been performed by creating a questionnaire and distributing it among DSOs and gas associations to collect relevant data (i.e. type of materials, year of installation, pipeline length, etc.).
- A review of the state-of-the-art of relevant standards useful for studying embrittlement phenomena in non-steel metallic materials has been performed.
- A literature review about hydrogen dissociation, solubility and diffusion in non-steel metallic materials was performed.
- The information extracted from the different reviews allowed the selection of the most representative materials to carry out the experimental campaign. In addition, it allowed the design of the experimental matrix to be followed in the campaign, which is currently underway.
- Experimental test matrix along with main characteristics of materials selected and specimen geometries were collected.
- Testing platforms were adapted to the new operating conditions (pressure level 16 bar) and to allocate the new kinds of non-steel metallic components.
- The selected testing materials were acquired and machining is under progress. The first specimens for slow strain rate testing were distributed among partners and testing is ongoing.

FUTURE STEPS AND PLANS

- Completing the machining of specimens for the Round Robin Test and begin the machining of specimens for individual testing.
- Continue with the experimental campaign, finish the Round Robin Test and start the complementary tests on non-steel metallic materials.
- Analyse the empirical testing results and start developing a semi-empirical method to relate the quantitative parameters obtained to the characteristics of each material.
- Create a database of gas grid metallic materials behaviour to serve as a repository of technical data.

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PROJECT TARGETS

Target source	Parameter	Unit	Target	Achieved to date by the project	Target achieved?
Project's own objectives	Inventory of distribution grid materials	Km	Collect as much information as possible from European DSOs	2 471 198.91	✓
	Review of SoA standards related to hydrogen embrittlement tests	Number of standards	Review as many standards as possible	9	
	Database with compatible non-steel metallic materials	Number	Create one database	-	
	Study the impact of hydrogen on non-steel metallic materials	Number of materials analysed	Cover at least 5 materials	-	
	Semi-empirical model	Number	Construct 1 model to anticipate embrittlement	-	
	Harmonised guidelines	Number	Propose harmonised guidelines for future standardisation	-	

COSMHYC DEMO

COMBINED SOLUTION OF METAL HYDRIDE AND MECHANICAL COMPRESSORS: DEMONSTRATION IN THE HYSOPARC GREEN H_2 MOBILITY PROJECT

Project ID	101007173
PRR 2025	Pillar 2 - H_2 Storage and Distribution
Call topic	FCH-01-8-2020
Project total cost	EUR 3 773 858.75
Clean H_2 JU max. contribution	EUR 2 999 637.13
Project period	01-01-2021 - 30-09-2025
Coordinator Beneficiary	EIFER EUROPAISCHES INSTITUT FUR ENERGIEFORSCHUNG EDF KIT EWIV, DE
Beneficiaries	COMMUNAUTE DE COMMUNES TOURAINE VALLEE DE L'INDRE, EIFHYTEC, MAHYTEC SARL, Cavendish Hydrogen A/S, STEINBEIS INNOVATION GGMBH, DE

https://cosmhyc.eu

PROJECT AND GENERAL OBJECTIVES

To meet the demands of a growing hydrogen economy, new technologies in the hydrogen-refuelling infrastructure, including those for hydrogen compression, are necessary. In COSMHYC DEMO, the innovative COSMHYC compression solution, which combines a metal hydride and mechanical compressor, has been shown to be ready for commercial deployment. At the test site in France, a public hydrogen-refuelling station (HRS) has been installed for a variety of vehicles (e.g. vehicle fleets and garbage trucks). The hybrid compressor will be used to supply hydrogen at both 350 bar and 700 bar.

NON-QUANTITATIVE OBJECTIVES

- COSMHYC DEMO will accelerate the deployment of hydrogen mobility by integration of the new compressor in a local ecosystem in which there have been previous hydrogen mobility activities and demonstration projects.
- COSMHYC DEMO will aim to increase public acceptance of hydrogen mobility.
- COSMHYC DEMO aims to include a smart gas hub for switching between on-site hydrogen supply storage, a hydrogen refuelling station and a filling centre for trailers. Therefore, a new gas panel will be designed which allows for smart switching between the filling centre, the hydrogen supply storage and the hydrogen refuelling station.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

The main achievement is the installation of the new hydrogen refuelling station on the demonstration site and the start of refuelling operation, mainly with the garbage truck of the HECTOR Interreg NWE project. Other main progress and achievements:

- The new membrane mechanical compressor as well as the innovative metal hydride compressor were designed, manufactured and installed on the new HRS site.
- The compositions of the metal hydrides for all compression stages, were selected, without rare earth materials. These hydrides were produced in high quantities (approx. 1 000 kg per compression stage), and the compressive reactors have been manufactured and certified, including a brand-new heat exchanger, specifically developed within the project's scope.
- Also, the filling center gas panel is completed including safety studies. Indeed, the refuelling demonstration site of CCTVI will also be equipped with green hydrogen production, funded within the scope of the "Hy Touraine" initiative. The COSMHYC DEMO metal hydride compressor and filling center gas panel will also be used to compress hydrogen produced at HYSOPARC.
- The permitting process related to the installation of the metal hydride compressor on the demonstration site has been successfully completed.

FUTURE STEPS AND PLANS

- The testing phase can now continue at the HRS demonstration site in Sorigny (France), with all elements operational, including the newly commissioned metal hydride compressor.
- Certification of the metal hydride compressor is well advanced but still requires documentation.
- Data collection for the demonstration is ongoing, and the collected data will be integrated into a techno-economic analysis to demonstrate the expected economic performance of the entire system.
- The official inauguration event for the HRS and all related components will be organised in spring 2025 to bring together local stakeholders and the general public, including EU officials, at the demonstration site.

PROJECT TARGETS

Target source	Parameter	Unit	Target	Target achieved?
Project's own objectives	Refuelling protocol	-	SAE J2601 (light duty vehicles)|SAE J2601-2 (heavy duty vehicles)	✓
	Noise	dBA	60	⚙

DELHYVEHR

DELIVERY OF LIQUID HYDROGEN FOR VARIOUS ENVIRONMENT AT HIGH RATE

Project ID	101137743
PRR 2025	Pillar 2 – H_2 storage and distribution
Call topic	HORIZON-JTI-CLEANH$_2$-2023-02-05
Project total cost	EUR 5 064 971.25
Clean H_2 JU max. contribution	EUR 3 711 901.13
Project period	01-01-2024 - 31-12-2026
Coordinator Beneficiary	ENGIE, FR
Beneficiaries	TRELLEBORG CLERMONT FERRAND SAS, Fives Cryomec AG, CESAME-EXADEBIT SA, TRELLEBORG SEALING SOLUTIONS UK LIMITED, DEKRA SERVICES SA, ASOCIATIA ENERGY POLICY GROUP, EUROPEAN RESEARCH INSTITUTE FOR GAS AND ENERGY INNOVATION, BENKEI, ARIANEGROUP SAS, ABSOLUT SYSTEM SAS, ELENGY SA, UNIVERSITY OF ULSTER

https://delhyvehr.eu/the-project/

PROJECT AND GENERAL OBJECTIVES

DeLHyVEHR, coordinated by ENGIE, will develop a liquid hydrogen high-rate bunkering station with a refueling flowrate over 5 TPH and zero boil-off losses, dedicated to maritime, aviation and railroad applications. The project is expected to complete its demonstration by 2026. Alongside market maturity the cost of distribution is expected to be halved by 2030. DeLHyVEHR will drive the maturation of each main system constituting the large-scale refuelling station, with a specific focus on pumping (FIVES Cryomec AG), metering (CESAME-Exadébit SA), loading (TRELLEBORG) and boil-off gas management systems (ABSOLUT SYSTEM SAS) to the full demonstration apparatus (ArianeGroup SAS). Throughout the project, hydrogen safety management activities (UNIVERSITY of ULSTER) will support the maturation plan and de-risk design and operation. Technology, economic and environmental, policy and governance studies will allow the assessment and replication of the demonstration's performance.

NON-QUANTITATIVE OBJECTIVES

- Facilitate the industrialisation of high-rate refuelling stations for aviation, maritime, and rail applications.
- Reduce helium consumption—which could become a showstopper in liquid hydrogen development—by using gaseous nitrogen for sanitation.
- Provide harmonised guidelines and recommendations for the deployment of bunkering stations.
- Decarbonise heavy-duty vehicle transport and dedicated infrastructure to achieve a hydrogen-related carbon footprint in line with the second edition of the Renewable Energy Directive (below 3.38 kg CO_2/kg H_2).

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

The first designs of each component and their integration have been explored to prepare for the prototyping phase. This comprises the following activities:

- A global assumption book was created and presented at the project kick-off meeting, allowing to frame each partner's work and highlight their interdependency.
- The minimum requirements for the cryogenic pump have been defined, while sub-systems' design and quotation have been performed with selected suppliers.
- Following iterative improvement, FIVES delivered a prototype design and started the manufacturing process.
- A conceptual design review of the coupling system for the loading line has been conducted and is still ongoing, while a prototype has been tested with liquid hydrogen by Trelleborg UK.
- The vacuum jacketed flexible hose size has been frozen, and a first prototype has been manufactured and is ready to be tested.
- Technologies for liquid hydrogen and gaseous hydrogen and flowmeters for gaseous hydrogen have been analysed and pre-selected.
- Preliminary simulations performed with in-house model allowed to feed the consortium with first boil-off gas inventory. A qualitative selection of boil-off gas management strategies have been performed by AS and the preferred technologies will be studied in depth.
- Alongside the functional analysis performed that pre-defined the station's general architecture, a test bench design has been developed, validated and its most critical components are under contracting.

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- Refinement of planning and budgeting for the prototyping and demonstration phases is ongoing.
- Preliminary cost estimations of the liquid hydrogen station for maritime and aviation business cases have been completed, including a Class IV estimate and a deep dive of operational expenses.
- An analysis of liquid hydrogen and refuelling station markets within the EU and worldwide has been launched and will be finalised.
- Finally, the safety studies identified the list of hazards to be considered for safety engineering and informed the initial project safety plan, which has now been completed.
- Multi-phase computational fluid dynamics model of liquid hydrogen fuelling through the entire equipment of LS-LHRS is under development. In parallel the identified hazards are being studied with computational fluid dynamics simulations.

FUTURE STEPS AND PLANS

DeLHyVEHR will first define each application's high-level requirements based on a functional design analysis with the support of end-users from the advisory board. Through modeling, design, manufacturing and functional testings, the project will increase the technological maturity of each key component of the refuelling line in a dedicated track. These developments will feed into the integrated design and associated protocol specifications, forming components that will be assembled into a demonstration unit at ArianeGroup SAS's unique European facility in Vernon, France.

PROJECT TARGETS

Target source	Parameter	Unit	Target	Target achieved?
Project's own objectives	LH_2 flowmeter calibration uncertainty on the mass flow rate	%weight	0.6	
	Delivered liquid hydrogen flowrate	kg/h	5 000	
	Cryogenic pump design hydraulic efficiency	%	60	
	Endurance test duration on demonstrator	hours	10	
	Gas for connection/disconnection inserting operation	-	GN2	
	Number of connection-disconnection tested	Number	20	
	BOG recovery rate achievable	%	80	

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EUH$_2$STARS

EUROPEAN UNDERGROUND H$_2$ STORAGE REFERENCE SYSTEM

Project ID	101137798
PRR 2025	Pillar 2 – H$_2$ storage and distribution
Call topic	HORIZON-JTI-CLEANH$_2$-2023-02-01
Project total cost	EUR 27 228 904.25
Clean H$_2$ JU max. contribution	EUR 19 655 460.13
Project period	01-01-2024 - 30-09-2029
Coordinator Beneficiary	RAG AUSTRIA AG, AT
Beneficiaries	AXIOM POLSKA SP ZOO, TRINITY CAPITAL SL, AGGM AUSTRIAN GAS GRID MANAGEMENT AG, MAGYAR FOLDGAZTAROLO ZARTKORUEN MUKODO RESZVENYTARSASAG, EBN BV ENERGIE BEHEER NEDERLAND BV, AXIOM ANGEWANDTE PROZESSTECHNIK GES.M.B.H., ENERGIEINSTITUT AN DER JOHANNES KEPLER UNIVERSITAT LINZ VEREIN, LINZ STROM GAS WARME GMBH FUR ENERGIEDIENSTLEISTUNGEN UND TELEKOMMUNIKATION,SHELL GLOBAL SOLUTIONS INTERNATIONAL BV, MONTANUNIVERSITAET LEOBEN, NEDERLANDSE ORGANISATIE VOOR TOEGEPAST NATUURWETENSCHAPPELIJK ONDERZOEK TNO

http://euh2stars.eu

PROJECT AND GENERAL OBJECTIVES

EUH$_2$STARS (European Underground Hydrogen STorAge Reference System) is an ambitious, industry-driven flagship project with the motto 'Paving the way towards the future of European underground hydrogen storage'. EUH$_2$STARS aims to demonstrate competitive, complete and qualified underground hydrogen storage (UHS) in depleted porous natural gas reservoirs at technology readiness level (TRL) 8, by the end of the decade. RAG Austria AG contributes with an existing UHS pilot facility, developed to TRL 6 within the Underground Sun Storage 2030 project. EUH$_2$STARS combines implementation experience from the Underground Sun Storage 2030 project, with UHS project experiences from consortium partners to develop and define overarching rules and recommendations for UHS development across Europe. Furthermore, EUH$_2$STARS addresses the conversion of existing underground natural gas reservoirs into underground hydrogen storages and their integration into the future European hydrogen infrastructure. This will be demonstrated via several UHS replicator sites located in Austria (RAG), Hungary (HGS), The Netherlands (SHELL), and Spain (TES). In this way EUH$_2$STARS aims to deliver the following key results:

- Demonstration of the storage of pure hydrogen in depleted, porous reservoirs by operating four seasonal storage cycles at RAG's demonstrator and two storage cycles at HGS's replicator site. Each storage cycle considers different operational characteristics to demonstrate market-driven UHS operation at the project's end.
- Development of a beyond state-of-the-art hydrogen purification system and integration into the withdrawal process of RAG's demonstrator with the objective to demonstrate a successful separation of impurities from hydrogen within a real-world set-up. During gas withdrawal from the demonstrator standardised hydrogen purification levels (e.g. hydrogen grade A or better) should be achieved.
- Achievement of a relevant green hydrogen certification for the demonstrator's power to hydrogen electrolysis and engage actively in green hydrogen certificate trading.
- Provision of guidelines to successfully manage all environmental, safety, legal and (future) regulatory, societal and market-related aspects to ensure a successful implementation of UHS facilities in Europe.
- Execution of an active stakeholder engagement strategy including an external expert advisory board to consider third parties' opinions and maximise public acceptance, transparency, visibility and exploitation of the project results.
- Set-up of a generic framework on the topic of health, safety, environment and quality, including a facility site monitoring plan to ensure UHS at an 'as low as reasonably practicable' risk level when operating RAG's demonstrator, the replicator and future commercial UHS sites.
- Presentation of transformation pathways to replicate demonstrator findings in full-scale commercial settings, both at existing underground natural gas storage facilities and at newly developed UHS sites in depleted natural gas reservoirs across Europe. This includes subsurface design, surface facilities engineering, and a comprehensive CAPEX assessment.
- Provision of best practice examples on how to integrate UHS facilities into regional, national and European energy infrastructure and markets by showcasing specific use cases in Austria, Hungary, the Netherlands and Spain, including integration into the European Hydrogen Backbone.

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PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

- EUH_2STARS started with a kick-off meeting.
- WP1 specified the to-be-used Societal Embeddedness Level methodology and guidelines for implementation.
- WP2 published a measurement, monitoring and verification plan for the UHS Rubensdorf demonstration facility and a Hydrogen safety planning.
- WP4 started initial works on UHS scale-up studies.
- In WP6 a communication and dissemination plan as well as a stakeholder survey and mapping including stakeholder engagement plan were developed.
- In WP6 a report on hydrogen value chain programs and structures, and on European development projects was created.
- In WP7 the Data Management Plan as well as a project homepage and project folder were created.

FUTURE STEPS AND PLANS

In 2025 the consortium will physically meet in the Netherlands, allowing an in-person exchange between the partners across several topics. The project is expected to progress according to the Grant Agreement. Communication, exploitation and dissemination activities are expected to be carried out according to individual plans and gain traction as more results become available. After finalising and submitting the Rubensdorf operations plan, RAG's 100% hydrogen storage demonstration facility will commence its first of four seasonal storage cycles under the EUH_2STARS project in 2025.

PROJECT TARGETS

Target source	Parameter	Unit	Target	Target achieved?
Project's own objectives	Hydrogen purification achieved at exit of hydrogen purification unit	%	98 - Grade A according to ISO 14687	
	Hydrogen Recovery factor	%	95	

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FRHYGE

FULL QUALIFICATION IN FRANCE OF LARGE-SCALE HYDROGEN UNDERGROUND STORAGE AND REPLICATION FROM GERMANY TO ALL EUROPEAN COUNTRIES

Project ID	101137892
PRR 2025	Pillar 2 – H_2 storage and distribution
Call topic	HORIZON-JTI-CLEANH$_2$-2023-02-01
Project total cost	EUR 27 240 481.25
Clean H_2 JU max. contribution	EUR 19 994 886.40
Project period	01-03-2024 - 28-02-2029
Coordinator Beneficiary	STORENGY SAS, FR
Beneficiaries	GEOMETHANE, ECO MED, STORENGY DEUTSCHLAND BETRIEB GMBH, GRTGAZ, STORENGY DEUTSCHLAND GMBH, ESK GMBH, ARTELYS BELGIUM, GASNETZ HAMBURG GMBH, AXENS SA, STORENGY FRANCE, ENAGAS TRANSPORTE SA, CAPENERGIES ASSOCIATION, GEOSTOCK SAS, ARTELYS, ECOLE NATIONALE SUPERIEURE DES MINES DE PARIS, INSTITUT NATIONAL DE L ENVIRONNEMENT INDUSTRIEL ET DES RISQUES - INERIS, ASSOCIATION POUR LA RECHERCHE ET LE DEVELOPPEMENT DES METHODES ET PROCESSUS INDUSTRIELS, IFP Energies nouvelles

https://frhyge-project.eu

PROJECT AND GENERAL OBJECTIVES

The limited technical feasibility and economic viability of large-scale hydrogen storage, as a solution to the intermittency of renewable energy sources, continues to hinder broad EU market adoption of renewables for decarbonising industry and mobility. Therefore, FrHyGe's main goal is to demonstrate and qualify the injection and withdrawal of hydrogen in an existing natural gas commercial storage site in industrial locations in France. FrHyGe will also consider the conversion process and scale-up strategies to foster replication of hydrogen storage in caverns within the EU, starting with an ongoing project in Germany to accelerate know-how transfer and economic viability. FrHyGe's objectives are:

- Development and implementation of two conversion processes from natural gas or brine caverns to hydrogen storage caverns.
- Demonstration of hydrogen storage and cyclability in a 3 000 tons potential cavern with 100 cycles from one hour to one week.
- Study of the local hydrogen value chain and the techno-economic impacts on local actors and the upscale and deployment of hydrogen storage along the European Hydrogen Backbone.
- Assessment of the risks and environmental impacts of hydrogen cyclic storage in salt caverns.
- Proposal for guidelines on safety, regulation and normative adaptations in Europe.

FrHyGe will open a path towards a potential of 38 kt of commercial hydrogen storage in several EU countries by 2030, and up to 1.5 Mt by 2050, through conversion and creation of caverns, leading to a CAPEX below 10 €/kg of stored hydrogen. Therefore, FrHyGe gathers a consortium of leading hydrogen industries and research centres in the EU, led by the worldwide underground storage actor Storengy, willing to realise large-scale and multi-site hydrogen storage in caverns.

NON-QUANTITATIVE OBJECTIVES

- Propose a conceptual design for the demonstrator.

Carry out all the required studies, laboratory tests (kinetics of the hydrogen solubility in cavern brine, hydrogen permeation in salt during cycling etc.).

- Develop geomechanics and thermodynamic predictive models for hydrogen storage in largely brine-filled salt caverns.
- Provide guidance on mechanical integrity testing and tightness testing of hydrogen caverns, assess the impact of gas quality requirements on the deployment of salt cavern and porous media storage, and outline technical options for evolutive salt cavern completions with subsurface safety equipment. This guidance will enable industrial-scale replication (3 000-ton hydrogen storage potential) of findings obtained at demonstration scale and through technical and scientific studies.
- Deliver an off-grid layout connecting two neighboring caverns, including engineering and demonstrator design.
- Provide a cost-benefit-analysis for the hydrogen storage projects GeoH$_2$ and SaltHy.

Provide a market uptake plan for the hydrogen storage projects GeoH$_2$ and SaltHy.

Estimate the development costs for site-specific underground storage at European scale.

- Provide a comprehensive risk assessment and deliver a safety plan for the demonstrator. Test administrative permitting procedure for the demonstrator.

Assess the environmental impacts of salt cavern hydrogen storage, including greenhouse gases.

- Issue the project communication plan and carry out all communication actions.

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Coordinate the logistics and communication for events such as workshops, congresses.

Support for scientific publications and conference participation.

- Prepare a summary of the results in "Horizon, the EU research and Innovation Magazine".

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

- Project kick off - 20/03/2024.
- Participation in EU and national industry events: Club H_2 Sud, May and October 2024.
- HyUSPRe final conference, Utrecht - June 19, 2024; EAGE - GET24, November 6, 2024.
- European Hydrogen Week, at Brussels - Nov 18-22, 2024.
- Method definition and conceptual design in progress for the demonstrator, achieved by the end of February 2025

FUTURE STEPS AND PLANS

- 2024-2025: Study analyses for the Manosque demonstration site and SaltHy site replicability.
- 2026-2027: Construction phase.
- 2027-2029: Implementing 100 injections and withdrawal cycles, at Geomethane site. Studying Hydrogen reactions under various pressures. Comparing results with theoretical model forecast.
- From 2029: Commercial operations: 6 000 t capacity at Manosque demonstration site, 5 200 t at Harsefeld.

PROJECT TARGETS

Target source	Parameter	Target achieved?
Project's own objectives	To develop and implement two conversion processes from natural gas or brine cavern to hydrogen storage.	
	To perform 100 H_2 cycles with duration from 1 h to 1 week for a cavern having the potential of 3 000 tons of H_2. Flow rate variation of up to 1 t/h.	
	To study the local hydrogen value chain and the techno-economic impacts on local actors and to upscale and deploy H_2 storage along the European Hydrogen Backbone.	
	To demonstrate the safety and environmental acceptability of commercial storage of H_2 in salt caverns.	
	To deliver a replication roadmap of hydrogen storages at pan-EU level.	

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H_2REF-DEMO

HYDRAULIC COMPRESSION FOR HIGH CAPACITY HYDROGEN REFUELLING STATION DEMONSTRATION

Project ID	101101517
PRR 2025	Pillar 2 – H_2 storage and distribution
Call topic	HORIZON-JTI-CLEANH$_2$-2022-02-08
Project total cost	EUR 5 786 712.50
Clean H_2 JU max. contribution	EUR 4 617 384.88
Project period	01-01-2023 - 30-06-2026
Coordinator Beneficiary	CENTRE TECHNIQUE DES INDUSTRIES MECANIQUES, FR
Beneficiaries	FABER INDUSTRIE SPA, HYDAC TECHNOLOGY GMBH, HYDROGEN-REFUELING-SOLUTIONS, H2NOVA, UNIVERSITA DEGLI STUDI DI MODENA E REGGIO EMILIA, UNIVERSITE DE TECHNOLOGIE DE COMPIEGNE

https://heavy-v.h2ref.eu/

PROJECT AND GENERAL OBJECTIVES

H_2REF-DEMO aims to further develop and quintuple the innovative compression concept developed in H_2REF, in order to address large vehicle refuelling applications requiring hydrogen to be dispensed at rates of hundreds of kg/h, such as refuelling bus fleets every evening at bus depots and refuelling trucks and trains. The concept is particularly well-suited for scaling up, thanks to the scalability of fluid power and composite pressure vessel technologies. As it incorporates the intrinsic modularity of fluid power technology together with that of pressure vessel technology, this disruptive solution will allow the different expected hydrogen supply to be addressed in a cost effective and reliable manner, in particular those that are the most suitable for large-scale refuelling applications where daily consumptions exceed one tone.

- On-site production.
- Road-delivery with high pressure trailers (e.g. 500 bar, in carbon composite), as these have an effective payload of around one tone.

Large-scale hydrogen refuelling involves two distinct types of compression:

- **Compression of hydrogen production for storage**. As production is the supply chain function with the highest cost, it tends to be performed through continuous (24/7) operation of production devices sized on the basis of daily consumption. Storage of the hydrogen produced requires compression at the same rate in order to keep storage size and footprint within acceptable limits.
- **Compression of stored hydrogen for high-capacity dispensing**. This compression function brings hydrogen from storage – that is a fixed vessel storing hydrogen produced on-site, a fixed vessel into which hydrogen has been delivered by trailer, or a trailer - maintaining the pressure required for dispensing at the rate required when dispensing takes place, for example at the rate required when dispensing takes place, for example at any time of the day when vehicles pull-in to refuel, or almost continuously during a certain time frame (e.g. 4-6 hours per day at a bus depot). The feed pressure of compression for dispensing is typically higher than that of compression for storage, however the required throughput is also higher (as dispensing takes place only part of the time).

NON-QUANTITATIVE OBJECTIVES

The main goal of the project is to develop and test at full scale a high-capacity compression module (HCCM) capable of either hydrogen compression for storage prior to dispensing (1.2 tons/day) or hydrogen compression for high-capacity (35 MPa) dispensing (150 kg/h 2.5 kg/min), with 1 year's demonstration of use for high-capacity refuelling of heavy-duty vehicles in a commercially operated refuelling station. Particular attention will be given to design optimisation to minimise costs.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTSMULTIPHYSICAL MODELLING AND SIMULATION OF THE HCCM PROCESS AND INITIAL SIZING AND ESTIMATION OF POTENTIAL PERFORMANCE.

- Functional specification of the HCCM based on a bladder accumulator and an elementary compression unit.
- Functional specification and material selection for bladder and tests on material.
- Design of the accumulator's shell.
- Development of an initial safety plan.
- Specification and simulation of the global refuelling system.
- Specification and simulation of the hydraulic power pack.
- Review of existing regulations, codes and standards and identification of gaps within the project activities.

FUTURE STEPS AND PLANS

- Selection of bladder material and manufacturing of bladders.
- Manufacturing of shells.
- Development of the accumulator and performance of the first tests.
- Develop the hydraulic power pack.
- Start gas skid development.

PROJECT TARGETS

Target source	Parameter	Unit	Target	Target achieved?	SoA result achieved to date (by others)	Year for reported SoA result
Project's own objectives	CAPEX	k€/(kg/day)	1.2		2.2	2024
	Bladder durability	cycles	20 000		N/A	N/A

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HQE

HYQUALITY EUROPE

Project ID	101101447
PRR 2025	Pillar 2 – H_2 storage and distribution
Call topic	HORIZON-JTI-CLEANH$_2$-2022-02-09
Project total cost	EUR 3 453 685.00
Clean H_2 JU max. contribution	EUR 3 453 685.00
Project period	01-01-2023 - 31-12-2025
Coordinator Beneficiary	SINTEF AS, NO
Beneficiaries	ORLEN LABORATORIUM SPOLKA AKCYJNA, LINDE GMBH, ENGIE ENERGIE SERVICES, AIR LIQUIDE FRANCE INDUSTRIE, EMCEL GMBH, ZENTRUM FUR BRENNSTOFFZELLEN-TECHNIK GMBH, TOYOTA MOTOR EUROPE NV, EIFER EUROPAISCHES INSTITUT FUR ENERGIEFORSCHUNG EDF KIT EWIV, ZENTRUM FUR SONNENENERGIE - UND WASSERSTOFF-FORSCHUNG BADEN-WURTTEMBERG, NPL MANAGEMENT LIMITED, ENGIE, L AIR LIQUIDE SA, DEUTSCHES ZENTRUM FUR LUFT - UND RAUMFAHRT EV

http://hyqualityeurope.eu

PROJECT AND GENERAL OBJECTIVES

HQE's goal is to increase the reliability of hydrogen refueling stations (HRSs) and the confidence of investors, operators and consumers in them. The objectives are:

- Collect representative data on the quality of hydrogen in European HRSs (300 spot samples in 100 HRSs).
- Develop an occurrence class and promote a risk assessment approach.
- Establish an open-source database to compile the results to allow HRS operators to take a risk assessment approach to ensure hydrogen quality.
- Test a network of six hydrogen analysis laboratories in order to certify them at EU level.
- Demonstrate the effectiveness of online analysis.
- Standardise hydrogen quality sampling and analysis methodologies for EU HRSs.
- Aid future research by defining the occurrence class of at least four new impurities beyond those listed in EN17124:2022 and ISO 21087:2019.

NON-QUANTITATIVE OBJECTIVES

HQE has extensively contributed to the development of ISO 14687, 19880-9 and 19880-8.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

The work of collecting information from HRS operators and performing sampling and analysis has started. The first laboratory comparison has been completed, with nine laboratories participating. All impurities listed in ISO 14687 were present in the comparison, which is the first comparison to be conducted of this type. A hydrogen quality workshop was hosted by ISO, ASTM and the National Renewable Energy Laboratory to disseminate some of the early project results.

FUTURE STEPS AND PLANS

The project will continue the sampling and analysis work, working towards a target of collecting 300 samples and further laboratory intercomparisons will be conducted. The project will also install online quality monitoring at three HRSs.

PROJECT TARGETS

Target source	Parameter	Unit	Target	Achieved to date by the project	Target achieved?
Project's own objectives	Number of samples collected from HRS	Number	200	100	
	Online monitoring of HRS quality	Months	12	3	

HYGHER

HYDROGEN HIGH PRESSURE SUPPLY CHAIN FOR INNOVATIVE AND COST EFFICIENT DISTRIBUTION

Project ID	101137867
PRR 2025	Pillar 2 – H_2 storage and distribution
Call topic	HORIZON-JTI-CLEANH$_2$-2023-02-04
Project total cost	EUR 6 769 096.25
Clean H_2 JU max. contribution	EUR 4 991 009.88
Project period	01-01-2024 - 31-12-2026
Coordinator Beneficiary	EIFER EUROPAISCHES INSTITUT FUR ENERGIEFORSCHUNG EDF KIT EWIV, DE
Beneficiaries	RE.CO.MA. S.R.L., HYPE ASSETS, EIFHYTEC, HYPE, STEINBEIS INNOVATION GGMBH, UNIVERZA V LJUBLJANI, FRAUNHOFER GESELLSCHAFT ZUR FORDERUNG DER ANGEWANDTEN FORSCHUNG EV

https://hygher.eu/

PROJECT AND GENERAL OBJECTIVES

HYGHER aims to demonstrate the maturity of an innovative high-pressure hydrogen distribution value chain. This will include the installation of an innovative filling center able to compress hydrogen at high pressure, and the operation of two new high-pressure trailers to supply the fleet of taxis operated by HYPE in the Paris region. With a total budget of over 6.7 M € the seven consortium partners are working on improving and integrating all components along the new value chain. Through specific efforts on innovative compression, circularity and safety, HYGHER will allow sustainable and cost-efficient hydrogen distribution, removing one of the main barriers for the larger deployment of hydrogen mobility. The project started in 2024 and has an expected duration of 3 years.

NON-QUANTITATIVE OBJECTIVES

The main objective of HYGHER is to demonstrate the feasibility of an innovative, cost-efficient and reliable high-pressure value chain, by combining various innovative technologies ready for large-scale demonstration. The main progress expected beyond the state-of-the-art are:

- Build an innovative filling centre equipped with a metal hydride compressor, a mechanical booster, and cascade storage, enabling efficient distribution of over 2 t/day at 500 bar.
- Build two innovative trailers, each with a capacity of 1.25 t of hydrogen, operating at 500 bar and equipped with advanced control, monitoring, and communication systems to ensure efficiency and interoperability.
- Adapt a standard HRS by integrating 500bar trailers into smart storage cascade management, significantly improving efficiency and demonstrating increased capacity.
- Install and operate the entire value chain in the Paris region, close to trans-European transport network corridors, thereby strengthening the EU hydrogen infrastructure and preparing for replication and mass deployment.
- Demonstrate the new value chain under real commercial conditions by operating the equipment with HYPE's fleet of FCEV taxis and other 350bar and 700bar FCEVs.
- Validate the safety of the overall concept at 500 bar and prepare for a 700bar upgrade by reviewing regulations, codes, and standards, and performing safety analyses on system components and the overarching value chain.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

During the project's first year the consortium concentrated its efforts on the following activities:

- Definition of the overall high-pressure value-chain's specifications, setting the technical scope for seamless integration of all components to be developed along the hydrogen distribution value chain.
- Design of the subsystems of the HYGHER value chain, including an innovative metal hydride compressor, two high-pressure trailers, the filling center and a remote HRS to be adapted for high pressure supply.
- Analysis of the existing regulatory framework as a basis for technical developments within the project, and of proposed regulatory adjustments to accelerate the large-scale deployment of high-pressure hydrogen distribution.
- Development of a robust safety plan, establishing a joint safety approach for all development. In addition, preliminary safety studies considering all the components in the project's scope have been carried out. This will serve as the basis for the detailed and full hazard and operability studies that are scheduled for 2025.
- Preparatory work to set common assumption, scope and models for the different analyses to be conducted within the project, such as circularity, life cycle analysis and techno-economic analysis.

FUTURE STEPS AND PLANS

Main first steps of the project to be conducted in 2025 are:

- Optimisation of the design of sub-systems.
- Preparation of the construction phase for all subsystems (ordering of components and planning the construction in the workshops).
- Data collection for the techno economic assessment study, life cycle analysis and scale-up analysis.
- Preparation of a promotional project video.

PROJECT TARGETS

Target source	Parameter	Unit	Target	Target achieved?
Project's own objectives	Number of trailers filled @ high pressure (500-700 bar)	Number/ day	2	
	Filling centers @hp pressure (500-700 bar)	t/day	2.15	
	HRS quantities delivered	kg/day	2 500	

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HYLICAL

DEVELOPMENT AND VALIDATION OF A NEW MAGNETOCALORIC HIGH-PERFORMANCE HYDROGEN LIQUEFIER PROTOTYPE

Project ID	101101461
PRR 2025	Pillar 2 – H_2 storage and distribution
Call topic	HORIZON-JTI-CLEANH$_2$-2022-02-03
Project total cost	EUR 4 677 848.75
Clean H_2 JU max. contribution	EUR 4 677 848.75
Project period	01-01-2023 - 31-12-2027
Coordinator Beneficiary	INSTITUTT FOR ENERGITEKNIKK, NO
Beneficiaries	MAGNOTHERM SOLUTIONS GMBH, ASOCIATIA ENERGY POLICY GROUP, FIVES CRYO, SUBRA A/S, IBERDROLA CLIENTES SOCIEDAD ANONIMA, SHELL GLOBAL SOLUTIONS INTERNATIONAL BV, HELMHOLTZ-ZENTRUM DRESDEN-ROSSENDORF EV, UNIVERSIDAD DE SEVILLA, UNIVERSITA DI PISA, UNIVERSITY OF ULSTER, ENGIE, TECHNISCHE UNIVERSITAT DARMSTADT, DANMARKS TEKNISKE UNIVERSITET

https://www.hylical.eu

PROJECT AND GENERAL OBJECTIVES

HyLICAL will contribute to:

- Achieving an energy demand of 8 kWh/kg and a reduction in liquefaction cost of 20% for small liquefaction volumes of 1-5 TPD/day.
- Reduced capital expenditures (CAPEX) and operating expenses (OPEX) by at least 20% in addition to the targeted energy savings.
- Decentralised (local) production of liquid hydrogen (LH_2), reducing the need for distribution and transport across long distances.
- Coupling of the magnetocaloric hydrogen liquefaction technology to hydrogen production from renewables (green hydrogen) for off-grid configurations.
- Integration into conventional liquefaction plants to increase their overall energy efficiency.
- Application of the processes for liquefaction of hydrogen and boil-off management of LH_2 tanks.
- Development and validation of a new magnetocaloric high-performance hydrogen liquefier prototype.

NON-QUANTITATIVE OBJECTIVES

- Development of an innovative concept for hydrogen liquefaction that is different from what is used today.
- Increased efficiency and reduced costs of hydrogen liquefaction technologies.
- Contribution to the roll-out of next generation liquefaction technology to new bulk hydrogen production plants.
- Positive impact on other Hydrogen Europe roadmaps related to liquid hydrogen.
- Improvement of the sustainability and circularity aspects related to the liquefaction of hydrogen.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

- Prediction of more than 150 new materials and compositions via machine-learning and computational materials design.
- Characterisation of more than 30 materials with respect to their thermo-magnetic and structural properties.
- Initial simulations of an active magnetic regenerator operating in the cryogenic region.
- Construction of a test bench for characterising magnetocaloric materials in the cryogenic region under process-relevant conditions.

FUTURE STEPS AND PLANS

- Up-scaling and processing of five to seven of the most promising materials to bridge the necessary temperature span (20-80 K).
- More detailed device simulations for the active magnetic regenerator and its integration into the liquefaction process, including heat exchangers, coldbox, liquid nitrogen pre-cooling etc.
- Construction of the liquefier prototype and performance test with optimised materials.

PROJECT TARGETS

Target source	Parameter	Unit	Target	Target achieved?
Project's own objectives	Energy efficiency	kWh/kg	8	
	Liquefaction cost	€/kg	1.5	

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HYPSTER

HYDROGEN PILOT STORAGE FOR LARGE ECOSYSTEM REPLICATION

Project ID	101006751
PRR 2025	Pillar 2 – H_2 storage and distribution
Call topic	FCH-02-7-2020
Project total cost	EUR 15 514 301.73
Clean H_2 JU max. contribution	EUR 4 999 999.00
Project period	01-01-2021 - 30-06-2025
Coordinator Beneficiary	STORENGY SAS, FR
Beneficiaries	ERM FRANCE, ESK GMBH, ELEMENT ENERGY, S.A.S. BROUARD CONSULTING, STORENGY FRANCE, INOVYN CHLORVINYLS LIMITED, ENVIRONMENTAL RESOURCES MANAGEMENT LIMITED, EQUINOR ENERGY AS, AXELERA - ASSOCIATION CHIMIE-ENVIRONNEMENT LYON ET RHONE-ALPES, ELEMENT ENERGY LIMITED, ECOLE POLYTECHNIQUE, INSTITUT NATIONAL DE L ENVIRONNEMENT INDUSTRIEL ET DES RISQUES – INERIS, ASSOCIATION POUR LA RECHERCHE ET LE DEVELOPPEMENT DES METHODES ET PROCESSUS INDUSTRIELS

https://hypster-project.eu/

PROJECT AND GENERAL OBJECTIVES

HyPSTER aims to demonstrate the industrial-scale operation of cyclical hydrogen storage in salt caverns to support the emergence of the hydrogen energy economy in Europe in line with Hydrogen Europe's overall road mapping. The cavern is located in Etrez in Auvergne-Rhône-Alpes, France. For the production of green hydrogen, the Etrez storage site will rely on local renewable energy sources and a 1 MW PEM electrolyser. In the long run, this facility will produce 400 kg of hydrogen per day (equivalent to the consumption of 16 hydrogen-powered buses). The project's objective is to test industrial-scale green hydrogen production and storage in salt caverns and the technical and economic reproducibility of the process to other sites throughout Europe.

NON-QUANTITATIVE OBJECTIVES

- Assessment of the economic feasibility of cyclical hydrogen storage in salt caverns.
- Analysis of risk and environmental impacts.
- Definition of guidelines for regulation and normative adaptation in Europe.
- Study of the techno-economic replicability in Europe.
- Microbiological analysis.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

- The workover of well EZ53 was successfully completed in 2023.
- All works (civil, piping, electrical, instrumentation, automation) have been carried out and all procured equipment has been installed and connected.
- Numerical simulation models for hydrogen storage in the salt cavern have been adapted.
- A risk analysis of underground hydrogen storage in the salt cavern has been performed.
- Commercial and microbiological analysis have started.
- The inauguration of the site was held in September 2023 in presence of Catherine Macgregor, CEO of Engie, and Mirela Atanasiu, Head of Unit Operations and Communications of the Clean Hydrogen Partnership. It was a key milestone and a highlight in the project's life.
- Nitrogen tightness test was successfully conducted in November 2023.
- Hot commissioning of the electrolyser was interrupted in October 2024 due to faulty transformers.
- A hydrogen tightness test was successfully conducted in October and November 2024.
- Cyclic tests started in December 2024.
- A public workshop was held in Paris in December 2024 with 140 participants, both in-person and online.

FUTURE STEPS AND PLANS

- Cycling tests finalised and post-trial assessments completed in summer 2025.
- Hydrogen production by electrolyser to resume in June 2025.
- Project wrap-up in summer 2025.

PROJECT TARGETS

Target source	Parameter	Unit	Target	Target achieved?
Project's own objectives	Power	MW	1	
	H_2 Mass	kg	2 000	

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HYUSPRE

HYDROGEN UNDERGROUND STORAGE IN POROUS RESERVOIRS

Project ID	101006632
PRR 2025	Pillar 2 – H_2 storage and distribution
Call topic	FCH-02-5-2020
Project total cost	EUR 3 714 850.00
Clean H_2 JU max. contribution	EUR 2 499 850.00
Project period	01-10-2021 - 30-06-2024
Coordinator Beneficiary	NEDERLANDSE ORGANISATIE VOOR TOEGEPAST NATUURWETENSCHAPPELIJK ONDERZOEK TNO, NL
Beneficiaries	CENTRICA STORAGE LIMITED, MAGYAR FOLDGAZTAROLO ZARTKORUEN MUKODO RESZVENYTARSASAG, NAFTA AS, NEPTUNE ENERGY HYDROGEN BV, SNAM S.P.A., RAG AUSTRIA AG, EBN BV ENERGIE BEHEER NEDERLAND BV, UNIPER ENERGY STORAGE GMBH, ENERGIEINSTITUT AN DER JOHANNES KEPLER UNIVERSITAT LINZ VEREIN, EQUINOR ENERGY AS, SHELL GLOBAL SOLUTIONS INTERNATIONAL BV, FONDAZIONE BRUNO KESSLER, TECHNISCHE UNIVERSITAT CLAUSTHAL, THE UNIVERSITY OF EDINBURGH, FORSCHUNGSZENTRUM JULICH GMBH, WAGENINGEN UNIVERSITY

https://www.hyuspre.eu/

PROJECT AND GENERAL OBJECTIVES

HyUSPRe studied the potential of large-scale hydrogen storage in porous reservoirs in Europe. This includes the identification of suitable geological storage reservoirs and technical and economic assessments for large-scale hydrogen storage in these reservoirs. HyUSPRe addressed specific technical challenges regarding storage in porous reservoirs and conducted an economic analysis to facilitate the decision-making process to develop a portfolio of potential field pilots. The techno-economic assessment, accompanied by environmental, social, and regulatory perspectives on implementation enabled the development of a roadmap for widespread hydrogen storage by 2050.

Main objectives:

- To establish the important geochemical, microbiological, flow, and transport processes in porous reservoirs in the presence of hydrogen via a combination of laboratory scale experiments and integrated modelling.
- To establish more accurate cost estimates to identify the potential business case for hydrogen storage in porous reservoirs.
- To identify suitable storage sites, and to assess their hydrogen storage potential.
- To develop a roadmap for the deployment of geological hydrogen storage up to 2050, including the evaluation of underground storage sites' proximity to large renewable energy production, the transport and import infrastructure and the amount of renewable energy that can be buffered to meet time varying demands. This will form a basis for developing future scenario roadmaps and preparing for demonstrations.

NON-QUANTITATIVE OBJECTIVES

- HyUSPRe aimed to conduct a study assessing the potential match between hydrogen supply and demand sites, including the need for hydrogen to buffer time-varying renewable energy demands.
- HyUSPRe aimed to conduct a study on the potential of European underground hydrogen storage to facilitate the achievement of a zero-emission energy system by 2050.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

The project concluded in June 2024.

PROJECT TARGETS

Target source	Parameter	Target achieved?
Project's own objectives	GIS-based visualisation of suitable H_2 underground stores and their H_2 storage potential.	✓
	Develop future scenario roadmaps for EU-wide implementation.	
	Evaluate the amount of renewable energy that can be buffered versus time varying demands.	
	Establish cost estimate and identify the business case for H_2 storage in porous reservoirs.	
	Establish geochemical, microbial, flow and transport, and geomechanical processes of H_2 in porous reservoirs.	
	Map the proximity of hydrogen stores to large renewable energy infrastructure.	

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NICOLHY

NOVEL INSULATION CONCEPTS FOR LH_2 STORAGE TANKS

Project ID	101137629
PRR 2025	Pillar 2 – H_2 storage and distribution
Call topic	HORIZON-JTI-CLEANH$_2$-2023-02-03
Project total cost	EUR 1 999 628.75
Clean H_2 JU max. contribution	EUR 1 999 585.00
Project period	01-01-2024 - 31-12-2026
Coordinator Beneficiary	BUNDESANSTALT FUER MATERIALFORSCHUNG UND -PRUEFUNG, DE
Beneficiaries	NORGES TEKNISK-NATURVITENSKAPELIGE UNIVERSITET NTNU, ETHNICON METSOVION POLYTECHNION, DEUTSCHES ZENTRUM FUR LUFT - UND RAUMFAHRT EV, ALMA MATER STUDIORUM - UNIVERSITA DI BOLOGNA

http://nicolhy.eu

PROJECT AND GENERAL OBJECTIVES

NICOLHy aims to develop a novel insulation concept based on vacuum insulation panels that enables safe, cost and energy efficient storage of large quantities of liquid hydrogen (LH_2). Such large scale LH_2 storage technology is needed for establishing a hydrogen storage facility with dimensions from 40 000 m to over 200 000 m of LH_2. However, new design concepts are needed because the currently available technologies used in small and medium sized storage facilities are not suitable for upscaling. The main problems preventing upscaling are the long production time due to the process chain, the low failure tolerance and the spherical shape, which reduces the payload in technical applications by around 50% compared to other shapes. The novel NICOLHy concept will change these conditions by using a system which is modular, open-form, end time and cost efficient, while ensuring multi-failure tolerant production, operation and service, for onshore and offshore applications. The NICOLHy consortium consists of experts from the fields of cryothermodynamics, marine, chemistry, process, and safety engineering.

NICOLHy's technical objectives:

- Design a tank, along with its thermal insulation and supporting structure, which is suitable for the large-scale storage of LH_2, scalable, energy-efficient, sustainable, with low construction and operation costs, and with improved safety standards.
- Define materials and predict overall thermal insulation performance.

- Test novel insulation concept at laboratory scale.
- Perform safety and risk analyses during operation and fire scenarios.
- Perform circularity, sustainability and scalability assessments of the concept developed.

FUTURE STEPS AND PLANS

- Design and produce a test rig.
- Design and test diverse novel insulation concepts for LH_2 storage.
- Perform manufacturing, assembly, safety, circularity, sustainability, and scalability studies.

PROJECT TARGETS

Target source	Parameter	Unit	Target	Target achieved?	SoA result achieved to date (by others)	Year for reported SoA result
Project's own objectives	LH_2 tank capex	€/kg	20		100	2020
	LH_2 boil-off	Mass-%	0.1		0.3	2020

OPTHYCS

OPTIC FIBRE-BASED HYDROGEN LEAK CONTROL SYSTEMS

Project ID	101101415
PRR 2025	Pillar 2 – H_2 storage and distribution
Call topic	HORIZON-JTI-CLEANH$_2$-2022-02-02
Project total cost	EUR 2 499 428.75
Clean H_2 JU max. contribution	EUR 2 499 428.75
Project period	01-01-2023 - 31-12-2025
Coordinator Beneficiary	ENAGAS TRANSPORTE SA, ES
Beneficiaries	GRTGAZ, FEBUS OPTICS, LUMIKER APLICACIONES TECNOLOGICAS SOCIEDAD LIMITADA, GERG LE GROUPE EUROPEEN DE RECHERCHES GAZIERES, FUNDACION PARA EL DESARROLLO DE LAS NUEVAS TECNOLOGIAS DEL HIDROGENO EN ARAGON, FUNDACION TECNALIA RESEARCH and INNOVATION

https://opthycs.eu

PROJECT AND GENERAL OBJECTIVES

OPTHYCS aims to develop a new system for continuous leak detection based on optic fiber sensor technologies, ensuring the safety and sustainability of a hydrogen-based energy system. Acknowledging the critical need for effective leak detection methods in light of the environmental impact of hydrogen emissions, OPTHYCS introduces an innovative approach by developing a solution that includes cutting-edge coating materials for fibre Bragg gratings (FBGs) and the creation of a combined detection system merging FBGs with distributed acoustic and temperature-based detection technologies.

NON-QUANTITATIVE OBJECTIVES

The outcomes OPTHYCS are poised to significantly impact the field, offering safer and more reliable solutions for the hydrogen-based energy landscape.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

Evaluation under laboratory conditions:

- Design baseline specifications and technical requirements for the H_2 sensing system were defined, in collaboration with all consortium partners, during the initial months of the project.
- Evaluation of FBG H_2 leak detection sensor prototypes under laboratory conditions.
- Ongoing assessment of H_2 sensor configurations.
- Development of coating materials for FBG sensors using advanced plasma techniques to ensure strong adhesion and enhanced hydrogen sensitivity.
- Initial evaluation of sensor configurations using Palladium and Tungsten Oxide, providing valuable insights for future prototype development and assessing the performance and adaptability of these materials in hydrogen detection applications.

Prototyping and manufacturing:

- Development and manufacturing of the first hydrogen leak detection sensor prototypes, exploring various coatings and configurations, and representing a significant advancement toward improving leak detection technology.

Development of a proof of concept and laboratory testing protocol:

- Establishment of protocols for proof of concept and laboratory tests to ensure proper control of critical variables such as humidity, temperature, and hydrogen concentration.
- A first field campaign in 2025, allowing for system optimisation, including the FBG interrogator and interpretative software. Subsequent field tests throughout 2025 will be crucial in assessing the system's performance and identifying the most efficient use cases within the H_2 industry.

FUTURE STEPS AND PLANS

- Ongoing optimisation of coating materials for FBG sensors using advanced plasma techniques.
- Laboratory tests enabling the evaluation of sensor responses under controlled environmental conditions, managing variables such as temperature, humidity, and hydrogen concentration.
- Development of FBG interrogators with focus on integrating optical components for signal amplification and testing configurations that enable a single interrogator to measure a large number of sensors. This breakthrough will significantly enhance the system's scalability while maintaining accuracy and response time.
- Multiple field campaigns throughout 2025 to further optimise the FBG sensors, interrogator, integration of various technologies, and final software solution. This marks the final stage of the OPTHYCS project, including validation of the combined H_2 detection system in predefined use cases, such as pipelines, flanges, valves, and an operational hydrogen refueling station.

PROJECT TARGETS

Target source	Parameter	Unit	Target	Target achieved?
Project's own objectives	Minimum leak concentration detected	%	0.4	
	Time of response	sec	30 (Max. response time of 1 sec at a concentration of 0.4% -vol.)	
	Detection threshold	ln/min	0.4 (blending operation) 1.2 in pure H_2)	
	Time of recovery	sec	20 – 60 (depending on application)	
	Potential interferences	-	The sensor's sensitivity to hydrogen is not affected by the presence of other gases.	

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PILGRHYM

PRE-NORMATIVE RESEARCH ON INTEGRITY ASSESSMENT PROTOCOLS OF GAS PIPES REPURPOSED TO HYDROGEN AND MITIGATION GUIDELINES

Project ID	101137592
PRR 2025	Pillar 2 – H_2 storage and distribution
Call topic	HORIZON-JTI-CLEANH$_2$-2023-02-02
Project total cost	EUR 3 999 073.75
Clean H_2 JU max. contribution	EUR 3 999 073.75
Project period	01-01-2024 - 31-12-2027
Coordinator Beneficiary	GRTGAZ, FR
Beneficiaries	SNAM S.P.A., SINTEF AS, ENAGAS TRANSPORTE SA, GERG LE GROUPE EUROPEEN DE RECHERCHES GAZIERES, FLUXYS BELGIUM SA, FUNDACION PARA EL DESARROLLO DE LAS NUEVAS TECNOLOGIAS DEL HIDROGENO EN ARAGON, UNIVERSIDAD DE BURGOS, ONDERZOEKSCENTRUM VOOR AANWENDING VAN STAAL NV, FUNDACION TECNALIA RESEARCH and INNOVATION, FRAUNHOFER GESELLSCHAFT ZUR FORDERUNG DER ANGEWANDTEN FORSCHUNG EV, COMMISSARIAT A L ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES

https://pilgrhym.eu/

PROJECT AND GENERAL OBJECTIVES

PilgrHYm is an interdisciplinary project which aims to contribute to the decarbonisation of the energy sector by providing a European roadmap with comprehensive guidelines to assess the feasibility of safely and efficiently integrating pure H_2 into existing natural gas infrastructure.

NON-QUANTITATIVE OBJECTIVES

- Develop a database of material characterisation testing on representative steel grades of the EU gas grids, including tensile, fracture toughness and fatigue crack growth (FCG) properties.
- Establish harmonised testing protocols to support the repurposing of natural gas lines to accommodate hydrogen.
- Develop a numerical modelling approach for simulating and predicting hydrogen assisted fracture and fatigue.
- Optimise a more realistic fatigue crack growth rate master curve for the purpose of assessing fitness-for-service, in particular for low delta K values corresponding to the actual operating domain of the EU gas grids.
- Identify existing and/or innovative technologies for mitigation compatible with operational constraints.
- Engage with stakeholders to ensure cooperation and awareness.
- Facilitate the uptake and exploitation of PilgrHYm results by the academic community, technology developers and end-users.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

PilgrHYm delivered three main public reports in 2024:

- A literature and standard review focused on material mechanical testing in pressurised hydrogen gas. This review describes the testing procedures from more than 27 standards, highlighting their incongruencies and gaps when it comes to pressurised hydrogen testing environments.
- A literature review of innovative modelling approaches, including more than 30 papers and four model frameworks, covering state-of-the-art modelling for fracture and fatigue applications.
- A transmission system operator (TSO) inventory which collects data on the transmission steel networks present in Europe. The questionnaire was sent out to all EU TSOs and various associations (GERG, ENTSOG, EPRG and CEN TC234) representing EU TSOs. A total of 23 onshore TSOs replied, accounting for a global length of more than 78% of the total European grid.

PilgrHYm has selected twelve materials to be tested (two for round robin tests and ten for the main testing campaign). The materials will be dispatched to the project's testing laboratories in 2025. The testing protocols have been established. The round robin test ended in June 2025. The results will be shared in a later update.

FUTURE STEPS AND PLANS

Following the round robin test, the main testing campaign on the other ten materials will be performed. In parallel numerical models will be developed. The expected outcomes of the project are:

- Definition of optimised testing procedures for hydrogen compatibility assessment of pipeline steels.
- Assessment of novel time and cost effective experimental procedures for material qualification in a hydrogen environment.
- Development of a database summarising the characterised relevant properties of pipeline materials in hydrogen gas.
- New and innovative models for hydrogen-induced fracture and fatigue cracking simulation.
- Development of improved and more cost-effective FCG-master curves, with a reduced number of experimental tests.

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PROJECT TARGETS

Target source	Parameter	Unit	Target	Target achieved?
Project's own objectives	Number of km of the European grid covered - Information collected on the EU and connected countries H_2 grid.	**km**	156 054	✓ (182 469)
	Different steel microstructures to be assessed (including 8 base materials, 2 welds and 2 heat affected zones).	Number	12	
	Dedicated testing protocols for H_2 environments (tensile test, fracture toughness test and test on hollow specimen).	Number	3	
	Reports on suitable innovative technologies with proposed testing protocols.	Number	1	
	Guidelines (reports) on experimental characterisation of mechanical properties, mitigation techniques and master curves.	Number	2	
	Mitigation techniques identified.	Number	10	
	Numerical approach based on the performed experimental results.	Number	1	
	Optimisation of design codes and standards with reduced over-conservatism vs ASME B31.12 (reduction of over-conservatism on the master curve).	%	60	
	Fracture models	Number	1	
	Fatigue models	Number	1	
	Reduction of total testing time for fracture toughness (time reduction).	%	20	
	Dissemination of stakeholder analysis for the use cases and organised workshops and events.	Number	5	
	Dissemination of PilgrHYm's results towards the scientific, academic and standardisation community.	Number	2	

RHEADHY

REFUELLING HEAVY DUTY WITH VERY HIGH FLOW HYDROGEN

Project ID	101101443
PRR 2025	Pillar 2 – H_2 storage and distribution
Call topic	HORIZON-JTI-CLEANH$_2$-2022-02-10
Project total cost	EUR 4 734 730.00
Clean H_2 JU max. contribution	EUR 3 999 381.50
Project period	01-02-2023 - 31-01-2027
Coordinator Beneficiary	ENGIE, FR
Beneficiaries	EMERSON PROCESS MANAGEMENT FLOW B.V, LAUDA DR. R. WOBSER GMBH and CO KG, TESCOM EUROPE GMBH CO KG, HYDROGEN-REFUELING-SOLUTIONS, ENGIE ENERGIE SERVICES, BENKEI, FAURECIA SYSTEMES D ECHAPPEMENT SAS, ALFA LAVAL VICARB SAS, ZENTRUM FUR BRENNSTOFFZELLEN-TECHNIK GMBH

https://rheadhy.eu/

PROJECT AND GENERAL OBJECTIVES

RHeaDHy's main goal is to develop components and hydrogen refuelling stations to enable the implementation, testing and market introduction of new very-high-flow refuelling protocols for heavy-duty vehicles.

NON-QUANTITATIVE OBJECTIVES

- Design and assemble a very-high-flow hydrogen refuelling line. The main goal is to provide components and refuelling lines for the required performance and operating conditions (very-high-flow rate, pressure, temperature, dynamic behaviour) with optimal trade-off between performance and constraint repartition among components.
- Develop new components needed for high-flow refuelling. The main goals are (i) to develop new very-high-flow components, such as cooling technology, flow meters, valves, heat exchanger, and make them ready-to-commercialise; (ii) to develop an advanced bidirectional communication interface; (iii) to test, optimise and adapt components already in the prototype phase of their development, such as breakaway, hose, nozzle and receptable assembly.
- Develop and demonstrate a new protocol for refilling storage systems (WP4 and WP5). The main goal is the demonstration of new standardised refuelling protocols for heavy-duty vehicle developed in ISO TC 197 WG24 or other standardisation bodies.
- Ensure the fast and efficient refill of storage systems with H_2 at low cost. The main goal is to demonstrate the protocols, by using components, under the conditions mentioned above.
- Standardise and certify components for hydrogen refuelling stations to ensure a fast deployment (WP6). The main goal is to contribute to standard development through participation in ISO TC 197 and CEN 268 WG5, and obtain certifications for all the components according to relevant standards (ISO TC 197, CEN 268 WG5, OIML R139).

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

- All partners (product manufacturers) have manufactured their new products and the majority have planned the delivery to hydrogen refuelling stations.
- More than 350 simulations were done in order to aid the design of the different components. ENGIE Crigen worked mostly on pressure drop of the complete line, on the high-pressure storage configuration, and on the cooling system design.
- All external communication tools are in place (website and LinkedIn page) and are seen by the community. The profiles of the individuals of the community are in line with the project objectives.
- All management tools are in place (Dashboard, Benkeitori (for sharing of files), meeting planification and rules etc.).

FUTURE STEPS AND PLANS

The components for RHeaDHy are being produced; cooling unit- LAUDA, heat exchanger - ALFA LAVAL, flow sensor - EMERSON MicroMotion, control valve and safety valves - EMERSON TESCOM, truck storage test system - FORVIA. They will be delivered to HRS for the assembly of the hydrogen high-flow distribution lines. In parallel, the testing sites (HRS and ZBT) are being prepared. Groundworks are well advanced, and the last pending decisions are being made to host the two hydrogen refuelling stations. Afterward, the two high-flow distribution lines will be tested on these two stations in order to validate the project's key performance indicators.

PROJECT TARGETS

Target source	Parameter	Unit	Target	Target achieved?
Project's own objectives	Time for refill for a 100 kg HD truck storage test system.	min	10	
	Time for refuelling - heat exchanger and cooling system hydrogen dispensed below -30C.	min	10	
	Pressure regulator and shut-off valve compatible with very high flow rate and high pressure (1 000 bar).	g/s	170 (mean flow rate) 300 (peak flow)	
	Peak flow for prototype breakaway, nozzle, hose.	g/s	300	
	Number of refuelling events demonstrated for the fully integrated chain.	Number	300	
	Number of refuelling simulations performed.	Number	1 000	
	Flow measuring device compatible with very high flow rate, targeting >100 kg total mass per refuelling.	g/s	170 (mean flow rate) 300 (peak flow)	

ROAD TRHYP

ROAD TRAILER DESIGN - USE OF TYPE V THERMOPLASTIC TUBE WITH LIGHT COMPOSITE STRUCTURE FOR HYDROGEN TRANSPORT

Project ID	101101422
PRR 2025	Pillar 2 – H_2 storage and distribution
Call topic	HORIZON-JTI-CLEANH$_2$-2022-02-07
Project total cost	EUR 2 642 912.59
Clean H_2 JU max. contribution	EUR 2 499 999.50
Project period	01-01-2023 - 31-12-2025
Coordinator Beneficiary	L AIR LIQUIDE SA, FR
Beneficiaries	ENVITEST J. PACHOLSKI SPOLKA JAWNA, SEGULA SLOVENSKO S.R.O, SEGULA ENGINEERING, COVESS NV, EFECTIS FRANCE, ECOLE NATIONALE SUPERIEURE DE MECANIQUE ET D'AEROTECHNIQUE, ARKEMA FRANCE SA, POLITECHNIKA WROCLAWSKA, UNIVERSITE DE POITIERS, CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS

http://https://road-trhyp.eu/

PROJECT AND GENERAL OBJECTIVES

Today, hydrogen transportation solutions use tubes with a working pressure between 200 - 300 bar. ROAD TRHYP's overall objective is to demonstrate that using a trailer made out of new thermoplastic composite tubes (Type V) is a suitable solution to maximise the quantity of hydrogen transported while satisfying end-user requirements on safety and ability to be decontaminated, and enforced regulations, with a low total cost of ownership.

Therefore, ROAD TRHYP will design a trailer capable of handling a payload of 1.5 ton of hydrogen with 700 bar tubes and a capex lower than 400 €/kg. This enables the reduction of the number of transport rotations between the hydrogen production site and the delivery site, and thus a reduction of the environmental footprint of compressed hydrogen transport, but also a downsizing of the compressor at the hydrogen refueling station. In addition, ROAD TRHYP will investigate new fire testing methodologies and safety barriers for Type V adoption.

ROAD TRHYP's overall ambition is to develop Europe's value chain of Type V cylinder technologies. Beyond the targeted commercial Type V trailer applications, the knowledge developed on composite materials could benefit main actors in the mobility sectors or the hydrogen storage for inter-seasonal energy storage. Therefore, ROAD TRHYP intends to address all manufacturers across Europe who may benefit from the project's innovative process and materials. Thus, ROAD TRHYP will contribute to the European Green Deal making hydrogen a widespread energy carrier by 2030.

NON-QUANTITATIVE OBJECTIVES

Formulation of regulatory recommendations aiming at the technology's faster deployment.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

- Design of Type V cylinder completed.
- First tests show a gravimetric index higher than 7%.
- One licence of Type V cylinder sold by Covess.
- Certification in progress.
- Design of the trailer is finalised and lifecycle analysis of Type I and Type IV trailers are completed.

FUTURE STEPS AND PLANS

- Develop a cylinder with 700 bar working pressure based on the 300 bar design.
- Perform key tests based on the EN 17339 norm, including cycling tests, extreme temperature cycling tests and bonfire and validate the burst/leak model.
- Perform key tests according to cylinder usage such as decontamination and filling/unfilling, with the objective to identify the key parameters to optimise decontamination and validate a model to predict temperatures in the cylinder during filling/unfilling.
- Finalise the characterisation of the compartment of the material in fire.
- Manufacture the demonstration system made out of three cylinders.
- Perform filing/unfilling test and bonfire tests to validate models.
- Make recommendations to the ISO WG TC 197 for the interoperability of hydrogen trailers at a hydrogen station.
- Perform a lifecycle analysis for Type V trailers.
- Continue efforts to sell more Type V licenses and identify exploitation opportunities for the multi-element gas container.

PROJECT TARGETS

Target source	Parameter	Unit	Target	Target achieved?
Project's own objectives	Design Type V 700 bar tube	%	5.3	⚙
	Water content in Hydrogen	ppm	<5	
	Ability of Type V tank to pass a bonfire test	-	-	
	CAPEX	€/kg H_2 stored	400	
	Formulation of regulatory recommendations aiming at faster deployment of the technology.	-	Present recommendation to WG ISO TC 197 regarding interoperability between HRS and trailers.	

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SHERLOHCK

SUSTAINABLE AND COST-EFFICIENT CATALYST FOR HYDROGEN AND ENERGY STORAGE APPLICATIONS BASED ON LIQUID ORGANIC HYDROGEN CARRIERS: ECONOMIC VIABILITY FOR MARKET UPTAKE

Project ID	101007223
PRR 2025	Pillar 2 – H_2 storage and distribution
Call topic	FCH-02-1-2020
Project total cost	EUR 2 563 322.50
Clean H_2 JU max. contribution	EUR 2 563 322.50
Project period	01-01-2021 - 30-06-2024
Coordinator Beneficiary	COMMISSARIAT A L ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES, FR
Beneficiaries	KUWAIT PETROLEUM RESEARCH and TECHNOLOGY BV, HYDROGENIOUS LOHC TECHNOLOGIES GMBH, NOORDWES-UNIVERSITEIT, UNIVERSIDAD DEL PAIS VASCO/ EUSKAL HERRIKO UNIBERTSITATEA, EVONIK OPERATIONS GMBH, FRIEDRICH-ALEXANDER-UNIVERSITAET ERLANGEN-NUERNBERG

http://sherlohck.eu

PROJECT AND GENERAL OBJECTIVES

Liquid organic hydrogen carriers are attractive due to their ability to safely store large amounts of hydrogen (up to 7 % wt or 2 300 KWh/ton) for a long time and to release pure hydrogen on demand. SHERLOHCK targets the development of (i) highly active and selective catalysts with partial/total substitution of platinum group metals (PGM), (ii) a novel catalytic system architecture, with components ranging from the catalyst to the heat exchanger, to minimise internal heat loss and to increase the space-time yield; and (iii) novel catalyst testing, system validation and demonstration through the demonstration unit (> 10 kW, > 200 hours).

PROGRESS AND MAIN ACHIEVEMENTS

- Requirements have been defined for the hydrogenation and dehydrogenation catalyst, the type and quality of liquid organic hydrogen carriers, hydrogen quality, testing routine, and energy consumption, to ensure compatibility with the project objectives. This initial work has laid the foundation for SHERLOHCK.
- Benzyltoluene was chosen as the reference molecule and Pt-based catalysts from Clariant were selected as the catalysts' benchmark.
- The catalyst design through density functional theory predictive analysis has reduced the use of PGM catalysts. Calculations were made for the dehydrogenation of methylcyclohexane (to toluene) as a reference molecule instead of benzyltoluene which was too complex for the calculation. The overall dehydrogenation energies calculated for the various considered alloys showed that Co, Co_3Pt, SnPt, Sn3Pt2, Sn2Pt, and Sn4Pt could be potentially low Pt-based catalytic materials.
- Catalyst materials have been synthesised and tested on a lab scale with a standardised test protocol. Some Pt-X (X=Fe, Zn, Co, Cu) catalysts supported on alumina outperform the benchmark catalyst in activity. Pt-Co, with a cobalt content of 0.5 wt.% achieved almost the same dehydrogenation activity and selectivity as catalysts with 1 wt.% Pt but with half the amount of this noble metal. PGM-free catalysts show very low activity.
- Experiments with model substances simulating by-product formation provided better insights into the dehydrogenation reaction and catalyst deactivation.
- Promising results have been obtained for the first catalyst reactivation procedures by oxidative regeneration with synthetic air executed in batch operation.
- Models and simulations were performed on structured heat-exchangers reactors combined with improved catalysts, in order to support the choice of possible reactor geometries, in particular, to define suitable heat conductive reactor structures. These results indicate that for both reactions, foam structure, catalyst activity, mass, and operating conditions are first-order parameters.
- 3D monolith structures have been prepared to integrate catalysts materials.
- A long-term test campaign has been launched and ran until June 2024.
- The communication activities carried out are integrated with the Project website (https://sherlohck.eu/), diffusion of activities on two social platforms: LinkedIn (https://www.linkedin.com/in/sherlohck/originalSubdomain=es) and 'X' (https://x.com/SherlohckProj) and participation to promotional events (conferences, workshops, newsletters, and press releases).

FUTURE STEPS AND PLANS

- SherLOHCk has integrated the catalyst into the thermal conductive support structure.
- Long-term testing in continuous operation (> 200 hours) was ongoing until June 2024.
- Testing of the resistance of catalysts to different poisons was ongoing.
- The modelling of the reaction kinetics for the design of new reactors has started for the dehydrogenation reaction.

PROJECT TARGETS

Target source	Parameter	Unit	Target	Achieved to date by the project	Target achieved?	SoA result achieved to date (by others)	Year for reported SoA result
Project's own objectives	Catalyst selectivity	%	99.8	99.4		~100	2022
	Degree of conversion	%	90	88		~100	2022
	Catalyst productivity in dehydrogenation	g H_2/ g catalyst/ min	3	5.3	✓	0.85	2022

SINGLE

ELECTRIFIED SINGLE STAGE AMMONIA CRACKING TO COMPRESSED HYDROGEN

Project ID	101112144
PRR 2025	Pillar 2 – H_2 storage and distribution
Call topic	HORIZON-JTI-CLEANH$_2$-2022-02-04
Project total cost	EUR 2 989 671.25
Clean H_2 JU max. contribution	EUR 2 989 671.25
Project period	01-05-2023 - 30-04-2026
Coordinator Beneficiary	COORSTEK MEMBRANE SCIENCES AS, NO
Beneficiaries	GEA ENERGIA CRIO SL, SINTEF AS, FONDAZIONE ICONS, UNIVERZA V LJUBLJANI, UNIVERSITAT POLITECNICA DE CATALUNYA, AGENCIA ESTATAL CONSEJO SUPERIOR DE INVESTIGACIONES CIENTIFICAS

https://singleh2.eu/

PROJECT AND GENERAL OBJECTIVES

SINGLE aims to demonstrate the competitive advantages of proton ceramic electrochemical reactors for the production of high-purity, pressurised hydrogen (up to 20 bar) from ammonia. This goal will be achieved through the implementation of an innovative proton ceramic electrochemical reactor stack design integrated into a module capable for operation at a scale of 10 kg hydrogen per day. To reach this capacity the module will comprise of twenty individual stacks.

NON-QUANTITATIVE OBJECTIVES

- Optimise the proton ceramic electrochemical reactor catalytic activity for ammonia dehydrogenation.
- Optimise and qualify proton ceramic electrochemical reactor stacks and system components.
- Fabricate proton ceramic electrochemical reactor stacks including design, assembly, construction and testing of the 10 kg H_2/day module.
- Assess the life cycle, value chain economics and critical raw materials.
- Carry on dissemination, communication and standardisation activities.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

- Ni/BCZY support catalytic activity and stability had been optimised by infiltration of active metal.
- Candidate alloy materials have been identified for constructing and safe operating reactor housing under ammonia conditions.
- Cells, KETs and stacks have been manufactured.

FUTURE STEPS AND PLANS

- Stacks for 10kg H_2/day module will be fabricated.
- Design, assembly, construction, and testing of the 10 kg H_2/day module.
- The life cycle, value chain economics and critical raw materials will be assessed.

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PROJECT TARGETS

Target source	Parameter	Unit	Target	Achieved to date by the project	Target achieved?	SoA result achieved to date (by others)	Year for reported SoA result
Project's own objectives	Ammonia conversion (CATALYST)	%	> 98 at 600 °C	99.2	✓	98 % at 650 °C	2022
	Durability (CATALYST)	%	< 1 %/kh decrease in conversion at 600 °C	-		N/D for >1kh	2022
	Current density (CELL)	A/cm2	> 1	-		0.8	2022
	ASR (Current collector/electrode/ electrolyte) (CELL)	Ωcm2	< 0.5	-		1.2	2022
	NH_3 conversion (CELL)	%	> 99.9	-		> 99.98	2022
	Faradaic efficiency (CELL)	%	> 98	-		98	2022
	Hydrogen recovery (CELL)	%	> 99	-		99	2022
	Durability (CELL)	%/kh voltage degradation on cell level at 0.75 Acm	0.8	-		0.8	2022
	Total current (STACK)	A	>85	44		67	2022
	NH_3 conversion (STACK)	%	>99.8	98.4 (at 750°C)		N/A	N/A
	Faradaic efficiency (STACK)	%	95	96 (at 10 bar, 700°C)		>98	2022
	Hydrogen Recovery (STACK)	%	>98	86 (at 650°C)		98	2022
	Pressure Tolerance	Bar	30	15		31	2022
	Hydrogen Purity	%	>99.99	-		>99.995	2022
	Efficiency HHV	%	>90	-		N/A	N/A
	NH_3 Conversion (10kg/day MODULE)	%	>90	-			
	NH_3 Conversion (10kg/day MODULE)	%	>99.5	-			
	Hydrogen Recovery (10kg/day MODULE)	%	>95	-			
	Number of hours operated at 10 kg/day	h	>500	-			
	Pressure tolerance	bar	25	-			

UNLOHCKED

UNLOCKING THE POTENTIAL OF LOHCS THROUGH THE DEVELOPMENT OF KEY SUSTAINABLE AND EFFICIENT SYSTEMS FOR DEHYDROGENATION

Project ID	101111964
PRR 2025	Pillar 2 – H_2 storage and distribution
Call topic	HORIZON-JTI-CLEANH$_2$-2022-02-05
Project total cost	EUR 2 941 312.75
Clean H_2 JU max. contribution	EUR 2 941 312.75
Project period	01-06-2023 - 31-05-2026, ES
Coordinator Beneficiary	UNIVERSIDAD DEL PAIS VASCO/ EUSKAL HERRIKO UNIBERTSITATEA,
Beneficiaries	HyGear Fuel Cell Systems B.V., HYGEAR OPERATIONS BV, HYGEAR HYDROGEN PLANT BV, FRAMATOME GMBH, HYGEAR TECHNOLOGY AND SERVICES BV, HERAEUS DEUTSCHLAND GMBH and CO KG, HYGEAR FUEL CELL SYSTEMS BV, HYGEAR BV, NOORDWES-UNIVERSITEIT, COMMISSARIAT A L ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES, CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS

https://unlohcked.cnrs.fr/

PROJECT AND GENERAL OBJECTIVES

By advancing breakthrough research on liquid organic hydrogen carrier (LOHC) technologies, UnLOHCked aims to develop a radically disruptive, versatile and scalable LOHC-dehydrogenation plant. Firstly, highly active and stable catalysts without critical raw materials will be developed to reduce LOHC dehydrogenation at moderate temperatures. Secondly, a solid oxide fuel cell system will be developed to be thermally integrated in the dehydrogenation process. The heat demand of the dehydrogenation unit will be fully covered by the fuel cell, while generating electric power. The surplus of hydrogen will be exported. These innovative systems, when fully integrated, will allow significant increase of overall efficiency (>50%) of hydrogen and electric power production from LOHC.

The main objectives of this project are:

- To develop a critical raw material (CRM) free or low CRM-catalyst with high conversion rate, selectivity and productivity for dehydrogenation.
- To scale-up of one of the developed catalysts from a gram at laboratory scale to multiple kilograms for the demonstration plant.
- To develop a breakthrough integrated system in which the reactor is thermally coupled to an SOFC simplifying the dehydrogenation plant and improving the thermal efficiency.
- To demonstrate the feasibility of producing hydrogen and generating renewable electricity from LOHC-stored hydrogen by heat integration between endothermic hydrogen release and exothermic fuel cell operation.

NON-QUANTITATIVE OBJECTIVES

- To reduce capital expenditure (i.e. owing to the use of less expensive materials, no chemical reagents, no cleaning cycles and extended materials lifetime) and operational expenditure (i.e. owing to continuous mode of operation and optimised process controls).
- To decrease the cost of hydrogen transport and to demonstrate the feasibility and cost-effectiveness of LOHC technologies, from on-shore tank to on-shore tank, all inclusive.
- To develop a scale-up plan, through a techno-economic analysis, in order to improve techno-economic viability and to include comparisons with alternative hydrogen technologies for long distance transport.
- To develop a dissemination, exploitation and communication plan targeting key stakeholders and end-users at EU and international level to maximise the impact of UnLOHCked results.
- To put the EU at the forefront of hydrogen technologies ensuring a competitive and commercial advantage in Europe in order to incentivise future investments.
- To reduce the environmental impact of hydrogen technologies by reducing the use and release of toxic substances and CRMs with a huge environmental impact.
- To contribute to the European Green Deal Goals through a fully CO_2-free dehydrogenation system.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

After the first year and a half UnLOHCked is in the middle of the scale-up of a low CRM catalyst. So far UnLOHCked has achieved catalysts with conversions, selectivities and productivities higher than the state-of-the-art and is reaching the project's key performance indicators.

FUTURE STEPS AND PLANS

- Continue scaling up a catalyst from lab scale to industrial scale that reach the project targets.
- Continue the reactor design for the dehydrogenation unit integrated with a solid state fuel cell unit.

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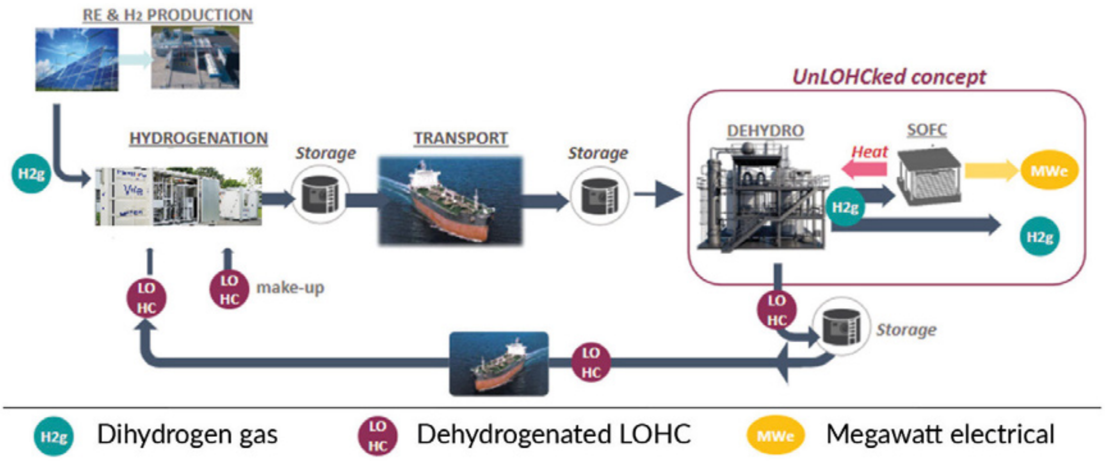


PROJECT TARGETS

Target source	Parameter	Unit	Target	Achieved to date by the project	Target achieved?
	Grade of conversion	%	>95	96.6	✓
	Catalyst selectivity	%	>99.8	99.8	
	Catalyst productivity in dehydrogenation	g H_2/g catalyst/min	>0.02	0.031	
Project's own objectives	No dissemination materials	Number	>8 (website, social media, videos etc.)	6	
	No peer-reviewed scientific publications and patents	Number	>10 publications and ≥1 patents	2 publications	
	Catalyst productivity in dehydrogenation	kg H_2/day	10	-	
	Catalytic stability	%	Leaching of active material <0.1%/cycle Loss of performance < 0.1%/cycle: Grade of conversion >95%	-	
	Catalyst selectivity	%	>99	-	
	Hydrogen carrier specific energy consumption	kWh input/kg H_2 recovered	>17	-	
	Operating hours	hours	>500	-	
	Overall efficiency	%	>50	-	
	H_2 production	kg/day	10	-	
	Overall efficiency (electrical)	%	>50	-	
	Reduction in CAPEX and OPEX	%	CAPEX: 65 OPEX: 80	-	
	Hydrogen carrier delivery cost	€/kg	<2.5	-	
	H_2 Production (TEA)	kg H_2/day	100-1 000	-	
	Reduction in the footprint	%	75	-	
	Reduction in CO_2 emissions	% in the end-to-end UnLOHCked process	>90	-	

WINNER

WORLD CLASS INNOVATIVE NOVEL NANOSCALE OPTIMIZED ELECTRODES AND ELECTROLYTES FOR ELECTROCHEMICAL REACTIONS

Project ID	101007165
PRR 2025	Pillar 2 – H_2 storage and distribution
Call topic	FCH-03-1-2020
Project total cost	EUR 2 931 788.75
Clean H_2 JU max. contribution	EUR 2 931 788.75
Project period	01-01-2021 - 31-03-2024
Coordinator Beneficiary	SINTEF AS, NO
Beneficiaries	COORSTEK MEMBRANE SCIENCES AS, SHELL GLOBAL SOLUTIONS INTERNATIONAL BV, ALLEIMA TUBE AB, ENGIE, UNIVERSITETET I OSLO, DANMARKS TEKNISKE UNIVERSITET, AGENCIA ESTATAL CONSEJO SUPERIOR DE INVESTIGACIONES CIENTIFICAS

https://www.sintef.no/projectweb/winner/

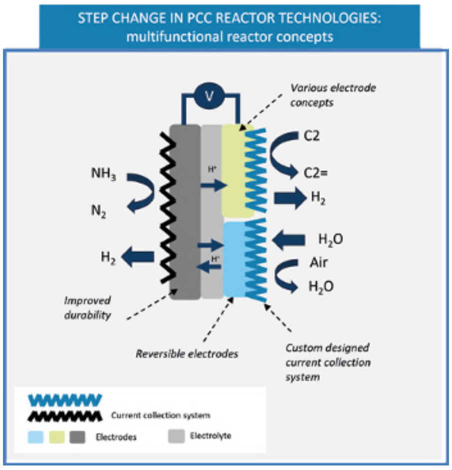
PROJECT AND GENERAL OBJECTIVES

WINNER contributes to the shift towards a more sustainable energy future by developing an efficient and durable technology platform based on electrochemical proton ceramic conducting (PCC) cells designed to unlock a path towards commercially viable production, extraction, purification and compression of hydrogen at small to medium scale through three process chains.

- Cracking of ammonia to produce pressurised hydrogen or power, where PCC reactors provide an innovative solution for flexible, secure and profitable storage and utilisation of energy in the form of green ammonia.
- Dehydrogenation of ethane to produce ethylene and pressurised hydrogen, where PCC reactors open new sustainable pathways for electrically driven processes in the chemical industry.
- Reversible steam electrolysis (using reversible protonic ceramic electrochemical cells), where PCC reactors allow the shifting of electric power generation to hydrogen production enabling grid balancing, improved matching of the demand and supply of electricity and more efficient use of renewable energy source.

NON-QUANTITATIVE OBJECTIVES

WINNER is developing a multi-scale multi-physics modelling platform integrating various disciplines (atomistic, electro-chemical, mechanical, fluid flow, reactor engineering, electric, heat) with the goal of establishing the rate-determining steps at a meso-scale in the electrochemical cell, and the most efficient dimensioning and arrangement of the cells in the multi-tube reactor design. The work is supported by relevant experimental data and enhanced experimentation methodologies applied in the project.



PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

SoA cells development:

- WINNER has developed novel tubular cells based on the production line established at CTMS. The half-tubular cells consist of Ni-BZCY72 electrode with BZCY81 dense electrolyte. Various electrode materials and architectures have been screened for the project's multiple applications.
- The following performance criteria were successfully met for the reversible electrolysis cells and ammonia to hydrogen cells: a cell area-specific resistance below 1 ohm.cm2 at 650C, a faradaic efficiency of 80-90%, and a degradation rate below 1.2% k/hour under reversible operation.

For the ammonia to hydrogen:

- WINNER has established an ammonia conversion above 99% with a hydrogen extraction above 98%.
- A tubular cell was successfully operating in reversible operation for more than 4 000 hours at 4 bar at 650 °C.

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- Post-characterisation analysis showed some evolution of the cathode microstructure with the formation of Co-based nanoparticles, while no changes were observed in the other functional layers.

Engineering model:

- The partners initially created a communication platform to define common nomenclature, parameters and models and to establish a link between the different models and competences from atomistic scale to process scale.
- An engineering model has been defined for each of the WINNER applications, which is available in excel format and converted in an ASPEN file. The model is built based on the definition of the process flowsheet with necessary balance of plant and operating conditions, electrochemistry, kinetic and heat balance, etc.
- The tool is now functioning with multiple models integrated together (e.g. integrated atomistic + kinetics + electrochemistry models at cell levels, engineering tool + ASPEN models at cells, reactors and process levels, mechanical model).
- A computational fluid dynamics model has been initiated although its full integration into the engineering model is not completed.
- The outputs of the engineering tool are the energy demand per balance of plant and for the overall process for the selected input parameters (temperature, selectivity, conversion efficiency, cell voltage, Faradaic efficiency, etc.).
- The tool has been integrated in ASPEN for the establishment of the integrated process flowsheet and setting up the techno-economic assessment of WINNER applications.
- Several deliverables and one master thesis report on the findings from this assessment which will be discussed in a public exploitation workshop.

Life cycle assessment:

- A life cycle assessment evaluation for three applications has been conducted with user cases and benchmark cases defined for all applications. The results show the benefits of proton ceramic-based technologies versus the benchmark cases.

Multi tube testing demonstration:

- A multi-tube testing unit has been prepared at Consejo Superior de Investigaciones Científicas.
- Extensive software and hardware upgrades have been implemented to ensure high operational safety and functionality.
- Operational protocols have been defined, and commissioning has been done.
- Cells needed for testing have been produced.

FUTURE STEPS AND PLANS

WINNER was finalised in March 2024 with the delivery of the techno-economic analysis and lifecycle analysis. An exploitation workshop was organised in March 2024 together with HYDROGNi.

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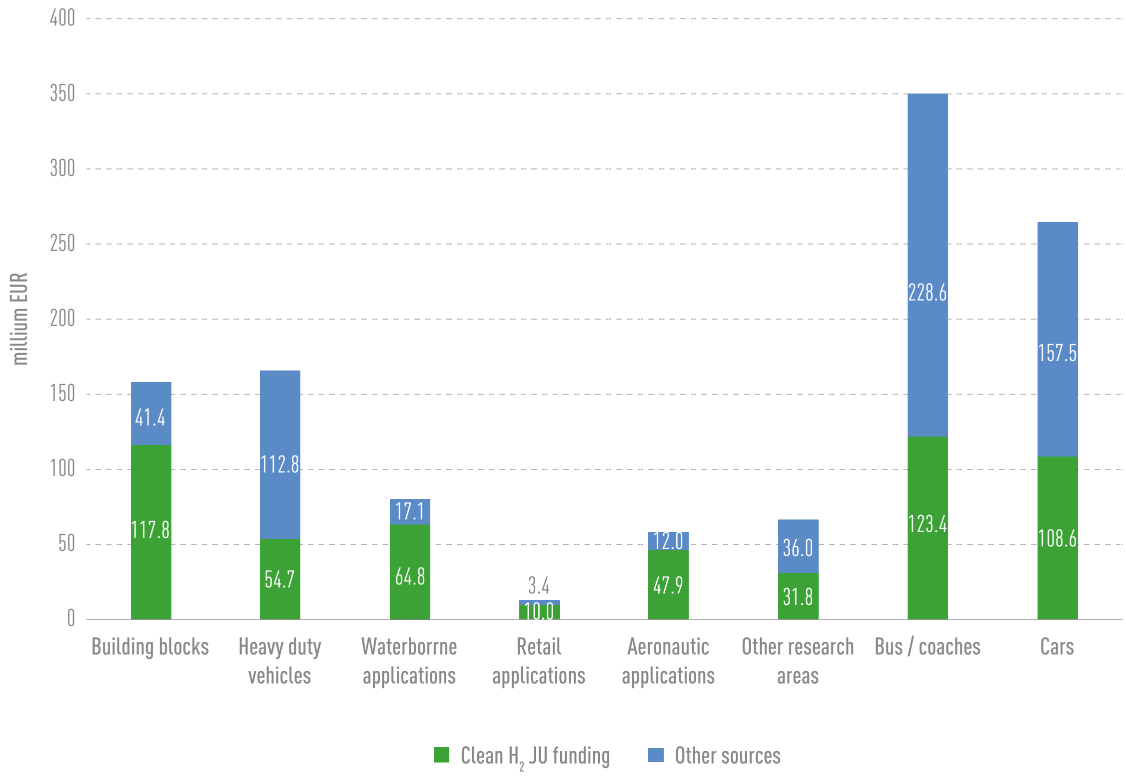
XII. PILLAR 3: H_2 END-USES: TRANSPORT APPLICATIONS

OBJECTIVES: Pillar 3 encompasses both research projects and demonstration initiatives. The Clean Hydrogen JU's SRIA identifies KPIs and quantitative targets for FC building blocks, on-board hydrogen storage, maritime, trains, and aviation. The pillar is divided into five research areas, as described below.

- **Aeronautic applications**: addresses optimisation of BoP components and architecture design to meet aviation needs.
- **Building blocks:** focuses on material design and system optimisation for both LT and HT PEMFCs.
- **Heavy Duty Vehicles, including Buses/Coaches:** addresses optimisation of BoP architectures to meet HDV needs.
- **Rail applications:** has the objective of enabling hydrogen to be recognised as the leading option for trains on non-electrified routes or partially electrified routes.
- **Waterborne applications:** focuses on improving access to the market for hydrogen, its derivatives, and FCs, including large-scale demonstrations.

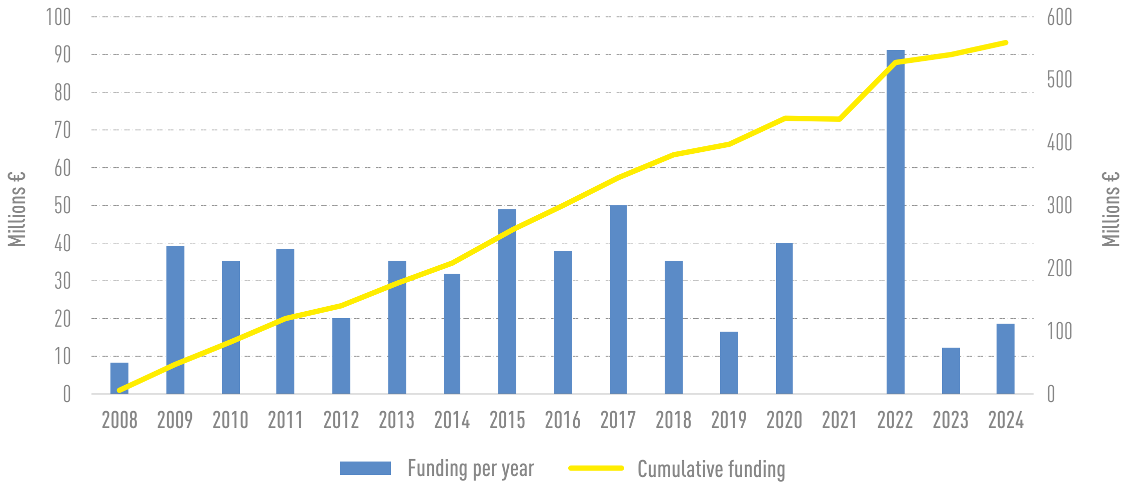
OPERATIONAL BUDGET: Between 2008 and 2024, projects under Pillar 3 received a total of EUR 559 million in funding from the Clean Hydrogen JU, complemented by EUR 608.8 million in partner contributions (Figure 32). Among the different research areas, the deployment of buses and coaches emerged as the most heavily funded, with a cumulative EUR 442 million, including EUR 123.4 million directly from the Clean Hydrogen JU. As shown in Figure 33, cumulative funding for Pillar 3 projects has grown significantly over time, with support for transport applications accelerating since 2020. Notably, the programme allocated substantial funding in recent years, reaching EUR 39 million in 2022 and EUR 54 million in 2023, reflecting the increasing strategic importance of clean hydrogen mobility solutions.

Figure 32: Funding per research area for Pillar 3 projects from 2008 to 2024



Source: Clean Hydrogen Joint Undertaking

Figure 33: Funding (per year in blue/left axis and cumulative in grey/right axis) for Pillar 3 projects from 2008 to 2024

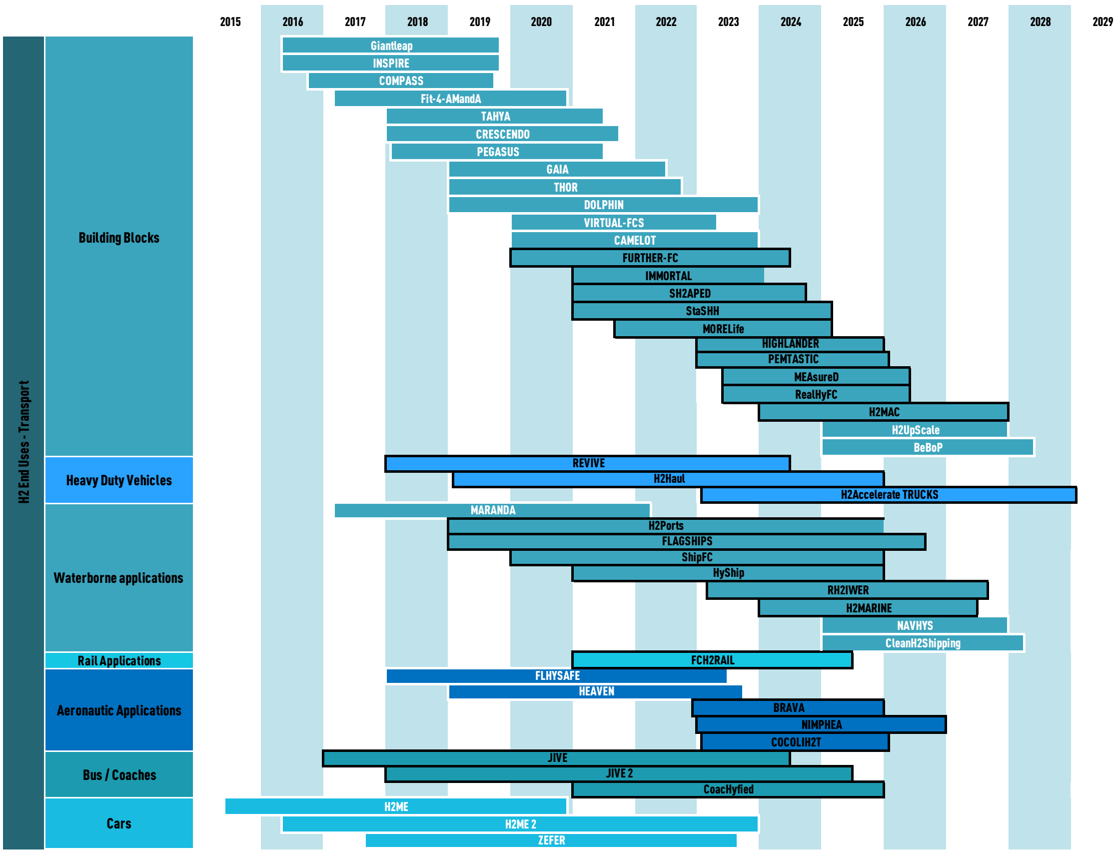


Source: Clean Hydrogen Joint Undertaking

PILLAR IN BRIEF: The timelines of the projects under Pillar 3 are shown in Figure 34. The 26 projects included in the 2025 programme technical assessment are highlighted in black.

Figure 35 shows that Germany, France, and the Netherlands lead project participation in Pillar 3 with more than 20 projects each, followed by Italy, Sweden, and Austria, while engagement decreases progressively across other countries, with Romania, Ireland, and Cyprus contributing to only a handful of projects. The collaboration network in Figure 36 highlights dense regional clusters, with Germany and France acting as central hubs, maintaining strong bilateral ties and wide-reaching connections across Europe. A distinct northern cluster links Sweden, Latvia, Belgium, and Estonia, while another cluster connects the Netherlands, Ireland, and Italy, demonstrating dynamic cooperation. Eastern European countries such as the Czech Republic, Slovenia, Poland, and Romania appear more peripheral but remain connected to the broader collaborative landscape. In terms of organisation types, Figure 37 shows that private companies (26), SMEs (23), and research institutions (21) are the most active participants in Pillar 3, followed by higher education institutions (18), other organisations (11), and public bodies (7). The Sankey diagram in Figure 38 further illustrates a growing dominance of private companies and SMEs in recent years, particularly in 2023 and 2024, while academic and research institutions have sustained steady participation throughout the entire period. Finally, Figure 39 presents the scientific publication output of the projects in Pillar 3 by year. The highest number was recorded in 2023: 25 publications (of which 18 peer-reviewed), followed by 24 publications (14 peer-reviewed) in 2024.

Figure 34: Project timelines of Pillar 3: H_2 End-Uses: Transport applications



Source: Clean Hydrogen Joint Undertaking

Figure 35: Pillar 3: Project participation by EU country

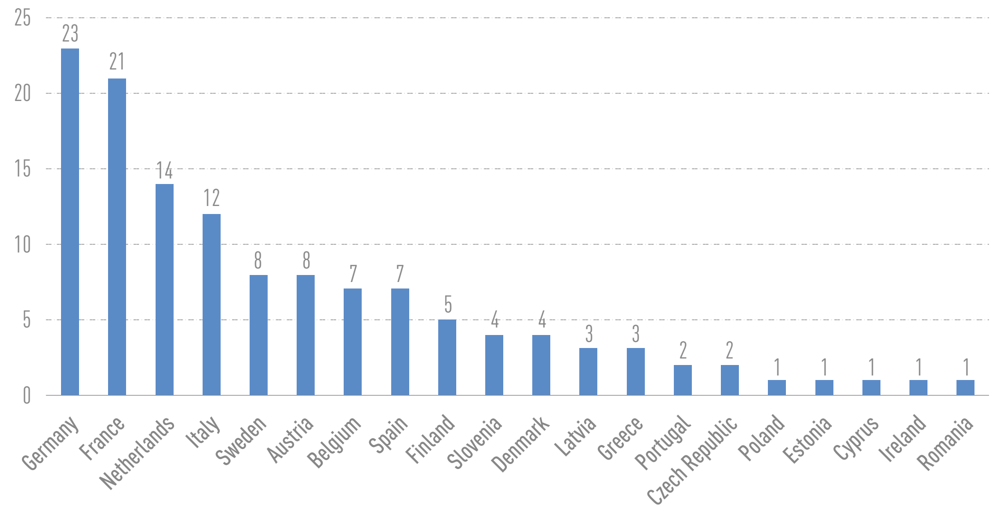


Figure 36: Pillar 3: Collaboration network of EU countries

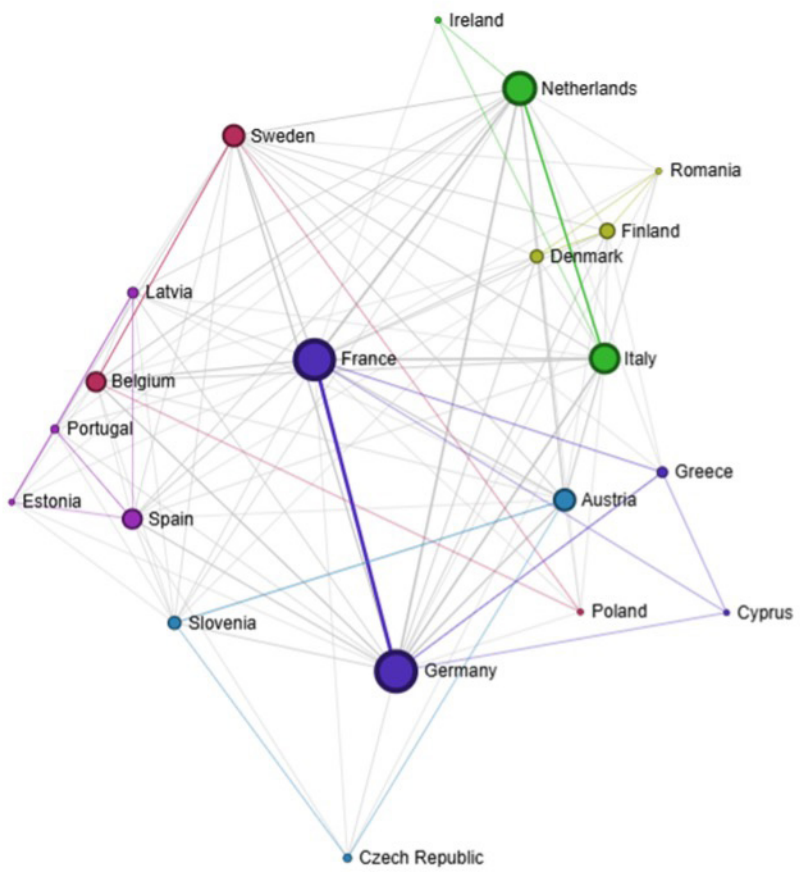


Figure 37: Pillar 3: Breakdown of projects by participating entity type

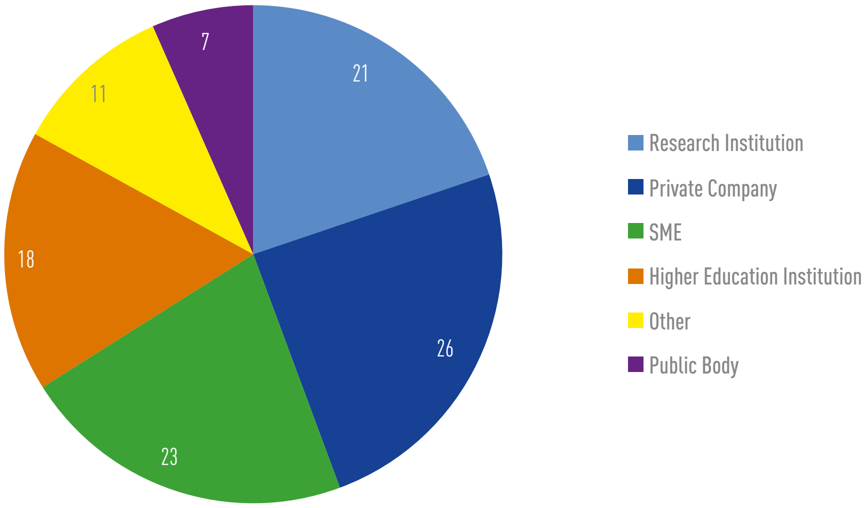


Figure 38: Pillar 3: Participation by organisation type across years

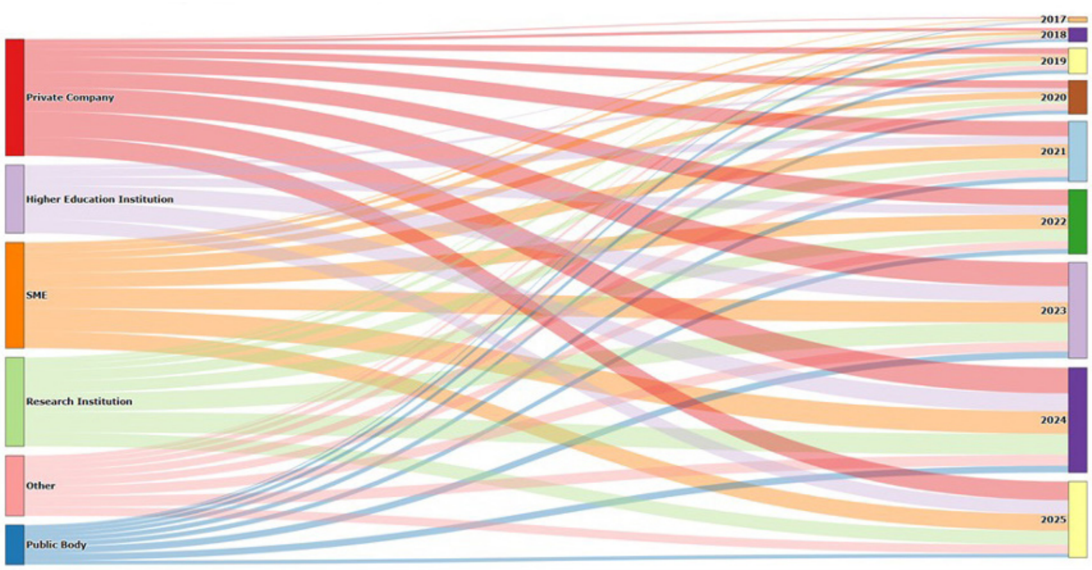
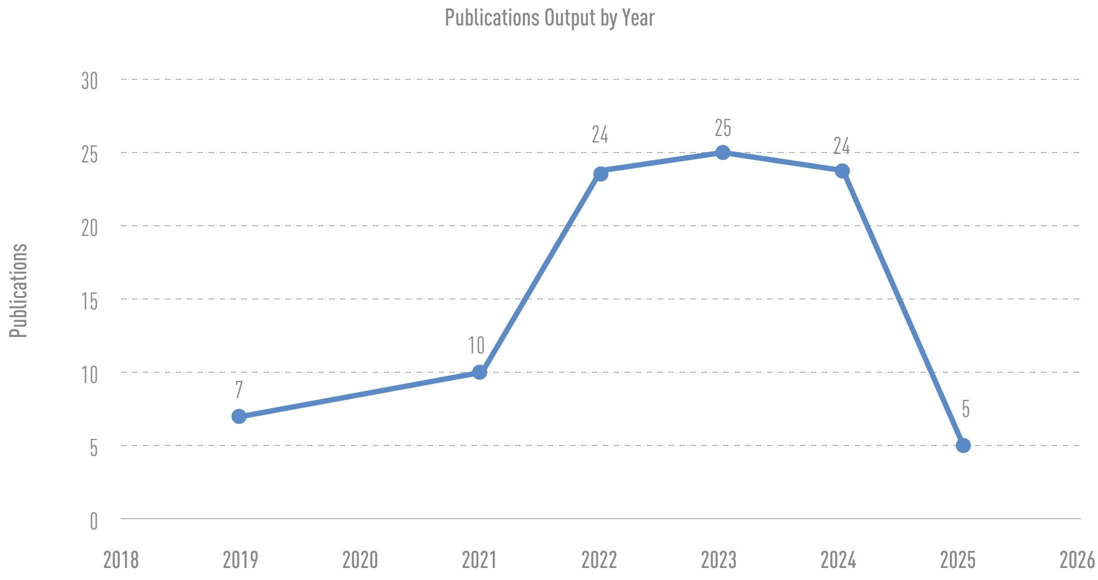
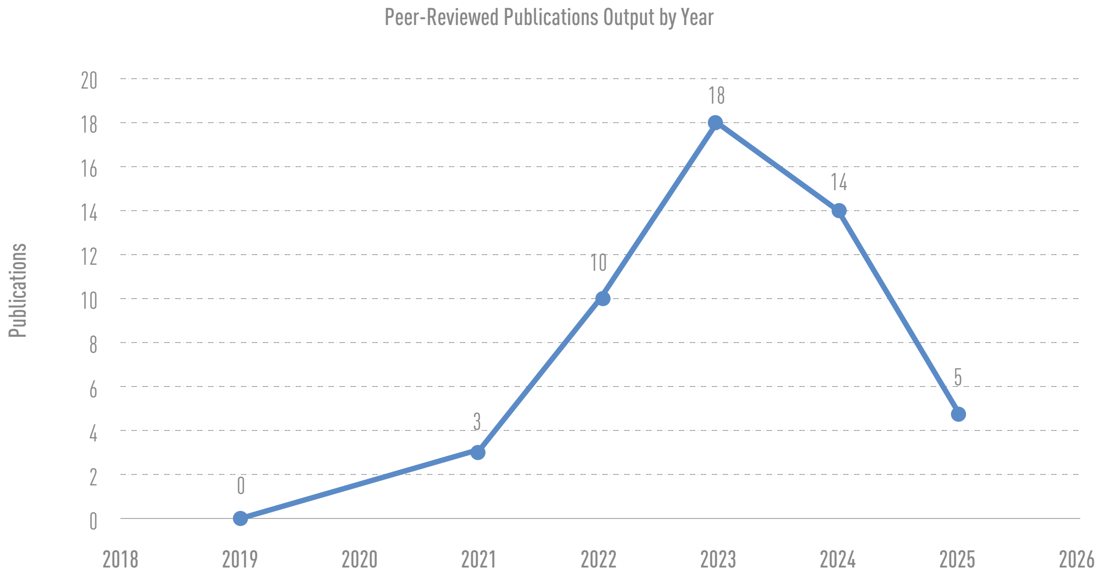


Figure 39: Pillar 3: Number of publications per year





PROJECTS FACTSHEETS

BRAVA

BREAKTHROUGH FUEL CELL TECHNOLOGIES FOR AVIATION

Project ID	101101409
PRR 2025	Pillar 3 - H_2 End Uses - Transport
Call Topic	HORIZON-JTI-CLEANH$_2$-2022-03-06
Project Total Costs	19 986 841.75
Clean H_2 JU Max. Contribution	19 986 841.75
Project Period	01-12-2022 - 31-12-2025
Coordinator Beneficiary	AIRBUS OPERATIONS GMBH, DE
Beneficiaries	RHODIA OPERATIONS, SPECIALTY OPERATIONS FRANCE, AEROSTACK GMBH, MADIT METAL SOCIEDAD LIMITADA, UNIVERSITE DE MONTPELLIER, MORPHEUS DESIGNS SOCIEDAD LIMITADA, HERAEUS DEUTSCHLAND GMBH and CO KG, Rhodia Laboratoire du Futur, SOLVAY SPECIALTY POLYMERS ITALY SPA, AIRBUS OPERATIONS SL, LIEBHERR AEROSPACE TOULOUSE SAS, TECHNISCHE UNIVERSITAT BERLIN, STICHTING KONINKLIJK NEDERLANDS LUCHT - EN RUIMTEVAARTCENTRUM, AIRBUS DEFENCE AND SPACE GMBH, CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS

http://brava-project.eu/

PROJECT AND GENERAL OBJECTIVES

- Define fuel-cell based Power Generation system architecture and safety requirements based on the higher-level fuel cell propulsion system requirements (considering weight balance).
- Design, develop, test and validate 2-phase cooling system for fuel cell stack.
- Design, develop, test and validate compact and form-flexible (air to liquid) heat exchangers via additive manufacturing.
- Develop, optimise, test and validate a high-performance fuel cell stack.
- Develop, test and validate an air supply subsystem for fuel cell system for aviation.
- Design a fuel cell power generation system with high efficiency and high gravimetric power density compatible with aeronautical specifications and constraints based on integration of developed subsystems.

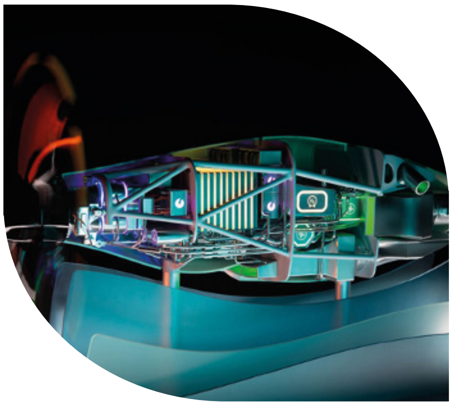
NON-QUANTITATIVE OBJECTIVES

Within the scope of BRAVA, we will embark on a preliminary design phase, conceptualising a complete PGS that seamlessly integrates the various subsystems. While the project's focus remains on subsystem-level advancements, we acknowledge that further integration into the power propulsion system and eventual aircraft-level implementation lies outside the project's immediate purview. The underlying concepts, models, assumptions, and methodologies for the fuel cell stack form the project's bedrock and work in harmony with developments in the other subsystems (air supply and thermal management system) to ensure the realisation of BRAVA's overall objectives.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

Within BRAVA, the fuel cell subsystems will deliver a range of pivotal project results, revolutionising the future of aviation:

- 2-PC based thermal management system. Our pioneering thermal management system (TMS) embraces a 2-PC design, incorporating a newly engineered fuel cell stack. By prioritising compactness and weight reduction, we aim to significantly minimise fuel consumption and maximise efficiency.



- Advanced heat exchangers. We introduce the Advanced Heat Exchanger technology, optimising heat rejection while ensuring seamless integration, reduced weight, and minimal aerodynamic drag. This breakthrough innovation contributes to enhanced performance and fuel efficiency.
- Advanced stack cell catalysts and membranes. BRAVA pushes the boundaries of stack cell catalysts and membranes, unlocking higher levels of performance, durability, and operational temperature capabilities. These advancements facilitate the integration of new membrane electrode assemblies (MEAs) that deliver unparalleled efficiency, compactness, reduced weight, and extended lifetimes.
- Innovative air supply architecture. Our team has meticulously designed and optimised a state-of-the-art air supply architecture, bolstered by components specifically tailored to aviation requirements. This forward-thinking approach minimises parasitic power, reduces weight, and ultimately lowers fuel consumption and equipment costs.

- Optimised fuel cell system architecture. Embracing a holistic approach, BRAVA presents an optimised fuel cell system architecture that encompasses innovative concepts such as anode and cathode path recirculation. These advancements promote compactness, lightweight design and elevated operational reliability, propelling aviation power systems to new heights.

FUTURE STEPS AND PLANS

In our pursuit of excellence, we will utilise a reference system, a robust MW fuel cell power generation system developed, constructed, and tested independently from the BRAVA project. This reference system will serve as the benchmark against which we will measure our progress and accomplishments in subsystem development. By surpassing the performance of the reference subsystems and meeting the key performance indicators defined early in the project, BRAVA will be well positioned to undertake a follow-up project, such as Phase 2 of the Clean Aviation programme. The follow-up project will focus on the development of an integrated fuel cell propulsion system, encompassing both ground and flight testing. This ambitious endeavour will elevate the product specifications and performance of future aviation power generation systems to unprecedented heights. The result will be a revolutionary fuel cell system designed specifically for aviation applications, paving the way for a new era of high-performance, decarbonised flight through hydrogen fuel cell technology.

PROJECT TARGETS

Target source	Parameter	Unit	Target	Achieved to date by the project	Target achieved?
Project's own objectives	FC system gravimetric power density (ecl. electrical and thrust generation)	KW_el/kg	> 1.5	-	
	FC system durability	hours	20 000	-	
	Additive Manufactured Heat exchanger (HEX) mass reduction vs standard HEX	%	> 20	-	
	Additive Manufactured Heat exchanger (HEX) volume reduction vs standard HEX	%	> 30	-	
	Protonic conductivity ionomer (> 100 deg C < 20%RH)	S/cm	> 0.1	0.278- 0.285 (@RH95% @80 deg C)	
	MEA performance	A/Cm^2 @0.74V	1.3	0.5-0.6	
	Compression ratio air supply system	ratio	5.2	> 5.2 (in simulated performance)	
	Two-phase cooling system weight reduction vs conventional cooling systems	%	20	25% (incl. accumulator of 2-PC), without accumulator can be higher (> 50%)	✓
	Pt mass activity catalysts in FC stack	A/mg Pt @ 0.9V	0.6	> 0.6 (small scale, depending on catalyst synthesis method)	✓

COCOLIH_2T

COMPOSITE CONFORMAL LIQUID H_2 TANK

Project ID	101101404
PRR 2025	Pillar 3 - H_2 End Uses - Transport
Call Topic	HORIZON-JTI-CLEANH$_2$-2022-03-07
Project Total Costs	8 726 769.50
Clean H_2 JU Max. Contribution	8 726 769.50
Project Period	01-02-2023 - 31-01-2026
Coordinator Beneficiary	COLLINS AEROSPACE IRELAND, LIMITED, IE
Beneficiaries	Simmonds Precision Products Inc., a part of Collins Aerospace, GOODRICH AEROSPACE EUROPE SAS, UNIFIED INTERNATIONAL, UTC AEROSPACE SYSTEMS WROCLAW SPOLKA Z OGRANICZONA ODPOWIEDZIALNOSCIA, MICROTECNICA SRL, CROMPTON TECHNOLOGY GROUP LTD, NOVOTECH AEROSPACE ADVANCED TECHNOLOGY SRL, AVIONS DE TRANSPORT REGIONAL, TECHNISCHE UNIVERSITEIT DELFT, STICHTING KONINKLIJK NEDERLANDS LUCHT - EN RUIMTEVAARTCENTRUM

PROJECT AND GENERAL OBJECTIVES

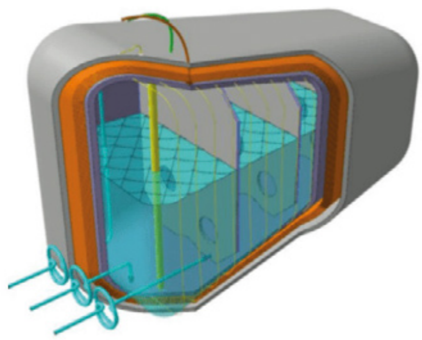
Improvements to existing state-of-the-art solutions include better utilisation of the available space for fuel storage, adequate insulation techniques to minimise heat leak, continued safe operations, and weight reduction through the use of low-weight materials, such as thermoset or thermoplastic composites, all while addressing those materials' inherent challenges (permeability, microcracking, thermal fatigue).

NON-QUANTITATIVE OBJECTIVES

The project aims to push the boundaries of the composite design of liquid hydrogen storage systems, and those of pressure management systems, cryogenic fluid controls, prognostic and structural health systems, hazard analyses, integration and systems testing, gauging sensors, leak sensors and much more.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

- Completion of preliminary critical design and manufacturing readiness level reviews of the COCOLIH2T liquid hydrogen storage system.



- TRL3 development cryogenic valves, prognostic health monitoring algorithms and liquid hydrogen fuel gauging technology.

FUTURE STEPS AND PLANS

A manufacturing readiness level review is planned, and the first demonstrator system is planned to be tested in the Netherlands Aerospace Centre in Q2. The second manufacturing demonstrator will be completed by Q4.

PROJECT TARGETS

Target source	Parameter	Unit	Target	Target achieved?
Project's own objectives	Maximum diameter	min	< 1	
	Venting rate	%/ day	< 2	
	Dormancy	hours	> 24	
	Insulation vacuum	mbar	10^{-5}	

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FCH$_2$RAIL

FUEL CELL HYBRID POWERPACK FOR RAIL APPLICATIONS

Project ID	101006633
PRR 2025	Pillar 3 - H_2 End Uses - Transport
Call Topic	FCH-01-7-2020
Project Total Costs	13 378 484.93
Clean H_2 JU Max. Contribution	9 999 999.12
Project Period	01-01-2021 - 30-06-2025
Coordinator Beneficiary	DEUTSCHES ZENTRUM FUR LUFT - UND RAUMFAHRT EV, DE
Beneficiaries	CONSTRUCCIONES Y AUXILIAR DE FERROCARRILES INVESTIGACION Y DESARROLLO SL, CAF DIGITAL and DESIGN SOLUTIONS SOCIEDAD ANONIMA, FAIVELEY TRANSPORT LEIPZIG GMBH and CO. KG, RENFE INGENIERIA Y MANTENIMIENTO SME, RENFE VIAJEROS SA, CENTRO DE ENSAYOS Y ANALISIS CETEST SL, CAF TURNKEY and ENGINEERING SOCIEDAD LIMITADA, CAF POWER and AUTOMATION SL, CENTRO NACIONAL DE EXPERIMENTACIONDE TECNOLOGIAS DE HIDROGENO Y PILASDE COMBUSTIBLE CONSORCIO, STEMMANN-TECHNIK GMBH, Renfe Operadora, TOYOTA MOTOR EUROPE NV, INFRAESTRUTURAS DE PORTUGAL SA, Construcciones y Auxiliar de Ferrocarriles S.A., ADMINISTRADOR DE INFRAESTRUCTURAS FERROVIARIAS

https://www.fch2rail.eu/en/projects/fch2rail

PROJECT AND GENERAL OBJECTIVES

The project consortium is developing and testing a new train prototype. At the heart of the project is a hybrid, bimodal driving system that combines the advantages of an electrical power supply from an overhead line with a hybrid power pack consisting of fuel cells and batteries. This system enables more sustainable and energy-efficient rail transport. The project will show that this type of bimodal power pack is a competitive and environmentally friendly alternative to diesel power.

NON-QUANTITATIVE OBJECTIVES

An expert network with external stakeholders has been created to support the analysis of gaps in the normative framework. Network meetings were held in 2023 and the gap analysis was shared with and commented on by the WP7 network.

Exchanges and collaboration have taken place with other EU projects, including STASHH (standard-sized heavy-duty hydrogen), Virtual-FCH (virtual and physical platform for fuel cell system development), HyResponder (European hydrogen train-the-trainer programme for responders), and Rail4Earth (Europe's Rail Flagship Project 4 – sustainable and green rail systems), as well as national projects such as H2goesRail and H2BAR (use of hydrogen fuel cell drives in local transport in the Barnim district, operated with 100% renewable hydrogen).

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

- Fuel cell hybrid power pack (FCHPP) development and tests on a Centro Nacional del Hidrógeno test bench were successfully completed.
- The physical Integration of two FCHPPs into the demonstrator train was successfully completed.
- The first static test of a FCHPP in a train was conducted.
- The dynamic testing of the demonstrator train on closed tracks was conducted.
- TRL7 authorisation was obtained for Spain's demonstrator system.
- The functioning of the first H_2-powered train was demonstrated on the Spanish railway network.
- The train demonstration was finalised in Madrid and Galicia.
- TRL7 authorisation for Portugal.
- More than 4 600 km were demonstrated in H_2 mode before the end of 2023.
- Train demonstration is ongoing on several lines in Spain.

FUTURE STEPS AND PLANS

- Demonstration of a bimodal train in Portugal.
- Receipt of theoretical track authorisation for Germany.

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FLAGSHIPS

CLEAN WATERBORNE TRANSPORT IN EUROPE

Project ID	826215
PRR 2025	Pillar 3 - H_2 End Uses - Transport
Call Topic	FCH-01-2-2018
Project Total Costs	6 766 811.83
Clean H_2 JU Max. Contribution	4 999 978.75
Project Period	01-01-2019 - 30-09-2026
Coordinator Beneficiary	TEKNOLOGIAN TUTKIMUSKESKUS VTT OY, FI
Beneficiaries	SOGESTRAN, SOGESTION, FUTURE PROOF SHIPPING BV, LMG MARIN FRANCE, LMG MARIN AS, NORLED AS, SEAM AS, MARITIME CLEANTECH, PERSEE, Compagnie Fluviale de Transport, BALLARD POWER SYSTEMS EUROPE AS, ABB OY, KONGSBERG MARITIME AS

https://flagships.eu/

PROJECT AND GENERAL OBJECTIVES

Two commercially operated hydrogen fuel cell vessels will be demonstrated, one in France (Paris) and one in the Netherlands (Rotterdam). The Paris demonstration vessel is a self-propelled barge operating as a goods transport vessel in the city centre and the Rotterdam demonstration vessel is a container vessel transporting goods between Rotterdam and Duisburg. The Rotterdam demonstrator started its operation in April 2024 and the Paris demo will follow during 2025.

NON-QUANTITATIVE OBJECTIVES

- The project aims to develop and demonstrate bunkering technologies based on swapping gaseous hydrogen fuel containers.
- Procedures for hydrogen bunkering by swapping hydrogen storage containers are being developed.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

- The FCwave fuel cell module has gained type approval by DNV.
- The H_2 Barge II demonstration vessel (Rotterdam) has been launched and started its operation in April 2024.

- The Zulu demonstration vessel (Paris) is ready and taking its last steps in the approval process.

FUTURE STEPS AND PLANS

- The commercial operation of both vessels will be demonstrated for 18 months.
- The results of the demonstration vessels will be analysed.

PROJECT TARGETS

Target source	Parameter	Unit	Target	Achieved to date by the project	Target achieved?
Project's own objectives	Develop necessary safety measures of H_2 and FC vessels to enable their class' approval.	-	Class approval gained	CCNR approval gained for both vessels	✓
	Demonstrate the operation of a hydrogen-fuelled 1.2 MW power class cargo vessel in the Rotterdam-Duisburg route for at least 18 months.	Months	18	10	
	Demonstrate the operation of a hydrogen-fuelled 400 kW power class self-propelled barge in the Paris area, France for at least 18 months.	Months	18	-	

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FURTHER-FC

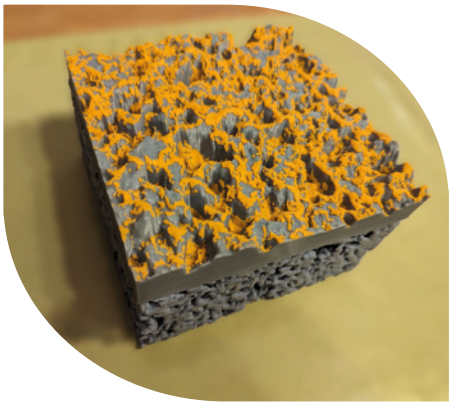
FURTHER UNDERSTANDING RELATED TO TRANSPORT LIMITATIONS AT HIGH CURRENT DENSITY TOWARDS FUTURE ELECTRODES FOR FUEL CELLS

Project ID	875025
PRR 2025	Pillar 3 - H_2 End Uses - Transport
Call Topic	FCH-01-4-2019
Project Total Costs	2 735 031.25
Clean H_2 JU Max. Contribution	2 199 567.35
Project Period	01-01-2020 - 31-08-2024
Coordinator Beneficiary	COMMISSARIAT A L ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES, FR
Beneficiaries	UNIVERSITE DE MONTPELLIER, UNIVERSITE DE MONTPELLIER, CHEMOURS FRANCE SAS, THE CHEMOURS COMPANY FC, LLC, HOCHSCHULE ESSLINGEN, TOYOTA MOTOR EUROPE NV, ECOLE NATIONALE SUPERIEURE DE CHIMIE DE MONTPELLIER, University of Calgary, INSTITUT NATIONAL POLYTECHNIQUE DE TOULOUSE, DEUTSCHES ZENTRUM FUR LUFT - UND RAUMFAHRT EV, IMPERIAL COLLEGE OF SCIENCE TECHNOLOGY AND MEDICINE, PAUL SCHERRER INSTITUT, CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS

https://further-fc.eu/

PROJECT AND GENERAL OBJECTIVES

FURTHER-FC proposes an innovative route towards a better understanding of performance limitations inside proton exchange membrane fuel cells (PEMFC), focusing on the performance cost and durability of the cathode catalyst layer (CCL) for innovative high performing low-Pt loaded PEMFCs for automotive application. The approach is based on the development of innovative and/or improved modelling and experimental tools to analyse the performance from the ionomer film layer scale to the full CCL scale.



NON-QUANTITATIVE OBJECTIVES

- Combine original and advanced methods with fundamental characterisations and advanced models on CCL to investigate transport and electrochemical issues.
- Describe the CCL structure, transport properties and mechanisms, at its different scales.
- Characterise local conditions in the CCL during operation.
- Establish the link between the structure and properties of the CCL, local operating conditions, and performance.
- Validate CCL with improved catalyst efficiency and durability.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

Components and Testing:

- Development and testing of various membrane electrode assemblies (MEAs) with different Pt loadings, ionomer types (D2020 vs. HOPI), and carbon supports, and ultra-low catalyst loadings (10–50 µg/cm²) have been developed and tested.
- Performance analyses of MEAs using techniques like limiting current analysis, electrochemical impedance spectroscopy, and I-V curves.
- Selection and testing of a final high-performance MEA.

Ex-Situ Characterisation:

- Analysis of cathodic catalyst layers and gas diffusion layers through advanced imaging (X-ray, FIB-SEM, TEM, AFM, SAXS, SANS), focusing on Pt nanoparticle distribution, ionomer coverage, and microstructural properties.
- Measurement of key properties such as electronic, protonic, thermal conductivities, wettability, and oxygen transport resistance in thin ionomer films (~6.5 nm).

Performance Limitations and Water Management:

- Investigation of local water content and distribution during operation.
- Analysis of performance limits related to oxygen reduction reaction and hydrogen oxidation reaction kinetics.

Modelling, Simulation, and Development of multi-scale models:

- Sub-micron scale: Lattice-Boltzmann simulations of local ORR rates and transport processes.
- GDL/MPL scale: Heat conductivity and gas diffusion simulations based on 3D imaging.
- CCL scale: Modelling of oxygen diffusion, proton conductivity, and ionomer distribution.

- Cell scale: Integration of these properties into performance models for improved accuracy.

Dissemination and Impact:

- Organisation of workshops, publication of 16 peer-reviewed articles, participation in 21 conferences, and sharing of results via newsletters and social media.
- Preparation of a 3D printed model consolidating data from project partners.

Advances Beyond State-of-the-Art:

- Enhanced electron tomography techniques for detailed 3D imaging of Pt distribution.
- Improved quantification of ionomer distribution using combined microscopy methods.
- Measurement of transport properties of ultra-thin ionomer films under various conditions.
- Used operando Small Angle Neutron Scattering (SANS) to characterise water content in MEAs.
- Development of advanced modelling tools linking microstructure to cell performance, validated by experiments.

Key Findings on CCL Structure and Transport:

- Achievement of a better agreement between simulations and experiments for proton conductivity using real microstructural images and ionomer reconstruction.
- Confirmation of significant proton transport through liquid water in primary pores.
- Computation of water retention curves consistent with experimental data based on microstructural imaging.

Performance Limitations and Future Work:

- Deeper understanding of the impact of ionomer type, carbon support, and catalyst loading under various conditions.
- Proposed explanations for performance limits, some that are validated and others that require further study.
- Suggested experiments to further improve catalyst layer performance and durability with reduced catalyst amounts.
- Manufactured CCLs showing enhanced performance and durability, notably with HOPI ionomer for automotive applications and heavy-duty conditions.

FUTURE STEPS AND PLANS

- TOYOTA MOTOR EUROPE, a leading actor in fuel cell vehicles, provided FURTHER-FC access to a wide network of characterisation and modelling technologies.
- Knowledge developed by FURTHER-FC in terms of material developments, analysis of performance limitations and developments of innovative modelling tools has been provided to European industrial partners.
- A methodology developed within FURTHER-FC will be applied for batteries through the recruitment of a PhD student who was involved in FURTHER-FC.

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H_2ACCELERATE TRUCKS

LARGE SCALE DEPLOYMENT PROJECT TO ACCELERATE THE UPTAKE OF HYDROGEN TRUCKS IN EUROPE

Project ID	101101446
PRR 2025	Pillar 3 - H_2 End Uses - Transport
Call Topic	HORIZON-JTI-CLEANH$_2$-2022-03-03
Project Total Costs	110 961 308.68
Clean H_2 JU Max. Contribution	29 991 488.50
Project Period	01-02-2023 - 31-01-2029
Coordinator Beneficiary	SINTEF AS, NO
Beneficiaries	FIAP SERVICE SRL SOCIETA BENEFIT, FEDERAZIONE ITALIANA AUTOTRASPORTATORI PROFESSIONALI, ERM FRANCE, EVERFUEL A S,SHELL NEDERLAND VERKOOPMAATSCHAPPIJ BV, TOTALENERGIES GAS MOBILITY BV, DAIMLER TRUCK AG, LINDE GMBH, UNIUNEA NATIONALA A TRANSPORTATORILOR RUTIERI DIN ROMANIA, TEKNOLOGIAN TUTKIMUSKESKUS VTT OY, OMV DOWNSTREAM GMBH, ENVIRONMENTAL RESOURCES MANAGEMENT LIMITED, IVECO SPA, ELEMENT ENERGY LIMITED, UNION INTERNATIONALE DES TRANSPORTS ROUTIERS (IRU), VOLVO LASTVAGNAR AB, WIRTSCHAFTSKAMMER OSTERREICH, VOLVO TECHNOLOGY AB

https://h2accelerate.eu/trucks/

PROJECT AND GENERAL OBJECTIVES

The overall project goal is to support the transition of fuel cell trucks from technically proven but high-cost demonstrators to a viable commercial choice for operators across Europe. To achieve the above goal, the general objectives are to:

- Deploy 150 fuel cell trucks weighing between 41 t and 44 t in nine European countries by the end of 2029.
- Operate the trucks on an HRS network designed for zero-emission truck deployment, operated by Everfuel, Shell and TotalEnergies.
- Analyse technical, environmental, economic and attitudinal data to determine the viability of H_2 fuel cell trucks as a solution to decarbonise road freight.
- Raise awareness of the benefits of using green H_2 for trucking in Europe through a wide range of targeted communication activities.

PROGRESS AND ACHIEVEMENTS

- The adaptation of manufacturing facilities to accommodate fuel cell truck production.
- Preparations for homologation and type approval.
- The initial preparations by original equipment manufacturers for fleet launch.

MAIN RESULTS

- Dialogue with heavy-duty truck end users and HRS network operators.
- The development of, and agreement on, protocols for data monitoring and analysis.
- First batch of "artificial" truck operation data transferred to VTT for assessment.
- The assessment of health and safety issues and submission of an adequate safety plan.
- The launch of the project's website and LinkedIn, X accounts.
- The establishment of a dissemination and exploitation plan.
- The submission of OEMs annual progress reports.

Clean Hydrogen Partnership
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PROJECT TARGETS

Target source	Parameter	Unit	Target	Target achieved?
Project's own objectives	Deployed HD Trucks' gross weight	t	41-44	
	Vehicle range under heavy load	km	> 600 km for compressed H_2 and > 1 000 km for liquid hydrogen	
	Annual CO_2 emission savings	t/year	Confirmation (by LCA) of a saving across the fleet of 21 000 t/year	
	End user groups to allow detailed discussion of hydrogen trucks with users not in the project.	Number	3	
	Dataset covering the performance of 150 trucks.	Number	Shareable separate reports (including regular updates) of the technical, economic performance of and end users' attitudes to hydrogen trucks in day-to-day operation.	
	Trucks cost	€	< 450 000	
	Central and eastern European potential truck operators in end user groups.	Number	> 20	
	Vehicle availability	%	> 95	
	Green hydrogen demand created	t/year	2 100	
	Data monitoring and analyses of trucks' performance.	% of deployed trucks	20 (corresponding to 30 trucks of the full fleet of 150 trucks)	
	Monitored operational period per truck.	Months	24	
	Demand for electrolyser capacity created.	MW	26 (assuming 50% load factor to match green supply)	
	Dedicated truck road tour visits in EU Member States.	Number of MS	5	
	Number of H_2/FC powered HD trucks deployed.	Number	150	
	Presentations at events and conferences.	Number/ year	5	✓
	Visible social media and web presence.	Number	2	

H2HAUL

HYDROGEN FUEL CELL TRUCKS FOR HEAVY-DUTY, ZERO EMISSION LOGISTICS

Project ID	826236
PRR 2025	Pillar 3 - H_2 End Uses - Transport
Call Topic	FCH-01-1-2018
Project Total Costs	28 110 126.80
Clean H_2 JU Max. Contribution	12 000 000.00
Project Period	01-02-2019 - 31-12-2025
Coordinator Beneficiary	ENVIRONMENTAL RESOURCES MANAGEMENT LIMITED, UK
Beneficiaries	ELEMENT ENERGY, VDL SPECIAL VEHICLES BV, ERM FRANCE, DATS 24, PLASTIC OMNIUM NEW ENERGIES WELS GMBH, H2 ENERGY AG, AIR LIQUIDE FRANCE INDUSTRIE, VDL ENABLING TRANSPORT SOLUTIONS BV, VDL BUS EINDHOVEN BV, EOLY, FPT MOTORENFORSCHUNG AG, HYDROGENICS GMBH, IRU PROJECTS ASBL, FPT INDUSTRIAL SPA, AIR LIQUIDE ADVANCED TECHNOLOGIES SA, SPHERA SOLUTIONS GMBH, IVECO SPA, ELRINGKLINGER AG, ETABLISSEMENTEN FRANZ COLRUYT NV, WATERSTOFNET VZW, AIR LIQUIDE ADVANCED BUSINESS, TOTALENERGIES MARKETING DEUTSCHLAND GMBH, Powercell Sweden AB, ELEMENT ENERGY LIMITED, UNION INTERNATIONALE DES TRANSPORTS ROUTIERS (IRU), BAYERISCHE MOTOREN WERKE AKTIENGESELLSCHAFT, ROBERT BOSCH GMBH, HYDROGEN EUROPE

http://www.h2haul.eu

PROJECT AND GENERAL OBJECTIVES

H2Haul brings together two major European truck OEMs (IVECO and VDL) and three fuel cell stack/system suppliers (Plastic Omnium, Bosch and PowerCell) to develop and demonstrate fleets of heavy-duty trucks in day-to-day commercial operations in four sites across four countries. The overall objective of H2Haul is to prove that hydrogen trucks can be a practical zero-emission and zero-carbon solution for much of Europe's trucking needs and, in doing so, pave the way for the commercialisation of fuel cell trucks in Europe. The project is currently at the end of the planning and pre-deployment phase, and all trucks and HRS funded by the project are expected to be deployed in the next months.

NON-QUANTITATIVE OBJECTIVES

- H2Haul aims to develop long-haul heavy-duty (26 t and 44 t) fuel cell trucks that meet customers' requirements in a range of operating environments. The trucks' design and specifications are being finalised in alignment with specific customer requirements and mission profiles. The objectives are expected to be met.
- The project aims to homologate three fuel cell truck types to certify that they are safe to use on European roads. Original truck OEMs are working closely with hydrogen safety experts and the relevant certification bodies to secure all necessary safety approvals for using the trucks on public roads in Europe.
- The project aims to develop the business case for the further roll-out of heavy-duty fuel cell trucks. H2Haul will provide a valuable database of real-world performance information and insights into the next steps required for the sector's commercialisation. The business case will be developed based on fuel cell truck designs that meet customers' needs. The operation of fuel cell trucks and the subsequent data collection will highlight the technology's costs. Analysis will be carried out to highlight the economics of more ambitious deployment of tens of vehicles or more.
- H2Haul aims to prepare the European market for the further roll-out of fuel cell trucks through (i) the development of innovative commercial models and (ii) the dissemination of information from the project to a wide audience of relevant stakeholders. H2Hauls dissemination activities will share key findings with relevant audiences to prepare the market for the wider roll-out of fuel cell trucks on a commercial basis.
- Communication activities in the first and second year of the project have stimulated significant interest from relevant audiences.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

- The fuel cell truck technical specifications were finalised. Data were gathered on the technical specifications of the fuel cell trucks and hydrogen-refuelling stations (HRSs).
- All three project-funded HRSs were deployed.
- The second observer group meeting took place.

FUTURE STEPS AND PLANS

- H2Haul will deploy the VDL and Iveco trucks. The Iveco beta trucks are currently being assembled with fuel cells from Bosch and will serve as prototypes for the 12 gamma trucks which will be delivered to end users in France, Switzerland and Germany.
- The H2Haul will continue high-profile dissemination and lobbying work through attending and delivering presentations at key conferences and events. Other stakeholder engagement activities will also continue. The results will be disseminated extensively.

PROJECT TARGETS

Target source	Parameter	Unit	Target	Target achieved?
Project's own objectives	WtW CO_2 emissions	kg CO_2/km	kg CO_2/ vehicle km (per vehicle type, average across fleet)	

H_2MAC

HYDROGEN FUEL CELL ELECTRIC NON-ROAD MOBILE MACHINERY FOR MINING AND CONSTRUCTION: AN INNOVATIVE, EFFICIENT, SCALABLE, SILENT AND MODULAR POWER-TRAIN CONCEPT

Project ID	101137786
PRR 2025	Pillar 3 - H_2 End Uses - Transport
Call Topic	HORIZON-JTI-CLEANH$_2$-2023-03-01
Project Total Costs	6 563 805.00
Clean H_2 JU Max. Contribution	4 990 769.76
Project Period	01-01-2024 - 31-12-2027
Coordinator Beneficiary	INSTITUTO TECNOLOGICO DE ARAGON, ES
Beneficiaries	ASOCIACION ESPANOLA DE FABRICANTES EXPORTADORES DE MAQUINARIA PARA CONSTRUCCION, OBRAS PUBLICAS Y MINERIA, ZAMALBIDESERVICE2021 SL, TALLERES ZB S.A., HIDROMEK MAQUINARIA DE CONSTRUCCION ESPAÑA S.L., HIDROMEK-HYDROLIK VE MEKANIK MAKINA IMALAT SANAYI VE TICARET ANONIM SIRKETI, TAMPEREEN KORKEAKOULUSAATIO SR, MANN + HUMMEL GMBH, BALLARD POWER SYSTEMS EUROPE AS, Powercell Sweden AB, FUNDACION PARA EL DESARROLLO DE LAS NUEVAS TECNOLOGIAS DEL HIDROGENO EN ARAGON

https://h2mac.eu/

PROJECT AND GENERAL OBJECTIVES

- The objective of H_2Mac is to develop zero emissions heavy-duty mobile machinery for mining and construction sectors.
- Therefore, H_2MAC will develop an excavator and a shredder with integrated fuel cell powertrains and related subsystems.
- The power trains will be innovative, efficient, scalable, silent and modular. The excavator will be powered by one 120 kW fuel cell module. The shredder will upscale the concept using two modules to enlarge the power to 240 kW.
- The operation of both heavy-duty mobile machines is complementary, as the excavator has a load profile derived of its movement during operation, while the shredder is a more static machine when operating.
- H_2MAC includes a simultaneous demonstration of both machines during 1000 hours in a single real environment. The results should allow the H_2MAC consortium to develop solutions for operation in different sectors under different operational conditions.
- The consortium is composed of a variety of technological partners, component manufacturers, machinery manufacturers and associations that will help communication, dissemination and exploitation through standardisation.

ACHIEVEMENT

- H_2MAC General Assembly in Tampere (Finland) on the 11th and 12th of March 2024.

PROJECT TARGETS

Target source	Parameter	Unit	Target	Target achieved?
Project's own objectives	Noise reduction	dBA	< 100	
	New technology feasible and commercially viable	Number/project	2	
	Emission reduction	CO_2-eq /year	0	
	FC system efficiency (TCO reduction)	%	50	

Clean Hydrogen Partnership
Co-funded by the European Union

H$_2$MARINE

HYDROGEN PEM FUEL CELL STACK FOR MARINE APPLICATIONS

Project ID	101137965
PRR 2025	Pillar 3 - H$_2$ End Uses - Transport
Call Topic	HORIZON-JTI-CLEANH$_2$-2023-03-02
Project Total Costs	7 499 171.50
Clean H$_2$ JU Max. Contribution	7 499 171.50
Project Period	01-01-2024 - 30-06-2027
Coordinator Beneficiary	ETHNIKO KENTRO EREVNAS KAI TECHNOLOGIKIS ANAPTYXIS, EL
Beneficiaries	CLEOS IDIOTIKI KEFALAIOUCHIKI ETAIREIA, Beyond Gravity Schweiz AG, EH GROUP ENGINEERING SA, GREENERITY GMBH, TEKNOLOGIAN TUTKIMUSKESKUS VTT OY, CLUSTER VIOOIKONOMIAS KAI PERIVALLONTOS DYTIKIS MAKEDONIAS, THYSSENKRUPP MARINE SYSTEMS GMBH, Powercell Sweden AB, ZENTRUM FUR SONNENENERGIE- UND WASSERSTOFF-FORSCHUNG BADEN-WURTTEMBERG, ALBERT-LUDWIGS-UNIVERSITAET FREIBURG, REINZ-DICHTUNGS GMBH, ECOLE POLYTECHNIQUE FEDERALE DE LAUSANNE

https://h2marineproject.eu/

PROJECT AND GENERAL OBJECTIVES

The overarching objective of the H$_2$MARINE project is to design, build, test and validate two PEM stacks generating 250 - 300 kW electrical power designed for marine applications. The H$_2$MARINE project takes a top-down approach, building on a proof of concept of two PEM stacks that are being developed in the EU and Switzerland. The H$_2$MARINE project will:

- Identify the requirements for the tests and conditions as well as load curves that the dual cell stacks will have to be tested against, using the combined knowledge of a major ship-building industry (Thyssen-Krupp Marine Systems) and ship owners (Cleos).
- Enable both the PowerCell and the EH Group stack manufacturers to benefit from a great consortium surrounding their development, testing and upscaling with unique testing facilities (Beyond Gravity, Zentrum für Sonnenenergie- und Wasserstoff-Forschung Baden-Württemberg, Greenerity, University of Freiburg), industrial partners such as DANA, the upscaling of stacks by Ethniko Kentro Erevnas kai Technologikis Anaptyxis and École polytechnique fédérale de Lausanne and novel diagnostics development by VTT, which will allow them to enhance the state-of-the-art of PEMFC stacks, and advance and scale up the system to reach ambitious targets set in the call which will be disseminated by CLUBE (a member of numerous fuel cell and hydrogen projects).
- Test the proposed solutions in a relevant environment/ecosystem, designed to represent actual marine conditions.
- Design the stack modules in an optimum manner for up-scaling up to 10 MW power train systems.
- Test several diagnostics for the integrity of the stack and overall system and for the health status of critical components.
- Assess the technology and economic feasibility of the solution, in order to determine its valuable end-use, which will allow the partners to research the potential market(s) and identify the best opportunities.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

The project officially started on January 1, 2024 and the associated work is on-going.

PROJECT TARGETS

Target source	Parameter	Unit	Target	Target achieved?
Project's own objectives	Module Rating	kW	250	
	Hours of test for each FC	hours	2 000	

H_2PORTS

IMPLEMENTING FUEL CELLS AND HYDROGEN TECHNOLOGIES IN PORTS

Project ID	826339
PRR 2025	Pillar 3 - H_2 End Uses - Transport
Call Topic	FCH-03-1-2018
Project Total Costs	4 117 197.50
Clean H_2 JU Max. Contribution	3 999 947.50
Project Period	01-01-2019 - 31-12-2025
Coordinator Beneficiary	FUNDACION DE LA COMUNIDAD VALENCIANA PARA LA INVESTIGACION, PROMOCION Y ESTUDIOS COMERCIALES DE VALENCIAPORT, ES
Beneficiaries	SCALE GAS SOLUTIONS, S.L., VALENCIA TERMINAL EUROPA SA,CANTIERI DEL MEDITERRANEO SPA, HYSTER-YALE NEDERLAND BV,ATENA SCARL - DISTRETTO ALTA TECNOLOGIA ENERGIA AMBIENTE, MEDITERRANEAN SHIPPING COMPANY TERMINAL VALENCIA SA, CENTRO NACIONAL DE EXPERIMENTACIONDE TECNOLOGIAS DE HIDROGENO Y PILASDE COMBUSTIBLE CONSORCIO, GRIMALDI EUROMED SPA, BALLARD POWER SYSTEMS EUROPE AS, SOCIEDAD ESPANOLA DE CARBUROS METALICOS SA, AUTORIDAD PORTUARIA DE VALENCIA, ENAGAS SA,UNIVERSITA DEGLI STUDI DI NAPOLI PARTHENOPE, UNIVERSITA DEGLI STUDI DI SALERNO, AGENZIA NAZIONALE PER LE NUOVE TECNOLOGIE, L'ENERGIA E LO SVILUPPO ECONOMICO SOSTENIBILE

https://h2ports.eu/

PROJECT AND GENERAL OBJECTIVES

The H2ports project will demonstrate and validate two innovative solutions based on fuel cell technologies. A reach stacker and a terminal tractor will be tested on a daily basis during real operational activities at the port of Valencia. The required hydrogen will be provided via a mobile hydrogen-refuelling station (HRS) designed and built during the project.

NON-QUANTITATIVE OBJECTIVES

- The project aims to disseminate H_2 technologies to the port and maritime sector. This goal has been accomplished through the organisation of the stakeholder advisory group.
- H2Ports will gather information on the use of H_2 in port environments.
- H2Ports will gather information on the use of H_2 as fuel for vessels.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

Both the reach stacker and yard tractor have been commissioned.

FUTURE STEPS AND PLANS

It is envisaged that the two applications (reach stacker and 4 x 4 terminal tractor) will undergo two years of piloting under normal operative conditions.

PROJECT TARGETS

Target source	Parameter	Unit	Target	Target Achieved?
Project's own objectives	Amount of H_2 dispensed	kg/day	60	
	Tank to wheel efficiency	%	50	
	Hydrogen storage cost	€/kg	650	
	HRS daily capacity	kg/day	60	
	Reach stacker vehicle Power	kW	90	
	Vehicle Power	kW	70	
	Noise level	dBa	< 60	
	Specific maintenance cost	€/output	TBD	
	Hydrogen refuelling time	min	< 30	
	Vehicle over cost (target percentage over CNG and diesel port trucks)	%	100	
	Cost of fuel cell system	€/kW	3 500	
	Duration of the testing period	hours-years	5 000-2	
	Total installed power of fuel cell system	kW	175-205 (225-285)	
	HRS specific maintenance cost	€/kg	1	
	HRS CAPEX	€	575 000	

HIGHLANDER

HIGH PERFORMING ULTRA-DURABLE MEMBRANE ELECTRODE ASSEMBLIES FOR TRUCKS

Project ID	101101346
PRR 2025	Pillar 3 - H_2 End Uses - Transport
Call Topic	HORIZON-JTI-CLEANH$_2$-2022-03-02
Project Total Costs	3 331 247.50
Clean H_2 JU Max. Contribution	3 331 247.50
Project Period	01-01-2023 - 31-12-2025
Coordinator Beneficiary	CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS, FR
Beneficiaries	RHODIA OPERATIONS, SPECIALTY OPERATIONS FRANCE, UNIVERSITE DE MONTPELLIER, JOHNSON MATTHEY HYDROGEN TECHNOLOGIES LIMITED, PRETEXO, ELMARCO SRO, Rhodia Laboratoire du Futur, ROBERT BOSCH GMBH, SOLVAY SPECIALTY POLYMERS ITALY SPA, JOHNSON MATTHEY PLC, FORSCHUNGSZENTRUM JULICH GMBH, TECHNISCHE UNIVERSITAT BERLIN

https://highlander-fuelcell.eu/

PROJECT AND GENERAL OBJECTIVES

The objective of HIGHLANDER is to develop membrane electrode assemblies (MEAs) for heavy-duty vehicles (HDVs) with disruptive, novel components, targeting stack cost and size, durability, and fuel efficiency. The project will design, fabricate, and validate the HDV MEAs at cell and short stack level against heavy-duty relevant accelerated stress test and load profile test protocols. Materials-screening efforts will be supported by the development and use of improved predictive degradation models bridging scales from reaction sites to cell level. Model parameterisation is implemented using experimental characterisation data at materials, component, and cell level. HIGHLANDER aims to bring about a significant reduction in stack cost and fuel consumption through improving catalyst-coated membrane performance and the development of a new, lower cost single-layer gas diffusion layer. It also aims to achieve the 1.2 W/cm^2 at 0.65 V performance target at 0.3 g Pt/kW or less, meeting a lifetime target of 20 000h. Sustainability considerations include benchmarking fluorine-free membranes for HDV MEA application and reuse of platinum in the context of a circular economy.

NON-QUANTITATIVE RESULTS

HIGHLANDER launched a project website, published two annual newsletters, disseminated project results through ten presentations at conferences and has published five journal publications to date. A project workshop will be conducted in year 3.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

- Development of novel intermetallic electrocatalysts for the oxygen reduction reaction at the fuel cell cathode. Selected catalysts display better retention of electrochemical surface area and equivalent or higher mass activity in rotating disc electrode conditions than the project reference catalyst.
- Progress in the development of two series of novel sulfonated hydrocarbon ionomers for fluorine-free membranes and their benchmarking against perfluorosulfonic acid (PFSA) membranes.
- Formulation of a hierarchical degradation modelling framework and its implementation as a software code, available in the open access modelling platform (GitLab), accessible at https://go.fzj.de/jumper.
- Progress in the elaboration of low-cost gas diffusion layers (GDLs). The developed anode gas diffusion layer provides the same in situ performance as commercial GDLs, at a lower cost.
- Progress in the development of catalyst coated membranes. Baseline catalyst coated membranes have been submitted to load profile testing over 500 hours, demonstrating that the degradation rate of a membrane electrode assembly with a novel catalyst and the Syensqo PFSA ionomer was reduced to 50 µV/h. The final performance and platinum group metal loading targets of the project were achieved.

FUTURE STEPS AND PLANS

- Upscale of selected catalysts for catalyst layer development and single-cell characterisation.
- Preparation of nanofiber-reinforced membranes and their delivery for catalyst coating and testing of project MEAs against project performance and durability targets.
- Pursuit of development of a novel low-cost cathode GDL, catalyst and ionomer, along with support materials and other membrane components.

PROJECT TARGETS

Target source	Parameter	Unit	Target	Achieved to date by the project	Target achieved?
Project's own objectives	Power density @ 0.65 V	W/cm^2	1.2	1.2	✓
	PGM loading	g Pt/kW	< 0.3	0.292	
	Durability	hours	20 000	Durability testing to take place in the project's last 6 months.	⚙

Clean Hydrogen Partnership
Co-funded by the European Union

HYSHIP

DEMONSTRATING LIQUID HYDROGEN FOR THE MARITIME SECTOR

Project ID	101007205
PRR 2025	Pillar 3 - H_2 End Uses – Transport
Call Topic	FCH-01-6-2020
Project Total Costs	10 796 560.00
Clean H_2 JU Max. Contribution	7 993 942.00
Project Period	01-01-2021 - 31-12-2025
Coordinator Beneficiary	WILH WILHELMSEN HOLDING ASA, NO
Beneficiaries	NORSEA GROUP AS, DIANA SHIPPING SERVICES SA, WILHELMSEN SHIP MANAGEMENT NORWAY AS, AIR LIQUIDE NORWAY AS, STOLT TANKERS B.V., MASSTERLY AS, LMG MARIN FRANCE, LMG MARIN AS, NORLED AS, MARITIME CLEANTECH, PERSEE, DNV SE, EQUINOR ENERGY AS, KONGSBERG MARITIME AS, DNV AS, UNIVERSITY OF STRATHCLYDE, NATIONAL CENTER FOR SCIENTIFIC RESEARCH "DEMOKRITOS", EIDGENOESSISCHE TECHNISCHE HOCHSCHULE ZUERICH

https://hyship.eu/

PROJECT AND GENERAL OBJECTIVES

HyShip is building two vessels that will run on liquid hydrogen (LH_2). The vessels will transport goods from port to port along the west coast of Norway, and transport LH_2 for bunkering stations for other vessels/trucks running on hydrogen. The project aims to replace trucks on the roads between the ports, demonstrate the use of LH_2 on a vessel and distribute LH_2 to ports to facilitate a LH_2 supply chain. The project's main key performance indicator is to demonstrate 3 000 hours of operation of 3 MW fuel cells. The design of the vessels is ongoing, and the vessels have not been ordered yet.

NON-QUANTITATIVE OBJECTIVES

- Conceptually design a full range of vessel and hydrogen systems.
- Develop and describe a business ecosystem with a timeline for cost-efficient operation.
- Integrate the demonstration system into a larger sociotechnical system, with business models, policy models and LH_2 supply, that will help the transition towards the use of LH_2.
- Use robust holistic design methods, that lower the cost of conducting complex projects with novel fuel and infrastructure, allowing real-time data collection on the effects of the use of novel fuels (no real-time data provided yet).
- Develop input to the International Maritime Organization, which will help the systems transition to its rules instead of following the alternative design approach.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

The preliminary design of vessel and liquid hydrogen propulsion systems is complete.

FUTURE STEPS AND PLANS

- The ship building contract will be signed.
- The vessels will be delivered.
- Vessel operations will begin.

PROJECT TARGETS

Target source	Parameter	Unit	Target	Target achieved?
Project's own objectives	Develop an intelligent Energy Management Systems that lets us reduce CAPEX of the energy system by more than 5%.	%	5	
	Reduction of design and ship integration costs related to the hydrogen/fuel cell systems by more than 40%.	%	40	

IMMORTAL

IMPROVED LIFETIME STACKS FOR HEAVY DUTY TRUCKS THROUGH ULTRA-DURABLE COMPONENTS

Project ID	101006641
PRR 2025	Pillar 3 - H_2 End Uses - Transport
Call Topic	FCH-01-2-2020
Project Total Costs	3 825 927.50
Clean H_2 JU Max. Contribution	3 825 927.50
Project Period	01-01-2021 - 31-03-2024
Coordinator Beneficiary	CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS, FR
Beneficiaries	UNIVERSITE DE MONTPELLIER, UNIVERSITE DE MONTPELLIER, FPT MOTORENFORSCHUNG AG, FPT INDUSTRIAL SPA, JOHNSON MATTHEY HYDROGEN TECHNOLOGIES LIMITED, PRETEXO, ALBERT-LUDWIGS-UNIVERSITAET FREIBURG, ROBERT BOSCH GMBH, JOHNSON MATTHEY PLC, AVL LIST GMBH

http://www.immortal-fuelcell.eu

PROJECT AND GENERAL OBJECTIVES

IMMORTAL aimed to develop high-performance and high-durability membrane electrode assemblies (MEAs), and their components, specifically designed for use in heavy-duty (HD) truck applications. The project intended to develop load profile tests specific to HD truck application, and apply these tests, and accelerated stress tests, to MEAs at both sub-scale and short stack levels. The results of load profile testing have also been used to validate a novel lifetime prediction method, and the method used to predict the lifetime of project MEAs. The project assessed the results through a technoeconomic evaluation and provided HD fuel cell powertrain validation and system recommendations.

NON-QUANTITATIVE OBJECTIVES

IMMORTAL contributed to activities in Mission Innovation's hydrogen innovation challenge through cooperation with the US Department of Energy's Million Mile Fuel Cell Truck Consortium. Several workshops were held with the consortium and Japan's fuel cell platform. These included discussions on, inter alia, heavy-duty stressors, the second-generation Toyota Mirai and advanced characterisation techniques.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

- Developed a nanofiber-reinforced membrane with exceptional durability in an MEA in accelerated stress testing at 90 C, comprising 120 000 wet/dry cycles at open-circuit voltage corresponding to 2 200 hours in an accelerated stress test, without rupture.
- Developed MEAs comprising project materials that reached the 2024 SRIA target for heavy-duty vehicles of 1.2 W/cm^2 at 0.65 V, and came within 5% of the AWP target of 1.2 W/cm^2 at 0.675 V (for generation 2 MEAs), giving a Pt loading of 0.32 g Pt/kW.
- Developed a regression model for fuel cell degradation forecasting with emphasis on the prediction confidence interval (uncertainty).
- Developed a method for creating accelerated durability tests for fuel cells, based on Markov chains.
- Established a lifetime prediction method and validated it using 1 500 hours of load profile testing.
- Obtained a predicted power loss of 10% after 30 000 hours (baseline MEAs), which corresponds to the AWP target.
- Identified the principal contributor to power loss during load profile testing as the loss of electrochemically active surface area from the cathode catalyst.
- Developed a modal load profile test from actual truck mission profiles.
- Achieved more than 7 500 hours of load profile testing on short stacks without catastrophic failure.

FUTURE STEPS AND PLANS

IMMORTAL finished in March 2024. Future plans include carrying forward the learning and most prospective materials from IMMORTAL to future heavy-duty MEA development projects, in particular in 'High performing ultra-durable membrane electrode assemblies for trucks' (HIGHLANDER).

PROJECT TARGETS

Target source	Parameter	Unit	Target	Achieved to date by the project	Target achieved?
Project's own objectives	Catalyst surface area and mass activity	cm^2/g Pt and A/mg Pt	Exceeds the performance of reference Pt and demonstrates better retention after accelerated degradation cycles than reference Pt/C.	2 catalyst designs achieve this objective	✓
	Membrane durability in MEA AST cycles	cycles	50 000	110 000	

Clean Hydrogen Partnership

Co-funded by the European Union

JIVE

JOINT INITIATIVE FOR HYDROGEN VEHICLES ACROSS EUROPE

Project ID	735582
PRR 2025	Pillar 3 - H_2 End Uses - Transport
Call Topic	FCH-01-9-2016
Project Total Costs	89 176 155.23
Clean H_2 JU Max. Contribution	32 000 000.00
Project Period	01-01-2017 - 30-06-2024
Coordinator Beneficiary	ENVIRONMENTAL RESOURCES MANAGEMENT LIMITED, UK
Beneficiaries	IN-DER-CITY-BUS GMBH, ESWE VERKEHRSGESELLSCHAFT MBH, MAINZER VERKEHRSGESELLSCHAFT MBH, GELDERLAND, ERM FRANCE, ERM FRANCE, REBELGROUP ADVISORY BV, ESWE VERKEHRSGESELLSCHAFT MBH, LATVIJAS UDENRAZA ASOCIACIJA, VERKEHRS-VERBUND MAINZ-WIESBADEN GESELLSCHAFT MIT BESCHRANKTER HAFTUNG, REGIONALVERKEHR KOLN GMBH, EUE APS, DUNDEE CITY COUNCIL, WEST MIDLANDS TRAVEL LIMITED, SASA SPA AG SOCIETA AUTOBUS SERVIZID'AREA SPA, HERNING KOMMUNE, WSW MOBIL GMBH, RIGAS SATIKSME SIA, TRENTINO TRASPORTI SPA, EE ENERGY ENGINEERS GMBH, SPHERA SOLUTIONS GMBH, hySOLUTIONS GmbH, ABERDEEN CITY COUNCIL*, SUEDTIROLER TRANSPORTSTRUKTUREN AG, HyCologne - Wasserstoff Region Rheinland e.V., LONDON BUS SERVICES LIMITED, ELEMENT ENERGY LIMITED, PLANET PLANUNGSGRUPPE ENERGIE UND TECHNIK GBR, BIRMINGHAM CITY COUNCIL, FONDAZIONE BRUNO KESSLER, UNION INTERNATIONALE DES TRANSPORTS PUBLICS, HYDROGEN EUROPE

http://www.fuelcellbuses.eu

PROJECT AND GENERAL OBJECTIVES

JIVE exists to assist the commercialisation of fuel cell buses (FCBs) as a zero-emission public transport option across Europe. The project aims to address the current high ownership cost of FCBs relative to conventionally powered buses and the lack of hydrogen-refuelling infrastructure across Europe by supporting the deployment of 131 FCBs in seven locations - Aberdeen (UK), Birmingham (UK), Cologne (DE), Gelderland (NL), London (UK), South Tyrol (IT), and Wuppertal (DE). Combined with its sister project, JIVE 2, nearly 300 fuel cell buses will be deployed at sixteen sites by 2025 - the largest deployment in Europe to date.

NON-QUANTITATIVE OBJECTIVES

- JIVE aims to demonstrate the suitability and provide experience of FCBs for wider roll-out. Through the publication of project deliverables, such as a best practice and commercialisation report, information flows to interested observer parties have been established.
- JIVE aims to raise awareness of the readiness of fuel cell technology for wider roll-out, with a focus on bus purchasers and regulators. A strong observer group within the JIVE consortium has been established, to monitor discussions and best practices emerging from the project. This will ensure continuation of the momentum for FCB uptake in Europe beyond the project.
- JIVE aims to deliver positive environmental impacts by operating FCBs for extended periods. As per the project's objective, all buses deployed thus far in the project are replacing diesel technology. This means that the buses will lead to CO_2 abatement and will not simply operate as a 'visible extra'.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

The project closed in June 2024 with the following key achievements:

- Deployment of 131 fuel cell buses operational across seven sites in four countries.
- Total travel distance for buses deployed in JIVE of 10 703 187 kms, with average travel distance per bus of 30 070 km/year, until June 2024.
- Reduction in average bus price within the project since 2018 (across JIVE and JIVE 2) and in comparison with other projects.
- Achievement of technical improvements, including a reduction in fuel consumption well below the target (9 kg H_2/100 km), consistently high FCB availability, and long daily travel distances.

- Significant experience has been gained by operators in the integration and management of large fleets of hydrogen buses.
- Expansion of hydrogen infrastructure in the partner regions, alongside stimulation of future growth of the hydrogen refuelling station network and of FCB fleets.
- Successful large-scale dissemination activities promoting the project and hydrogen technology across Europe and around the world, e.g. FCB Roadshow.

FUTURE STEPS AND PLANS

- Operations of the JIVE buses will continue post-project.
- Continued expansion of FCB fleets for several sites.

PROJECT TARGETS

Target source	Parameter	Unit	Target	Achieved to date by the project	Target achieved?
Project's own objectives	Vehicle operational lifetime	years	8	-	⚙
	Distance travelled	km/year/bus	> 44 000	30 070 km/year/bus (all years included) / 33 168 km/year/bus excludes 2024 (data available only until June 2023).	
	Operating hours per fuel cell system	hours/bus	> 20 000	7 244	
	Efficiency	%	> 42	-	
	Availability	%	> 90	83.6	
	Specific fuel consumption	kg/100km/bus	< 9.0	7.6	✓
	Vehicle CAPEX	€	< 650 000	-	
	Vehicle OPEX	€	max. 100% more than diesel bus OPEX	-	
	Mean time (distance) between failures (MDBF)	km/bus	> 2 500	24 174	

JIVE 2

JOINT INITIATIVE FOR HYDROGEN VEHICLES ACROSS EUROPE 2

Project ID	779563
PRR 2025	Pillar 3 - H_2 End Uses - Transport
Call Topic	FCH-01-5-2017
Project Total Costs	86 926 760.59
Clean H_2 JU Max. Contribution	25 000 000.00
Project Period	01-01-2018 - 30-06-2025
Coordinator Beneficiary	ENVIRONMENTAL RESOURCES MANAGEMENT LIMITED, UK
Beneficiaries	ELEMENT ENERGY, ZEROBUS OU, ERM FRANCE, ERM FRANCE, TRANSDEV OCCITANIE OUEST, HYPORT, OBCINA SOSTANJ, ENGIE ENERGIE SERVICES, CA DE L'AUXERROIS, CONNEXXION VLOOT BV, RHEINSCHE BAHNGESSELLSCHAFT AKTIENGESELLSCHAFT, SOCIETE PUBLIQUE LOCALE D'EXPLOITATION DES TRANSPORTS PUBLICS ET DES SERVICES A LA MOBILITE DE L'AGGLOMERATION PALOISE, STRAETO BS, TWYNSTRA GUDDE MOBILITEIT and INFRASTRUCTUUR BV, OPENBAAR LICHAAM OV-BUREAU GRONINGEN EN DRENTHE, PAU BEARN PYRENEES MOBILITES, LANDSTINGET GAVLEBORG, REBELGROUP ADVISORY BV, REGIONALVERKEHR KOLN GMBH, DUNDEE CITY COUNCIL, CONNEXXION OPENBAAR VERVOER NV, MESSER SE and CO. KGAA, WSW MOBIL GMBH, RIGAS PASVALDIBAS SABIEDRIBA AR IEROBEZOTU ATBILDIBU RIGAS SATIKSME, MESTNA OBCINA VELENJE, KOLDING KOMMUNE, EE ENERGY ENGINEERS GMBH, TRANSPORTS DE BARCELONA SA, SPHERA SOLUTIONS GMBH, BRIGHTON and HOVE BUS AND COACH COMPANY LIMITED, RUTER AS, Provincie Zuid-Holland, PETROGAL SA, VATGAS SVERIGE IDEELL FORENING, ELEMENT ENERGY LIMITED, NOORD-BRABANT PROVINCIE, UNION INTERNATIONALE DES TRANSPORTS PUBLICS, HYDROGEN EUROPE

https://www.fuelcellbuses.eu/

PROJECT AND GENERAL OBJECTIVES

The JIVE 2 project aims to deploy 160 fuel cell buses (FCBs) in eleven locations - Auxerre (FR), Barcelona (ES), Brighton/Crawley (UK), Cologne (DE), Emmen (NL), Groningen (NL), Jelgava (LV), Pau (FR), South Holland (NL), Toulouse (FR), Wuppertal (DE). Combined with its sister project, JIVE 2, nearly 300 fuel cell buses will be deployed at sixteen sites by 2025 - the largest deployment in Europe to date.

NON-QUANTITATIVE OBJECTIVES

- JIVE 2 aims to demonstrate the suitability and provide experience of FCBs for wider roll-out. Through the publication of project deliverables, such as a best practice and commercialisation report, information flows to interested observer parties have been established.
- JIVE 2 aims to raise awareness of the readiness of fuel cell technology for wider roll-out – with a focus on bus purchasers and regulators. A strong observer group within the JIVE consortium has been established, to monitor discussions and best practices emerging from the project. This will ensure continuation of the momentum for FCB uptake in Europe continues beyond the project.
- JIVE 2 aims to deliver positive environmental impacts by operating FCBs for extended periods. As per the project's objective, all buses deployed thus far in the project are replacing diesel technology. This means that the buses will lead to CO_2 abatement and will not simply operate as a 'visible extra'.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

- To date, all 160 buses have been ordered.
- To date, 150 buses have been delivered and 124 are operational.
- 12 599 637 km travelled by the buses deployed through JIVE 2.
- Average travel distance per bus of 38 521 km/year/ bus until December 2024. Excluding 2020, the average travel distance was 44 925 km/year/bus.
- One site has been operating its FCBs for over three years.
- One site (Jelgava) has joined as a demonstration site following the successful completion of one of the FCB Roadshows under the project's "Stimulating Further Demand".

- Expansion of hydrogen infrastructure in the partner regions, alongside stimulation of future growth of the hydrogen refuelling station network and FCB fleets.
- Successful large-scale dissemination activities promoting the project and hydrogen technology across Europe and around the world (FCB Roadshows, participation in conferences and events - such as the Hydrogen Week, November 18-22 at Brussels Expo, participation in public dissemination events such as Hydrogen Solutions for European Cities: Learnings from JIVE II and REVIVE for Future Buses and Trucks workshop in Novembers 2024).

FUTURE STEPS AND PLANS

- Continued operation of the buses until the end of the project.
- Final buses enter operation: Brighton/Crawley and Jelgava.
- Final dissemination activities such as the 4th and final roadshow in the Nordic countries, specifically Sweden and Finland.
- Project knowledge will be preserved through a digital archive, speaker briefs for consortium members and a short video showcasing the JIVE projects.

PROJECT TARGETS

Target source	Parameter	Unit	Target	Achieved to date by the project	Target achieved?
Project's own objectives	Vehicle operational lifetime	years	8	-	
	Distance travelled	km/year/bus	>50 000	38 521 km/year/bus project to date (all years) / 44 925 km/year/bus project to date, excludes 2024 (data only available until June 2023)	
	Operating hours per fuel cell system	hours/bus	> 20 000	10 367	
	Availability	%	>90	83.6	
	Efficiency	%	> 42	-	
	Specific fuel consumption	kg/100km/bus	< 9.0	7.4	✓
	Vehicle CAPEX	€	<625 000	-	
	Vehicle OPEX	€	max. 100% more than diesel bus OPEX	-	
	Mean time (distance) between failures (MDBF)	km/bus	> 3 500	24 913	

MEASURED

ADVANCED MEAS ENSURING HIGH EFFICIENCY HDV

Project ID	101101420
PRR 2025	Pillar 3 - H_2 End Uses - Transport
Call Topic	HORIZON-JTI-CLEANH$_2$-2022-03-02
Project Total Costs	2 989 060.00
Clean H_2 JU Max. Contribution	2 989 060.00
Project Period	01-06-2023 - 31-05-2026
Coordinator Beneficiary	ADVANCED ENERGY TECHNOLOGIES AE EREUNAS and ANAPTYXIS YLIKON and PROIONTONANANEOSIMON PIGON ENERGEIAS and SYNAFON SYMVOULEFTIKON Y PIRESION, EL
Beneficiaries	AVL-AST NAPREDNE SIMULACIJSKE TEHNOLOGIJE DOO, HONEYWELL INTERNATIONAL SRO, UNIVERSITAT POLITECNICA DE VALENCIA, UNIVERZA V LJUBLJANI, AVL LIST GMBH, UNIVERSITY OF STUTTGART, TECHNISCHE UNIVERSITAET GRAZ

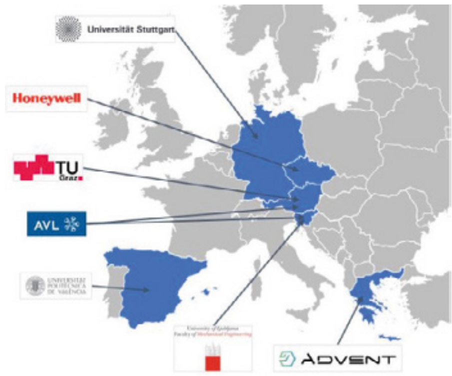
https://measured-horizon.eu/

PROJECT AND GENERAL OBJECTIVES

MEAsureD aims to advance High-Temperature membrane electrode assemblies (MEAs) for heavy-duty vehicles. The focus is on the development of a cost-effective MEA, operating above 160 °C, featuring minimal phosphoric acid uptake and a stable porous ionomer microstructure, combined with novel platinum-based catalysts. The MEA will be integrated in a short stack and its performance will be evaluated according to the project's key performance indicators. In parallel, fuel cell stack integration will be validated under heavy-duty vehicles conditions to ensure operational reliability. The project will also define optimal configurations for balance-of-plant components tailored to high-temperature proton exchange membranes (HT-PEM) systems. Beyond automotive applications, the potential of fuel cell technology will be explored for use in the aviation, maritime, and rail sectors. To support these efforts, advanced digital tools will be developed for system design and performance monitoring, including simulations of flow field behaviour and degradation mechanisms. In addition, MEAsureD will develop design and monitoring modelling simulation tools, carry out testing-, harmonisation- and standardisation-related activities. Finally, MeasureD will execute an environmental assessment of the fuel cell manufacturing process, targeting cost reduction and improved recycling of waste materials.

NON-QUANTITATIVE OBJECTIVES

- Ensure innovation and collaboration among project partners to advance the MEA's technical development.
- Cultivate expertise in digital modelling techniques, enabling the team to develop sophisticated simulations that enhance understanding and inform design decisions.
- Conduct vehicle-level simulations, fostering a deep understanding of system-wide implications and interdependencies.



- Check and promote sustainability and economic viability, integrating environmental and economic assessments to guide decision-making and promote responsible innovation.
- Enhance the project's visibility and impact through strategic communication and dissemination efforts, engaging stakeholders and fostering dialogue to maximise the project's reach and influence.
- Implement project management practices, promoting efficiency, transparency and accountability to ensure smooth project execution and the timely achievement of milestones.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

Deliverable (hereinafter D) 1.8: Requirements and key performance indicators for the polymer membranes for high-temperature fuel cells for aerospace applications from Honeywell.

D 4.1: Requirements of heavy-duty fuel cell electric vehicles' system architecture, performance lifetime and components' sizing and characterisation from AVL.

D 6.1. Project logo and visual identity 6 from Advent.

D 6.2. Website and social media presence from Advent.

D 6.3. Measured newsletter from Advent.

D 6.4. Measured promotional material from Advent.

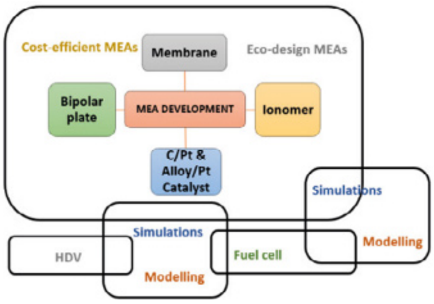
D 6.5. Plan for communication, dissemination and exploitation from Advent.

D 7.1. Project management handbook from Advent.

D 7.2. Quality management plan from Advent.

D 7.3. Risk management plan from Advent.

D 7.4. Data management plan from Advent.



FUTURE STEPS AND PLANS

- Technical development of the MEA (both membrane and electrode) and the single cell assembly through experiments and testing methodologies to optimise performance.
- Digital models to simulate the characteristics of project innovations.
- Progress of vehicle-level simulations enabling assessment of the overall performance and integration of novel technologies within the context of larger systems.
- Environmental and economic assessments, to gauge the impact, recyclability, and manufacturing costs associated with project advancements.
- Communication, dissemination, and exploitation strategies to ensure effective outreach and maximise the impact of project advancements.
- Project management activities, ensuring effective and efficient project progress.

PROJECT TARGETS

Target source	Parameter	Unit	Target	Target achieved?
Project's own objectives	Fuel Cell stack cost	€/kW	< 75	

MORELIFE

MATERIAL, OPERATING STRATEGY AND RELIABILITY OPTIMISATION FOR LIFETIME IMPROVEMENTS IN HEAVY DUTY TRUCKS

Project ID	101007170
PRR 2025	Pillar 3 - H_2 End Uses - Transport
Call Topic	FCH-01-2-2020
Project Total Costs	3 288 941.24
Clean H_2 JU Max. Contribution	3 499 913.75
Project Period	01-09-2021 - 28-02-2025
Coordinator Beneficiary	AVL LIST GMBH, AT
Beneficiaries	EKPO FUEL CELL TECHNOLOGIES GMBH, MEBIUS, RAZISKOVALNO RAZVOJNA DEJAVNOST, ZASTOPANJE IN TRGOVINA, DOO, NEDSTACK FUEL CELL TECHNOLOGY BV, UNIVERZA V LJUBLJANI, TECHNISCHE UNIVERSITEIT EINDHOVEN, TECHNISCHE UNIVERSITAET MUENCHEN

https://morelife-info.eu/

PROJECT AND GENERAL OBJECTIVES

MORELife addresses the need for highly efficient material utilisation, maximised durability and optimised matching of operation conditions for a proton-exchange membrane fuel cell in heavy-duty applications. The objectives are to:

- Perform accelerated stress tests for the shortened test duration for lifetime verification.
- Make improvements at material and operation strategy levels.
- Create advanced degradation models.
- Find the optimal operating conditions and validate them based on the improved materials.
- Achieve a predicted lifetime for fuel cells of 30 000 hours.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

- Accelerated stress test and accelerated durability test protocols and after treatment systems for state-of-the-art and advanced catalyst material have been created.
- A third generation of novel catalyst material has been developed with promising first results of rotating disc electrode investigations.
- Post-mortem analysis on aged state-of-the-art material has been performed in order to improve mechanistic degradation models created in this project.

FUTURE STEPS AND PLANS

If proven sufficient, the third generation catalyst will be integrated in a 5 to 10 cell short stack for validation in order to prove its durability and performance.

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NIMPHEA

NEXT GENERATION OF IMPROVED HIGH TEMPERATURE MEMBRANE ELECTRODE ASSEMBLY FOR AVIATION

Project ID	101101407
PRR 2025	Pillar 3 - H_2 End Uses - Transport
Call Topic	HORIZON-JTI-CLEANH$_2$-2022-03-08
Project Total Costs	4 942 898.75
Clean H_2 JU Max. Contribution	4 942 898.50
Project Period	01-01-2023 - 31-12-2026
Coordinator Beneficiary	SAFRAN POWER UNITS, FR
Beneficiaries	ADVANCED ENERGY TECHNOLOGIES AE EREUNAS and ANAPTYXIS YLIKON and PROIONTON ANANEOSIMON PIGON ENERGEIAS and SYNAFON SYMVOULEFTIKON YPIRESION, UNIVERSITE DE STRASBOURG, Fundacion IMDEA Energia, SAFRAN SA, FRAUNHOFER GESELLSCHAFT ZUR FORDERUNG DER ANGEWANDTEN FORSCHUNG EV, COMMISSARIAT A L ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES, CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS

https://www.nimphea.eu/

PROJECT AND GENERAL OBJECTIVES

The overall objective of the NIMPHEA project is to develop and validate, at technology readiness level 4, a new-generation high-temperature membrane electrode assembly (MEA) addressing the challenging requirements of fuel cells for aviation. The MEA developed will operate above 120°C and thus overcome the thermal management issues of high-power systems.

NON-QUANTITATIVE OBJECTIVES

- Design the concept of the new-generation disruptive MEA operating above 120°C and develop its components.
- Upscale the small-scale MEA with a view to prepare for manufacturing and future integration at fuel cell stack level.
- Validate and demonstrate the performances of the new-generation MEA developed at TRL4.
- Evaluate and validate the suitability of the new-generation MEA by performing a complete life-cycle assessment.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

- The technical specifications have been described for the new NIMPHEA MEA).
- The consortium has harmonised its testing strategy for all products.
- The components of the first-generation MEA have been developed and delivered for its assembly. The first generation of NIMPHEA MEAs has been produced and tested.
- The expected results have not been achieved, however, less platinum has been used in the catalysts compared to the project's state-of-the-art.
- Components have been identified for the second generation MEA, which shows an increasing performance at lab scale.

FUTURE STEPS AND PLANS

- Assembly and characterisation of the second-generation MEA.
- Development of the third generation MEA components.
- Maturation of the LCA model.

PROJECT TARGETS

Target source	Parameter	Unit	Target	Achieved to date by the project	Target achieved?	SoA result achieved to date (by others)	Year for reported SoA result
Project's own objectives	Power density (nominal conditions)	W/cm²	0.75	0.13 (160°C, 0.75V)		0.1 W/cm² (160°C, 0.65V)	2024
	Power density (optimal conditions)	W/cm²	1.25	0.3 (180°C, 0.5V)		0.29 W/cm² (180°C, 0.5V)	2024
	Degradation rate	µV/h	3-5	-			
	Membrane uniformity (thickness)	%	± 7	-		N/A	N/A
	GDE uniformity (PGM variation)	%	± 5	1.7			

PEMTASTIC

ROBUST PEMFC MEA DERIVED FROM MODEL-BASED UNDERSTANDING OF DURABILITY LIMITATIONS FOR HEAVY DUTY APPLICATIONS

Project ID	101101433
PRR 2025	Pillar 3 - H_2 End Uses - Transport
Call Topic	HORIZON-JTI-CLEANH$_2$-2022-03-02
Project Total Costs	2 748 608.75
Clean H_2 JU Max. Contribution	2 998 608.50
Project Period	01-02-2023 - 31-01-2026
Coordinator Beneficiary	DEUTSCHES ZENTRUM FUR LUFT - UND RAUMFAHRT EV, DE
Beneficiaries	SYMBIO FRANCE, IMERYS GRAPHITE and CARBON BELGIUM, CHEMOURS FRANCE SAS, CHEMOURS BELGIUM, THE CHEMOURS COMPANY FC, LLC, HERAEUS DEUTSCHLAND GMBH and CO KG, IMERYS GRAPHITE and CARBON SWITZERLAND SA, IRD FUEL CELLS A/S, ZURCHER HOCHSCHULE FUR ANGEWANDTE WISSENSCHAFTEN, COMMISSARIAT A L ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES

https://pemtastic-project.eu/

PROJECT AND GENERAL OBJECTIVES

PEMTASTIC aims to tackle the key technical challenges to increase durability of membrane electrode assemblies (MEAs) for heavy-duty applications. These challenges are approached with a combination of model-based design and the development of a durable catalyst-coated membrane (CCM) using innovative materials tailored for heavy-duty operation at high temperature (105 °C). The quantitative targets correspond to a durability of 20 000 hours maintaining a state-of-the art power density of 1.2 W/cm^2 at 0.65 V at a Pt loading of 0.30 g/kW.

NON-QUANTITATIVE OBJECTIVES

- Definition of fuel cell operation protocols and cycling tests for heavy-duty applications.
- Definition of operational strategy for high fuel efficiency.
- Parametrisation of degradation models to predict MEA lifetime and identify specific improvements of the CCM and its components.
- Development of robust catalyst (Pt/C) support deposition process for oxygen reduction reaction catalysts.
- Development of membrane and ionomer for operation at high temperature.
- Catalyst layers and CCM with increased durability and state-of-the-art performance tailored for heavy-duty operation.
- Dissemination and promotion of project results, through ad-hoc strategies through target groups and key stakeholders and definition of an exploitation strategy of the PEMTASTIC outcomes.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

- Definition of protocols for testing of materials as well as single cells and stacks.
- Development of a multiscale modelling approach to predict cell performance and degradation processes from the mesoscale to the single-cell level, improving understanding of which characterisations are needed or available to parametrise the models.
- Implementation, validation and revision of new testing protocols into test benches ensuring reproducibility among testing partners.
- Durability tests up to 1 500 hours using PEMTATIC heavy-duty load cycle along with in-situ and ex-situ characterisation.
- Sensitivity study on Gen0 and Gen1 MEAs and ongoing stressor tests.
- Use of innovative materials from IMERYS, Herae-

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us and Chemours to design the first generation PEMTASTIC MEA.

- Identification of promising materials the second generation PEMTASTIC MEA.
- Very good visibility of PEMTASTIC achieved (website, LinkedIn, workshops, fairs).

FUTURE STEPS AND PLANS

- Finalise tests on the first generation PEMTASTIC MEA.
- Assembly of the second generation PEMTASTIC MEA.
- Improvement of degradation model using experimental results of the first-generation MEA.
- Demonstration that model outcomes can guide the MEA development to improve MEA performance and durability.
- Disseminate project results in conferences and journals.

PROJECT TARGETS

Target source	Parameter	Unit	Target	Achieved to date by the project	Target achieved?	SoA result achieved to date (by others)	Year for reported SoA result
Project's own objectives	MEA Durability	hours	20 000	Performance models extended to degradation models. Gen2 Pt/C outperforms Gen1 without compromising durability. Stable prototype membrane used with 2.5-fold higher AST durability. HD-load profile to benchmark durability (500-1500 h) was developed.		15 000	2020
	PGM loading	mg cm-2	0.3	Pt loading of project MEA Gen1 was reduced to 0.3 mgcm-2.		0.4	2020
	Power density	W cm-2	1.2@0.65 V	Adjustment of I/C ratio to optimise performance. In differential conditions Gen1 exhibits power of 1.2 Wcm-2 at 650 mV and Pt loading of 0.3 mg cm-2.		1.0 @ 0.65 V	2020
	Operation temperature	°C	95-105	Gen1 MEA equipped with highly stable prototype membrane. HD-cycling and Stressor test will be carried out at 105°C to allow identification of degradation at targeted temperature.		N/A	N/A

REALHYFC

RELIABLE DURABLE HIGH POWER HYDROGEN FUELED PEM FUEL CELL STACK

RealHyFC

Project ID	101111904
PRR 2025	Pillar 3 - H_2 End Uses – Transport
Call Topic	HORIZON-JTI-CLEANH$_2$-2022-03-01
Project Total Costs	3 487 157.50
Clean H_2 JU Max. Contribution	3 487 156.00
Project Period	01-06-2023 - 31-05-2026
Coordinator Beneficiary	COMMISSARIAT A L ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES, FR
Beneficiaries	UNITED MOTION IDEAS, DYNERGIE, Powercell Sweden AB, IRD FUEL CELLS A/S, ZENTRUM FUR SONNENENERGIE- UND WASSERSTOFF-FORSCHUNG BADEN-WURTTEMBERG, UNIVERZA V LJUBLJANI, AVL LIST GMBH, DEUTSCHES ZENTRUM FUR LUFT - UND RAUMFAHRT EV

https://realhyfc-project.eu/

PROJECT AND GENERAL OBJECTIVES

RealHyFC has targets in efficiency, reliability and durability for proton exchange membrane fuel cells (PEMFC) stacks towards cost-competitive exploitation in heavy-duty transport. Key improvements are:

- A new stable stack design, taking advantage of two consolidated technologies with carbon and metal bipolar plates, from stationary and light duty applications respectively, with improved balance of stack, to hinder irreversible degradation of components.
- Optimised operational monitoring options precluding avoidable performance losses.

In line with the Clean Hydrogen JU SRIA, the proposed solutions will demonstrate key performance indicators in terms of efficiency, performance (>1W/cm² at 0.675V) and durability (over 20 000 hrs with less than 10% losses), assessed in both representative conditions and scale based on heavy-duty use-cases with at least 280 cm² cells in stacks of 3 to 10 kW advancing towards a TRL5 of the technical components and tools developed at stack level and at stack / system interface.

RealHyFC will deliver evidence-based insights and models characterising the escalation of reversible and non-reversible losses attributed to critical characteristics of the heavy-duty use case:

- Enhanced physical degradation of the core components of the unit cell (leading to irreversible losses) with significant risk of actual corrosion due to longer and harsher usage.
- Increased local issues due to appreciable heterogeneities associated with the large surface area needed to achieve a high power demand and coupled to driving cycles.
- More challenging control of operating conditions at the stack - system interface within acceptable boundaries for preventing faults and sustaining ultra-low imposed degradation rates.

The investigations and further developments will be carried out using metallic bipolar plates, and move towards carbon-based bipolar plates. Preventing the local degradation of stack components and better controlling the stack operations to hinder conditions promoting reversible or irreversible losses are the selected predominant means to improve stacks lifetime. Meanwhile, to enable heavy-duty-vehicle specific improvements aiming at selected use-cases, RealHyFC's research and innovation will yield generic ideas and versatile solutions, enabling the PEMFC stack to be recognised as a building-block for all heavy-duty transport. This will be achieved by including an open-design approach and understanding-based-developments.

NON-QUANTITATIVE OBJECTIVES

- Identification of performance and durability issues for the metal and carbon stack reference platforms for heavy-duty transport applications.
- Development of model-based new diagnostics and monitoring tools with the aim of optimising hybridisation and operating strategies.
- Improvement of two complementary key stack components: using best-suited bipolar plates to reduce corrosion risk and optimising mechanical assembly to address heterogeneity issues, thereby enhancing overall stack durability.
- Demonstration of performance and durability improvements in representative conditions at stack scale.
- Reduction of risks related to industrial empowerment based on RealHyFC results, through identification of pain points, and strategies on how to manage them to ensure industrial exploitation.
- Increased awareness on hydrogen for heavy-duty applications in all relevant scopes (industries, regulatory bodies, policy makers, citizens).

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PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

- Definition and manufacturing of reference metallic stacks for PEMFC and for a new graphite composite stack.
- Definition of a project-specific MEA for all the stack platforms identified for the investigations and technical solutions developments: Commercial Design Metal (CDM), Open Design Metal (ODM) and Open Design Carbon (ODC).
- Definition of test protocols for the quantification of performance and durability testing including a heavy-duty cycle.
- Two metallic stack platforms showed similar performance and good reproducibility in tests conducted at three partners.
- Confirmation of appropriate level of performance of the newly tested open-design, compared to the state-of-the-art design providing confidence in the database to be used for further developments.
- The heterogeneities within the stacks have been studied with simulations and measurements on the ODM stack. The catalyst degradation modelling framework was extended to accommodate bimetallic nanoparticles, and a model reduction strategy was introduced to optimise simulation performance. The metal BPP corrosion model was enhanced, enabling more accurate predictions. Multiple machine learning techniques were implemented to estimate remaining useful life and state of health. Reduced order models have been created to improve computational efficiency in energy management systems. A spatially resolved operational condition observer was developed to provide real-time insights. Advanced models and test systems were utilised to simulate real-world conditions, integrating virtual sensors and digital twin models for real-time operational condition assessments.
- An open graphite-composite design was devised for optimal BPPs, offering the best achievable comparability to the open metal design. This graphite composite open design will enable direct valuable comparison between metal and graphite composite technology. Furthermore, this reference carbon composite design will form the basis for the development of an optimised stack featuring improved BoS components and BPPs to enhance homogeneity and durability.
- Increased understanding of inhomogeneity issues is achieved through significant progress on characterisation of mechanical component properties and modelling of constraints within large stacks.
- Communication and dissemination activities, through social media, as well as a first successful workshop dedicated to industry stakeholders, have raised awareness around the hydrogen market and PEMFC developments realised through RealHyFC.
- Active synergies with sister projects allowed to pave the way towards the common objective of supporting future industrial empowerment of RealHyFC results.

FUTURE STEPS AND PLANS

- Additional tests on available CDM, ODM and ODC short-stacks with selected protocols and test program: performance, sensitivity, durability.
- Ex-situ analyses on pristine and MEA samples, aged in the project stacks, and of metal bipolar plates from available other sources, for determination and understanding of mechanisms and for validation of the performance and degradation models related to the stack core materials.
- Model and algorithms validation based on RealHyFC stack performance data.
- Continuation of model implementation to develop control algorithms for monitoring operational conditions, state of health, and remaining useful life.
- Continuation of developments for optimisation of control and energy management system, based on a representative description of the application conditions and usage profile.
- Continuation of developments on the open design carbon bipolar plates and stacks.
- Validation of simulations of heterogeneity in the open-design stack by coupling cell performance models with mechanical constraint models.
- Further dissemination and communication actions are foreseen with more scientific publications, continuous website updates, posts on LinkedIn about RealHyFC and the hydrogen market, and the organisation of the second project workshop (due by the end of 2025).

PROJECT TARGETS

Target source	Parameter	Unit	Target	Achieved to date by the project	Target achieved?
Project's own objectives	Power density at BoL	kW/cm²	1	1	✓
	Voltage degradation rate (10% for 20 000 hours)	μV/h	3	50	⚙

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REVIVE

REFUSE VEHICLE INNOVATION AND VALIDATION IN EUROPE

Project ID	779589
PRR 2025	Pillar 3 - H_2 End Uses - Transport
Call Topic	FCH-01-7-2017
Project Total Costs	9 760 023.65
Clean H_2 JU Max. Contribution	4 993 851.00
Project Period	01-01-2018 - 31-12-2024
Coordinator Beneficiary	TRACTEBEL ENGINEERING S.A., BE
Beneficiaries	ERM FRANCE, GEMEENTE GRONINGEN, ERM FRANCE, GEMEENTE NOORDENVELD, ENGIE IMPACT BELGIUM, GEMEENTE GRONINGEN, SAVER NV, PREZERO NEDERLAND HOLDING BV, AZIENDA SERVIZI MUNICIPALIZZATI DI MERANO SPA, SEAB SERVIZI ENERGIA AMBIENTE BOLZANO SPA, SWISS HYDROGEN SA, RENOVA AKTIEBOLAG, E-TRUCKS EUROPE, ENVIRONMENTAL RESOURCES MANAGEMENT LIMITED, GEMEENTE BREDA, SYMBIO, STAD ANTWERPEN,WATERSTOFNET VZW, Powercell Sweden AB, ELEMENT ENERGY LIMITED, Proton Motor Fuel Cell GmbH, GEMEENTE AMSTERDAM, COMMISSARIAT A L ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES

https://h2revive.eu/

PROJECT AND GENERAL OBJECTIVES

REVIVE will significantly advance the state of development of fuel cell bin lorries by integrating fuel cell power trains into eleven vehicles and deploying them at eight sites across Europe. The project will deliver substantial technical progress by integrating fuel cell systems from four major suppliers and by developing effective hardware and control strategies to meet highly demanding refuse truck duty cycles., All trucks are in operation.

NON-QUANTITATIVE OBJECTIVES

- REVIVE aims to involve EU fuel cell suppliers. Currently, two EU fuel cell suppliers are involved in the project, Proton Motor and PowerCell Sweden. In addition, two trucks are equipped with Hydrogenics fuel cell systems.
- REVIVE aims to demonstrate a route to high utilisation of hydrogen refuelling stations to support the roll-out of H_2 mobility for light-duty vehicles. Even with limited running hours, the three trucks deployed in the project have already consumed 4.2 t of hydrogen during the project.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

- The first Proton Motor fuel cell system has been delivered and successfully integrated.
- The first REVIVE trucks have been deployed.
- A new electric driveline has been developed, tested and deployed.
- All trucks have been constructed and have obtained all the certifications required to be deployed.

FUTURE STEPS AND PLANS

- Increase dissemination activities. To catch up following the delays experienced in 2020, a plan for dissemination will be developed.
- Decrease teething issues.
- Carry out an in-depth performance analysis of truck deployment and focus on completing the remaining deliverables.

PROJECT SRIA TARGETS

Target source	Parameter	Unit	Target	Achieved to date by the project	Target achieved?	SoA result achieved to date (by others)
Project's own objectives	FC Power	kW	>40	45	✓	90
	Tank-to-wheel efficiency	%	50	55		N/A

RH$_2$IWER

RENEWABLE HYDROGEN FOR INLAND WATERWAY EMISSION REDUCTION

Project ID	101101358
PRR 2025	Pillar 3 - H_2 End Uses - Transport
Call Topic	HORIZON-JTI-CLEANH$_2$-2022-03-05
Project Total Costs	20 531 971.50
Clean H$_2$ JU Max. Contribution	14 998 541.38
Project Period	01-03-2023 - 31-08-2027
Coordinator Beneficiary	TEKNOLOGIAN TUTKIMUSKESKUS VTT OY, FI
Beneficiaries	MTS DUISBURG GMBH, H2BOAT SRL, VERENIGDE TANKREDERIJ B.V., SOGESTION, AIR LIQUIDE BV, FUTURE PROOF SHIPPING BV, L'AIR LIQUIDE BELGE, DFDS AS, STICHTING PROJECTEN BINNENVAART, Compagnie Fluviale de Transport, THEO POUW BV, BALLARD POWER SYSTEMS EUROPE AS, NEDSTACK FUEL CELL TECHNOLOGY BV, L AIR LIQUIDE SA, UNIVERSITA DEGLI STUDI DI GENOVA

http://rh2iwer.eu/

PROJECT AND GENERAL OBJECTIVES

RH$_2$IWER aims to create a solid basis for the acceleration of hydrogen fuel cell powered vessels in inland waterway shipping by demonstrating six commercially operated vessels. These vessels are of varying lengths and types; 86 m, 110 m and 135 m; and container, bulk and tanker vessels with installed power ranging from 0.6 MW to around 2 MW. RH$_2$IWER will also work to standardise containerised fuel cell and hydrogen solutions. Through demonstration, standardisation work and multilevel analyses, combined with vigorous dissemination and communication measures, RH$_2$IWER will create a basis on which the shipping industry can significantly reduce its environmental footprint and remove emissions from its entire fleet in the future.

NON-QUANTITATIVE OBJECTIVES

- Demonstration of the use of inland waterway vessels powered by hydrogen fuel cells.
- Accelerated adoption by facilitating cooperation and exploiting synergies within the European maritime sector.
- Promotion of the acceptance of inland waterway vessels powered by hydrogen fuel cells as a viable zero emission solution.
- Increase the impact of inland waterway transport on decarbonisation.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

RH$_2$IWER partners have been working to develop the demonstration vessels' general design as well as the business cases. Partners have also started to work on standardised fuel cell and hydrogen storage containers in order to alleviate the risks for shipowners in the future when adopting these technologies.

FUTURE STEPS AND PLANS

Moving forward in the project, the hydrogen and fuel cell systems on board of the vessels will be designed in more detail and subsequently the vessels will be built or retrofitted and their use will be demonstrated.

PROJECT TARGETS

Target source	Parameter	Unit	Target	Target achieved?
Project's own objectives	H_2andFC vessels demonstrated	Number	6	
	Maritime FCH lifetime	hours	40 000	
	Safety, PNR/RCS workshops	Number/ year	1	✓

SH$_2$APED

STORAGE OF HYDROGEN: ALTERNATIVE PRESSURE ENCLOSURE DEVELOPMENT

Project ID	101007182
PRR 2025	Pillar 3 - H_2 End Uses - Transport
Call Topic	FCH-01-1-2020
Project Total Costs	1 993 550.00
Clean H_2 JU Max. Contribution	1 993 550.00
Project Period	01-01-2021 - 30-09-2024
Coordinator Beneficiary	PLASTIC OMNIUM NEW ENERGIES, FR
Beneficiaries	MISAL SRL, OPTIMUM CPV, OMB SALERI SPA, PLASTIC OMNIUM ADVANCED INNOVATION AND RESEARCH, BUNDESANSTALT FUER MATERIALFORSCHUNG UND -PRUEFUNG, UNIVERSITY OF ULSTER

https://sh2aped.eu/

PROJECT AND GENERAL OBJECTIVES

The goal of the SH$_2$APED project is to develop and test, at technology readiness level 4, a conformable and cost-effective hydrogen 70 MPa hydrogen storage system with increased efficiency and exceptional safety performance.

NON-QUANTITATIVE OBJECTIVES

Regarding certification procedures, the project aims to contribute to the revision of regulations.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

The project has achieved significant technical advancements, such as:

- Integration of fiber optic sensors in composite pressure vessels.
- Improved safety design of 70 MPa hydrogen storage system.
- Advanced computational fluid dynamics modeling.
- Development of a conformable hydrogen storage system with microleaks-no-burst technology.
- Improved manifold design for hydrogen tanks.
- Enhanced manufacturing processes, ex. blow modeling technology for liners.

PROJECT TARGETS

Target source	Parameter	Unit	Target	Achieved to date by the project	Target achieved?	SoA result achieved to date (by others)	Year for reported SoA result
Project's own objectives	H_2 storage volume for estimated design space	%	> 45	42		41	2021
	Cost for tank system	€/kg H_2	400	>850		DOE target	2022
	Low-cost process for liner	1M	1M	3M	✓	N/A	2021
	Burst pressure (R134)	MPa	> 157.5	170	✓	157	2022
	Hydraulic Pressure Cycle test 87,5MPa, 20C	-	22 000	> 22 000	✓	N/A	N/A
	Gravimetric efficiency	%	> 5.7	6.10	✓	N/A	N/A
	Permeation	cm³/h/l at 55°C	< 46	< 46	✓	N/A	N/A

SHIPFC

PILOTING MULTI MW AMMONIA SHIP FUEL CELLS

Project ID	875156
PRR 2025	Pillar 3 - H_2 End Uses - Transport
Call Topic	FCH-01-2-2019
Project Total Costs	13 179 056.25
Clean H_2 JU Max. Contribution	9 975 477.50
Project Period	01-01-2020 - 31-12-2025
Coordinator Beneficiary	MARITIME CLEANTECH, NO
Beneficiaries	YARA CLEAN AMMONIA NORGE AS, ALMA CLEAN POWER AS, EIDESVIK SHIPPING AS, Wärtsilä Gas Solutions Norway AS, SUSTAINABLE ENERGY AS, NORTH SEA SHIPPING AS, STAR BULK SHIP MANAGEMENT CO. (CYPRUS) LTD, WARTSILA NORWAY AS, CAPITAL-EXECUTIVE SHIP MANAGEMENT CORP, PERSEE, CLARA VENTURE LABS AS, EQUINOR ENERGY AS, Yara International ASA,UNIVERSITY OF STRATHCLYDE, NATIONAL CENTER FOR SCIENTIFIC RESEARCH "DEMOKRITOS", FRAUNHOFER GESELLSCHAFT ZUR FORDERUNG DER ANGEWANDTEN FORSCHUNG EV

http://shipfc.eu

PROJECT AND GENERAL OBJECTIVES

ShipFC's main mission is to prove and demonstrate the case for large-scale zero-emission shipping through developing, piloting and replicating a modular 2 MW fuel cell technology using ammonia as fuel. The project will also prove the case for large-scale, zero-emission fuel infrastructure through a realistic business model. Currently, the fuel cells are being scaled up and going through laboratory testing.

NON-QUANTITATIVE OBJECTIVES

- ShipFC aims to integrate ammonia fuel cell and fuel systems into ship power systems. The integrated ship design is now used in the ongoing vessel's approval process. Initial discussions with key players from the industry have been completed and follow-up actions have been identified. The vessel design and approval process will contribute to updated knowledge in the industry, as this is the first vessel with MW-scale ammonia-powered solid oxide fuel cells (SOFCs) on board.
- For the replicators, the fourth-generation design for the container ship has now been established.
- Concept evaluations of bulk carrier are ongoing.
- ShipFC aims to demonstrate the wider use of the system and scale-up of the system by 20 MW. The first-generation design for the 5 000 twenty-foot equivalent unit container ship has been established. As the detailed designs of all systems for Viking Energy progress, the container ship design will be modified through several iterations.
- As part of the work, the project will also perform a safety assessment of the ammonia fuel gas system and of the solid oxide fuel cell system.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

- The project has signed an agreement for the delivery of green ammonia fuel for the duration of the project (not analysed or published).
- Detailed designs for the fuel system have been developed.
- The vessel design has been developed for the ammonia fuel cell installation, including the fuel gas system.
- The approval process for ammonia-powered vessels is ongoing with the class and the flag state.
- A purchase order for two MW SOFC Stacks has been placed.

FUTURE STEPS AND PLANS

- ShipFC will scale up and test the SOFC.
- The project partner Alma is currently performing laboratory-scale testing of SOFCs, and is preparing for the first large-scale SOFC test (100 kW).
- The project partner Sustainable energy has set-up the test-infrastructure required to facilitate the 100 kW test, including the necessary ammonia tank and fuel gas system.
- The consortium will follow up and monitor the delivery of stacks for the 2 MW system. A further plan is to refine the design for the 2 MW system based on results from the 100 kW tests.

PROJECT TARGETS

Target source	Parameter	Unit	Target	Achieved to date by the project	Target achieved?
Project's own objectives	GHG reduction by use of ammonia Fuel	%	70	-	
	Ammonia SOFC system Power	MW	2	6 kW	

Clean Hydrogen Partnership
Co-funded by the European Union

STASHH

STANDARD-SIZED HEAVY-DUTY HYDROGEN

Project ID	101005934
PRR 2025	Pillar 3 - H_2 End Uses – Transport
Call Topic	FCH-01-4-2020
Project Total Costs	14 310 447.80
Clean H_2 JU Max. Contribution	7 500 000.00
Project Period	01-01-2021 - 28-02-2025
Coordinator Beneficiary	SINTEF AS, NO
Beneficiaries	FEV SOFTWARE AND TESTING SOLUTIONS GMBH, PLASTIC OMNIUM NEW ENERGIES WELS GMBH, VDL SPECIAL VEHICLES BV, DAMEN RESEARCH DEVELOPMENT and INNOVATION BV, FREUDENBERG FUEL CELL E POWER SYSTEMS GMBH, DAMEN GLOBAL SUPPORT BV, VDL ENERGY SYSTEMS, PLASTIC OMNIUM NEW ENERGIES WELS GMBH, FUTURE PROOF SHIPPING BV, HYSTER-YALE ITALIA SPA, FCP FUEL CELL POWERTRAIN GMBH, VDL ENABLING TRANSPORT SOLUTIONS BV, HYUNDAI MOTOR EUROPE TECHNICAL CENTER GMBH, HYDROGENICS GMBH, FREUDENBERG FST GMBH,AKTIEBOLAGET VOLVO PENTA, SYMBIO,SCHEEPSWERF DAMEN GORINCHEM BV,INTELLIGENT ENERGY LIMITED, VOLVO CONSTRUCTION EQUIPMENT A+B, WATERSTOFNET VZW, BALLARD POWER SYSTEMS EUROPE AS, SOLARIS BUS and COACH SPOLKA Z OGRANICZONA ODPOWIEDZIALNOSCIA, Proton Motor Fuel Cell GmbH, TOYOTA MOTOR EUROPE NV, CETENA SPA CENTRO PER GLI STUDI DI TECNICA NAVALE, NEDSTACK FUEL CELL TECHNOLOGY BV, FEV EUROPE GMBH, ALSTOM TRANSPORT SA, AVL LIST GMBH, VOLVO TECHNOLOGY AB, NEDERLANDSE ORGANISATIE VOOR TOEGEPAST NATUURWETENSCHAPPELIJK ONDERZOEK TNO, COMMISSARIAT A L ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES

https://stashh.eu

PROJECT AND GENERAL OBJECTIVES

StasHH's objectives are to agree on a standard for fuel cell modules across the heavy-duty sector (trucks, buses, ships, generators, trains, etc.), to build prototypes in accordance with this standard and to test them in accordance with agreed-upon methods. The project has produced three documents for standards covering sizes, interfaces and communication, all fuel cell module suppliers have provided their prototypes, and all have undergone rigorous testing.

NON-QUANTITATIVE OBJECTIVES

- The project aims to disseminate the standard. It has established contact with the Society of Automotive Engineers and the International Organization for Standardization.
- StasHH has submitted the standard to IEC TC105.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

- A standard definition has been agreed upon.
- Eight fuel cell modules have been designed, built and tested.
- A truck prototype has been deployed at VDL.
- Publication of several public reports, including a detailed overview of regulations, codes and standards, an OEM best practices manual, a techno-economic analysis, a market assessment, X-in-the-loop software and a test report.

FUTURE STEPS AND PLANS

Finalisation of the last public designs for FCMs.

PROJECT TARGETS

Target source	Parameter	Unit	Target	Target achieved?
Project's own objectives	Standard documents	Pcs	3	✓
	Number of FC module partners	Pcs	8	
	Units tested	Pcs	8	

XIII.PILLAR 4: H_2 END-USES: CLEAN HEAT AND POWER

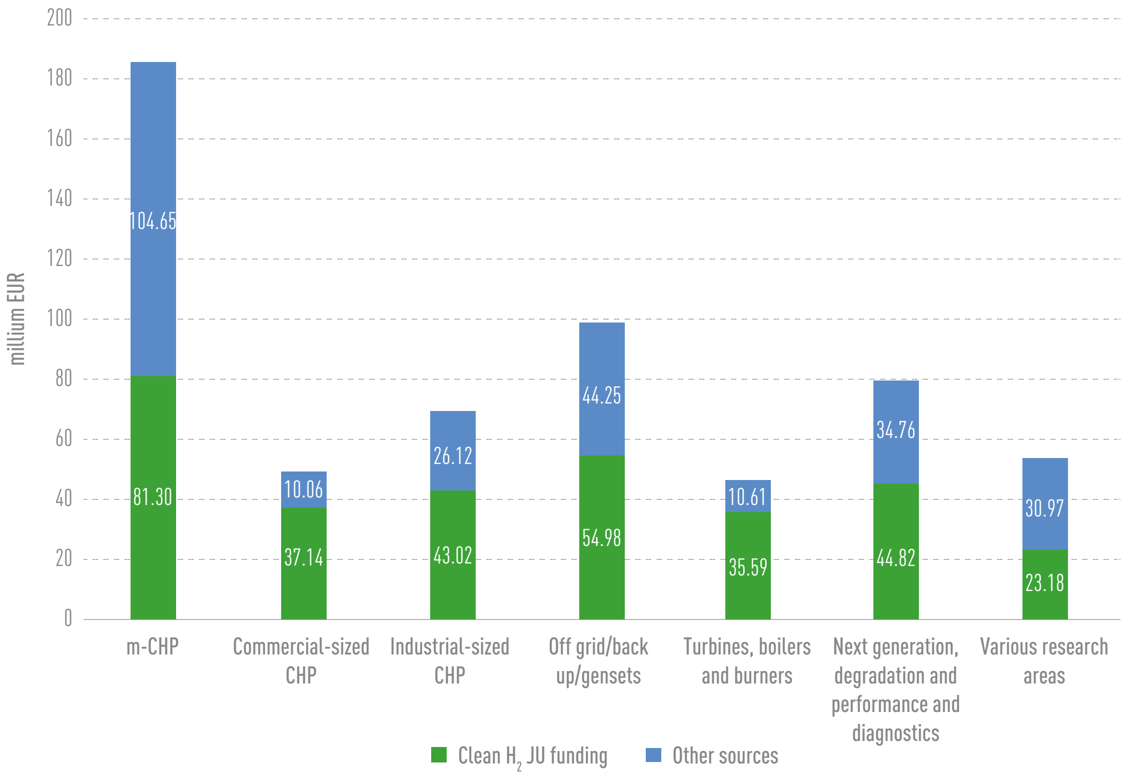
OBJECTIVES: Pillar 4 focuses on advancing renewable and flexible heat and power generation systems tailored to diverse end-users, ranging from households to large-scale power plants. While priority is given to systems operating entirely on hydrogen, SRIA also supports transitional solutions that integrate hydrogen mixtures of up to 20% into the gas grid. The portfolio of supported technologies includes stationary fuel cells, gas turbines, boilers, and burners, all contributing to the broader goal of enabling hydrogen's integration into Europe's energy system.

The following RAs are covered in Pillar 4:

- **Commercial and Industrial size CHP**: related to the use of SOFC and HT PEMFC for commercial buildings and service sectors, as well as reversible SO and PEMFC technologies for industrial applications.
- **Next generation, degradation and performance & diagnostics**: dedicated to the use of EIS technology for monitoring & diagnostic purposes.
- **Turbines, boilers and burners**: focusing on using the existing infrastructure, gas turbine combustors and boiler burners, to burn mixtures of hydrogen, ammonia, and natural gas.

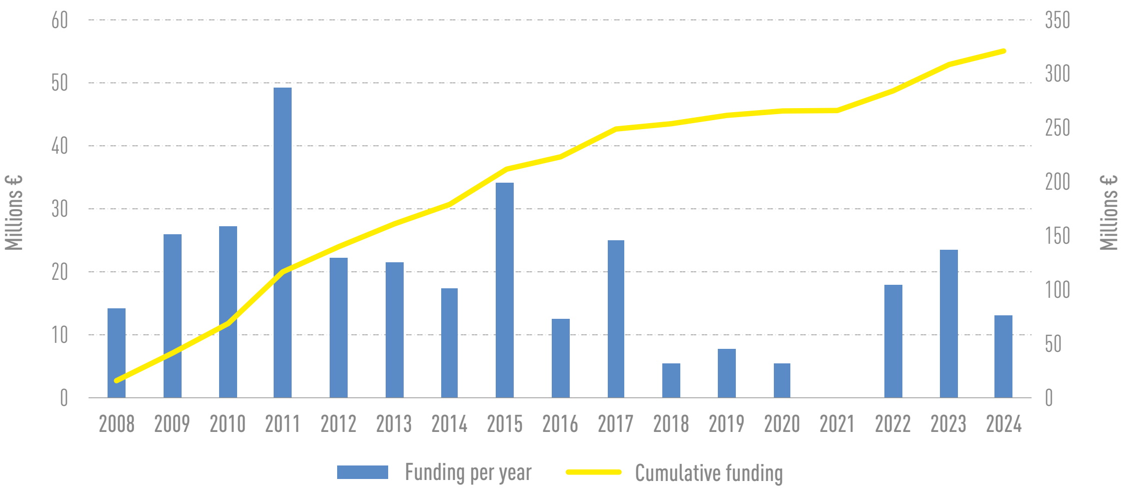
OPERATIONAL BUDGET: Since 2008, Pillar 4 has received substantial investment, with the largest share of funding directed towards micro-CHP projects, followed by allocations to off-grid, backup, and genset applications as well as next-generation technologies focusing on degradation, performance, and diagnostics (Figure 40). Over the 2008–2024 period, a total of 92 projects were funded under this pillar, representing more than EUR 300 million in support from the Clean Hydrogen JU (Figure 41), underscoring the programme's commitment to advancing hydrogen-based heat and power generation across a wide range of applications.

Figure 40: Funding per research area for Pillar 4 projects from 2008 to 2024



Source: Clean Hydrogen Joint Undertaking

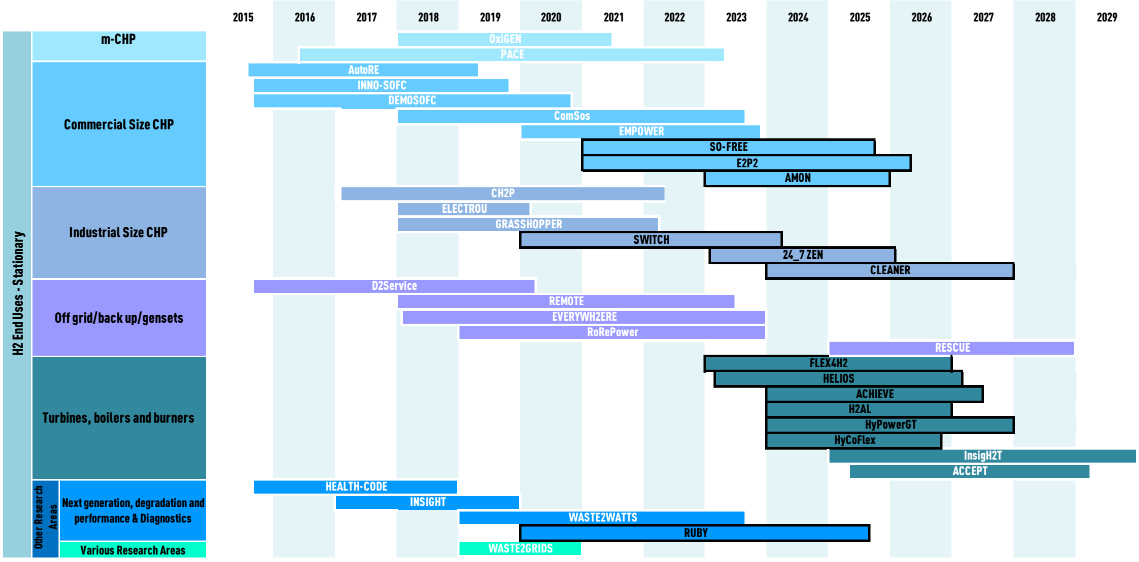
Figure 41: Funding (per year in blue/left axis and cumulative in grey/right axis) for Pillar 4 projects from 2008 to 2024



Source: Clean Hydrogen Joint Undertaking

PILLAR IN BRIEF: Pillar 4 covers 13 projects in 2025, including 6 projects allocated to the Commercial and Industrial size CHP research areas, 6 projects related to turbines, boilers and burners research area, and 1 project related to next generation degradation and performance & diagnostics research area (Figure 42).

Figure 42: Project timelines of Pillar 4: H_2 End-Uses: Clean Heat and Power



Source: Clean Hydrogen Joint Undertaking

Funding under Pillar 4 has increased significantly over the past two years, with 4 projects in 2023 and 5 projects in 2024 (see Figure 43). This growth is due to the introduction of a new research area focusing on turbines, boilers, and burners, which has driven greater investment and project activity.

Figure 44 shows that Italy (12 projects), Germany (10), and the Netherlands (8) are the leading contributors in Pillar 4, followed by France, Belgium, and Sweden, while other countries have a more limited presence. The collaboration network (Figure 45) highlights Italy and Germany as central actors with strong bilateral ties and broad connectivity, while the Netherlands forms a cluster with Denmark, Sweden, and Croatia, and Germany links with Austria, Poland, and Slovenia in a cohesive Central European group; more peripheral but still engaged are Spain, Greece, and Belgium. Project participation is evenly distributed across organisation types (Figure 46), with private companies and research institutions each involved in 13 projects, higher education institutions in 12, SMEs in 10, and other entities in 3, while the Sankey diagram (Figure 47) shows steady involvement of research and academic organisations from 2020–2024, with private companies and SMEs expanding participation from 2023 onward. Figure 48 identifies SolydEra, DLR, and Fondazione Bruno Kessler as the most active institutions, alongside SINTEF, EPFL, VTT, and Kiwa Group, representing a balanced mix of research bodies, technical universities, and industrial partners, while the collaboration network (Figure 49) reveals dense clusters (such as EPFL, VTT, and SolydEra at the centre of applied research and technology development, and DLR anchoring another cluster with SINTEF) complemented by smaller, industry-led consortia around Kiwa Group and IREC. Finally, Figure 50 presents the scientific publication output of Pillar 4 projects by year. The highest number was recorded in 2023, with 13 publications, 6 of which were peer-reviewed. Publication output declined to 6 in 2024. Projects funded in 2024 have not yet produced any publications, likely due to their recent start.

Figure 43: Pillar 4: Trend in number of projects per year

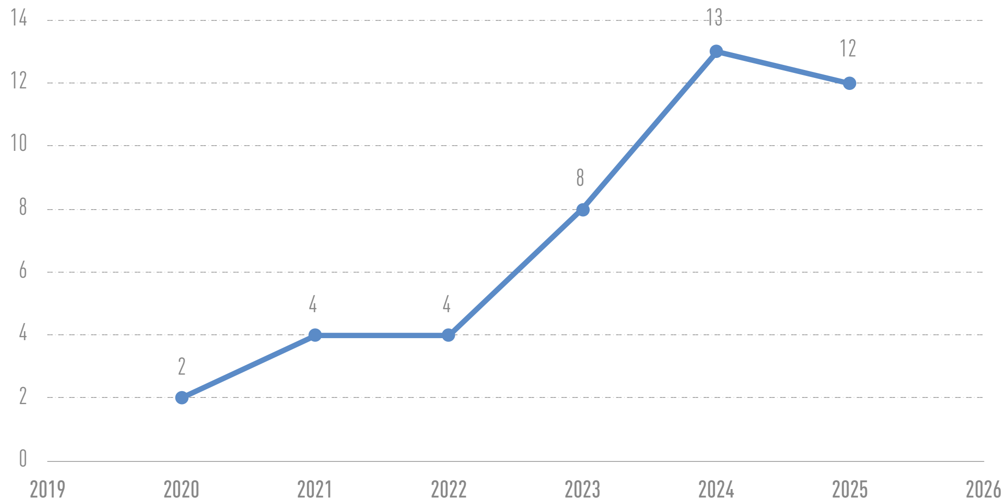


Figure 44: Pillar 4: Project participation by EU country

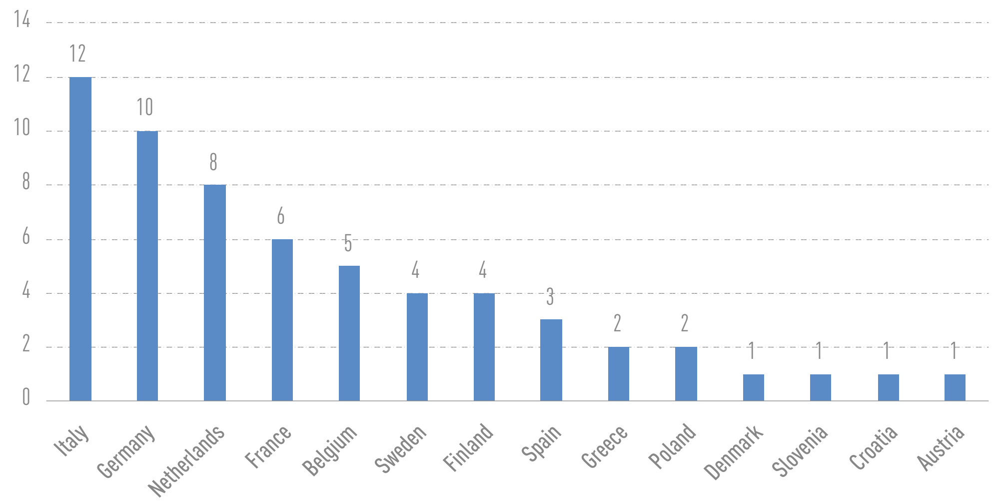


Figure 45: Pillar 4: Collaboration network of EU countries

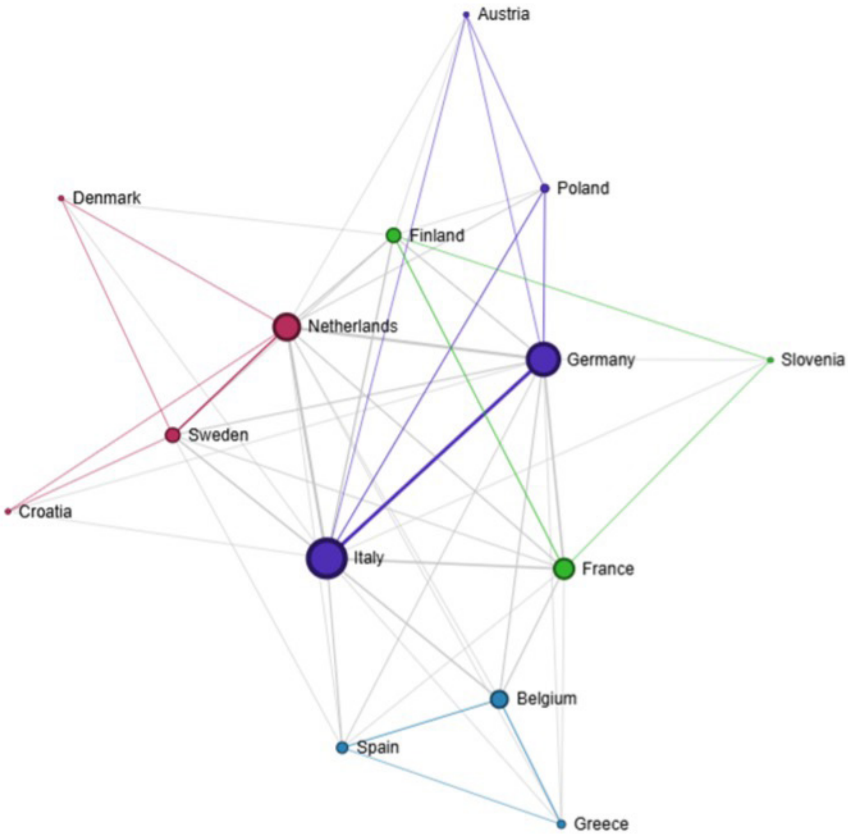


Figure 46: Pillar 4: Breakdown of projects by participating entity type

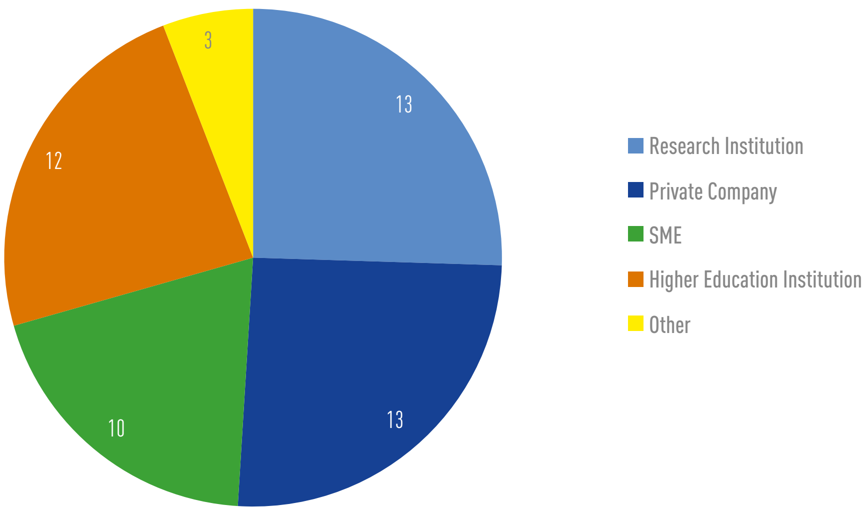


Figure 47: Pillar 4: Participation by organisation type across years

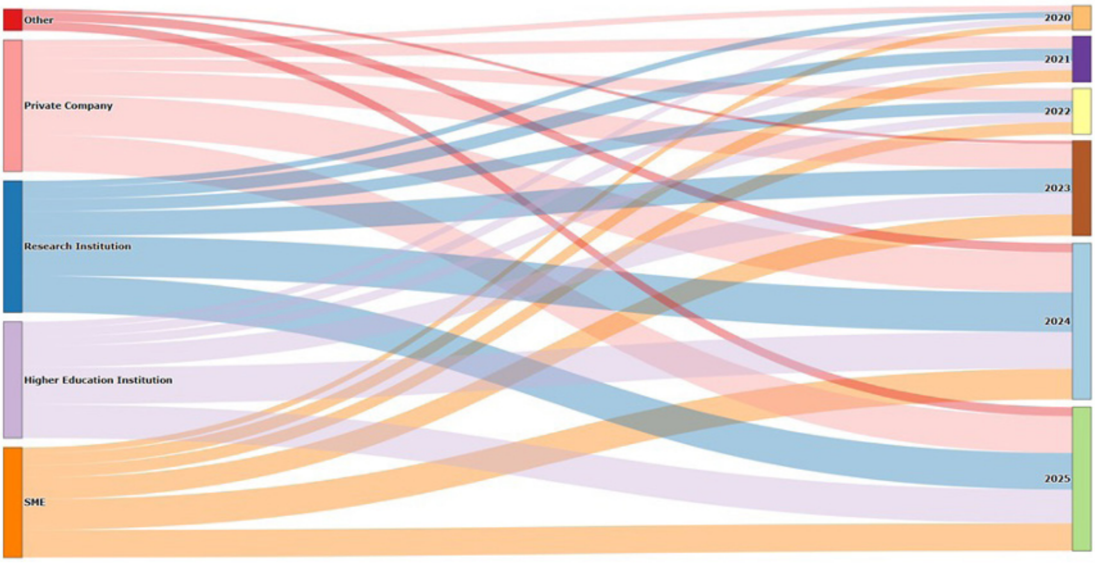


Figure 48: Pillar 4: Top institutions by number of projects

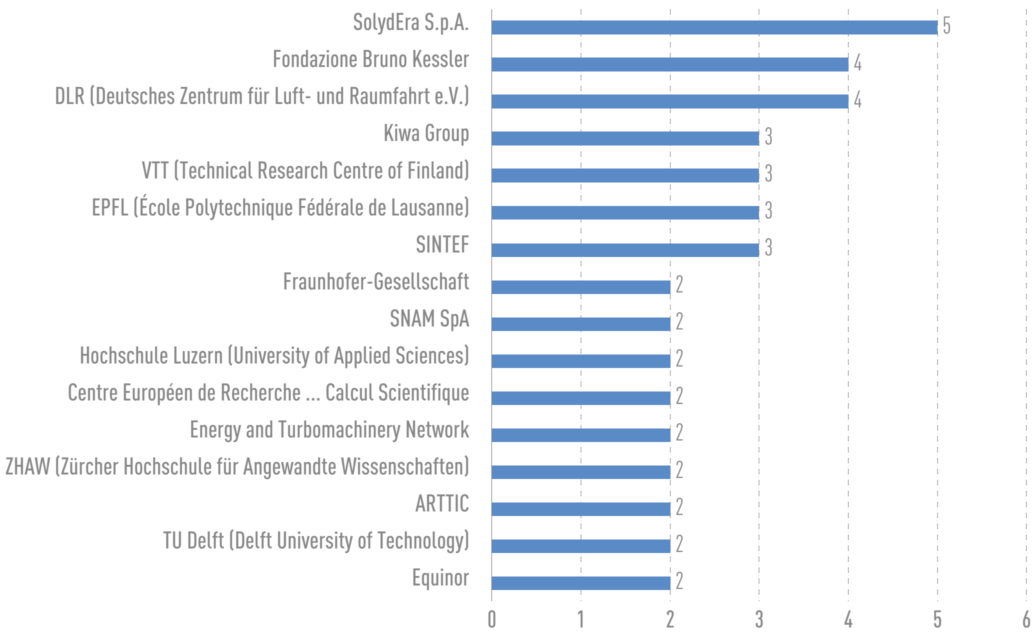


Figure 49: Pillar 4: Collaboration network of top participating institutions

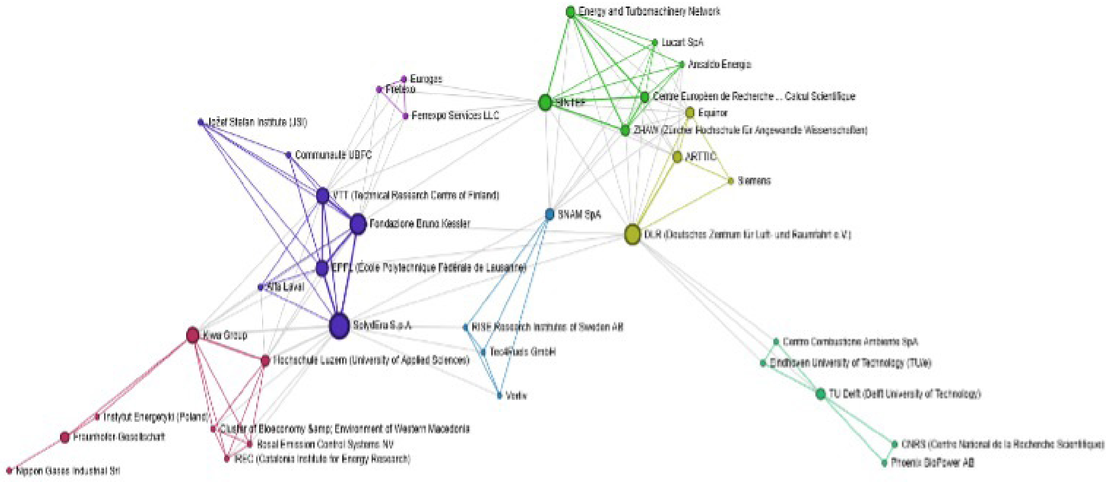
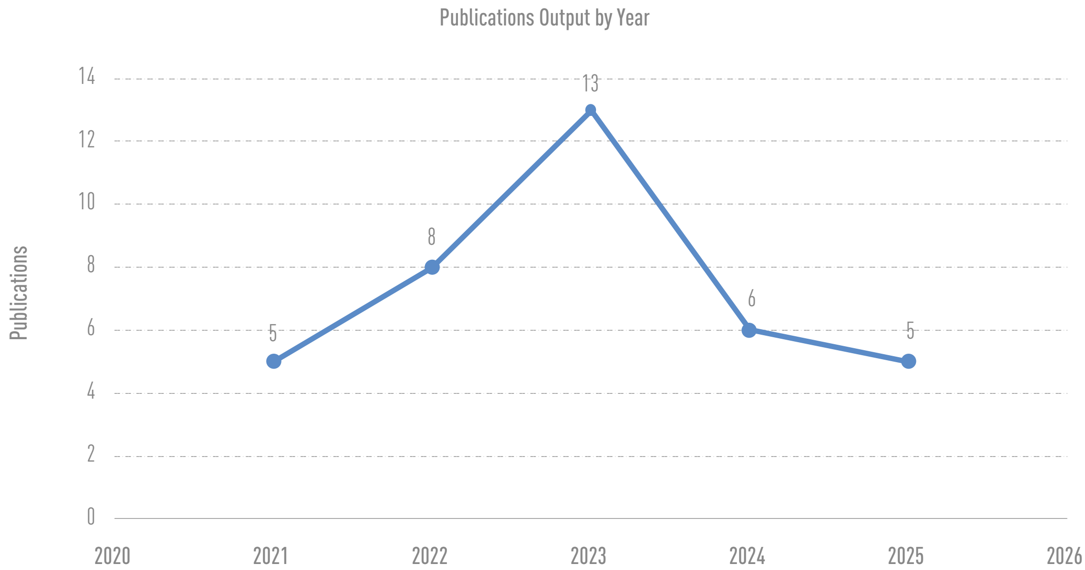
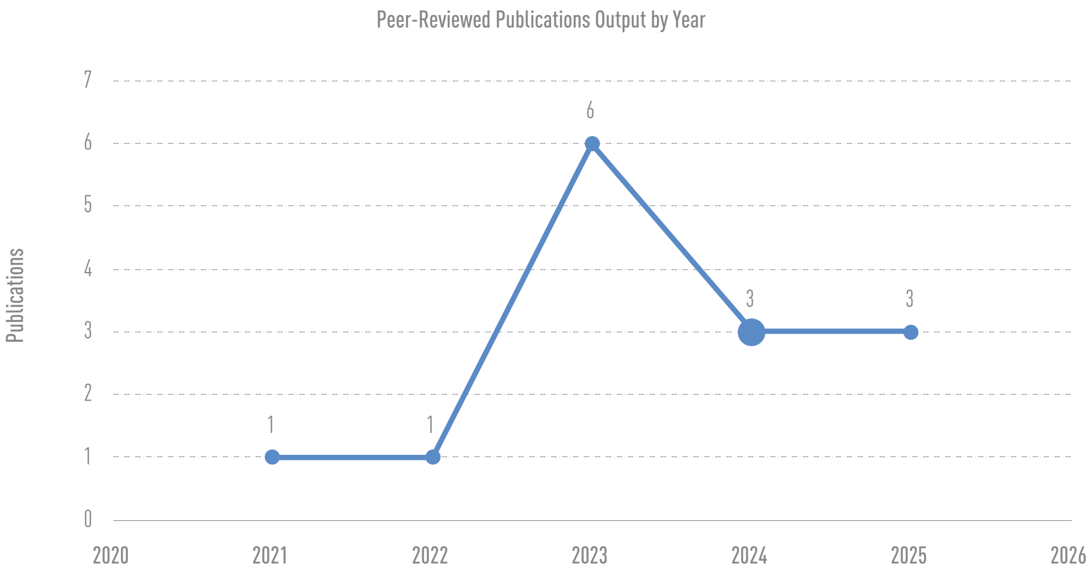


Figure 50: Pillar 4: Number of publications per year





PROJECTS FACTSHEETS

24_7 ZEN

REVERSIBLE SOEC/SOEFC SYSTEM FOR A ZERO EMISSIONS NETWORK ENERGY SYSTEM

Project ID	101101418
PRR 2025	Pillar 4 - H_2 End Uses - Stationary Applications
Call Topic	HORIZON-JTI-CLEANH$_2$-2022-04-03
Project Total Costs	5 499 822.50
Clean H_2 JU Max. Contribution	5 499 822.50
Project Period	01-02-2023 - 31-01-2026
Coordinator Beneficiary	FUNDACIO INSTITUT DE RECERCA DE L'ENERGIA DE CATALUNYA, ES
Beneficiaries	DIAXIRISTIS ETHNIKOU SISTIMATOS FISIKOU AERIOU ANONIMI ETERIA. HELLENIC GAS TRANSMISSION SYSTEM OPERATOR, KIWA CREIVEN S.R.L., OST - OSTSCHWEIZER FACHHOCHSCHULE, EUNICE LABORATORIES MONOPROSOPI ANONYMI ETAIREIA, KIWA CERMET ITALIA SPA, CLUSTER VIOOIKONOMIAS KAI PERIVALLONTOS DYTIKIS MAKEDONIAS,INERCO INGENIERIA, TECNOLOGIA Y CONSULTORIA, SA, SOLYDERA SPA, BOSAL EMISSION CONTROL SYSTEMS NV, SOLYDERA SA, FACHHOCHSCHULE ZENTRALSCHWEIZ - HOCHSCHULE LUZERN, ETHNIKO KENTRO EREVNAS KAI TECHNOLOGIKIS ANAPTYXIS, POLITECNICO DI TORINO,IDRYMA TECHNOLOGIAS KAI EREVNAS

https://24-7zenproject.eu/

PROJECT AND GENERAL OBJECTIVES

24_7 ZEN aims to design and construct a highly efficient 33/100kW reversible solid oxide cell (rSOC) power-balancing plant, showcasing its compatibility with both electricity and gas grids. The project consortium, comprising diverse expertise, leads innovation in energy management and rSOC system development. The consortium pioneers' advancements across the value chain, from cell-level material to fully operational rSOC systems and plug-and-play grid interconnection ecosystems on the demo site. Key players include an organisation involved in renewable energy generation (EUNICE), a transmission system operator (DESFA), and international quality assurance (KIWA). The 24_7 ZEN ecosystem will showcase efficient power-to-gas-to-power routes, utilising H_2 or natural gas as fuel, enabling H_2 grid injection, transitioning in less than 30 minutes and achieving a round-trip efficiency of 45 %, all while adhering to standards and safety regulations.

The consortium aims to develop and validate a scalable ecosystem applicable to multi-MW installations. Further research will focus on improving rSOC performance (targeting degradation rates of 0.4 %/kh for 1 000 hours and a current density of 1.5 A/cm^2 in both modes) and enhancing cost-competitiveness (reducing CAPEX from EUR 6 000 / kW to EUR 3 500 / kW).

NON-QUANTITATIVE OBJECTIVES

- Identify requirements for a 24_7 ZEN ecosystem compatible and interconnected to grid.
- Enhance 24_7 ZEN system performance by optimising rSOC cell and stack manufacturing.
- Design, manufacture and test to validate a scalabe full rSOC system.
- Full-scale demonstration of the 24_7 ZEN grid balancing ecosystem sustained for over 4 months.
- Set out a roadmap exploiting project results for the scaling up and deployment of grid balance rSOC systems.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

- Top-level requirements for rSOC system integration with electricity and gas grids have been defined, identifying three integration configurations. Establishment of the control strategy and energy management system based on operational profiles.
- Significant advancements have been made in enhancing rSOC components, particularly in electrode testing and interconnect development. The use of Co-free oxygen electrodes and new composition of Fe-AU doped fuel electrodes has achieved high current densities in both modes of operation.
- rSOC stack and hot BoP design and development has led to the creation of detailed designs and simulations of the innovative stack together with the thermal management components on a single body solution.
- Ongoing activities in system integration and design, including conceptual engineering and detailed design, have been conducted to ensure seamless integration of components.
- System requirements and use cases have been clearly defined, addressing critical aspects such as electricity supply, water flow, and natural gas supply.

These results signify a significant step forward in the development of the rSOC system, bringing the project closer to its goal of creating a high-performing solution for sustainable grid management.

FUTURE STEPS AND PLANS

- Advancing the scalability of the achieved outcomes.
- Scale-up of enhanced button cells to larger cell areas and stack levels to support increased power output and integration potential.
- Integration of key developed components, including the rSOC stack and heat exchangers, into the full system module, incorporating the pre-designed Balance of Plant (BoP).
- Final system integration activities to assemble a fully functional rSOC system module suitable for grid-scale application.
- Validation through demonstration testing of the fully integrated rSOC system within the Greek energy grid over a four-month period, focusing on its grid-balancing capability.

PROJECT TARGETS

Target source	Parameter	Unit	Target	Target achieved?	SoA result achieved to date (by others)	Year for reported SoA result
Project's own objectives	Efficiency on SOFC mode	%	57		50	2019
	Transient Time (SOFC/SOEC)	min	30		N/A	N/A
	Degradation rate cycling SOFC/SOEC	%/khr	0.4		1 (SOFC) 2 (SOEC)	N/A
	Current Density under Co-SOEC	A/cm^2	1		N/A	N/A
	Total System Power in rSOC	kW	33/100		25/75	N/A
	Efficiency on SOEC mode	%	80		81	2021

ACHIEVE

ADVANCING THE COMBUSTION OF HYDROGEN-AMMONIA BLENDS FOR IMPROVED EMISSIONS AND STABILITY

Project ID	101137955
PRR 2025	Pillar 4 - H_2 End Uses - Stationary Applications
Call Topic	HORIZON-JTI-CLEANH$_2$-2023-04-02
Project Total Costs	2 994 200.00
Clean H_2 JU Max. Contribution	2 994 200.00
Project Period	01-01-2024 - 30-06-2027
Coordinator Beneficiary	UNIVERSITA DEGLI STUDI DI ROMA LA SAPIENZA, IT
Beneficiaries	STATE ENTERPRISE ZORYA MASHPROEKT GAS TURBINE RESEARCH AND PRODUCTION COMPLEX, PHOENIX BIOPOWER SWITZERLAND GMBH, PHOENIX BIOPOWER AB, CENTRALESUPELEC, KING ABDULLAH UNIVERSITY OF SCIENCE AND TECHNOLOGY, ZABALA INNOVATION CONSULTING SA, UNIVERSITA DEGLI STUDI DI FIRENZE, TECHNISCHE UNIVERSITEIT DELFT, TECHNISCHE UNIVERSITAT BERLIN, CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS

https://achieve-project.eu/

PROJECT AND GENERAL OBJECTIVES

ACHIEVE (Advancing the Combustion of Hydrogen-AmmonIa blEnds for improVed Emissions and stability) aims to accelerate the transition of the gas turbine power generation industry from carbon-based natural gas combustion to carbon-free fuel blends. ACHIEVE seeks to achieve zero-carbon emissions, ultra-low NO_x emissions, and stable gas turbine operation by focusing on hydrogen (H_2) and ammonia (NH_3) mixtures. The project follows a three-pronged approach:

- Experimental campaigns to investigate combustion stability, emissions, and performance under increasingly realistic conditions.
- Numerical modeling to address challenges such as chemical kinetics, flame dynamics, and combustion instabilities.
- Engagement with industry stakeholders, including OEMs and end users, to facilitate technology adoption.

ACHIEVE aims to advance the technology readiness level (TRL) to 4, demonstrating its feasibility in a controlled environment and laying the groundwork for future industrial implementation.

NON-QUANTITATIVE OBJECTIVES

- Develop a deeper fundamental understanding of hydrogen-ammonia combustion processes.
- Investigate the stability, emissions, and operational feasibility of unconventional hydrogen-based fuel blends to overcome key scientific and technological barriers that currently limit widespread adoption.
- Focus on efficient burning while minimising harmful emissions and preventing flame instability, flashback, and thermoacoustic oscillations.
- Create advanced numerical modeling techniques that enhance the predictive capabilities of combustion simulations, contributing to more accurate and reliable gas turbine designs.
- Foster strong collaboration between academia, industry, and policymakers, ensuring that the project's findings are aligned with real-world energy demands and regulatory requirements and to support a smooth transition toward sustainable energy solutions, ultimately contributing to global decarbonisation efforts.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

ACHIEVE has made significant progress in the following:

- Understanding and implementation of hydrogen-ammonia combustion for gas turbines meeting key deliverables and milestones, including the completion of preliminary experimental and numerical studies aimed at improving combustion stability, reducing NO_x emissions, and optimising fuel blends for practical applications.
- Testing to assess the feasibility of hydrogen-based fuels under varying operating conditions, providing valuable insights into their behavior and potential integration into energy systems.
- Computational modeling efforts focusing on refining predictive tools for flame dynamics, emissions, and thermoacoustic stability, enhancing the accuracy of combustion simulations.
- Dissemination activities, with multiple publications and presentations showcasing results in scientific and industrial forums.

FUTURE STEPS AND PLANS

- Conduct more extensive experimental campaigns at progressively higher pressures and power levels to simulate real-world gas turbine conditions more accurately to refine the understanding of static and dynamic combustion stability, emissions control, and operational efficiency, ensuring that the proposed fuel blends meet industrial standards.
- Enhance combustion models by integrating improved chemical kinetics, turbulence-chemistry interactions, and predictive tools for NO_x emissions and thermoacoustic instabilities, contributing to more reliable and optimised simulations.
- Prioritise knowledge dissemination through scientific publications, conference presentations, and stakeholder engagement activities to maximise impact.

Clean Hydrogen Partnership
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ACHIEVE

PROJECT TARGETS

Target source	Parameter	Unit	Target	Target achieved?
Project's own objectives	H_2 range in gas turbine fuel	% mass	100% in conventional swirl-stabilised and novel burners	
	H_2 range in gas turbine fuel	% vol.	Up to 20% NH_3 (TUB burner)	
	H_2 range in gas turbine fuel	% vol.	Validation of models to within 5% accuracy	
	NO_x emissions	-	65% reduction NO_x in premixed, 80% in non-premixed operation (jet in hot coflow)	
	NO_x emissions	NO_x ppmv@15%O_2/dry	Validation of models to within 10% accuracy	
	NO_x emissions	NO_x mg/MJ fuel	NO_x < 25ppm with 100% H_2 (TUB burner)	
	NO_x emissions	NO_x mg/MJ fuel	NO_x < 100ppm with up to 20%NH_3 (TUB burner)	
	Ability to handle H_2 content fluctuations	% mass/min	Stable combustion with 100% H_2 (TUB burner)	
	Ability to handle H_2 content fluctuations	% vol./min	Stable combustion of H_2 blends with 20%NH_3 (TUB burner)	
	Ability to handle H_2 content fluctuations	% vol./min	Low combustion instabilities (lower than 0.15 % of the operating) for 100% H_2	
	Ability to handle H_2 content fluctuations	% vol./min	+/- 30 (TUB burner)	
	Ability to handle H_2 content fluctuations	% vol./min	Low combustion instabilities (lower than 0.15 % of the operating) for 100% H_2	
	Ability to handle H_2 content fluctuations	% vol./min	Stable operation with H_2 fluctuations +/- 30%vol./min (TUB burner), no instabilities p_RMS/p_op < 0.15%, no flashback, no lean blowout - Real-time monitoring system to achieve stable operation	
	Validated Computational Singular Perturbation (CSP) skeletal, and virtual-chemistry reduced mechanisms for a use case	-	28% thermal cracking of NH_3 yielding 32.8% H_2 / 10.9% N_2 / 56.3% NH_3 by volume	
	Events presenting the project per year and links with other EU projects	Number	3	
	Peer-reviewed papers published	Number	12	

Clean Hydrogen Partnership
Co-funded by the European Union

AMON

DEVELOPMENT OF A NEXT GENERATION AMMONIA FC SYSTEM

Project ID	101101521
PRR 2025	Pillar 4 - H_2 End Uses - Stationary Applications
Call Topic	HORIZON-JTI-CLEANH$_2$-2022-04-02
Project Total Costs	4 130 784.25
Clean H_2 JU Max. Contribution	3 998 028.75
Project Period	01-01-2023 - 31-03-2027
Coordinator Beneficiary	FONDAZIONE BRUNO KESSLER, IT
Beneficiaries	ALFA LAVAL SPA, KIWA CERMET ITALIA SPA, SAPIO PRODUZIONE IDROGENO OSSIGENO SRL, TEKNOLOGIAN TUTKIMUSKESKUS VTT OY, KIWA NEDERLAND BV, SOLYDERA SPA, EUROPEAN FUEL CELL FORUM AG, ALFA LAVAL TECHNOLOGIES AB, ALFA LAVAL AALBORG AS, FACHHOCHSCHULE ZENTRALSCHWEIZ - HOCHSCHULE LUZERN, ECOLE POLYTECHNIQUE FEDERALE DE LAUSANNE, DANMARKS TEKNISKE UNIVERSITET

https://amon-project.eu/

PROJECT AND GENERAL OBJECTIVES

AMON will develop a novel system for the utilisation and conversion of ammonia into electric power at high efficiency using a solid oxide fuel cell system. The project will deal with the design of the system's basic components including the fuel cell, an ammonia burner, and ammonia resistant heat exchangers, the engineering of the whole balance of plants, and the validation of compliance with ammonia use by all parts and components. Optionally, depending on system needs, an ammonia cracker and anode gas recirculation will be developed.

The general objectives are to:

- Design and develop a fuel cell stack module at a scale of 8 kWel, tested and qualified to convert ammonia into power, possibly using the internal reforming capacity of a solid oxide cell operating at high temperature and managing the power output through the control of the cell fuel utilisation.
- Certify all the components and related materials of a system as 100% tolerant to ammonia.
- Aim to make the system 70% electrically efficient.
- Certify the system for at least 3000 hours of operation, demonstrating an ammonia availability of 90% in the operating hours and a degradation rate less than 3% with nominal power measured over 1000 hours of continuous operation.

NON-QUANTITATIVE OBJECTIVES

- Diversify and secure the energy supply.
- Unlock wide markets potential and foster efficient conversion systems to decarbonise hard-to-abate sectors such as maritime and autonomous power systems, where volumetric density and long-term storage solutions are key requirements.
- Raise industrial interest in ammonia and foster the development of new markets and new jobs.
- Increase visibility and awareness of renewable hydrogen and ammonia potential.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

- Development of a conceptual system design, providing the targeted efficiency of more than 70 % and a safe system without so-called nitriding.
- Development of a multiscale multiphysics model concept to more precisely foresee possible challenges and obtain designs to avoid these.
- Implementation of single cell testing at EPFL to set a benchmark for the future testing of improved cells. The tests were done with ammonia (NH_3), a mixture of 75% H_2 and 25% N_2 mimicking fully cracked ammonia, and pure H_2 for comparison. Each test lasted 1000h in steady polarisation at 0.5 A/cm^2 and 750°C.
- Definition of testing protocols for ammonia-fuelled SOFC to establish common procedures and tests conducted during the project.
- Execution of experimental and numerical investigation of ammonia cracking demonstrating that the ammonia cracking rate is crucial for developing the external cracker and the importance to understand the internal cracking of ammonia in direct ammonia-fuelled SOFCs.
- Implementation of numerous activities with regards to communication and dissemination to lay the basis for a proper communication strategy and tools, such as definition of a dissemination and communication plan, creation of a visual identity and logo for AMON project as part of a communication toolkit, activation of the project website, participation at several conferences, fairs and workshops, organisation of a workshop at the Sustainable Shipping in July 2024.

FUTURE STEPS AND PLANS

- Techno-economic analysis.
- Design of the system at the tens of MW scale.
- Validation and testing of ammonia-fuelled 8 kW stack module.
- Design of advanced controls to operate the ammonia fuel cell system.
- Webinars.

PROJECT TARGETS

Target source	Parameter	Unit	Target	Target achieved?	SoA result achieved to date (by others)	Year for reported SoA result
Project's own objectives	FC system tolerance to Ammonia	%	System fed by 100% ammonia as fuel		N/A	N/A
	Pillar Heat and Power/ table 20: KPIs for Solid Oxide Stationary Fuel Cells: Degradation @CI and FU=75%	%/1 000 h	≤2.5		4	2019
	KPIs for Solid Oxide Stationary Fuel Cells: Efficiency	%	70-65		52.1	2020
	Pillar Heat and Power/ table 20: KPIs for Solid Oxide Stationary Fuel Cells: Availability	%	>90		N/A	N/A

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CLEANER

CLEAN HEAT AND POWER FROM HYDROGEN

Project ID	101137799
PRR 2025	Pillar 4 - H_2 End Uses - Stationary Applications
Call Topic	HORIZON-JTI-CLEANH$_2$-2023-04-01
Project Total Costs	3 949 959.50
Clean H_2 JU Max. Contribution	3 949 959.50
Project Period	01-01-2024 - 31-12-2027
Coordinator Beneficiary	SINTEF AS, NO
Beneficiaries	FERREXPO SERVICES LLC, NATIONAL GAS TRANSMISSION PLC, UKRGASVYDOBUVANNYA JOINT STOCK COMPANY, TEKNOLOGIAN TUTKIMUSKESKUS VTT OY, PRETEXO, Powercell Sweden AB, FONDAZIONE BRUNO KESSLER, ALBERT-LUDWIGS-UNIVERSITAET FREIBURG, EUROGAS - EUROPEAN UNION OF THE NATURAL GAS INDUSTRY, SCHIPHOL NEDERLAND BV

http://cleaner-h2project.eu

PROJECT AND GENERAL OBJECTIVES

Hydrogen storage in underground salt caverns structures is very limited; there are three sites in the USA and one in the United Kingdom. Since the hydrogen mainly origins from steam methane reforming (SMR), the purity is around 95%. Rock caverns (sealed) are being developed, one of them within the HYBRIT project in Sweden, where clean hydrogen from electrolysis will be stored. In most geological storages and pipelines hydrogen will be already, or become, contaminated with substances not suitable for use in all types of fuel cells (like N_2, CO, CO_2, hydrocarbon and sulphur compounds). Hydrogen produced through electrolysis is considered clean, the only impurities are oxygen and water. However, other sources of hydrogen, such as natural gas reforming, have impurities remaining from the production process.

While re-purification of this H_2 can and should be done for some applications, for example by pressure swing adsorption, it adds cost and complexity, and is not in all use cases economically feasible. Currently, there is no standard for the quality of H_2 coming from geological storage or pipelines, and the knowledge of which contaminants are present in hydrogen from these storage sites is extremely limited.

Large-scale stationary fuel cells in the MW-range should be able to operate on such industrial quality H_2 without repurification. They can offer a low-cost clean alternative for both large scale (peak) power and heat production and for small, medium and large-scale back-up power units for the critical infrastructure, thereby also improving the resilience of the energy system. The H_2 quality standard under development is expected to become around 98%, with CO and sulphur compounds as the main relevant poisoning impurities, in addition to inert gases such as CO_2 and N_2, so the fuel cell systems must tolerate these.

CLEANER will develop a stationary 100 kW PEMFC module capable of operating on industrial quality hydrogen.

NON-QUANTITATIVE OBJECTIVES

- Ensure economically and environmentally sustainable development of materials, components and system.
- Exploit project results through dissemination to and dialogue with key stakeholders.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

CLEANER will:

- Develop lower-cost and impurity-tolerant catalyst materials, mitigation operating strategies to avoid the impact of potential impurities.
- Evaluate new fluorine-free membranes.
- Develop a stationary PEM fuel cell system of more than 100 kW capable of operating with industrial-quality hydrogen.

FUTURE STEPS AND PLANS

In the first 12 months of the project, CLEANER will perform a hydrogen impurity survey, mapping the potential impurities expected in the hydrogen value chain. This will serve as basis for the first material development and testing. Preparations are ongoing on the fuel cell system by PowerCell and at VTT's test facilities.

PROJECT TARGETS

Target source	Parameter	Unit	Target	Target achieved?	SoA result achieved to date (by others)	Year for reported SoA result
Project's own objectives	O&M cost	€ct/kWh	< 1.7		5	2020
	Electrical Efficiency ηel	% LHV	52		50	
	Degradation @ CI	%/1 000 h	<0.2		0.4	
	Non-recoverable CRM as catalyst	mg/Wel	<0.05 gr/kWe for Pt based catalysts < 0.025 gr/kWe for IrRu single site catalysts at the anode Assumptions: Pt catalysts: anode 0.1 mg (Pt)/cm^2, cathode 0.4 mg (Pt)/cm^2, Pt recovery rate > 90 % à nr-PGM in the project < 0.05 mg/cm^2,	⚙	<0.1	
	Warm start time	sec	<15		60	
	CAPEX	€/kW	< 1 000		1 900	
	Availability	%	>98		98	

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E2P2

ECO EDGE PRIME POWER

Project ID	101007219
PRR 2025	Pillar 4 - H_2 End Uses - Stationary Applications
Call Topic	FCH-02-9-2020
Project Total Costs	3 576 409.45
Clean H_2 JU Max. Contribution	2 499 715.50
Project Period	01-01-2021 - 30-04-2026
Coordinator Beneficiary	RISE RESEARCH INSTITUTES OF SWEDEN AB, SE
Beneficiaries	VERTIV CROATIA DOO ZA TRGOVINU I USLUGE, VERTIV, INFRAPRIME GMBH, EQUINIX NETHERLANDS B.V., SNAM S.P.A., TEC4FUELS, SOLYDERA SPA

https://e2p2.eu/

PROJECT AND GENERAL OBJECTIVES

The main objectives of E2P2 are to define the concept of fuel cell prime power for data centres and create an authoritative open standard for the adaptation of fuel cells to power data centres. E2P2 will demonstrate and validate a proof-of-concept fuel-cell-based prime power module for data centres and evaluate the opportunities for improved energy efficiency and waste heat recovery. The project strongly anticipates opportunities for the European fuel cell suppliers to increase the uptake of their fuel cells across multiple markets, with improved energy efficiency and cost-effectiveness.

NON-QUANTITATIVE OBJECTIVES

- Define the concept of fuel cells for prime power for data centres.
- Create an authoritative open standard for adapting fuel cells to power data centres.
- Demonstrate and validate a proof-of-concept fuel cell based prime power module for data centres.
- Collect extensive operational data to support the use of fuel cells as prime power for data centres.
- Analyse the combined social, environmental and commercial impact on the European market.
- Evaluate opportunities for improved energy efficiency and waste heat recovery.
- Generate effective market uptake and create a business strategy.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

Vertiv, Tec4Fuels, and SolydEra have successfully developed their modules for the E2P2 project, with meticulous attention to detail. Comprehensive drawings and installation plans have been meticulously crafted. The location has been carefully selected, with Equinix ML 5 site outside Milan, Italy. Substantial data has been gathered for the Life Cycle Assessment, ensuring thorough analysis.

FUTURE STEPS AND PLANS

The subsequent phase involves conducting factory acceptance testing for the modules, followed by their shipment to Milan for installation. Research Institutes of Sweden will facilitate network connectivity to enable seamless data collection. Once all modules are installed, site acceptance testing will be performed. Subsequently, the E2P2 proof of concept will undergo rigorous testing under full operational conditions for one year.

PROJECT TARGETS

Target source	Parameter	Unit	Target	Target achieved?
Project's own objectives	Tolerated H_2 content in NG	%	20	

FLEX4H$_2$

FLEXIBILITY FOR HYDROGEN

Project ID	101101427
PRR 2025	Pillar 4 - H_2 End Uses - Stationary Applications
Call Topic	HORIZON-JTI-CLEANH$_2$-2022-04-04
Project Total Costs	4 872 197.50
Clean H_2 JU Max. Contribution	4 178 517.25
Project Period	01-01-2023 - 31-12-2026
Coordinator Beneficiary	ANSALDO ENERGIA SPA, IT
Beneficiaries	EUROPEAN TURBINE NETWORK, ARTTIC INNOVATION GMBH, ANSALDO ENERGIA SWITZERLAND AG, EDISON SPA, ENERGY AND TURBOMACHINERY NETWORK, ZURCHER HOCHSCHULE FUR ANGEWANDTE WISSENSCHAFTEN, SINTEF ENERGI AS, CENTRE EUROPEEN DE RECHERCHE ET DEFORMATION AVANCEE EN CALCUL SCIENTIFIQUE, DEUTSCHES ZENTRUM FUR LUFT - UND RAUMFAHRT EV

https://flex4h2.eu/

PROJECT AND GENERAL OBJECTIVES

FLEX4H$_2$ will design, develop, and validate a highly fuel-flexible sequential combustion system capable of operating with any concentration of hydrogen admixed with natural gas up to 100% at H-class operating temperatures, with the aim of maintaining rated power and efficiency.

FLEX4H$_2$ will:

- Tackle the challenges related to H_2 combustion by developing combustion technology through a combination of design optimisation, analytical research, and validation in a relevant environment.
- Validate scaled and full-size prototypes of the combustor through dedicated atmospheric and high-pressure test campaigns up to technology readiness level 6.
- Demonstrate the combustor's ability to operate in the presence of any mixture of hydrogen and natural gas during testing, without diluents while complying with emission limits.
- Demonstrate the possibility to start-up the engine on any amount of H_2 in natural gas.

NON-QUANTITATIVE OBJECTIVES

FLEX4H$_2$ will assess the replicability of the scientific methodologies applied and the transferability of the results to different gas turbine classes and evaluate the wider retrofit markets.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

Combustion system development and testing

- Execution of full-scale high-pressure testing, showing the possibility to operate the FLEX4H$_2$ prototypes with natural gas, hydrogen and all intermediate blends.
- Completion of high-pressure combustion tests in the small-scale optically accessible rig, providing characterisation of the flame stabilisation mechanism of hydrogen auto-ignition driven flames, enabling validation of the latest numerical simulations and providing valuable information for operation of gas turbines fired with high hydrogen contents or pure hydrogen.
- Design of second generation full-scale H_2-optimised prototypes, with an optimised injection system and mixing section aiming at improved operation with higher firing temperatures.
- Atmospheric testing of optimised first-stage burners, showing very promising results for wider flashback margin and improved flexibility.

Numerical modelling

- Execution of advanced high-resolution Large-Eddy Simulation of Ansaldo's 1st and 2nd stage combustors with realistic fuel injection pattern.
- Execution of model refinement to achieve best representation of flame stabilisation and flashback behaviour in the first combustion-stage.
- Conduction of additional numerical-modelling activities for thermo-acoustic assessment and low-order modelling (acoustic forcing of the flame).
- Execution of advanced high-resolution LES calculations of fuel-oxidiser mixing efficiency in second-generation geometry, focusing on aerodynamic improvement of the mixing section.
- Selection of DLR-rig experimental cases from October-2024 FLEX4H$_2$ campaign for additional second combustion-stage numerical model validation on stabilization of undiluted-hydrogen reheat flame.
- Sharing new geometry with SINTEF to conduct the Large Eddy Simulation calculations in 2025.

Thermoacoustics

- Conversion of the exact experimental rig geometry to a network modelling tool capable of predicting the system's overall behaviour regarding velocity and pressure fluctuations to reduce the deviation between model and measurements.

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- Establishment of an algorithm to relate the developed first-stage-only (FOS) network model to the full can setup (FCS), which includes the sequential combustor and additional geometry, to extract FSO behaviour from experimental data which was gained in the FCS configuration.

FUTURE STEPS AND PLANS

Combustion system development and testing:

- Testing of second-generation prototypes (Gen2) at high pressure conditions, focusing on operation with high hydrogen contents (>90%vol) and pure hydrogen.
- Design of Gen3 prototypes for demonstration and achievement of technology readiness level 6.
- Refinement of the burner design based the first two development cycles to optimise mixing section, injection schemes, cooling systems and damping configuration.
- Exploitation of full-scale high-pressure combustion tests to enhance combustor operation.
- Optimisation of the combustion system design considering cooling and mechanical integrity requirements for industrialisation of the developed technology.

Numerical Modelling:

- Execution of advanced high-resolution Large-Eddy Simulation (LES) of H_2-fired simplified 1st-stage burner using a dedicated reduced chemistry scheme (for NO_x-emissions prediction) at selected conditions of interest.
- Execution of thermoacoustically forced LES calculations of the simplified 1st-stage to retrieve the Flame-Transfer Function for model validation versus atmospheric-pressure measurements.
- Validation of LES model against the 2024 FLEX4H_2 DLR-rig measurements of hydrogen flame stabilisation at reheat conditions (relevant to Ansaldo's 2nd-stage combustor).
- Use of thermoacoustically forced LES calculations of the simplified 2nd-stage burner to retrieve the Flame-Transfer Function for model validation versus high-pressure measurements.
- Exploitation of advanced high-resolution LES calculations of fuel-oxidiser mixing efficiency in the third-generation geometry focusing on aerodynamic improvement of the mixing section.

Thermoacoustics:

- Conclusion of ongoing computational fluid dynamics simulation and evaluation of the Flame-Transfer Function (FTF) so as to relate heat release fluctuations to acoustic quantities.
- Improvement of the existing low order network models by inclusion of the FTF.
- Validation of the updated model with hot cases, i.e., experiments with a flame instead of just heated air.
- Setup and execution of an additional LES with adjustments to the boundary layer assumptions and similar configuration elements based on recent experiences and results. The resulting FTF is then used to improve the existing low order network models further.
- Setup of network model for Full Can Setup (FCS) to reflect real world behaviour for both cold and hot cases. This provides insight into the respective contributions and potential modifications of the first stage geometry/flame and the sequential stage.
- Damper manufacturing and testing as part of the second-generation configuration aiming at stable operation of the full-scale system in the upcoming high-pressure tests.

H2AL

FULL-SCALE DEMONSTRATION OF REPLICABLE TECHNOLOGIES FOR HYDROGEN COMBUSTION IN HARD TO ABATE INDUSTRIES: THE ALUMINIUM USE-CASE

Project ID	101137610
PRR 2025	Pillar 4 - H_2 End Uses - Stationary Applications
Call Topic	HORIZON-JTI-CLEANH$_2$-2023-04-04
Project Total Costs	7 005 639.25
Clean H_2 JU Max. Contribution	5 993 812.38
Project Period	01-01-2024 - 31-12-2026
Coordinator Beneficiary	UNIVERSITE LIBRE DE BRUXELLES, BE
Beneficiaries	BLUENERGY REVOLUTION SCRL, EKW GESELLSCHAFT MIT BESCHRANKTER HAFTUNG, NIPPON GASES INDUSTRIAL SRL, GHI HORNOS INDUSTRIALES, SL, 2A SPA, GASWARME-INSTITUT ESSEN EV, EUROPEAN ALUMINIUM, FUNDACION TECNALIA RESEARCH and INNOVATION, FRAUNHOFER GESELLSCHAFT ZUR FORDERUNG DER ANGEWANDTEN FORSCHUNG EV

PROJECT AND GENERAL OBJECTIVES

H2AL has the overall objective to develop, validate, implement, and demonstrate at full-scale in real operational conditions a set of technologies, such as an integrated hydrogen burner and support systems, refractory materials, and sensors, within heating furnaces in hard-to-abate industries - aluminium ingot and internal scrap recycling - by retrofitting an existing furnace at the demonstration site (2A facilities). The demonstration will run for more than six months, with at least one trial of 100 hours at 100% H_2 and with a thermal output of at least 2 MWth - ensuring that TRL7 is achieved at the project's end. The impact of H_2 combustion on the refractory materials, overall furnace structure, and product quality (aluminium) will also be investigated, and measures to minimise its effects will be implemented. H2AL will also develop and implement a set of data, documentation and guidelines ensuring that the project outcomes can be replicated in other industrial sites (in other hard-to-abate industries) in a cost-effective, sustainable and safe way.

NON-QUANTITATIVE OBJECTIVES

H2AL aims to develop and demonstrate safe, efficient hydrogen combustion technologies for the aluminium industry, with broader applications in hard-to-abate industrial sectors. Key goals include:

- Understanding hydrogen combustion: Conduct experiments and simulations to study H_2 combustion effects on process efficiency, emissions, and equipment wear.
- Burner development: Design burners compatible with 100% hydrogen and H_2/natural gas blends, achieving low NO_x emissions and high efficiency.
- Furnace retrofit: Equip an industrial furnace with new burners, optimised materials, and sensors for real-time monitoring and performance optimisation.
- Full-scale demonstration: Retrofit and operate a commercial-scale aluminium furnace on 100% hydrogen for at least 100 hours to reach TRL7.
- Safety procedures: Develop standard operating procedures for safe hydrogen integration in industrial settings.
- Impact assessment: Evaluate technical, economic, and environmental impacts of hydrogen substitution in industrial processes.
- Business models: Create viable business models and tools for scaling hydrogen-based heat solutions, promoting wider adoption in industrial decarbonisation.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

H2AL has achieved key milestones advancing hydrogen combustion technologies for aluminium production and beyond.

- Completed technology baseline analysis, system requirements, safety assessments, and updated hydrogen standards. Defined key performance indicators and a techno-economic baseline for hydrogen use.
- Developed and validated computational fluid dynamics models; conducted material testing to identify optimal refractory materials under hydrogen combustion conditions.
- Finalised H_2 supply system design via tube trailers, secured safety approvals, and initiated infrastructure preparations including gas regulation panels.
- Carried out a techno-economic analysis, showing external H_2 supply is more viable than on-site production for now. Assessed 2A's relevance as a model for EU foundries.

The project has also established strategic collaborations, enhancing its potential for replication and broader industrial impact. H2AL is on track to deliver cost-effective, safe, and scalable hydrogen solutions for industrial decarbonisation.

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FUTURE STEPS AND PLANS

H2AL will advance by adapting the combustion model to the specific burner geometry, focusing on pure hydrogen combustion. Experimental tests will be conducted at GWI, alongside further optimisation of refractory materials under H_2 and steam-rich atmospheres (up to 1 000°C), including microstructural analysis and the role of barium.

Infrastructure efforts will include:

- Building the pressure-reducing panel.
- Completing technical and safety documentation to obtain final approval from the Turin Fire Brigade.
- Securing the CE mark for the retrofitted furnace.

Strategic tasks ahead:

- Finalising EU aluminium foundry archetypes.
- Identifying replication sectors with similar burner needs.
- Finalising EU aluminium foundry archetypes.
- Identifying replication sectors with similar burner needs.

PROJECT TARGETS

Target source	Parameter	Target achieved?
Project's own objectives	Roadmap for 100% elimination of fossil fuels combustion in aluminium industry.	
	Enabling the utilisation of H_2-based heat production at 2A foundry and other aluminium and hard-to-abate industries.	
	Insights on process effect of e.g., H_2/O_2 ratio, flame temperature, emissions.	
	Comprehensive evaluation of KPI of H_2 combustion.	
	Technology roadmap for effective integration of 100% H_2 combustion for heat production in the aluminium industry.	
	Technology roadmap and industry best practices to (at least) maintain the quality of the final product (aluminium) in terms of melt quality, porosity, dimensional accuracy, and mechanical properties of the finished products.	
	Full-scale operational demonstration at 2A aluminium foundry, running at least 100h at 100% H_2.	
	Application of H_2 burners with low NO_x emissions (<100mg/kg, e.g.: as low as 20 mg/kg for SNCR enhanced flameless regenerative burners).	
	Better understanding of H_2 utilisation.	
	Systematic analysis and application of safety protocol and risk assessment applied to the use of H_2 in testing and demonstration site.	
	Optimised combustion models to further improve the consortium's simulation tools for H_2 combustion mechanisms.	
	Documented demonstrator at 2A including plant integration processes and procedures.	
	TRL9 roadmap for further industry integration, including business model opportunities for replication in other case scenarios, including GIS information.	
	New burners capable of using 0-100% of H_2/NG mixtures.	

HELIOS

STABLE HIGH HYDROGEN LOW NO_x COMBUSTION IN FULL SCALE GAS TURBINE COMBUSTOR AT HIGH FIRING TEMPERATURES

Project ID	101101462
PRR 2025	Pillar 4 - H_2 End Uses - Stationary Applications
Call Topic	HORIZON-JTI-CLEANH$_2$-2022-04-04
Project Total Costs	3 984 187.50
Clean H_2 JU Max. Contribution	3 984 187.00
Project Period	01-03-2023 - 28-02-2027
Coordinator Beneficiary	TECHNISCHE UNIVERSITEIT EINDHOVEN, NL
Beneficiaries	OPRA TURBINES INTERNATIONAL B.V., THOMASSEN ENERGY B.V., OPRA ENGINEERING SOLUTIONS BV, CENTRO COMBUSTIONE AMBIENTE SPA, TECHNISCHE UNIVERSITEIT DELFT, DEUTSCHES ZENTRUM FUR LUFT - UND RAUMFAHRT EV

https://www.h2gt-helios.eu/

PROJECT AND GENERAL OBJECTIVES

In addition to its technical advancements, HELIOS will play a crucial role in fostering a vast innovative ecosystem and facilitating the future adoption and commercialisation of this technology on a cost-effective and scalable basis. As Europe transitions towards renewable energy sources, the repurposing of existing power generation assets to decarbonised alternatives becomes essential. Gas turbines, providing grid inertia and stability along with dispatchable firming capacity, are pivotal in balancing the inherently intermittent renewable energy sources. HELIOS addresses these challenges, contributing significantly to securing, competitively pricing, cleaning, flexibly managing, and resiliently shaping Europe's energy system.

The HELIOS consortium, comprising five partners across three European countries is highly complementary.

HELIOS aims to achieve the following objectives:

- Enable Low NO_x combustion of hydrogen-enriched fuels in gas turbines.
- Operate the system across a wide range of mixtures, from 100% natural gas to 100% hydrogen.
- Achieve low NO_x emissions (below 9ppmv).
- Modify existing combustors to safely operate at high firing temperatures using 100% H_2, based on Thomassen Energy's FlameSheet technology.
- Provide the combustor as either a newly built option or retrofit for existing gas turbine systems ranging from 1MW to 500MW.
- Make the combustor applicable to various industrial and heavy systems, as well as industrial-scale gas turbines.

NON-QUANTITATIVE OBJECTIVES

HELIOS aims to advance scientific understanding and feasibility of hydrogen-enriched fuels in gas turbines, utilising the FlameSheet combustor framework. Economically, it strengthens European industrial technology by enhancing hydrogen-enriched gas-turbine technology and testing facilities, promoting Europe's leadership position and generating new industrial activities. Financially, it accelerates sustainable energy generation by retrofitting existing gas turbines, minimising social impact, and ensuring job security. Environmentally, HELIOS addresses societal acceptance through socio-economic evaluations and stakeholder involvement. Overall, HELIOS improves EU energy security by widening gas turbine operation capabilities, ensuring grid stability, and enhancing supply reliability.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

Preliminary data from a high-pressure campaign indicated good results, showing improvements in firing temperatures, particularly with 100% hydrogen. Preliminary data indicated promising results in terms of flashback resistance. Data are preliminary it is essential to double-check and verify the findings.

FUTURE STEPS AND PLANS

Helios has been running since 2023. At the end of the project, we will deliver a handbook of requirements and recommendations for the implementation of high-hydrogen gas turbines as one of the key outcomes.

PROJECT TARGETS

Target source	Parameter	Unit	Target	Target achieved?	SoA result achieved to date (by others)	Year for reported SoA result
	NO_x emissions	NO_x mg/MJ fuel	8.7		31	
	Max. efficiency reduction in H_2 operation	% points	< 10@100%H_2		10@30% H_2	
Project's own objectives	Ability to handle H_2 content fluctuations	%vol/min	15		10	2020
	Minimum ramp rate	% load/min	15@100%H_2		10@30%H_2	
	H_2 range in gas turbine fuel	%mass	0 - 100	✓	0 - 5	
	Max H_2 fuel content during startup	%mass	0-100	✓	0.7	

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HYCOFLEX

HYDROGEN FOR COGENERATION IN FLEXIBLE OPERATION

Project ID	101138002
PRR 2025	Pillar 4 - H_2 End Uses - Stationary Applications
Call Topic	HORIZON-JTI-CLEANH$_2$-2023-04-03
Project Total Costs	7 073 275.00
Clean H_2 JU Max. Contribution	4 442 550.75
Project Period	01-02-2024 - 31-10-2026
Coordinator Beneficiary	SIEMENS ENERGY GLOBAL GMBH and CO. KG, DE
Beneficiaries	SMURFIT KAPPA PAPER SERVICES BV, ARTTIC INNOVATION GMBH, SIEMENS ENERGY SAS, ENGIE ENERGIE SERVICES, SMURFIT WESTROCK PAPER SERVICES B.V., CENTRAX LIMITED, SIEMENS ENERGY INDUSTRIAL TURBOMACHINERY LIMITED, EQUINOR ENERGY AS, BELGISCH LABORATORIUM VAN ELEKTRICITEITSINDUSTRIE, ETHNICON METSOVION POLYTECHNION, DEUTSCHES ZENTRUM FUR LUFT - UND RAUMFAHRT EV

PROJECT AND GENERAL OBJECTIVES

HyCoFlex is developing a retrofittable decarbonisation solution package for combined heat and power plants by enabling gas turbines to operate on up to 100% hydrogen. This cutting-edge technology will be seamlessly integrated into an industrial cogeneration system at the Saillat-sur-Vienne site in France, where it will be demonstrated and validated.

Expanding on the achievements of the HYFLEXPOWER project, HyCoFlex will further enhance an industrial scale power-to-hydrogen-to-power facility, refining its infrastructure to improve efficiency and adaptability. HyCoFlex will:

- Develop operational strategies and flexible protocols tailored to the dynamic requirements of industrial cogeneration plants.
- Play a key role in accelerating the transition towards a low-carbon industrial and energy landscape by establishing viable pathways for scaling and replicating this solution.

NON-QUANTITATIVE OBJECTIVES

Enhancing advance plant concept for hydrogen cogeneration operation:

- HyCoFlex will upgrade of the power-to-H_2-to-power cogeneration plant developed for the HYFLEXPOWER initiative at Saillat-sur-Vienne, enabling its gas turbine to operate up to 100% hydrogen. The upgrades will focus on improving safety and plant integration, and enhancing monitoring accuracy through advanced fuel composition and exhaust analysis systems. Additional modifications will facilitate precise fuel blending via new gas lines and updated control systems.

Development and validation of H_2 gas turbine combustion technology:

- HyCoFlex will design, develop, and validate a highly fuel-flexible Dry-Low Emissions (DLE) combustion system capable of operating with hydrogen concentrations ranging from 0% to 100%. This includes:
  - An optimisation of the Siemens Energy's existing hydrogen DLE technology through advanced design techniques, analytical research, and validation in relevant environments and gas turbine operating conditions.
  - An enhanced burner with improved safety, operational flexibility, and emissions compliance in line with the Clean Hydrogen Strategic Research and Innovation Agenda (SRIA).
  - High-pressure rig tests followed by engine testing to validate optimal performance at the full-scale industrial plant.

Demonstration of enhanced operational flexibility in the cogeneration plant:

- Development of a demonstration gas turbine with a combustion system designed for 100% hydrogen operation.
- Two demonstration campaigns at the industrial cogeneration plant in Saillat-sur-Vienne to test the turbine's performance across various loads and fuel mixtures. These tests will validate the advanced plant with the H_2 gas turbine, confirming its efficiency with hydrogen concentrations up to 100% and showcasing the plant's enhanced operational flexibility for future hydrogen applications.

Pathways to decarbonised power generation using gas turbines:

- Development of a flexible dynamic simulation and optimisation tool to analyse the operational performance of the Saillat-sur-Vienne cogeneration unit under transient conditions. This tool will also be applied to upscaled cogeneration units to evaluate the scalability and replicability of hydrogen-based retrofitting solutions.
- Assessment of circularity and sustainability aspects, focusing on efficiency improvements, economic viability, and environmental impact.
- Simulation of real-world operations through digital twins.
- Identification of optimal sites across Europe for implementing HyCoFlex's decarbonisation solutions through an information mapping tool.

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HyCoFlex

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

Power-to-H_2-to-power advanced plant concept:

- Execution of preliminary studies, including process design analyses and updated safety reviews with risk assessments related to hydrogen combustion.
- Identification of key measurements, such as temperatures and emissions, and preparations for their implementation are ongoing.
- Execution of maintenance of existing installations, and preparation of necessary modifications to the mixing station, including the ordering of long lead items.

Combustion system:

- Identification of gaps in project key performance indicators based on insights through the HYFLEXPOWER demonstration engine test experience.
- Identification of operational improvements with hydrogen based on numerical simulations, manufacturing of new combustion system hardware, and high-pressure tests at the Siemens Energy combustion test facility Clean Energy Center (CEC).
- Manufacturing of combustion system components for validation in the gas turbine during the first demonstration campaign at the Saillat site, scheduled for 2025.

Demonstration and validation of the advanced plant concept:

- Utilisation of existing measurements from HYFLEXPOWER for preparation of a comprehensive data monitoring for the 2025 Test Campaign.
- Establishment of a detailed test schedule for the 2025 Test Campaign.
- Securing the test engine for the 2025 Test Campaign.
- Finalisation of the engine build specifications.
- Manufacturing and procurement of essential components, including burners, are ongoing.
- Performance of a works acceptance test of a test engine with a comparable H_2 combustor, using natural gas, to establish engine control parameters for transient operation, guiding the site testing strategy.

Dynamic simulations and upscaled scenarios:

- Establishment of the requirements and boundary conditions for the dynamic simulation framework of the power-to-H_2-to-power unit.
- Development of dynamic models to analyse the transient behaviour of the advanced plant.
- Performance of a multi-objective optimisation to minimise the Levelized Cost of Hydrogen and/or Hydrogen Carbon Intensity.
- Determination of the necessary capacity for the proton exchange membrane electrolyzer and hydrogen storage unit based on preliminary results for cost-optimal base load gas turbine operation at 50% H_2 by volume.

FUTURE STEPS AND PLANS

The initial test campaign is set and will last approximately 12 weeks. During this period, the operational and flexible performance of the gas turbine will be validated, starting with natural gas and progressively increasing to 100% hydrogen. The campaign will also include initial tests with the heat recovery steam generator. Key focus areas will include:

- The stability of the fuel supply system at varying hydrogen concentrations.
- Identification of operational limits.
- Correlation of the rig to engine combustor performance (including emissions).
- Safety considerations related to flashback and flameout detection.

PROJECT TARGETS

Target source	Parameter	Unit	Target	Target achieved?
Project's own objectives	Advance the HYFLEXPOWER plant concept and infrastructure for 100% H_2 cogeneration operation.	% H_2	up to 100	
	Design, develop and validate a safe and efficient, low-emission H_2 GT combustion system.	-	HyCoFlex will validate the combustor design at relevant gas turbine pressures and temperatures in dedicated high-pressure rig test campaigns at TRL6 and then finally achieve TRL7 by the 2nd engine validation test.	
	Demonstrate and validate the retrofitted cogeneration advanced plant for operational flexibility at varying natural gas/hydrogen mixtures and loads while achieving state-of-the-art efficiency and low NO_x emissions.	NO_x emission in ppm @ 15% O_2; Ramp rate in load/min; H_2 content fluctuations % vol. / min; power reduction in %points,	NO_x emission: <15 (0-30% H_2), <25 (30-100% H_2) ramp rate: >10, H_2 fluctuations ±30 % vol. / min power reduction 0.5-2	
	Present pathways for decarbonised power generation from gas turbines through retrofits, upscaling and uptake while addressing circularity aspects.	-	Technoeconomic and Environmental Assessment. Digital twins simulating annual operation in transient conditions of up to three real large scale cogeneration units. Information Mapping Tool	

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HYPOWERGT

DEMONSTRATING A HYDROGEN-POWERED GAS-TURBINE ENGINE FUELLED WITH UP TO 100% H_2 – (HYPOWERGT)

Project ID	101136656
PRR 2025	Pillar 4 - H_2 End Uses - Stationary Applications
Call Topic	HORIZON-JTI-CLEANH$_2$-2023-04-03
Project Total Costs	12 269 095.00
Clean H_2 JU Max. Contribution	6 000 000.00
Project Period	01-01-2024 - 31-12-2027
Coordinator Beneficiary	SINTEF ENERGI AS, NO
Beneficiaries	EUROPEAN TURBINE NETWORK, LUCART SPA, TOTALENERGIES ONETECH, NUOVO PIGNONE TECNOLOGIE SRL, SNAM S.P.A., EQUINOR ENERGY AS, ENERGY AND TURBOMACHINERY NETWORK, ZURCHER HOCHSCHULE FUR ANGEWANDTE WISSENSCHAFTEN, CENTRE EUROPEEN DE RECHERCHE ET DEFORMATION AVANCEE EN CALCUL SCIENTIFIQUE

http://hypowergt.eu

PROJECT AND GENERAL OBJECTIVES

HyPowerGT aims at to push technological boundaries to enable gas turbines to operate on hydrogen without dilution. The core technology is a novel dry-low emission combustion technology (DLE H_2) capable of handling mixtures of natural gas and hydrogen with concentrations up to 100% H_2. The combustion technology was successfully validated at technology readiness level (TRL) 5 (in early 2021), retrofitted on the combustion system of a 13 MWe industrial gas turbine (NovaLT12). Besides ensuring low emissions and high efficiency, the DLE H_2 combustion technology offers fuel flexibility and response capability on a par with modern gas-turbine engines fired with natural gas.

The new technology will be fully retrofittable to existing gas turbines, thereby providing opportunities for refurbishing existing assets in industry (combined het and power) and offering new capacities in the power sector for load levelling the grid system (unregulated power) and for mechanical drives. The DLE H_2 technology adheres to the strictest specifications for fuel flexibility, NO_x emissions, ramp-up rate, and safety, as stated in the Strategic Research and Innovation Agenda 2021-2027.

The new DLE H_2 combustion technology will be further refined and developed and, towards the end of HyPowerGT, demonstrated at TRL7 on a 16.9 MWe gas-turbine engine (NovaLT16) fired with fuel blends mixed with hydrogen from 0-100% H_2. Within this wide range, emphasis is placed on meeting pre-set targets for (i) fuel flexibility and handling capabilities, (ii) concentration of hydrogen fuel during the start-up phase, (iii) ability to operate at varying hydrogen contents, (iv) minimum ramp speed, and (v) safety aspects at any level with regard to related systems and applications targeting industrial gas-turbine engines in the 10-20 MWe class.

A digital twin will be developed to simulate performance and durability characteristics, emulating cyclic operations of a real cogeneration plant in the Italian paper industry.

NON-QUANTITATIVE OBJECTIVES

- To provide a safe and efficient low-emission H_2 combustion system retrofittable to gas-turbine engines in the 10-20 MWe class. HyPowerGT will provide a novel dry-low emission hydrogen combustion system retrofittable to gas turbines in the 10-20 MWe class, aimed at offering response power to stabilise and increase the reliability of the electrical energy system. Emphasis is placed on the ability to retrofit the existing heat and power generation systems with gas turbines capable of operating with up to 100% hydrogen, while guaranteeing high efficiency, low NO_x emissions, and operational flexibility at the level of typical values obtained under conditions similar to those of natural gas combustion, pursuant to the call.
- To demonstrate operating capabilities of a simple-cycle gas turbine at full operating conditions with fuel compositions admixed with hydrogen up to 100% H_2. The key-enabling technology will first be refined and demonstrated in relevant environment at TRL6. Then a system demonstrator will be planned, developed, and built into an operational environment, and subsequently demonstrated at TRL7. This endeavour will require at least 60 aggregated fired hours, and the following characteristics of the system will be concluded and documented. Emphasis is placed on (i) gas turbine flexibility, (ii) content of hydrogen fuel during the start-up phase, (iii) ability to operate at varying hydrogen content, (iv) minimum ramp speed, and (v) proper safety level with regard to related systems and applications.
- To present pathways for decarbonised power generation through retrofits and uptake of project's results. HyPowerGT will present credible ways in which its results can best be utilised, both commercially and economically. The work includes assessing the methods used, transferability of the results to other gas turbine types and brands, and evaluating the market for retrofitting.

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PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

- Project execution tools in place to facilitate the project implementation and internal financial and technical reporting.
- Performance of direct numerical simulations performed, increasing robustness of burning-rate scaling and improving flashback model predictions.
- Finalisation of designs for experimental setup, and development of purchase order.
- TRL 6 test campaign instrumentation and rig refurbishment on track for demonstration tests at the end of 2025.
- Establishment of health, safety and environment procedures and safety plan.
- Performance of preliminary de-risking simulations of H_2 operated GT and FMECA workshop.
- Start of road mapping work for positioning H_2 gas turbines towards the European energy transition initiated.
- Preparation of dissemination material including website, social media profile and presentation of the project at international conferences and other meetings.

FUTURE STEPS AND PLANS

- TRL 6 Demonstration tests at the end of 2025.
- Monitoring the safety engineering of the test campaigns.
- Application of available models and tools for risk assessment.
- Strengthen cooperation with sister projects.

PROJECT TARGETS

Target source	Parameter	Unit	Target	Target achieved?
Project's own objectives	Maximum H_2 content during start up	%vol H_2	100	
	Variability of H_2 admixing rate with natural gas	%H_2 volume/minute	±30	
	Maximum H_2 content during start up	%mass H_2	100	
	Minimum ramp up rate	% of load/minute	10	
	Efficiency loss in H_2 operations mode	% points	<2	
	Maximum power reduction in H_2 operations mode	%	<2	
	Fuel flexibility with full operational (load) capability - H_2 volume fraction	%vol H_2	0-100	
	Fuel flexibility with full operational (load) capability - H_2 mass fraction	%mass H_2	0-100	
	NO_x emission 0-30% vol H_2	mgw/MJth	< 26	
	NO_x emission 30-100% vol H_2	mgw/MJth	<43	

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RUBY

ROBUST AND RELIABLE GENERAL MANAGEMENT TOOL FOR PERFORMANCE AND DURABILITY IMPROVEMENT OF FUEL CELL STATIONARY UNITS

Project ID	875047
PRR 2025	Pillar 4 - H_2 End Uses - Stationary Applications
Call Topic	FCH-02-8-2019
Project Total Costs	3 024 715.00
Clean H_2 JU Max. Contribution	2 999 715.00
Project Period	01-01-2020 - 31-08-2025
Coordinator Beneficiary	UNIVERSITA DEGLI STUDI DI SALERNO, IT
Beneficiaries	NEW ENERDAY GMBH, BITRON ELECTRONICS SPA, MINERVAS SRL, COMMUNAUTE D' UNIVERSITES ET ETABLISSEMENTS UNIVERSITE BOURGOGNE - FRANCHE - COMTE, NEW ENERDAY GMBH, TEKNOLOGIAN TUTKIMUSKESKUS VTT OY, SOLIDPOWER SPA, BITRON SPA, BALLARD POWER SYSTEMS EUROPE AS, EIFER EUROPAISCHES INSTITUT FUR ENERGIEFORSCHUNG EDF KIT EWIV, FONDAZIONE BRUNO KESSLER, UNIVERSITE DE FRANCHE-COMTE, INSTITUT JOZEF STEFAN, ECOLE POLYTECHNIQUE FEDERALE DE LAUSANNE, COMMISSARIAT A L ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES

http://www.rubyproject.eu

PROJECT AND GENERAL OBJECTIVES

RUBY aims to exploit electrochemical impedance spectroscopy (EIS) for developing, integrating, engineering and testing a comprehensive and generalised monitoring, diagnostic, prognostic and control (MDPC) tool. Thanks to EIS features, RUBY will improve the efficiency, reliability and durability of solid oxide fuel cell (SOFC) and polymer electrolyte fuel cell (PEMFC) systems for stationary applications. The tool relies on advanced techniques and dedicated hardware, and will be embedded in the fuel cell systems for online validation in the relevant operational environments.

NON-QUANTITATIVE OBJECTIVES

The MDPC tool performs monitoring, diagnosis, prognosis control and mitigation of the stack and balance of plant (BoP) for PEMFC in back-up applications and for SOFCs for micro-combined-heat-and-power applications.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

- Tests on proton exchange membrane stacks and systems have been performed in nominal conditions.
- Tests on SOFC stacks have been commissioned.
- Preliminary tests on SOFC system have been performed in nominal conditions.
- Preliminary versions of monitoring, diagnostics and prognostics algorithms have been developed and tested.
- Hardware of the MDPC tool has been designed, manufactured and tested.
- Concept and preliminary design of hardware for EIS perturbation stimuli have been determined.

FUTURE STEPS AND PLANS

- RUBY will acquire conventional and advanced signals. The tool measures conventional signals from the balance of plant and stack (voltage, current, temperature, etc.) and the EIS for the stack.
- RUBY will advance the monitoring, diagnostic, prognostic and control (MDPC) activities. The tool monitors the state of health of the stacks and the systems, detects faults at stack and balance-of-plant levels, estimates the stacks lifetimes, applies advanced control actions and proposes mitigation strategies at system level.
- Tests will be performed on proton exchange membrane stacks and systems in faulty conditions
- Tests will be performed on SOFC stacks in nominal and faulty conditions.
- Tests will be carried out on the SOFC system in faulty conditions.
- MDPC tool algorithms will be integrated into the hardware.
- Hardware will be commissioned for EIS perturbation stimuli.
- The MDPC tool will be implemented and tested.

PROJECT TARGETS

Target source	Parameter	Unit	Target	Achieved to date by the project	Target achieved?	SoA result achieved to date (by others)	Year for reported SoA result
Project's own objectives	Lifetime of back-up applications (PEM)	years	15	12		12	2020
	Electrical efficiency of back-up applications (PEM)	% LHV	45	45		45	
	Reliability of back-up applications (PEM)	BX-Y	B10-15	B25-12		B25-12	
	Lifetime of micro-CHP applications (SOFC)	years	12	10		10	
	Maintenance costs of back-up applications (PEM)	€/year	452	617		617	
	Availability of micro-CHP applications (SOFC)	%	99	97		97	
	Availability of back-up applications (PEM)	%	99.99	99.99		99.99	
	Electrical efficiency of micro-CHP applications (SOFC)	% LHV	39	35		35	

SO-FREE

SOLID OXIDE FUEL CELL COMBINED HEAT AND POWER: FUTURE-READY ENERGY

Project ID	101006667
PRR 2025	Pillar 4 - H_2 End Uses - Stationary Applications
Call Topic	FCH-02-4-2020
Project Total Costs	2 835 807.75
Clean H_2 JU Max. Contribution	2 739 094.00
Project Period	01-01-2021 - 30-09-2025
Coordinator Beneficiary	AGENZIA NAZIONALE PER LE NUOVE TECNOLOGIE, L'ENERGIA E LO SVILUPPO ECONOMICO SOSTENIBILE, IT
Beneficiaries	INSTYTUT ENERGETYKI, KIWA TECHNOLOGY BV, KIWA LIMITED, ELCOGEN OY, KIWA NEDERLAND BV, UNIVERSITA DEGLI STUDI GUGLIELMO MARCONI - TELEMATICA, PGE POLSKA GRUPA ENERGETYCZNA SA, I.C.I CALDAIE SPA, INSTYTUT ENERGETYKI - PANSTWOWY INSTYTUT BADAWCZY, AVL LIST GMBH, FRAUNHOFER GESELLSCHAFT ZUR FORDERUNG DER ANGEWANDTEN FORSCHUNG EV

http://www.so-free.eu

PROJECT AND GENERAL OBJECTIVES

The development and demonstration of a fully future-ready system based on solid oxide fuel cells (SOFC) for combined heat and power generation allows for an operation window of 0-100 % of H_2 in natural gas, with additions of purified biogas. Furthermore, SO-FREE will endeavour to realise a standardised stack-system interface, allowing full interchangeability of SOFC stack types within a given SOFC combined heat and power system.

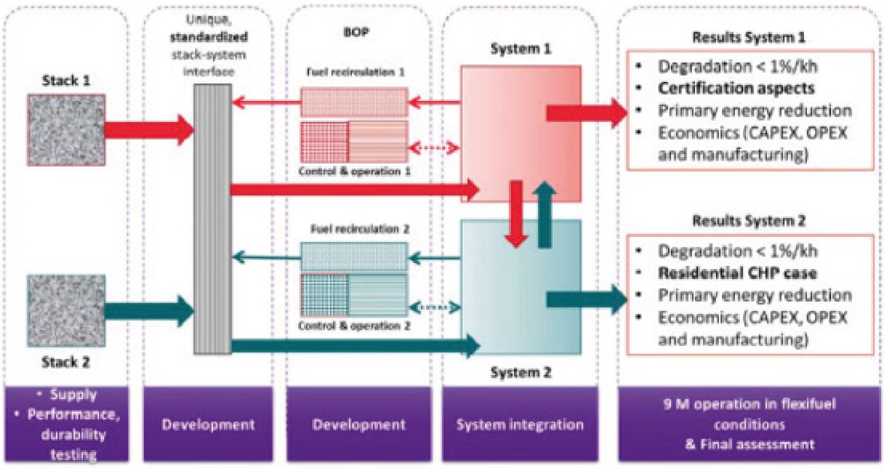
NON-QUANTITATIVE OBJECTIVES

SO-FREE aims to realise a unique, standardised stack module-system interface for flexible system integration. The initial alignment of two stack modules with a single interface has been proposed.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

SO-FREE has made two identical test stations for independent stack validation and designed a unique stack module-system interface for flexible system integration.

Stack validation and mapping were completed in February 2023 and the final design of the system in April 2023.



PROJECT TARGETS

Target source	Parameter	Unit	Target	Target achieved?	SoA result achieved to date (by others)	Year for reported SoA result
Project's own objectives	Electrical efficiency in CH_4	% LHV	40-55	⚙	35-55	2020
	Electrical efficiency in H_2	% LHV	48		47	

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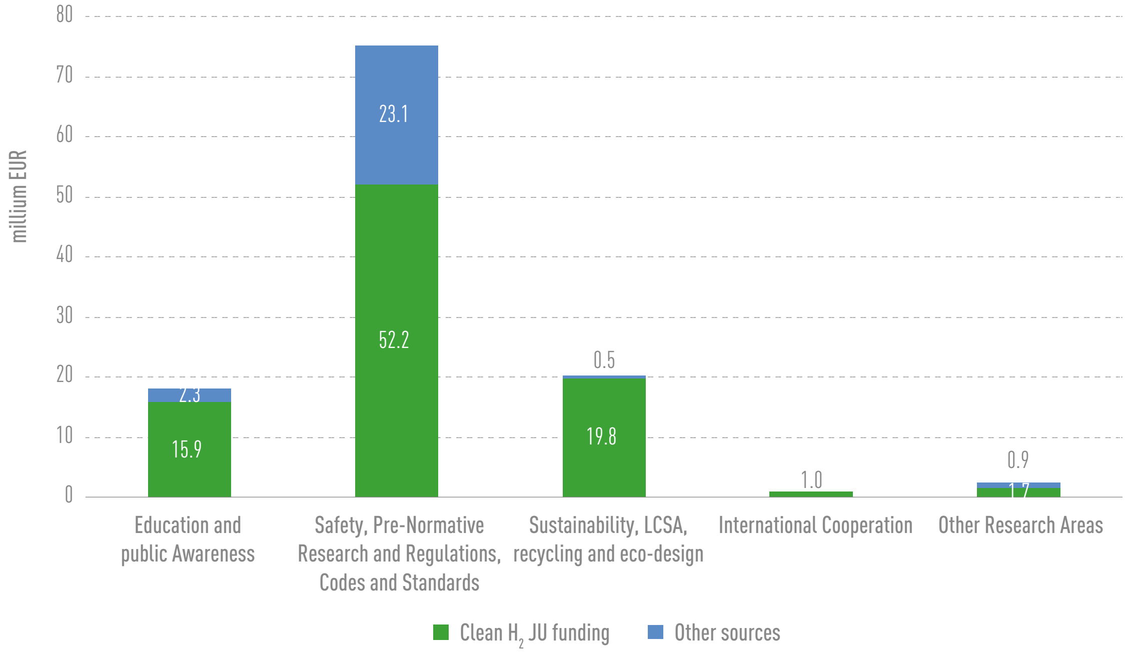
XIV. PILLAR 5: CROSS-CUTTING ISSUES

OBJECTIVES: The cross-cutting activities are structured around three broad research fields with the following overarching objectives.

- **Education and public awareness objectives:**
  - develop educational and training material and build training programmes on hydrogen and FCs for professionals and students;
  - raise public awareness and trust in hydrogen technologies and their benefits.
- **International cooperation:**
  - address the related strategy aiming at developing long-term partnerships around the hydrogen supply chain.
- **Safety, pre-normative research (PNR) and regulations, codes and standards (RCS):**
  - increase the level of safety of hydrogen technologies and applications;
  - support the development of RCS for hydrogen technologies and applications, with a focus on standards.
- **Sustainability, LCSA, recycling, and eco-design objectives:**
  - develop LCA tools addressing the three dimensions of sustainable development: economic, social, and environmental;
  - develop eco-design guidelines and eco-efficient processes;
  - develop enhanced recovery processes (recycling) for CRMs, particularly elements belonging to the platinum group, and for environmentally problematic substances such as PFASs.

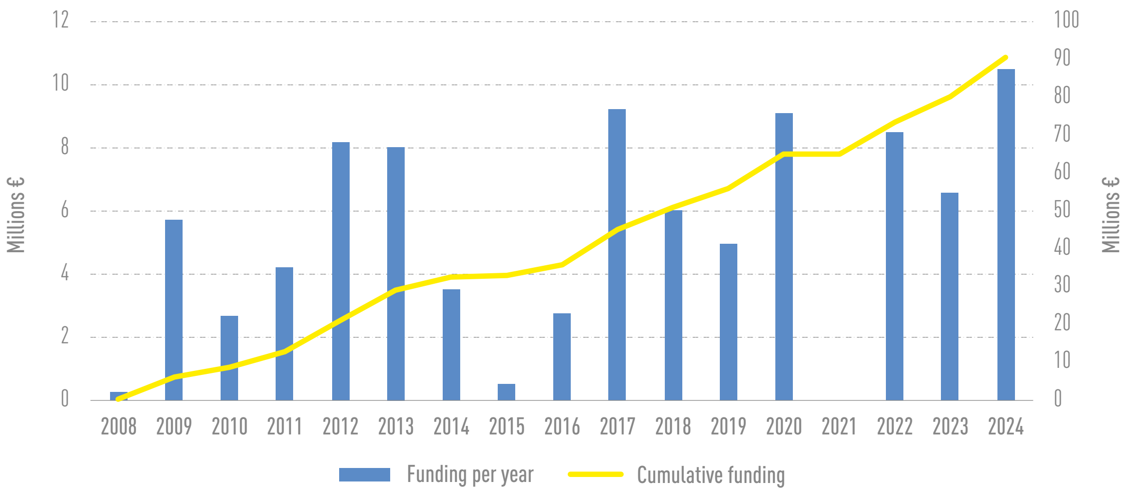
OPERATIONAL BUDGET: The Clean Hydrogen JU has funded approximately EUR 90 million to Pillar 5 (Figure 51), with the largest share directed to the research area of safety, pre-normative research and regulations, codes and standards (around EUR 50 million), followed by sustainability, LCSA, recycling and eco-design (approximately EUR 20 million), and education and public awareness (EUR 16 million). Notably, 2024 marked the peak year for funding in this pillar, with investments exceeding EUR 10 million (Figure 52).

Figure 51: Funding per research area for Pillar 5 projects from 2008 to 2024



Source: Clean Hydrogen Joint Undertaking

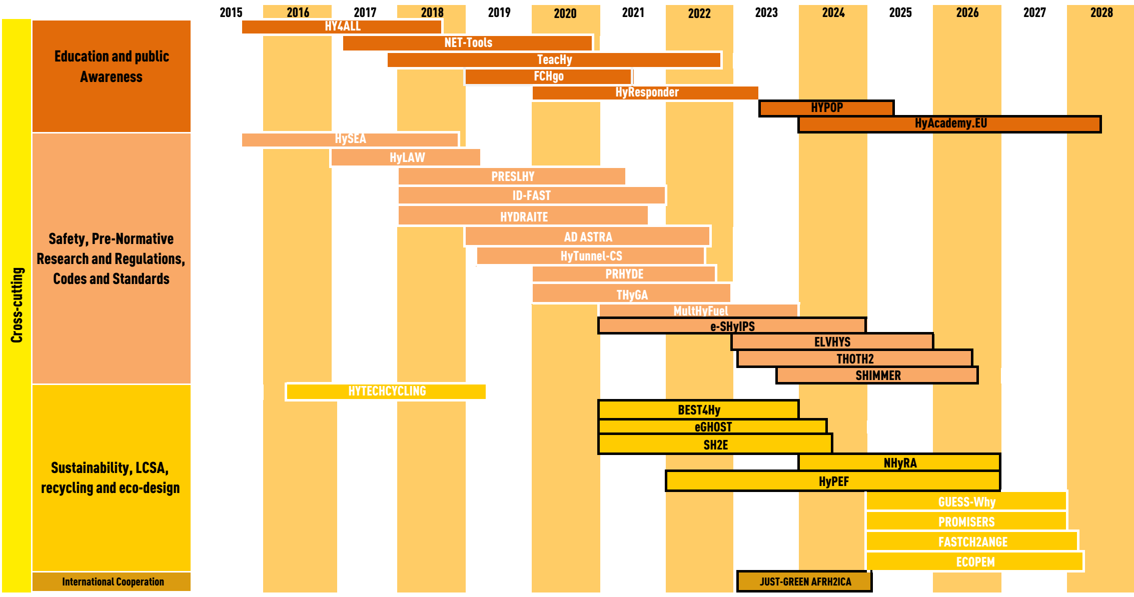
Figure 52: Funding (per year in yellow/left axis and cumulative in grey/right axis) for Pillar 5 projects from 2008 to 2024



Source: Clean Hydrogen Joint Undertaking

PILLAR IN BRIEF: The 2025 programme technical assessment covers 15 projects, those in black font in Figure 53.

Figure 53: Project timelines of Pillar 5: Cross-Cutting Issues



Source: Clean Hydrogen Joint Undertaking

To date, 33 projects have been funded under Pillar 5, with the majority receiving support in the past few years (Figure 54). Spain, Italy, France, and Germany are the leading contributors, forming a strong central cluster within the collaboration network, while Belgium, Poland, and the Netherlands provide supporting links, and more peripheral countries such as Slovenia, Finland, Cyprus, and Ireland maintain limited connections (Figure 55, Figure 56). Project participation is fairly balanced across organisation types, with private companies and research institutions most active (11 projects each), followed by SMEs and higher education institutions (8 each), and minor contributions from public bodies (2) and other organisations (3) (Figure 57, Figure 58). Fundación IMDEA Energía and Agenzia Nazionale per le Nuove Tecnologie lead in involvement, each participating in six projects, alongside other frequent contributors including CEA, Fundación Hidrógeno Aragón, GERG, and industrial actors such as Enagás, SNAM, and Symbio. Participation peaked in 2023, particularly among private companies, research institutions, and higher education institutions, while earlier years showed a more balanced distribution, and 2024 saw a slight decline across all types (Figure 59). Cross-sector partnerships are well represented, with collaboration clusters centred around IMDEA, CEA, and ENEA, another linking SNAM, Enagás, and Politecnico di Torino, and Fundación Hidrógeno Aragón connecting to a diverse international network including Japan's Institute of Applied Energy (Figure 60). Finally, scientific output from Pillar 5 increased gradually to 11 publications (out of which 8 were peer-reviewed) in 2023 and 19 publications (16 peer-reviewed) in 2024 (Figure 61).

Figure 54: Pillar 5: Trend in number of projects per year

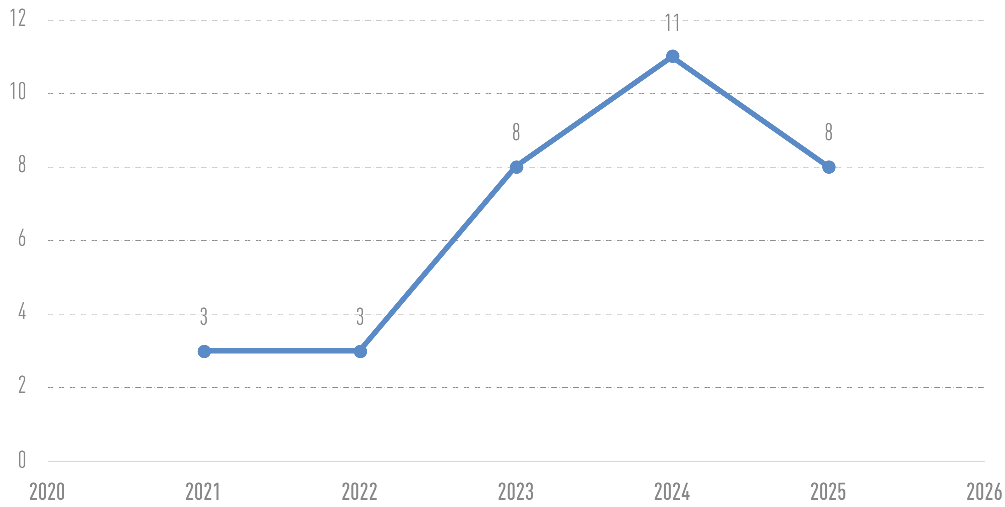


Figure 55: Pillar 5: Project participation by EU country

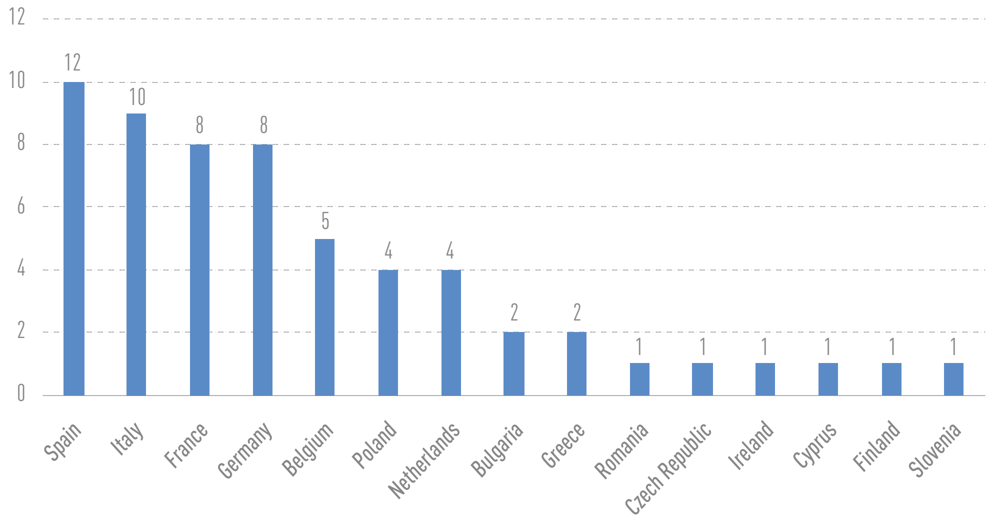


Figure 56: Pillar 5: Collaboration network of EU countries

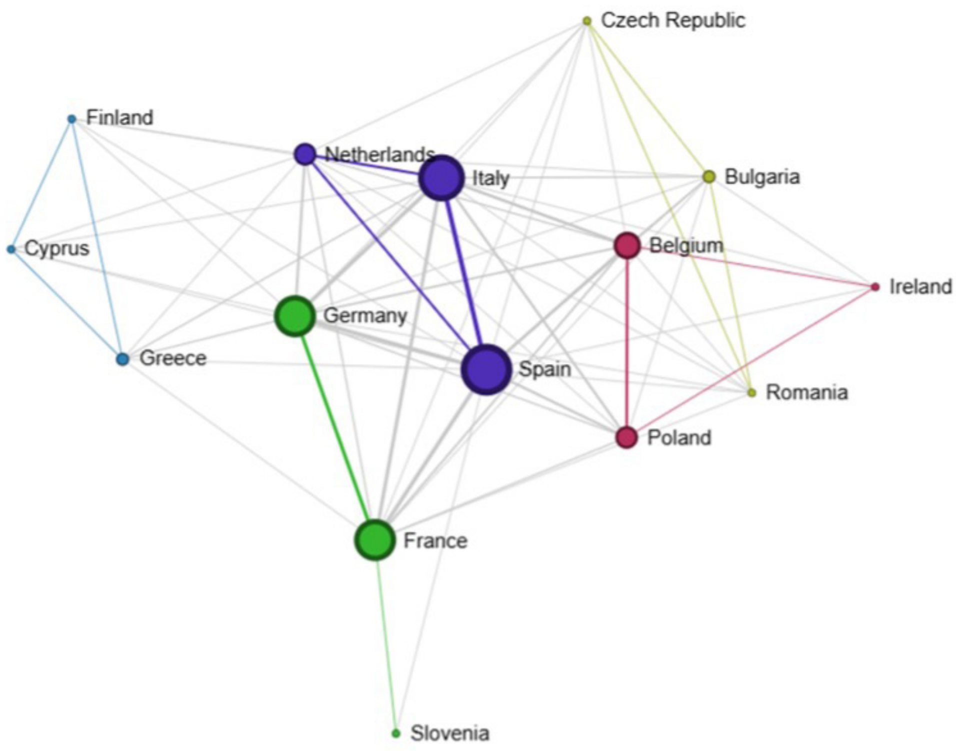


Figure 57: Pillar 5: Breakdown of projects by participating entity type

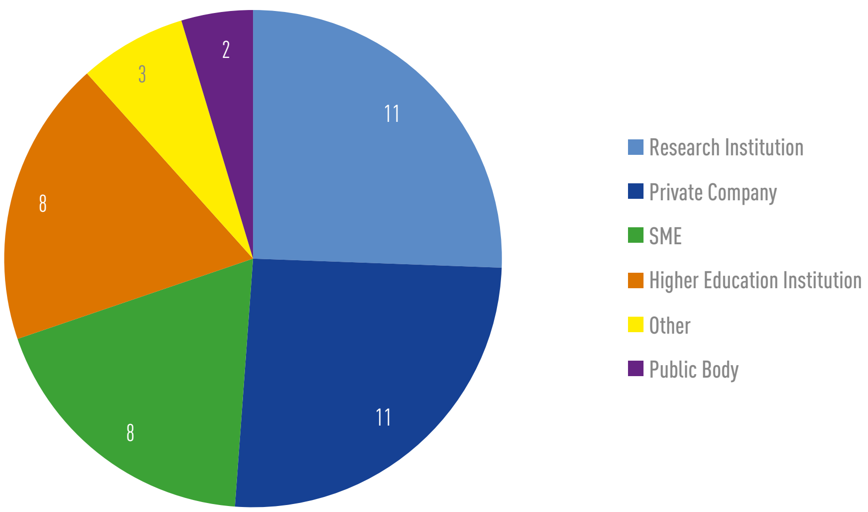


Figure 58: Pillar 5: Participation by organisation type across years

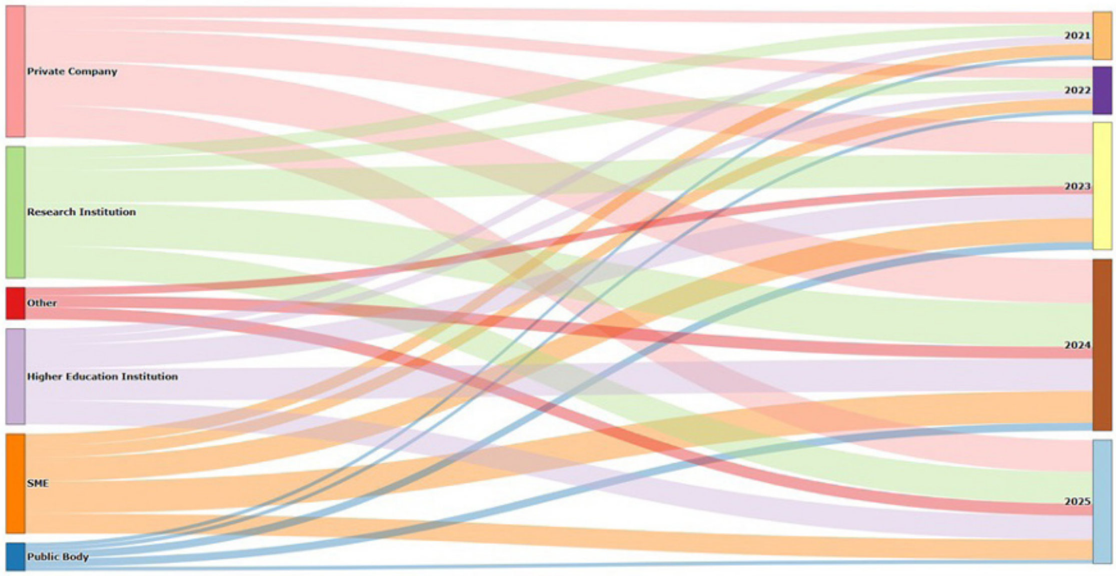


Figure 59: Pillar 5: Top institutions by number of projects

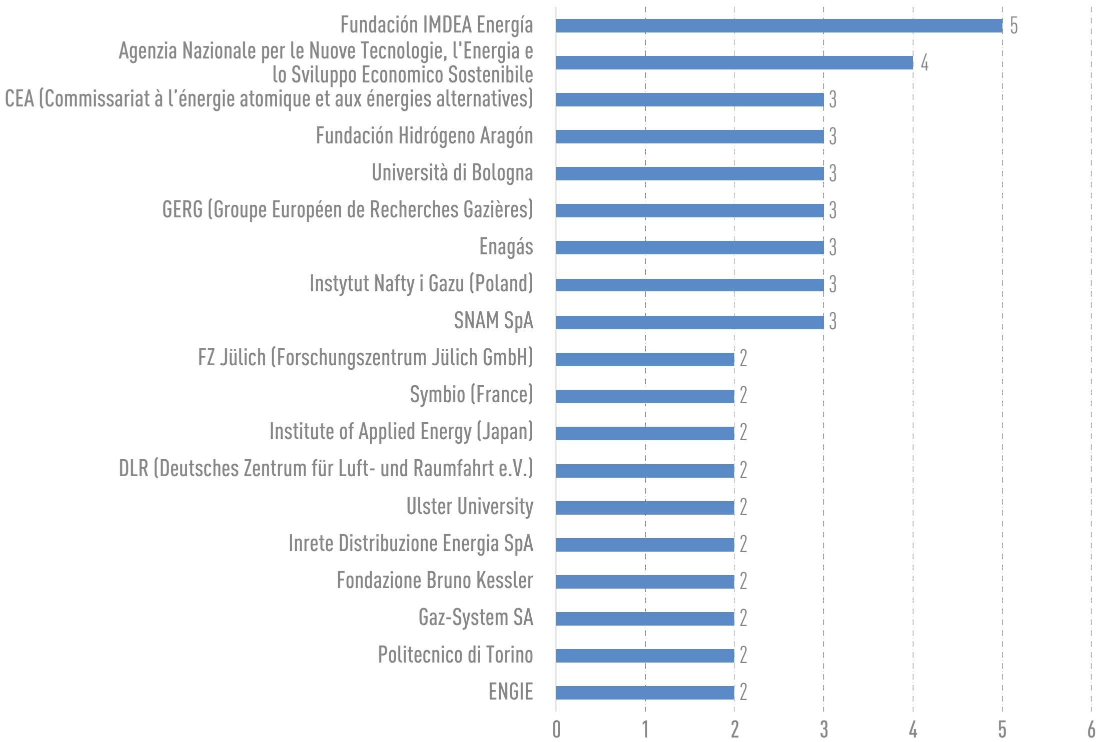


Figure 60: Pillar 5: Collaboration network of top participating institutions

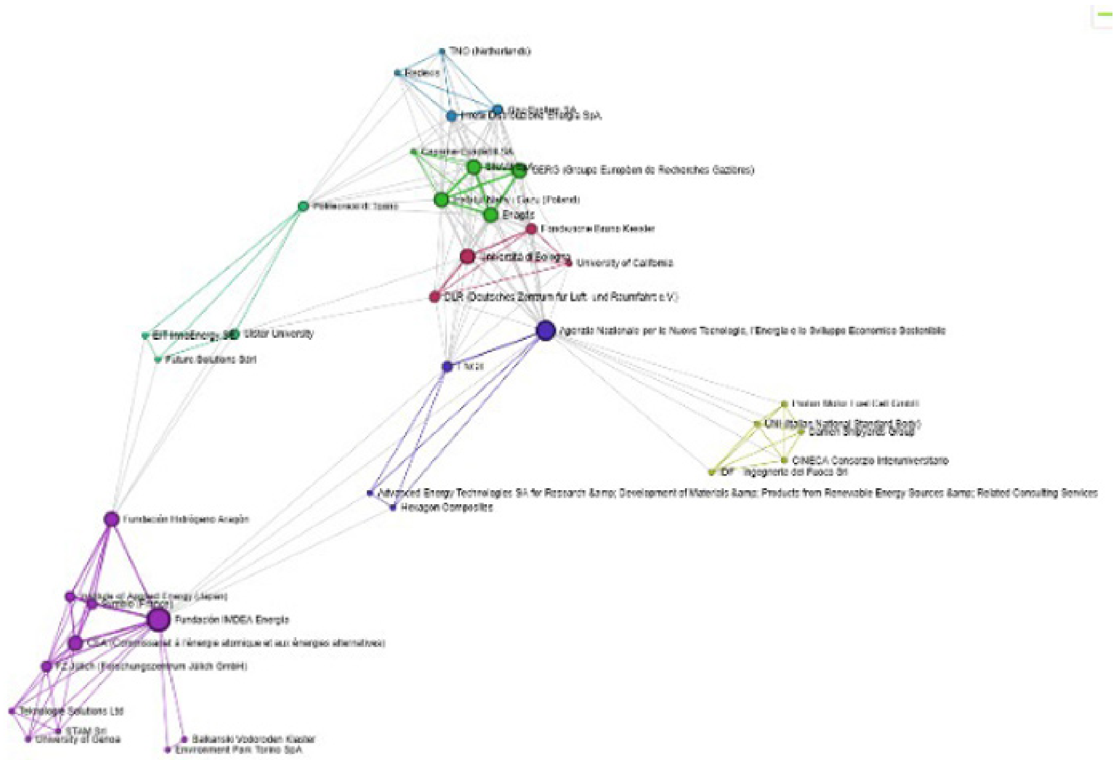
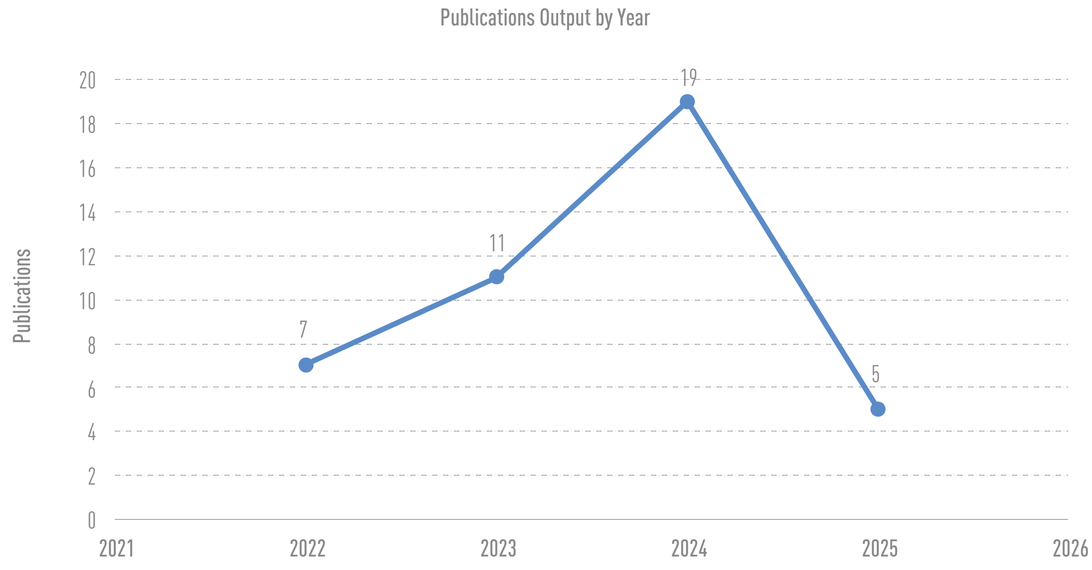
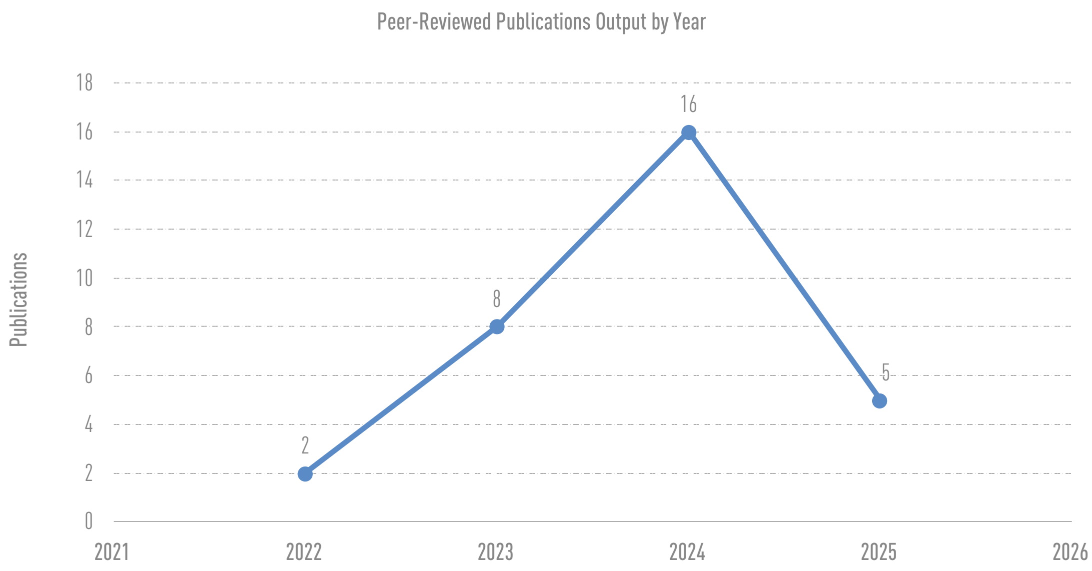


Figure 61: Pillar 5: Number of publications per year





PROJECTS FACTSHEETS

EGHOST

ESTABLISHING ECO-DESIGN GUIDELINES FOR HYDROGEN SYSTEMS AND TECHNOLOGIES

Project ID	101007166
PRR 2025	Pillar 5 - Cross-cutting
Call Topic	FCH-04-3-2020
Project Total Costs	1 133 541.25
Clean H_2 JU Max. Contribution	998 991.25
Project Period	01-01-2021 - 31-05-2024
Coordinator Beneficiary	Fundacion IMDEA Energia, ES
Beneficiaries	SYMBIO, SYMBIO FRANCE, THE INSTITUTE OF APPLIED ENERGY, FUNDACION PARA EL DESARROLLO DE LAS NUEVAS TECNOLOGIAS DEL HIDROGENO EN ARAGON, UNIVERZA V LJUBLJANI, COMMISSARIAT A L ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES

https://eghost.eu/

PROJECT AND GENERAL OBJECTIVES

eGHOST aims to establish the first milestone in the development of eco-design criteria in the European hydrogen sector by providing a framework for the eco-(re)design of mature and emerging products and by promotion of fuel cell hydrogen (FCH) technologies as a sustainable investment.

Two guidelines for specific fuel cell hydrogen (FCH) products will be prepared and the lessons learnt will be integrated into the eGHOST white book; a reference guidance book for any future eco-design project on FCH systems. It addresses the eco(re)design of mature products (proton-exchange membrane fuel cells) and those emerging with low technology readiness levels (solid oxide electrolysers) in such a way that sustainable design criteria can be incorporated from the earliest stages of product development.

Moreover, eGHOST will contribute to positioning FCH as a sustainable investment by developing the first preparatory study of a hydrogen product under the guiding principles of the Eco-design Directive.

NON-QUANTITATIVE OBJECTIVES

- eGHOST aimed to contribute to FCH systems´ sustainability; eco-designed products will improve their sustainability performance.
- eGHOST aimed to contribute to social acceptance.; sustainable products are better accepted by end users and stakeholders, including civil society.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

Two guidelines for specific FCH products (proton-exchange membrane fuel cells (PEMFC) and solid oxide electrolysis cell (SOEC) stacks) have been completed and the lessons learnt were integrated into the eGHOST White Book, a reference guidance book for any future eco-design project of FCH systems. Achievements included:

- Life cycle sustainability assessment of a PEMFC and SOEC stack.
- Evaluation of the PEMFC stack in accordance with the EU eco-design directive.
- Proposal for alternative design concepts for both PEMFC and SOEC stacks from a sustainability perspective.
- Prioritisation of product concepts as a function of the impact reduction goals.
- Issuing of methodological and technical eco-design guidelines for both PEMFC and SOEC stacks.

eGHOST has improved the understanding of FCH technologies as a sustainable investment under the EU Taxonomy. In addition, eGHOST has pioneered the development of a social life cycle assessment in hydrogen-related projects looking at sustainable-by-design technologies that minimise environmental, economic and social impacts from the product-design phase.

PROJECT TARGETS

Target source	Parameter	Unit	Target	Achieved to date by the project	Target achieved?	SoA result achieved to date (by others)	Year for reported SoA result
Project's own objectives	Eco-design guidelines	Number	2	2	✓	N/A	N/A
	Cumulative environmental reduction	%	10	37-86 depending on product concept		18-44% carbon footprint reduction	2013
	Cumulative cost reduction	%	3	28-52 depending on product concepts		from 2.6 % reduction to 46% increment	2013
	Eco-efficiency improvement	%	10	>100 for all product concepts		N/A	N/A

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ELVHYS

ENHANCING SAFETY OF LIQUID AND VAPORISED HYDROGEN TRANSFER TECHNOLOGIES IN PUBLIC AREAS FOR MOBILE APPLICATIONS

Project ID	101101381
PRR 2025	Pillar 5 - Cross-cutting
Call Topic	HORIZON-JTI-CLEANH$_2$-2022-05-02
Project Total Costs	1 433 960.00
Clean H$_2$ JU Max. Contribution	1 433 960.00
Project Period	01-01-2023 - 31-12-2025
Coordinator Beneficiary	NORGES TEKNISK-NATURVITENSKAPELIGE UNIVERSITET NTNU, NO
Beneficiaries	KARLSRUHER INSTITUT FUER TECHNOLOGIE, HEALTH AND SAFETY EXECUTIVE, UNIVERSITY OF ULSTER, L AIR LIQUIDE SA, NATIONAL CENTER FOR SCIENTIFIC RESEARCH "DEMOKRITOS", DEUTSCHES ZENTRUM FUR LUFT - UND RAUMFAHRT EV, ALMA MATER STUDIORUM - UNIVERSITA DI BOLOGNA

https://elvhys.eu/

PROJECT AND GENERAL OBJECTIVES

ELVHYS addresses a critical gap in international standards related to liquid and cryogenic hydrogen transferring technologies for mobile applications such as filling trucks, ships, and stationary tanks. Since there is limited experience in this area today, significant challenges for safety and efficiency in hydrogen transfer operations exist. ELVHYS has the overarching objective to develop inherently safer and more efficient liquid and cryogenic hydrogen technologies and protocols for mobile applications.

This objective is pursued through innovative safety strategies and engineering solutions, including the selection of effective safety barriers and hazard zoning strategies. The project utilises an interdisciplinary approach, combining experimental, theoretical, and numerical studies to address various aspects of liquid and cryogenic hydrogen transfer.

Key objectives of the ELVHYS project include:

- Providing a comprehensive report on the state-of-the-art of cryogenic hydrogen transfer operations, including knowledge gaps, international standards, regulatory challenges, and safety strategies.
- Identifying hazards and incident scenarios associated with cryogenic hydrogen transferring operations and prioritising areas with the highest risk and least knowledge.
- Conducting experimental campaigns to investigate cryogenic hydrogen transfer operations and associated phenomena, such as releases, fires, and explosions.
- Developing and validating numerical simulation models for cryogenic hydrogen transfer operations and mitigation techniques.
- Proposing innovative safety strategies and engineering solutions based on experimental and modelling results.
- Disseminating project results to the fuel cell and hydrogen community, including authorities, standard development organisations, and other stakeholders.
- Contributing to the development of international standards for cryogenic hydrogen transferring technologies.

These objectives are achievable thanks to the expertise and resources of the consortium members, who possess unique experimental facilities, theoretical and numerical research capabilities, and practical experience in hydrogen safety. ELVHYS aims to not only fill existing knowledge gaps but also to lay the groundwork for sustainable impact through continued collaboration and dissemination beyond the project duration. By addressing these objectives, ELVHYS seeks to significantly enhance the safety and efficiency of cryogenic hydrogen transferring technologies on a global scale.

NON-QUANTITATIVE OBJECTIVES

ELVHYS will contribute to many objectives of the Clean Hydrogen JU SRIA such as (i) increase the level of safety and (ii) support the development of regulations, codes and standards (RCS) for hydrogen technologies and applications.

- Increasing the safety level of hydrogen technologies and applications is the cornerstone of the ELVHYS project. It will be addressed through top-edge research that closes numerous knowledge gaps in the understanding of the underlying physical phenomena governing liquid hydrogen transfer, specifically heat and mass transfer at cryogenic temperatures and under multiphase flow conditions. The project will advance the state-of-the-art through the generation of new knowledge, the development of innovative prevention and mitigation strategies, and the proposal of risk-informed recommendations and guidelines for cryogenic hydrogen transfer technologies.
- Supporting the development of RCS for hydrogen technologies and applications, with the focus on standards that will be

addressed through the developed science-based recommendations for RCS, beyond the state-of-the-art guidelines on fuelling, bunkering and transfer procedures.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

Key Achievements of ELVHYS in the field of cryogenic and liquid hydrogen (LH_2) transfer technologies are:

- Operational insights and best practices: Extensive data collection from existing LH_2 facilities helped define best practices and establish a baseline for safe and effective transfer operations.
- Ecosystem Mapping: A comprehensive overview of the LH_2 transfer infrastructure, technologies, and applications was developed.
- System Design & Safety Devices: Detailed Piping and Instrumentation Diagrams (P&IDs) were created, along with an inventory of current safety devices used in LH_2 systems.
- Safety-Focused Research Programme: A dedicated research plan was established to address safety challenges specific to LH_2 transfer systems.
- Risk Analysis & Methodological Review: Initial risk analyses were conducted, and gaps in existing safety approaches were identified for further investigation.
- Regulations, Codes, and Standards (RCS): A complete list of relevant RCS and regulatory bodies was compiled to ensure alignment with international safety standards.
- Fire & Explosion Modelling Support: Computational models were selected to simulate fire and explosion scenarios, aiding in hazard assessment and mitigation planning.
- LH_2 Transfer Modelling Tools: Engineering tools were developed to simulate LH_2 transfer processes, which will be validated through physical tests.
- Experimental Testing:
  - Successful tests in November 2024 on (i) Condensed phase explosion scenarios and (ii) LH_2 release into cold environments.
  - Experimental setups for (i) Fire and BLEVE (Boiling Liquid Expanding Vapor Explosion) tests on LH_2 hoses; (ii) Material resistance tests under LH_2 jet impingement.
  - Transfer System Test Readiness: LH_2 transfer experimental setups were designed and reviewed, with readiness assessments ensuring test safety and effectiveness.
- Hazard Identification & Consequence Analysis: Comprehensive hazard assessments were completed, and preliminary consequence analyses were performed for selected LH_2 transfer scenarios.

FUTURE STEPS AND PLANS

ELVHYS aims to provide a supportive regulatory and standardisation framework.

PROJECT TARGETS

Target source	Parameter	Unit	Target	Achieved to date by the project	Target achieved?	SoA result achieved to date (by others)	Year for reported SoA result
Project's own objectives	Safety, PNR/RCS Workshops	Number/ year	2	2	✓	1	2020
	Impact on standards at scope	Number/ project	1	0.6	⚙	0.6	2020

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E-SHYIPS

ECOSYSTEMIC KNOWLEDGE IN STANDARDS FOR HYDROGEN IMPLEMENTATION ON PASSENGER SHIP

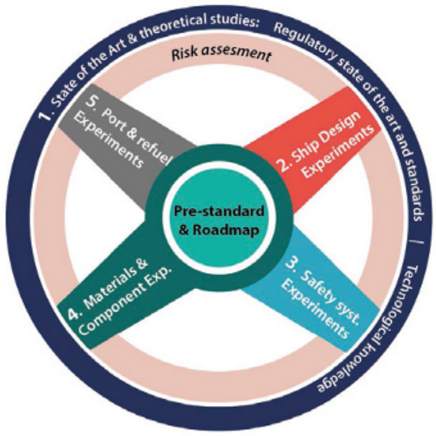
e·SHyIPS
ON THE WAVE OF HYDROGEN

Project ID	101007226
PRR 2025	Pillar 5 - Cross-cutting
Call Topic	FCH-04-2-2020
Project Total Costs	2 500 000.00
Clean H_2 JU Max. Contribution	2 500 000.00
Project Period	01-01-2021 - 31-12-2024
Coordinator Beneficiary	POLITECNICO DI MILANO, IT
Beneficiaries	DAMEN RESEARCH DEVELOPMENT and INNOVATION BV, DAMEN GLOBAL SUPPORT BV, IDF - INGEGNERIA DEL FUOCO SRL, LEVANTE FERRIES NAFTIKI ETAIREIA, DIMOS ANDRAVIDAS-KYLLINIS, ATENA SCARL - DISTRETTO ALTA TECNOLOGIA ENERGIA AMBIENTE, TEKNOLOGIAN TUTKIMUSKESKUS VTT OY, GHENOVA INGENIERIA SL, UNI - ENTE ITALIANO DI NORMAZIONE, DNV HELLAS SINGLE MEMBER SA, OY WOIKOSKI AB, SCHEEPSWERF DAMEN GORINCHEM BV, DANAOS SHIPPING COMPANY LIMITED, Proton Motor Fuel Cell GmbH, CINECA CONSORZIO INTERUNIVERSITARIO, UNIVERSITA DEGLI STUDI DI NAPOLI PARTHENOPE, AGENZIA NAZIONALE PER LE NUOVE TECNOLOGIE, L'ENERGIA E LO SVILUPPO ECONOMICO SOSTENIBILE

https://e-shyips.com/

PROJECT AND GENERAL OBJECTIVES

Hydrogen is considered an option for reaching emission reduction targets; however, a regulatory framework applicable to hydrogen-fuelled ships is not yet available. e-SHyIPS brings together hydrogen and maritime stakeholders to gather new knowledge based on a regulatory framework review and experimental data. The approach is vessel independent, and is focused on the risk and safety assessment methodologies. e-SHyIPS will define a pre-standardisation plan for an update of the International Code of Safety for Ships using Gases or other Low-flashpoint Fuels for hydrogen-based-fuels passenger ships and a roadmap to boost the hydrogen maritime economy.



NON-QUANTITATIVE OBJECTIVES

- e-SHyIPS aims to define project concept functional scenarios. In close cooperation with its industrial maritime partners, the technical and functional requirements of hydrogen-based-fuels passenger ships will be elicited in operational profile scenarios.
- Use cases for vessel design will be defined in line with the requirements of industrial maritime partners and the stakeholders.
- e-SHyIPS aims to determine vessel scenario and bunkering functional and technical requirements. The functional and technical requirements of hydrogen-based-fuels passenger ships, which are meant for a scenario report, were elicited from operational profile scenarios. The technical features will be described for the associated subsystem (e.g. pumps, hoses, etc.). The metrics and safety-related analyses to be conducted will be communicated and specified for the purposes of the risk assessment process. Operational features, such as bunkering procedures and hydrogen fuel conditions, will also be described, defining the limits for the scope of the analysis.
- e-SHyIPS aims to determine risk and safety best practices for the maritime sector. Therefore e-SHyIPS will report on technical knowledge gaps and models for risk assessment and risk management of gaseous hydrogen and liquid hydrogen, and hydrogen-based alternative fuels on ships, in 2024.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

- The analysis of emergency hydrogen discharge or major leaks from the vessel focusing on piping/venting mast arrangements for emergency hydrogen discharge, and the dispersion of hydrogen outside the ship.
- The guidelines for ship design and operation regarding emergency hydrogen discharge for different types and sizes of vessels and hydrogen storages.
- Fuel cell stack inclination testing (IR).
- Fuel cell salt spray testing.
- HAZID Analysis for Gas Compressed Hydrogen.
- Safety System Review.
- HAZID Analysis for Liquid Hydrogen.
- Explosion Risk Assessment.
- Testing of new forcing/damping methods in OpenFOAM.
- Optimisation of mesh focused on seakeeping.
- Validation of zero hull velocity wave-hull interaction simulation (LINCOSIM).
- Test of new LincoSim production web application to external expert users.

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FUTURE STEPS AND PLANS

- e-SHyIPS will continue to develop the hydrodynamic analysis. Implementation on the LINCOSIM platform using the updated mesh and wave-hull interaction simulation.
- The safety assessment for each vessel design for each scenario is completed.
- The H_2-based fuel bunkering systems basic design technical report has been completed.
- On-board H_2 dispersion and explosion model test
- Test results from material and component testing and postmortem analysis are expected

Initial results for the fuel delivery and bunkering solutions for ships are expected

PROJECT TARGETS

Target source	Parameter	Achieved to date by the project	Target achieved?
Project's own objectives	Constant operation of stack possible	-	✓
	To find materials which do not induce additional degradation to fuel cell compared to baseline	Certain EPDM materials identified which may be suitable for cathode side	
	Performance degradation (potential loss at constant current) (mV)	-10 to -20 mV (during UI curve) -13 mV during continuous operation	
	Generate new and missing knowledge to define a standardised knowledge database	150 Gaps in existing knowledge identified (literature) 90 gaps in IGF Code identified (35 matched to existing hydrogen standards)	
	Propose a pre-standardisation plan for IGF	Pre-normative plan for H_2 applications to passenger ships included in CWA WSESH001:2024 "e-Ships	
	Hydrogen-based fuels adoption roadmap definition for passenger ships	-	

HYACADEMY.EU

THE EUROPEAN HYDROGEN ACADEMY

Project ID	101137988
PRR 2025	Pillar 5 - Cross-cutting
Call Topic	HORIZON-JTI-CLEANH$_2$-2023-05-02
Project Total Costs	2 987 233.75
Clean H$_2$ JU Max. Contribution	2 987 233.75
Project Period	01-01-2024 - 30-06-2028
Coordinator Beneficiary	VYSOKA SKOLA CHEMICKO-TECHNOLOGICKA V PRAZE, CZ
Beneficiaries	RIJKSUNIVERSITEIT GRONINGEN, Future.Solutions Sàrl, BERTZ ASSOCIATES LTD, TECHNOKRATI LTD, KIC INNOENERGY SE, FUNDACION PARA EL DESARROLLO DE LAS NUEVAS TECNOLOGIAS DEL HIDROGENO EN ARAGON, EUREC EESV, DVGW DEUTSCHER VEREIN DES GAS- UNDWASSERFACHES - TECHNISCH-WISSENSCHAFTLICHER VEREIN EV, UNIVERSITE DE TECHNOLOGIE DE BELFORT - MONTBELIARD, UNIVERSITA DEGLI STUDI DI MODENA E REGGIO EMILIA, UNIVERSITATEA POLITEHNICA DIN BUCURESTI, TRAKIYSKI UNIVERSITET,UNIVERSITY OF ULSTER, THE UNIVERSITY OF BIRMINGHAM, POLITECNICO DI TORINO, UNIVERSITE LIBRE DE BRUXELLES

http://www.hyacademy.eu

PROJECT AND GENERAL OBJECTIVES

HyAcademy.EU will coordinate and support the delivery of hydrogen education and training across a network of over 600 educational institutions, providing education to over 5 000 individuals and tens of thousands of school children and young adults. It will also establish a network of more than five joint training laboratories for hydrogen technologies.

HyAcademy.EU will capitalise on the European Commission and Member States' investments in education and training activities. The consortium brings together representatives from multiple projects, enabling previous outputs to be consolidated and exploited, maximising the Academy's impact and reach.

To realise its objectives, by the project midterm, the European Hydrogen Academy aims to:

- Build and sustain a network of over 100 universities (the 'Network 100') offering recognised qualifications, specialisations, and degrees in hydrogen technologies.
- Build and sustain a network of over 500 schools integrating hydrogen topics into their science teaching, including technical schools and colleges offering more specific technical training.
- Create a network of five hands-on, physical training laboratories.
- Offer a portal to showcase and link the educational programmes available in the network and beyond, in order to supply prospective trainees with accurate and detailed information on training and career opportunities, allowing them to access documents focused on hydrogen topics at least 100 000 times.
- Provide lecturers and teachers with free training materials in all EU languages to enable educational staff to deliver the vast body of educational measures necessary.
- Develop and integrate novel (online) teaching methodologies into university, college and school curricula, and train educational staff to successfully employ these.
- Create and implement an organisational structure and a successful business case allowing for the the post-funding continuation of the project activities establishing a European Hydrogen Academy spanning all levels and types of education and training.

HyAcademy.EU will considerably contribute to the EU goals of offering access to high-quality education, supporting the creation of a highly-skilled workforce and more and better jobs

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in the European hydrogen industry. Through the school activities it will foster public awareness and acceptance of hydrogen technologies.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

- Universities, technical schools, training institutions, and schools are currently being contacted for information.
- Around 80 programmes and activities have been recorded in the web-based database.
- Network membership is being offered.
- Tables of content and authors have been compiled and identified for a series of 12 textbooks on Fuel cell hydrogen technologies (FCHT).

FUTURE STEPS AND PLANS

- First textbooks to be completed by December 2025.
- Growing networks and establishing the business entity to continue work beyond June 2028.
- Building the databases.
- Building an industry network.
- Trialing the Net-Zero Hydrogen Academy pilot on the KIC Skills Institute site.

PROJECT TARGETS

Target source	Parameter	Unit	Target	Achieved to date by the project	Target achieved?
Project's own objectives	Schools network (Network500)	Number	500	100	
	Network of universities (Network100)		105	70	
	Pupils trained		5 000		
	Social media followers		3 500	120	
	Training lab network		5	6	
	Access to project web site		100 000	1 000	
	Platform users		5 000	50	

HYPEF

PROMOTING AN ENVIRONMENTALLY-RESPONSIBLE HYDROGEN ECONOMY BY ENABLING PRODUCT ENVIRONMENTAL FOOTPRINT STUDIES

HyPEF
TRACING CLEAN HYDROGEN

Project ID	101137575
PRR 2025	Pillar 5 - Cross-cutting
Call Topic	HORIZON-JTI-CLEANH$_2$-2023-05-01
Project Total Costs	1 499 431.25
Clean H$_2$ JU Max. Contribution	1 499 431.25
Project Period	01-01-2024 - 31-12-2026
Coordinator Beneficiary	Fundacion IMDEA Energia, ES
Beneficiaries	ECOINNOVAZIONE SRL, ADVANCED ENERGY TECHNOLOGIES AE EREUNAS and ANAPTYXIS YLIKON and PROIONTONANANEOSIMON PIGON ENERGEIAS and SYNAFON SYMVOULEFTIKON Y PIRESION, EIFER EUROPAISCHES INSTITUT FUR ENERGIEFORSCHUNG EDF KIT EWIV, HEXAGON PURUS GMBH, ISTITUTO DI STUDI PER L'INTEGRAZIONE DEI SISTEMI (I.S.I.S) - SOCIETA'COOPERATIVA, ENGIE, AGENZIA NAZIONALE PER LE NUOVE TECNOLOGIE, L'ENERGIA E LO SVILUPPO ECONOMICO SOSTENIBILE

https://www.hypef.eu/

PROJECT AND GENERAL OBJECTIVES

Fuel cells and hydrogen (FCH) systems are increasingly considered in energy and climate policies, roadmaps and plans all over the world. In order to avoid past criticalities, such as those leading to a climate emergency situation, sustainability criteria are being progressively implemented in these initiatives, for example, by promoting low-carbon renewable hydrogen in Europe. In this regard, science-based criteria and procedures are required to guarantee the environmental suitability of FCH products, reporting their life-cycle environmental profile according to the principles of transparency, traceability, reproducibility, and consistency for comparability. While these principles are aligned with those of the general methodological guidance for product environmental footprint (PEF) studies, further specification is required to effectively implement them when addressing FCH products. Hence, the HyPEF project aspires to support and promote the establishment of an environmentally-responsible hydrogen economy by developing and testing the first product environmental footprint category rules (PEFCRs) specific to FCH products, while paving the way for subsequent related initiatives in the FCH sector.

NON-QUANTITATIVE OBJECTIVES

HyPEF advancements are expected to have a very large international impact as they will enable similar future PEF initiatives dealing with FCH product categories other than those addressed in HyPEF.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

The interdisciplinary approach behind HyPEF leads to crucial advancements regarding (i) the first development and application of well-accepted PEFCRs tailored to three selected FCH product categories (electrolysers for hydrogen production, tanks for hydrogen storage, and hydrogen fuel cells intended for electricity production), (ii) increased high-quality data availability for consistent environmental assessment and benchmarking of FCH products, and (iii) the first product environmental footprint -oriented policy recommendations regarding the official qualification of an FCH product as an environmentally-responsible investment.

FUTURE STEPS AND PLANS

HyPEF started in January 2024. During the first year of the project, scientific efforts focused on preparing the ground for FCH-PEFCRs by analysing relevant existing product environmental footprint (PEF) category rules (CRs) and exploring FCH systems for product categorisation. Moreover, the HyPEF Advisory Working Group and the Stakeholder Platform were set up. HyPEF efforts also address the definition and screening of the PEF for three representative products, and the management of the FCH-PEFCRs development process.

PROJECT TARGETS

Target source	Parameter	Unit	Target	Target achieved?
Project's own objectives	Set of policy recommendations based on the interplay between FCH-PEFCRs and RCS	Number	1	⚙
	Sets of drafted FCH-PEFCRs	Number	3	
	Life-cycle environmental profiles calculated for FCH products	Number	12	
	LCIs ready for implementation in the LCDN	Number	12	
	List of FCH product categories	Number	1	✓

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HYPOP

HYDROGEN PUBLIC OPINION AND ACCEPTANCE

Project ID	101111933
PRR 2025	Pillar 5 - Cross-cutting
Call Topic	HORIZON-JTI-CLEANH$_2$-2022-05-01
Project Total Costs	1 062 755.00
Clean H$_2$ JU Max. Contribution	1 062 754.50
Project Period	01-06-2023 - 30-09-2025
Coordinator Beneficiary	PARCO SCIENTIFICO TECNOLOGICO PER LAMBIENTE ENVIRONMENT PARK TORINO SPA, IT
Beneficiaries	CLUSTER TWEED, BALKANSKI VODORODEN KLASTER, REGIONALNA IZBA GOSPODARCZA POMORZA, INSTITUTE FOR METHODS INNOVATION, CLUSTER TECHNOLOGIES WALLONNE ENERGIE - ENVIRONNEMENT ET DEVELOPPEMENT DURABLE, CENTRO NACIONAL DE EXPERIMENTACIONDE TECNOLOGIAS DE HIDROGENO Y PILASDE COMBUSTIBLE CONSORCIO, Fundacion IMDEA Energia, AGENZIA PER LA PROMOZIONE DELLA RICERCA EUROPEA

http://www.hypop-project.eu/

PROJECT AND GENERAL OBJECTIVES

HYPOP will support hydrogen deployment in Europe by enhancing the involvement of citizens and providing guidelines to increase trust in hydrogen implementation. Clear communication will be key to hydrogen technological development with social acceptance. HYPOP's overall objective is to raise public awareness of and trust in hydrogen technologies and their systemic benefits, through: (i) the preparation of guidelines and good practices that will help to define more effectively how citizens, consumers/end-users and stakeholders can be involved in the implementation of H$_2$ technologies, and (ii) the creation of a web platform collecting communication material (mainly videos) on new hydrogen technologies, developed based on early findings of public engagement activities. HYPOP will focus on two applications of hydrogen technologies that will enter people's daily life, residential and mobility.

NON-QUANTITATIVE OBJECTIVES

- An assessment of current public opinion on hydrogen technologies will be undertaken resulting in a final scientific paper to share with the stakeholders and the scientific community.
- HYPOP will improve the availability of information, citizens' understanding of their own roles in hydrogen implementation and their ability to understand the topic of hydrogen and develop their own opinions on it and the transition strategy. Part of the information will come from the stakeholders' consultation and direct involvement in HYPOP.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

- Analysis of Member States' H$_2$ strategies to assess hydrogen implementation in Europe. The analysis also focuses on hydrogen-related public engagement activities at the national, regional and local levels (projects and hydrogen valleys).

- Analysis of survey data and public perceptions. Secondary data analysis of the Public Opinion Survey (Clean Hydrogen Partnership Joint Undertaking, May 2023) and state-of-the-art analysis of public perceptions, and reactions to hydrogen and fuel cell technologies are ongoing.
- Analysis of public engagement with H$_2$ via social media across the EU. This included the identification of the main individual-level determinants of public understanding and acceptance of FCH technologies.
- Stakeholders' requirements for H$_2$ technology installation. These are mainly permit-issuing, certification and safety requirements.
- Development of public information and engagement strategies as part of the hydrogen communication plan targeting decision-makers, industry stakeholders, and the general public.
- Local and international workshops to introduce the hydrogen systems potential and their applications to citizens.
- Local and international workshops to discuss permitting and safety procedures all over Europe, involving institutions and industry.

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- Finalisation of FCH tailored social life cycle assessment (SLCA) approach to support decision-makers into the hydrogen systems implementation considering socio-environmental dimensions.
- Launch of the digital H_2 projects showcase to show hydrogen technology installation evidences and their application in industrial cases or real-life situation, such as hydrogen refueling station (HRS) and mobility-synergic collaborations and meetings with over 30 EU Projects (e.g. hydrogen valleys, demo projects, Interreg Projects).

FUTURE STEPS AND PLANS

- Citizens' engagement workshops in each of the HYPOP countries (Italy, Spain, Belgium, Poland, Bulgaria, Ireland) and two international events to inform citizens about the project and increase public trust in H_2 implementation.
- Stakeholders' engagement workshops in each of the HYPOP countries (Italy, Spain, Belgium, Poland, Bulgaria, Ireland) to report the results from the requirement lists for permit issuing, safety and certification analysis.
- One public-oriented guideline reporting best practices to involve citizens.
- Three guidelines collecting the results coming from the involvement of stakeholders' groups (first responders, permitting authorities, certification bodies).
- A web platform gathering information on hydrogen projects and related initiatives.
- Videos and infographics to support the HYPOP hydrogen awareness campaign.

PROJECT TARGETS

Target source	Parameter	Unit	Target	Target achieved?
Project's own objectives	Number and type of target groups engaged.	Number	> 3 target groups reached/country across the 6 HYPOP countries (including 1 industrial group)	
	Trained professionals in TIER 2 (Belgium, Netherlands, Austria, Sweden, Norway, Finland, Latvia, Spain and Italy).	Number	> 50	
	Trained professionals in TIER 3 countries: rest of EU countries and associated countries.	Number	>30	

JUST-GREEN AFRH2ICA

PROMOTING A JUST TRANSITION TO GREEN HYDROGEN IN AFRICA

Project ID	101101469
PRR 2025	Pillar 5 - Cross-cutting
Call Topic	HORIZON-JTI-CLEANH$_2$-2022-05-05
Project Total Costs	999 995.00
Clean H$_2$ JU Max. Contribution	999 995.00
Project Period	01-02-2023 - 31-01-2025
Coordinator Beneficiary	UNIVERSITA DEGLI STUDI DI GENOVA, IT
Beneficiaries	TEKNOLOGIE SOLUTIONS LIMITED, AFRICAN HYDROGEN PARTNERSHIP, IMPACT HYDROGEN B.V., STAM SRL, BLUENERGY REVOLUTION SCRL, INSTITUT DE RECHERCHES EN ENERGIE SOLAIRE ET ENERGIES NOUVELLES, STRATHMORE UNIVERSITY, ARTELYS, Fundacion IMDEA Energia, NOORDWES-UNIVERSITEIT, FORSCHUNGSZENTRUM JULICH GMBH, COMMISSARIAT A L ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES

https://just-green-afrh2ica.eu/

PROJECT AND GENERAL OBJECTIVES

JUST GREEN AFRH2ICA aims to develop a green hydrogen just transition roadmap that would make African-European transition pathways to H$_2$ synergic, sustainable (from environmental and social points of view), while avoiding any new EU hydrogen colonisation of Africa, and promoting a mutually beneficial collaboration between the two continents for the development of independent and collaborative hydrogen economies, research and development ecosystems and value chains. To do so, JUST GREEN AFRH2ICA has involved key partners from both the EU and African Union (AU) sides, such as the African Hydrogen Partnership (AHP) and Hydrogen Europe, along with representatives from academia, research and technology organisations, and policymakers. JUST GREEN AFRH2ICA aims to be a stepping stone to a collaborative hydrogen roadmap that, based on the analysis of different AU green H$_2$ scenarios at the socio-economic-technical level via partners' tools (also assessing local resources for green hydrogen production, among which renewable energy sources and water are the key ones), will also drive future investments and policies and the setup of local manufacturing lines.

NON-QUANTITATIVE OBJECTIVES

- Support the mutual benefit collaboration between Africa and Europe on green hydrogen initiatives.
- Promote a Just Green Hydrogen transition in both continents.
- Stimulate the sharing of know-how between the continents.
- Identify the most interesting African countries for investing in green hydrogen looking at both domestic markets and exports to Europe.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

- Modelling of the identified use cases via techno-economic, sustainability assessment, socio-economic, hydrogen potential assessment, water availability assessment via tools developed and properly adapted to the African context.
- Assessment of the impact of green hydrogen import from Africa on the EU energy system.
- Continuous assessment of AU countries' national hydrogen strategies and updates.

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- Assessment of African manufacturing and knowledge capabilities to setup an EU green hydrogen manufacturing value chain.
- Assessment of financing instruments relevant to support green hydrogen transition in Africa.
- Realisation of JUST GREEN AFRH2ICA financing, policy and manufacturing roadmaps.
- Engagement with stakeholders through surveys and events to gather input for project tasks.
- Promotion of the second training package on the E-Learning platform.
- Organisation of fifteen physical training events and five web events.
- Participation in more than 35 events: speeches at international conferences, organisation of seven stakeholder workshops, robust social media campaign, release of project videos.
- Publication of three open access journal papers.

FUTURE STEPS AND PLANS

The project has been successfully completed in January 2025.

PROJECT TARGETS

Target source	Parameter	Unit	Target	Achieved to date by the project	Target achieved?
Project's own objectives	Modelling tools from the consortium updated.	Number	5	5	✓
	Number of trainees registered to trainings workshops/events and E-Learning.	Number	> 200	> 600	
	Number of AU countries' policies analysed.	Number	10	25	
	Approval from the stakeholders of the Project roadmaps.	%	> 70	60	
	Stakeholder interaction - Number of stakeholders engaged in activities.	Number	At least 25 stakeholders always present and active in foreseen stakeholders driven activities.	>25	
	Modelling AU Green H_2 scenarios via unique consortium tools.	Number	4		
	Number of Users of the JUST GREEN AFRH2ICA Matchmaking/stakeholder platform.	Number	> 150	157	

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NHYRA

PRE-NORMATIVE RESEARCH ON HYDROGEN RELEASES ASSESSMENT

Project ID	101137770
PRR 2025	Pillar 5 - Cross-cutting
Call Topic	HORIZON-JTI-CLEANH$_2$-2023-05-03
Project Total Costs	2 086 683.75
Clean H$_2$ JU Max. Contribution	2 086 683.75
Project Period	01-01-2024 - 31-12-2026
Coordinator Beneficiary	SNAM S.P.A., IT
Beneficiaries	LINDE GMBH, NUOVO PIGNONE TECNOLOGIE SRL, ENAGAS TRANSPORTE SA, GERG LE GROUPE EUROPEEN DE RECHERCHES GAZIERES, EQUINOR ENERGY AS, INSTYTUT NAFTY I GAZU - PANSTWOWY INSTYTUT BADAWCZY, THE REGENTS OF THE UNIVERSITY OF CALIFORNIA, FONDAZIONE BRUNO KESSLER, NPL MANAGEMENT LIMITED, ENGIE, DEUTSCHES ZENTRUM FUR LUFT - UND RAUMFAHRT EV, UNIVERSITY OF SURREY, AGENZIA NAZIONALE PER LE NUOVE TECNOLOGIE, L'ENERGIA E LO SVILUPPO ECONOMICO SOSTENIBILE, ALMA MATER STUDIORUM - UNIVERSITA DI BOLOGNA

https://nhyra.eu/

PROJECT AND GENERAL OBJECTIVES

Several studies and analyses indicate that by 2050 hydrogen will become a pillar of the energy system potentially accounting for up to 20% of global energy demand. As a result, anthropogenic hydrogen (H_2) emissions—which have an indirect impact on the greenhouse effect—are also expected to increase.

Furthermore, there are currently large uncertainties regarding both the total amount of hydrogen that will be released from the H_2 value chain, and the climate effect of the hydrogen released in the atmosphere.

The general objective of NHyRA is to perform an assessment of potential H_2 releases along the entire H_2 value chain. In particular, the project aims to:

- Fill the critical knowledge gaps regarding technologies, methodologies and protocols for detecting and quantifying the H_2 releases.
- Develop H_2 release scenarios that will allow for the identification of the most critical elements of the H_2 value chain in terms of emissions.
- Propose mitigation strategies, guidelines and recommendations for standardisation bodies in order to support the definition of a dedicated normative framework.

NON-QUANTITATIVE OBJECTIVES

- To increase knowledge, foster collaboration, and support standardisation bodies and policy makers.
- To enhance understanding of hydrogen (H_2) releases across its value chain, facilitating informed decision-making among policymakers, stakeholders, and industries.
- To support the development of regulations, codes, and standards (RCS) related to hydrogen technologies and systems, ensuring safer and more efficient deployment.
- To promote open science, dissemination of research findings, and engagement with stakeholders to maximise the project's impact beyond its direct technical goals.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

Insights into hydrogen supply chain dynamics and emissions inventory.

- Archetypes of the H_2 supply chain have been identified, detailing its components, operational conditions, and potential emission sources.
- Technologies with a readiness level above 6 have been evaluated through desk research and experts' input, focusing on parameters such as pressure and temperature.
- A report has been submitted covering a detailed dataset on primary technologies, pinpointing hydrogen losses and emissions.
- A report has been submitted addressing the data gap concerning hydrogen's environmental impact by developing a comprehensive emissions inventory. Leveraging natural gas (NG) methodologies, it categorises emissions into fugitives, vented, and incomplete combustion, facilitating scenario analyses and mitigation strategies. This inventory will be continuously updated throughout the NHyRA project to enhance data accuracy and standardisation.
- Advancing methodologies for quantifying hydrogen releases have been investigated.
- A report has been submitted identifying and evaluating hydrogen detection and measurement technologies, including both commercial and emerging solutions. The report establishes criteria for selecting and validating monitoring methods, defines data quality metrics, and sets reporting standards. Additionally, it provides a comparative analysis of existing techniques, highlighting their strengths and limitations, and concludes with a review of commercially available instruments.
- The first priority list of the most critical elements is about to be released.
- A qualitative multi-criteria approach has been developed to prioritise these elements across the value chain. To this end, different methodologies were compared, and all partners contributed through interviews, surveys, and other participatory methods.

FUTURE STEPS AND PLANS

- The first version of a hydrogen release inventory was accomplished, which is the core element of the NHyRA project.
- Once the most critical units processes of the H_2 value chain, in terms of H_2 release, have been identified, dedicated methodologies will be developed to determine suitable techniques and instruments for the detection and measurement of hydrogen leakages.
- Measurement-based methods will be developed for detecting and quantifying H_2 emissions, considering both fugitive and vented emissions, but also calculation-based methods will be defined in order to estimate the hydrogen emissions when

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direct measurement will be too complicated or even not possible (for example in cases of accidents or unburned fuel).

- The methodologies developed will be tested for validation, both in laboratories and in real cases, and these experimental data collected will also feed the hydrogen release inventory.
- The total potential H_2 releases will be quantified along the different H_2 supply chains and mitigation strategies will be developed.
- H_2 releases scenarios will be developed, including different H_2 supply chains, considering different time horizons.

PROJECT TARGETS

Target source	Parameter	Unit	Target	Achieved to date by the project	Target achieved?
Project's own objectives	Workshop for H_2 Production, 1 brochure with overview of H_2 leakage in production.	Number	1	-	
	Workshop for H_2 transport and storage, 1 brochure with overview of H_2 leakage in TandS.	Number	1	-	
	Workshop for H_2 end-use, 1 brochure with overview of H_2 leakage in end-use.	Number	1	-	
	Engagement with EU/national association.	Number	2	1	
	Dissemination in Clean Hydrogen Mission countries and universities from at least 9 countries.	Number	9	7	
	Workshop presenting results relevant to policy makers.	Number	1	-	
	Number of archetype technologies assessed in terms of H_2 releases and implemented into the simulation tool.	Number/ project	12	-	
	Measurement-based methods for detecting hydrogen emissions from individual elements of the value chain.	Number/ project	2	-	
	Measurement-based methods for quantifying fugitive or vent emissions for point or subarea sources.	Number/ project	2	-	
	Participation in 1 conference on energy markets/finance to engage financial stakeholders.	Number	1	-	
	Presentation at a suitable measurement related conference e.g CEM.	Number	1	-	
	At least 2 meetings with standardisation committees.	Number	2	-	
	Methods for estimating the amount of hydrogen emissions, from incomplete combustion, accidents, hard-to-measure sources using calculation-based methods.	Number/ project	18	-	
	Number of assessed hydrogen economy scenarios in terms of overall emissions from mitigated and unmitigated operating regimes.	Number/ Project	3	A selection will be performed on the basis of geographical boundaries and technological categorisation.	
	Prioritization of the critical elements for the detection and/or estimation of H_2 releases.	Number/ project	1	-	
	H_2 releases of H_2 economy scenarios and effects of mitigation actions.	Number/ project	1	-	
	H_2 supply chains' unit processes review.	Number/ project	1	1 Review of the main technologies related to H_2 production, transportation, storage and utilisation.	✓
	H_2 Release Inventory	Number/ project	1	1 First version issued to be updated continuously until the end of the project through literature review and surveys to industrial stakeholders.	
	Invitation to the Advisory Board: providers of H_2 detection technol. and equip. manufacturers.	Number	1	1	
	Communication toolkit tailored to non-technical audience.	Number	1	1	

SH_2E

SUSTAINABILITY ASSESSMENT OF HARMONISED HYDROGEN ENERGY SYSTEMS: GUIDELINES FOR LIFE CYCLE SUSTAINABILITY ASSESSMENT AND PROSPECTIVE BENCHMARKING

Project ID	101007163
PRR 2025	Pillar 5 - Cross-cutting
Call Topic	FCH-04-5-2020
Project Total Costs	2 142 778.75
Clean H_2 JU Max. Contribution	1 997 616.25
Project Period	01-01-2021 - 30-06-2024
Coordinator Beneficiary	Fundacion IMDEA Energia, ES
Beneficiaries	SYMBIO FRANCE, THE INSTITUTE OF APPLIED ENERGY, SYMBIO, FUNDACION PARA EL DESARROLLO DE LAS NUEVAS TECNOLOGIAS DEL HIDROGENO EN ARAGON, GREENDELTA GMBH, FORSCHUNGSZENTRUM JULICH GMBH, COMMISSARIAT A L ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES

https://sh2e.eu/

PROJECT AND GENERAL OBJECTIVES

The goal of SH_2E is to provide a harmonised (i.e. methodologically consistent) multidimensional framework for the life cycle sustainability assessment (LCSA) of fuel cells and hydrogen (FCH) systems. To that end, SH_2E will develop and demonstrate specific guidelines for the environmental, economic and social life cycle assessments (LCAs) and benchmarking of FCH systems, while addressing their consistent integration into robust FCH LCSA guidelines. The aim of these guidelines is to be globally accepted as the reference document for LCSA of FCH systems and to set the basis for future standardisation.

NON-QUANTITATIVE OBJECTIVES

- SH_2E aims to contribute to FCH systems´ sustainability. The development of harmonised guidelines contributes to assessing the sustainability of FCH systems.
- SH_2E aims to contribute to social acceptance. Better knowledge of FCH systems' social and environmental impacts will contribute to their acceptance.
- SH_2E aims to contribute to standardisation. Harmonised guidelines pave the way for a standard.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

- SH_2E reviewed the existing LCA guidelines.
- SH_2E reviewed case studies and projects.
- Environmental LCA guidelines have been issued.
- Life cycle cost assessment guidelines have been issued.
- Social life cycle assessment guidelines have been issued.
- Criticality indicator has been proposed.
- LCSA guidelines have been issued.
- The software tool for performing FCH life cycle studies has been issued.

FUTURE STEPS AND PLANS

SH_2E has been successfully completed.

PROJECT TARGETS

Target source	Parameter	Unit	Target	Target achieved?
Project's own objectives	1 document of FCH-LCA guidelines	Number	1	✓
	1 integrated FCH-LCA/LCC/SLCA/LCSA software tool	Number	1	
	1 document of FCH-LCSA guidelines with illustrative case studies after third-party review	Number	1	
	1 document FCH-LCSA guidelines	Number	1	
	Material criticality indicator	Number	1	
	1 document of FCH-LCC guidelines and 1 document of FCH-SLCA guidelines	Number	2	
	2 FCH systems assessed and benchmarked	Number	2	

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SHIMMER

SAFE HYDROGEN INJECTION MODELLING AND MANAGEMENT FOR EUROPEAN GAS NETWORK RESILIENCE

Project ID	101111888
PRR 2025	Pillar 5 - Cross-cutting
Call Topic	HORIZON-JTI-CLEANH$_2$-2022-05-03
Project Total Costs	3 037 265.00
Clean H$_2$ JU Max. Contribution	2 999 156.25
Project Period	01-09-2023 - 31-08-2026
Coordinator Beneficiary	SINTEF AS, NO
Beneficiaries	INRETE DISTRIBUZIONE ENERGIA S.P.A, REDEXIS GAS SERVICIOS SL, REDEXIS SA, SNAM S.P.A., ENAGAS TRANSPORTE SA, GERG LE GROUPE EUROPEEN DE RECHERCHES GAZIERES, OPERATOR GAZOCIAGOW PRZESYLOWYCH GAZ-SYSTEM SPOLKA AKCYJNA, INSTYTUT NAFTY I GAZU - PANSTWOWY INSTYTUT BADAWCZY, GASSCO AS, BUNDESANSTALT FUER MATERIALFORSCHUNG UND -PRUEFUNG, FUNDACION TECNALIA RESEARCH and INNOVATION, POLITECNICO DI TORINO, NEDERLANDSE ORGANISATIE VOOR TOEGEPAST NATUURWETENSCHAPPELIJK ONDERZOEK TNO

https://shimmerproject.eu/

PROJECT AND GENERAL OBJECTIVES

To accelerate the transition to a low-carbon economy while exploiting existing infrastructure, hydrogen can be injected into the natural gas network. However, there are many technical and regulatory gaps that should be closed and adaptations and investments that should be made to ensure that multi-gas networks across Europe will be able to operate in a reliable and safe way while providing gas of highly controllable quality and meeting energy demand. Recently, the European Committee for Standardization concluded that it was impossibility to set a common limiting value for hydrogen injected into the European gas infrastructure, instead recommending a case-by-case analysis. In addition, there are still uncertainties related to the material integrity of pipelines and networks components with regard to their reduced lifetimes in the presence of hydrogen.

Results from previous and ongoing projects on the hydrogen readiness of grid components should be summarised in a systematic manner together with the assessment of the existent transmission and distribution (T and D) infrastructure components at European level to provide stakeholders with decision support and risk reduction information to drive future investments and the development of regulations and standards.

SHIMMER aims to enable higher levels of hydrogen integration and safer hydrogen injection management in multi-gas networks by contributing to the knowledge and understanding of hydrogen projects and their risks and opportunities.

NON-QUANTITATIVE OBJECTIVES

- To map and address European gas T and D infrastructure in relation to materials, components, technology, and their readiness for hydrogen blends.
- To define methods, tools and technologies for multi-gas network management and quality tracking, including simulation, prediction, and safe management of transients, with a view to widespread hydrogen injection across Europe.
- To propose best practice guidelines for the safe handling of hydrogen in the natural gas infrastructure including risk management.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

- Selection of key information for the infrastructure database to be implemented as part of the SHIMMER homepage. This includes details on European infrastructure, pilot projects, material testing standards, test qualifications for hydrogen readiness, and operational conditions for gas networks under hydrogen injection.
- Ongoing data collection on gas grid components and materials to be included in the SHIMMER database.
- Evaluation of gas leakage monitoring and detection methods, concluding that current methods used by transmission system operators (TSOs) and distribution system operators (DSOs) are suitable for natural-hydrogen mixtures, though some calculation methods had to be adapted.
- Execution of a literature study on inspection methods for non-piggable pipes.

- Inspection of a high-pressure gas pipeline using the MFL tool method. The results will be used in 2025 as reference for three additional inspection methods (i) acoustic emission, (ii) metal magnetic memory and (iii) stress concentration tomography.
- Online workshops with all TSOs and DSOs in the project to establish realistic cases, test cases, and scenarios for modelling gas network infrastructures.
- Review of state-of-the-art modelling tools for gas networks simulations. In 2025 three modelling tools will be benchmarked to simulate the selected scenarios. Models will be used for infrastructure planning and predicting operational conditions and gas quality tracking along the network.
- Consortium meeting in San Sebastian in October 2024.
- Drafting of the communication and dissemination plan which is currently being updated.
- The SHIMMER project was showcased at the 1st CANDHy Cluster workshop in July 2024.
- Establishment of an advisory board and networking group.
- Organisation of an online workshop in 2025.
- Presentation of SHIMMER at two conferences in 2024 (IGRC and EGATEC).
- SHIMMER featured in an interview with H_2-Magazine (HZwei-Magazin).

Integrity management and safety:

- Gathering information about materials and components used in natural gas grid of participating TSOs and DSOs.
- Identifying critical material properties and component factors.
- Reviewing existing in-line inspection methods and involving technology providers in test campaigns.
- Gathering information on common leakage detection methods among operators.

Flow Assurance

- Definitions of network models and case studies.
- Organisation of workshops with TSOs and DSOs.
- A realistic case requirement document of needed components and data was achieved.

FUTURE STEPS AND PLANS

Continue working with the project activities as described in the workplan.

PROJECT TARGETS

Target source	Parameter	Unit	Target	Target achieved?
Project's own objectives	Capability to control hydrogen presence over a served area.	km^2	TSO < 100 DSO < 5	
	Capability to track hydrogen spreading through network structure.	[delta%H_2/ hour] [delta%H_2/ km^2]	< 1 < 2	

THOTH2

NOVEL METHODS OF TESTING FOR MEASUREMENT OF NATURAL GAS AND HYDROGEN MIXTURES

Project ID	101101540
PRR 2025	Pillar 5 - Cross-cutting
Call Topic	HORIZON-JTI-CLEANH$_2$-2022-05-04
Project Total Costs	1 997 361.25
Clean H_2 JU Max. Contribution	1 997 360.50
Project Period	01-02-2023 - 31-07-2025
Coordinator Beneficiary	SNAM S.P.A., IT
Beneficiaries	CESAME-EXADEBIT SA, INRETE DISTRIBUZIONE ENERGIA S.P.A, GRTGAZ, ENAGAS TRANSPORTE SA, GERG LE GROUPE EUROPEEN DE RECHERCHES GAZIERES, OPERATOR GAZOCIAGOW PRZESYLOWYCH GAZ-SYSTEM SPOLKA AKCYJNA, EIDGENOSSISCHES INSTITUT FUR METROLOGIE METAS, INSTYTUT NAFTY I GAZU - PANSTWOWY INSTYTUT BADAWCZY, ISTITUTO NAZIONALE DI RICERCA METROLOGICA, COMMONWEALTH SCIENTIFIC AND INDUSTRIAL RESEARCH ORGANISATION, FONDAZIONE BRUNO KESSLER, AGENZIA NAZIONALE PER LE NUOVE TECNOLOGIE, L'ENERGIA E LO SVILUPPO ECONOMICO SOSTENIBILE, ALMA MATER STUDIORUM - UNIVERSITA DI BOLOGNA

https://thoth2.eu/

PROJECT AND GENERAL OBJECTIVES

THOTH2 aims to cover the normative and standards gaps related to methodologies and protocols for evaluating the performances and identifying the limits and tolerances of state-of-the-art (SOA) measuring devices in transmission and distribution systems when carrying mixtures of hydrogen and natural gas or pure hydrogen. THOTH2 will design dedicated methodologies to test different types of measuring devices (gas meters, gas volume conversion devices, pressure and temperature transducers, gas quality analysers, and gas leak detectors) under various operating conditions.

NON-QUANTITATIVE OBJECTIVES

THOTH2 will help the scientific and industrial communities understand the potential impact of different H_2/NG mixtures on the performances of SOA measuring devices installed in the transmission and distribution gas infrastructures. European transmission system operators (TSOs) and distribution system operators (DSOs) will benefit from the project results, as they will obtain important information about the limits and tolerances of the measuring instruments under various operating conditions. As THOTH2 is a pre-normative research project, recommendations will be sent to the normative bodies to support the development of new standards and the update of existing ones.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

- Assessment of SOA, barriers and bias on metering devices for natural gas / hydrogen blends and pure hydrogen.
- Definition of the methodologies for testing the different measuring devices.
- Preparation of the test rigs and reporting procedure for experimental activities.
- Start of testing campaigns in December 2024, after the collection of the devices (gas meters, pressure transducers, water dew point analysers, leak detectors, flow computers) from manufacturers.
- Application of methodologies and testing protocols on selected devices to evaluate their performances under different operating conditions.

FUTURE STEPS AND PLANS

- Validation of the test methodologies to provide insights which will be included in recommendations, and subsequently be shared with relevant standardisation bodies and manufacturers through the THOTH2 Stakeholders Advisory Board.
- Development of a repurposing concept for an existing gas meters calibration facility for operation in the natural gas containing blended hydrogen.

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PROJECT TARGETS

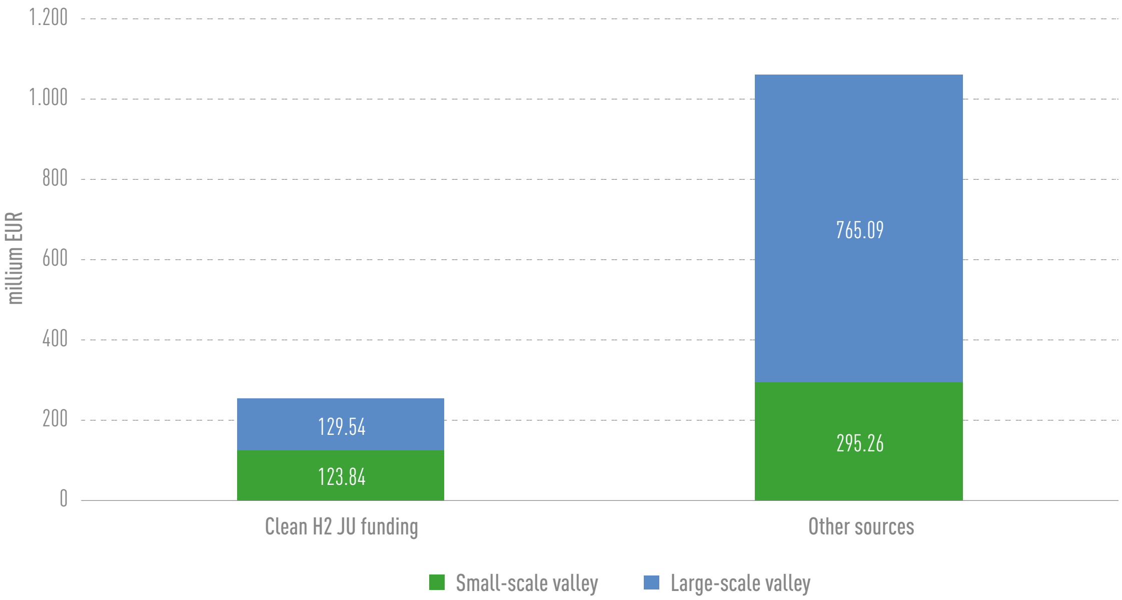
Target source	Parameter	Unit	Target	Achieved to date by the project	Target achieved?
Project's own objectives	Papers submitted to open access peer-reviewed journals during the project.	Number	4	3	✓
	Presentation of the project at at least 5 professional workshops/ exhibitions.	Number	5	3	
	Organisation of a closing workshop presenting the project results to all interested stakeholders.	Number	1	-	
	Presentation in international and other relevant conferences identified during the project.	Number	7	3	
	Safety, PNR/ RCS Workshops.	Number	2	1	
	Validation of new or modified test protocols and methods.	Number	5	-	
	Definition of preliminary guidelines and recommendations for new standards.	Number	1	-	
	Concept of repurposing of an existing gas meters calibration facility for operation in the natural gas containing blended hydrogen.	Number	1	-	
	Definition of SoA of measuring devices installed in NG transmission and distribution networks.	Number	1	1	
	Definition of methodologies and testing protocols for assessing the performances of measuring devices with H_2NG mixtures.	Number	5	5	
	Test rigs preparation and reporting procedure for experimental activities.	Number	1	1	
	Organisation of at least one Stakeholder Advisory Board workshop.	number	1	1	

XV. PILLAR 6: HYDROGEN VALLEYS

OBJECTIVES: The objective of Hydrogen valleys is to establish comprehensive regional green systems by integrating the entire hydrogen value chain, including production, storage, distribution, and end-use. The focus is on system efficiency and resilience, market creation, suitable regulation and standards development, and knowledge management. The call topics distinguish two types of valleys: large valleys and small valleys.

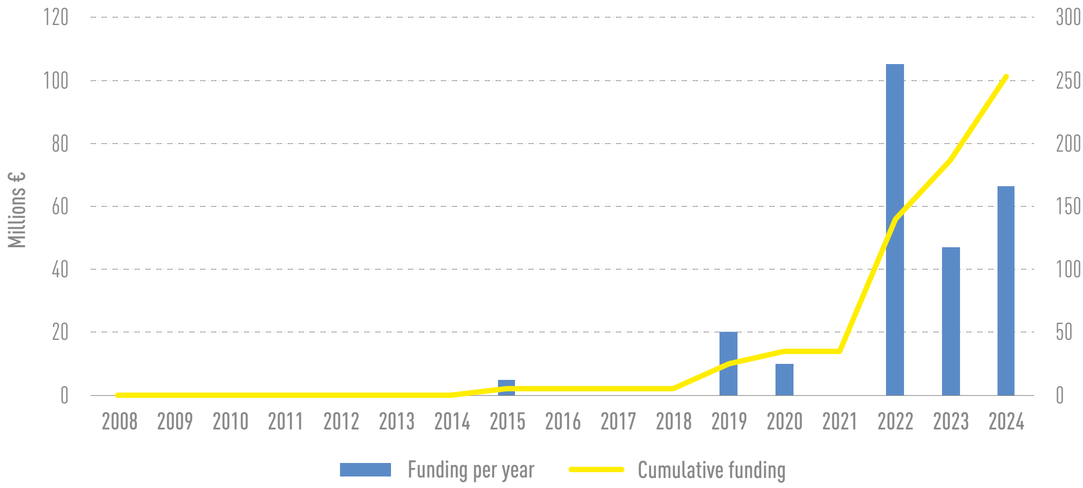
OPERATIONAL BUDGET: The Clean Hydrogen JU provided approximately EUR 250 million in funding for Pillar 6 projects, although not all project costs were fully covered, while partners contributed a significantly larger amount of around EUR 1 billion, with the majority of external funding directed toward large-scale Hydrogen Valleys. The distribution of funding by research area is illustrated in Figure 62. Cumulative funding for Pillar 6 projects from 2008 to 2024 is presented in Figure 63, highlighting that JU support peaked in 2022, as shown by the higher number of projects initiated during that year.

Figure 62: Funding per research area for Pillar 6 projects from 2008 to 2024



Source: Clean Hydrogen Joint Undertaking

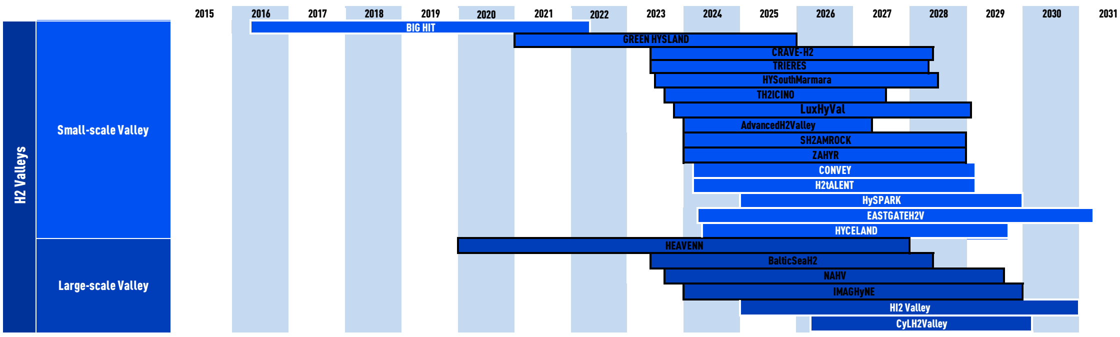
Figure 63: Funding (per year in blue/left axis and cumulative in grey/right axis) for Pillar 6 projects from 2008 to 2024



Source: Clean Hydrogen Joint Undertaking

PILLAR IN BRIEF: The projects under review in Pillar 6 are shown in Figure 64.

Figure 64: Project timelines of Pillar 6: Hydrogen Valleys



Source: Clean Hydrogen Joint Undertaking

Over the past two years, the number of Pillar 6 projects has expanded rapidly, with seven new projects initiated in 2023 and four additional ones at the start of 2024 (Figure 65). Spain leads in participation with eight projects, followed closely by France and Italy with seven each, while Germany, the Netherlands, Belgium, and Greece contribute to four to six projects each; most other countries are involved in only one or two projects (Figure 66). The collaboration network highlights strong ties among the most active countries, with Spain, Italy, and France at the core, closely linked to other participants, and Germany and the Netherlands connecting different regions across Europe (Figure 67). Nordic and Baltic countries, including Sweden, Finland, and Estonia, form a smaller cluster, while Eastern European countries such as Hungary and Bulgaria occupy the periphery with fewer connections. Participation spans private companies and research institutions (13 each), followed by higher education institutions, SMEs, and public bodies (12 each), with other entities contributing to nine projects (Figure 68). Private companies and research institutions have consistently engaged across the years, while SME involvement has grown notably in 2023 and 2024 (Figure 69). Leading participants include Fundación Hidrógeno Aragón, New Energy Coalition (Netherlands), and Lhyfe, representing a diverse mix of research centres, universities, consultancies, and energy companies. The collaboration network further shows how these institutions are interconnected, with central hubs such as Fundación Hidrógeno Aragón and CEA playing key roles in linking broader European project networks (Figure 70). Finally, following a slow start with just one publication in 2022 and none in 2023, Pillar 6 saw a significant increase in scientific output in 2024, with 10 publications released, including 7 that underwent peer review (Figure 71).

Figure 65: Pillar 6: Trend in number of projects per year

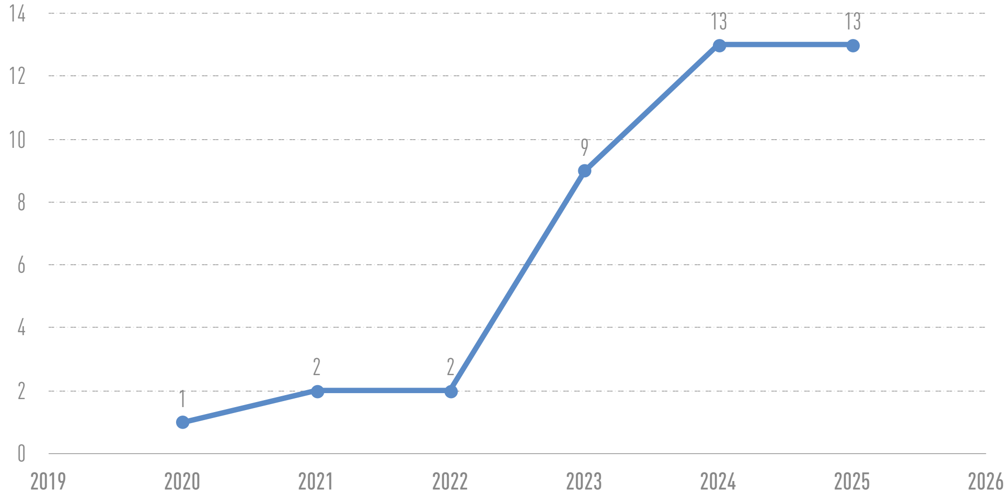


Figure 66: Pillar 6: Project participation by EU country

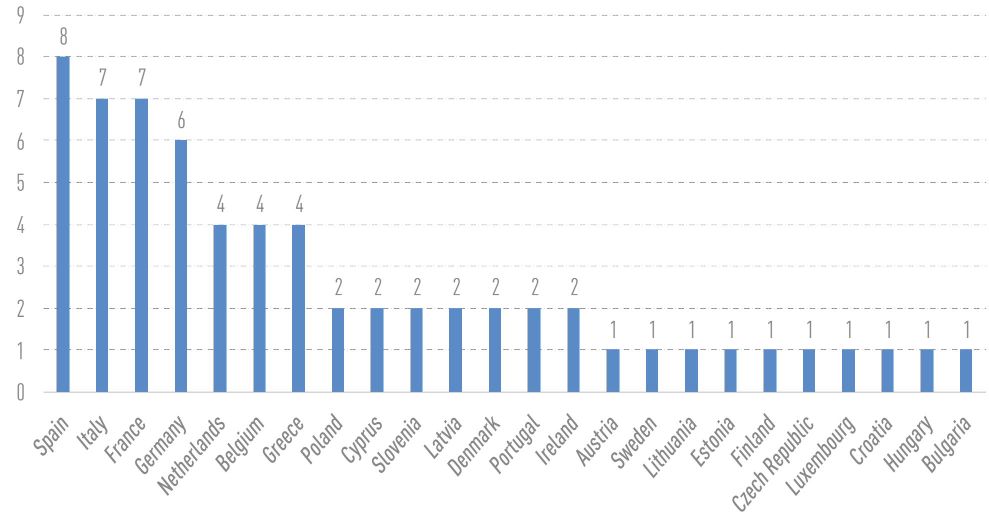


Figure 67: Pillar 6: Collaboration network of EU countries

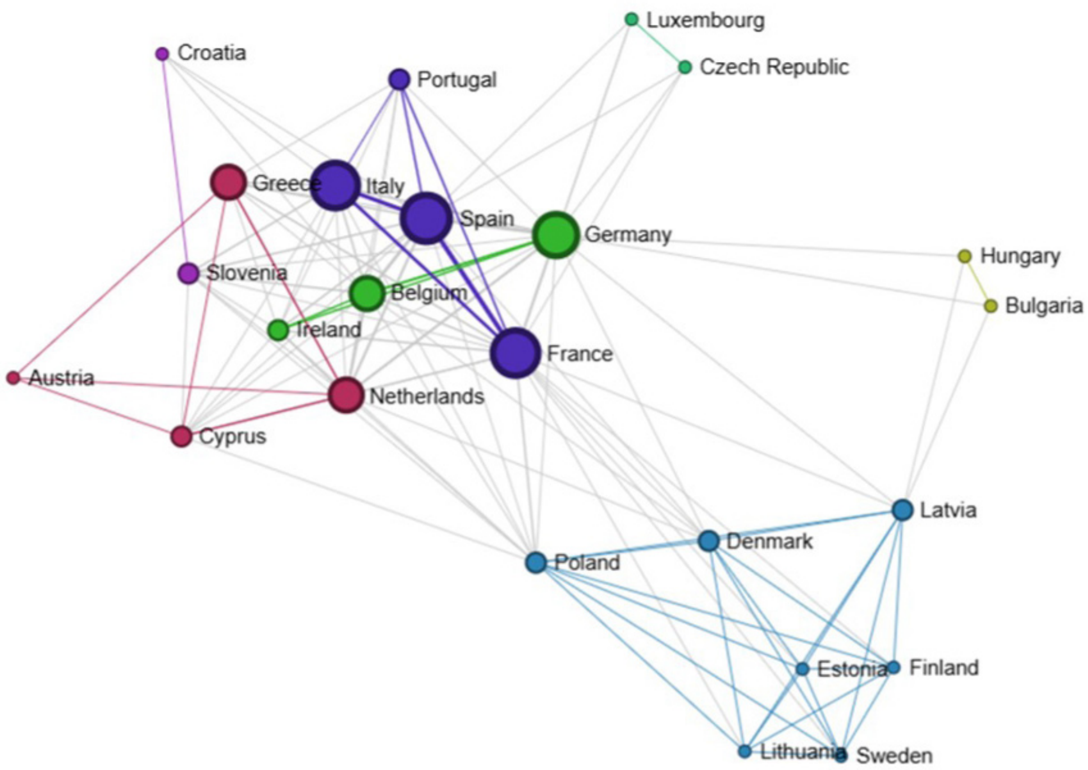


Figure 68: Pillar 6: Breakdown of projects by participating entity type

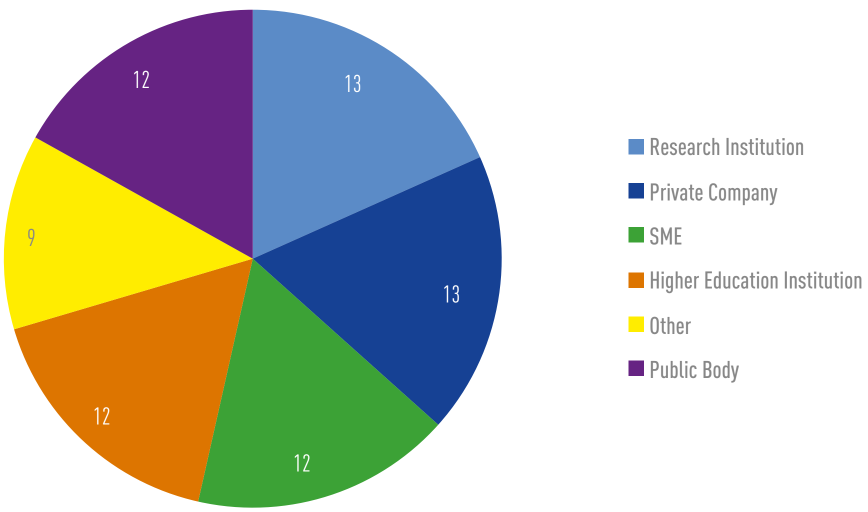


Figure 69: Pillar 6: Participation by organisation type across years

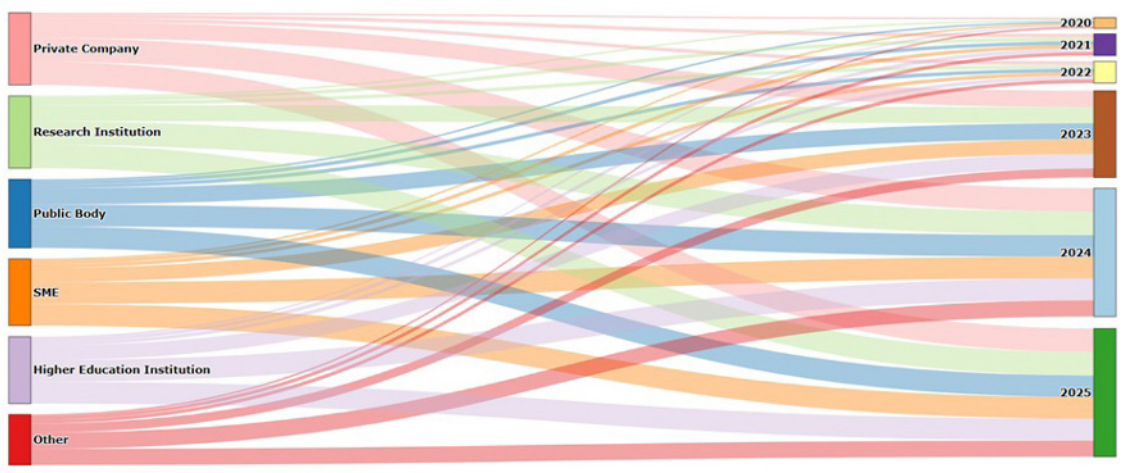


Figure 70: Pillar 6: Collaboration network of top participating institutions

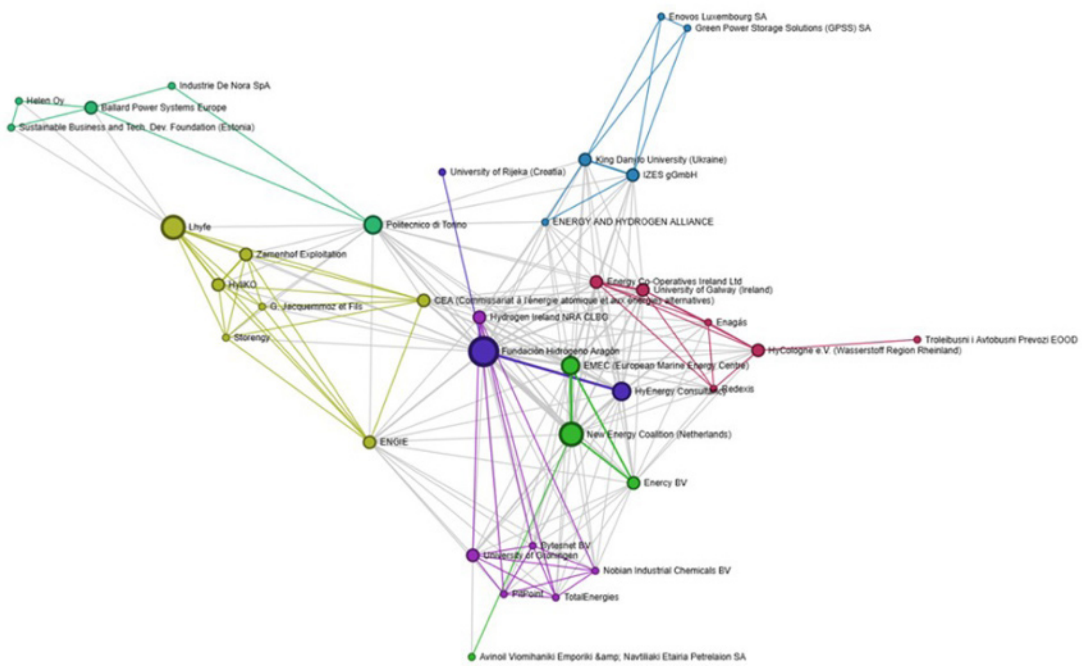
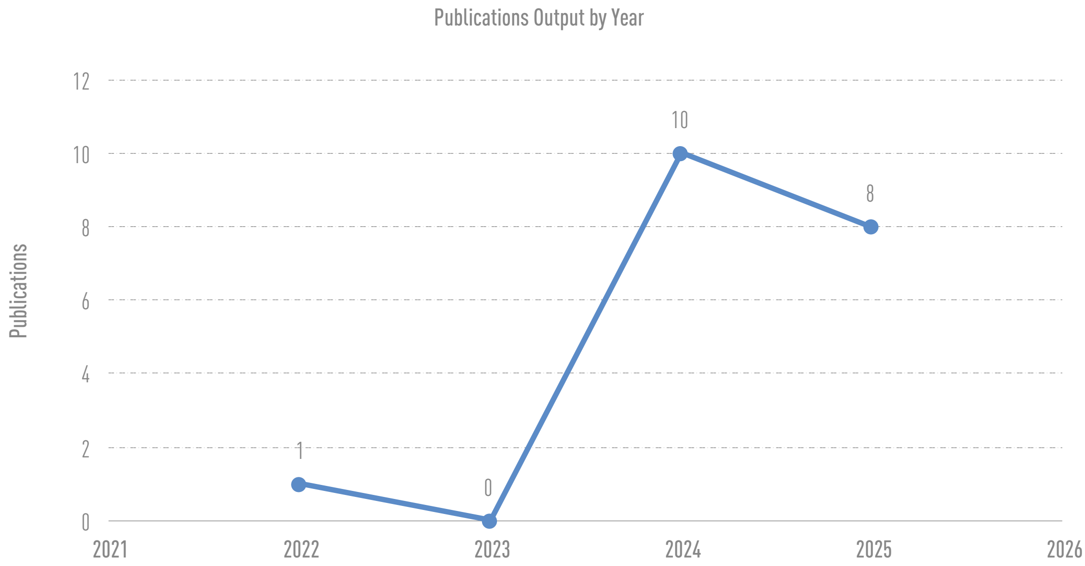
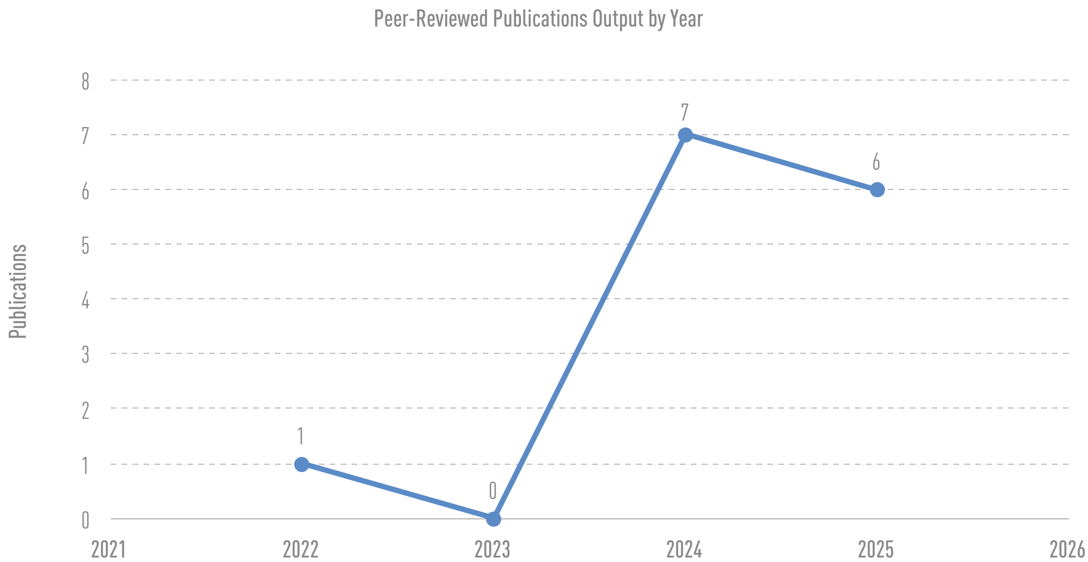


Figure 71: **Pillar 6: Number of publications per year**



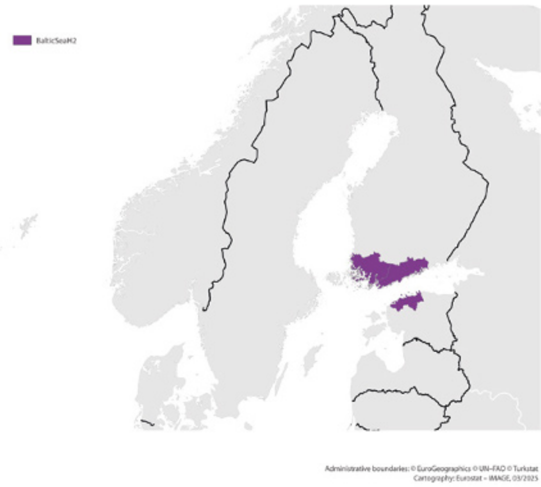


PROJECTS FACTSHEETS

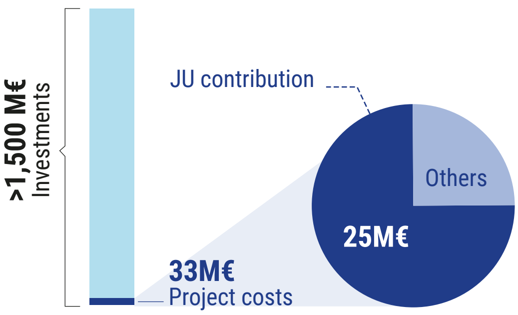
BalticSeaH2

CROSS-BORDER HYDROGEN VALLEY AROUND THE BALTIC SEA

Project ID	101112047
PRR 2025	Pillar 6 – H_2 Valleys
Call Topic	HORIZON-JTI-CLEANH2-2022-06-01
Coordinator Beneficiary	CLIC INNOVATION OY, FI
Project Period	01-06-2023 - 31-05-2028
Location	Crossborder Finland – Estonia

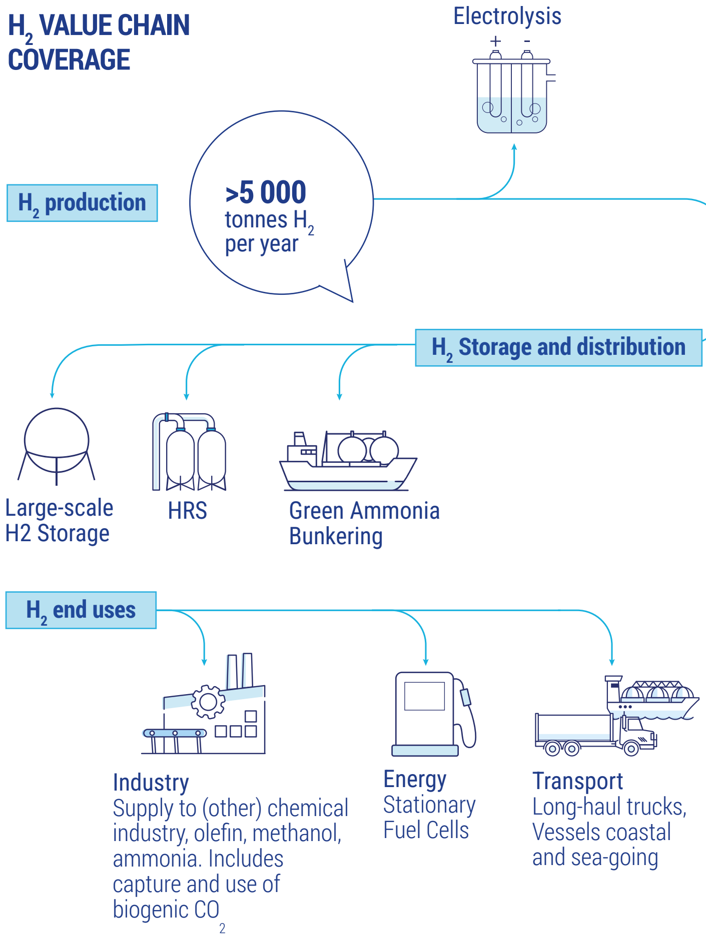


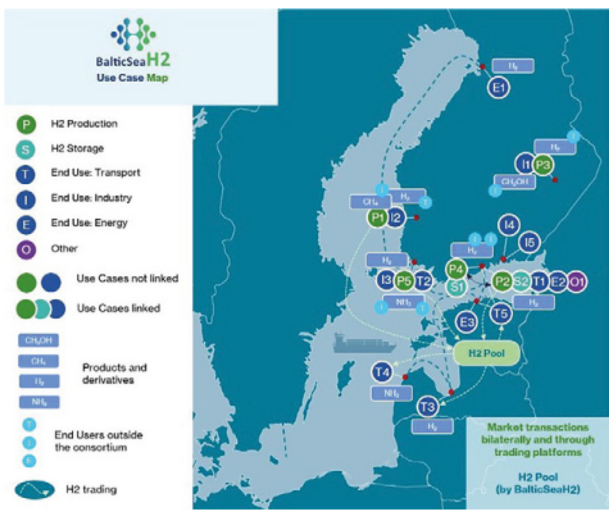
Finances



https://balticseah2valley.eu/

H_2 VALUE CHAIN COVERAGE





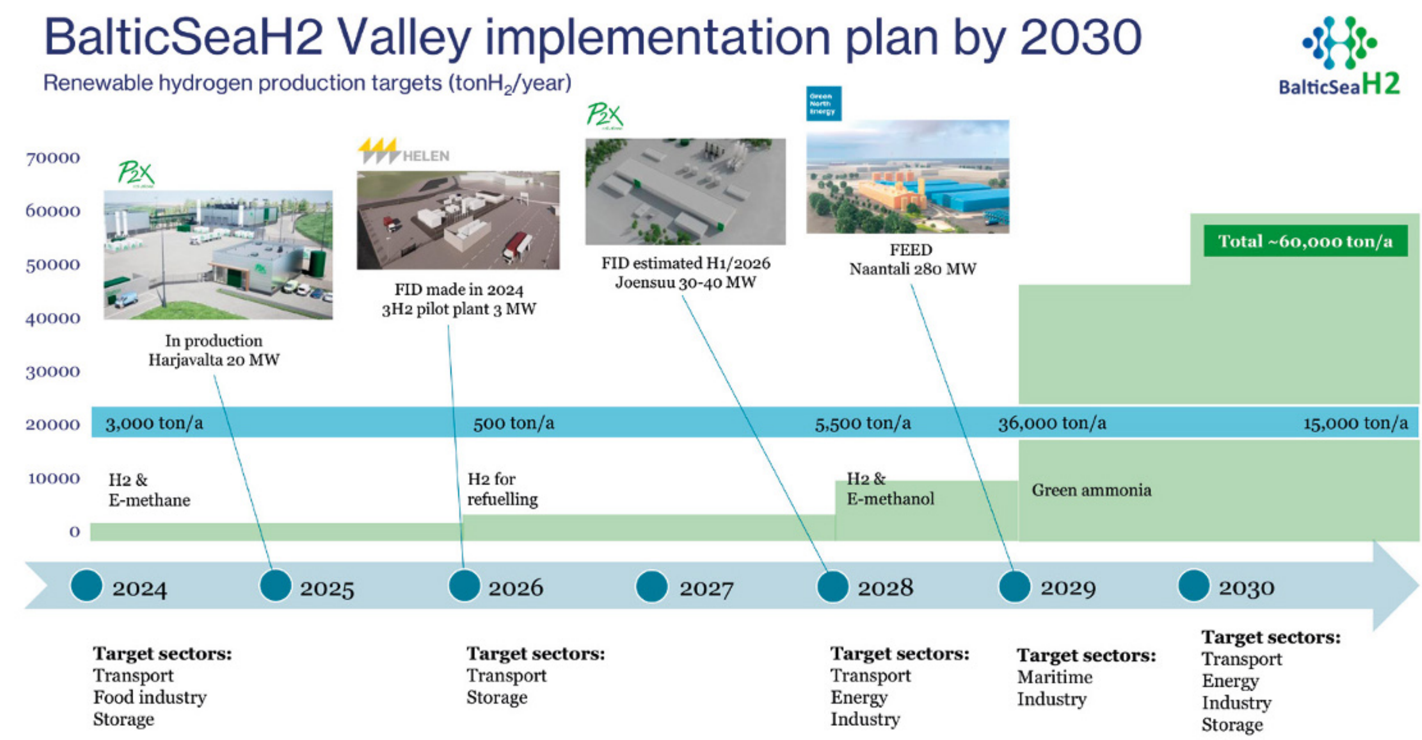
BalticSeaH$_2$ is building the largest cross-border hydrogen valley in Europe, between Finland and Estonia. The goal is to create an integrated hydrogen economy around the Baltic Sea to enable self-sufficiency of energy and minimise carbon emissions from different industries. Combining local areas into a broader valley supports creating a genuinely integrated, interregional hydrogen economy.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

- participation in events creating awareness of the valley's activities.
- development of the use cases and investment cases has started.
- as of February 2025, the valley has started producing green hydrogen

FUTURE STEPS AND PLANS

- Connected valleys are planned in Sweden, Denmark, Norway, Latvia, Lithuania, Poland and Germany
- Connected valleys are already actively involved in BalticSeaH$_2$ project activities but a replication toolkit and a best practices handbook are planned, to disseminate knowledge and lessons learned on building a local hydrogen economy featuring the whole hydrogen value chain.



Note: The plants that are already under construction have received investment financing from the Innovation Fund, IPCEI, RRF, or other funding from the Finnish ministry or the Finnish Climate Fund.

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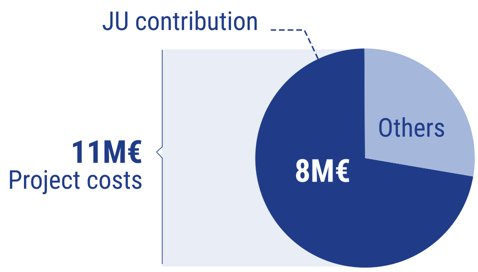
CRAVE-H$_2$

CRETE AEGEAN H$_2$ VALLEY

Project ID	101112169
PRR 2025	Pillar 6 – H$_2$ Valleys
Call Topic	HORIZON-JTI-CLEANH2-2022-06-02
Coordinator Beneficiary	EUNICE, EL
Project Period	01-06-2023 - 31-05-2028
Location	Greece

Finances



https://www.crave-h2.eu/

H$_2$ VALUE CHAIN COVERAGE

H$_2$ production

>500 tonnes H$_2$ per year

Electrolysis

H$_2$ Storage and distribution

HRS

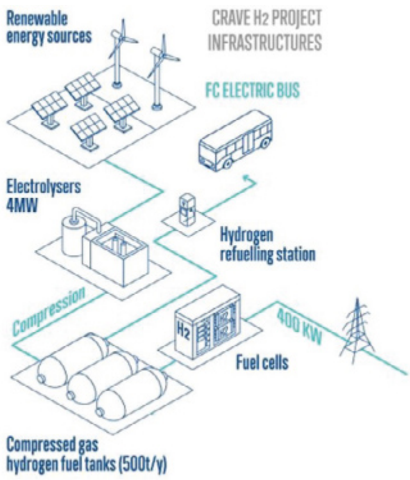
CGH$_2$ above-ground storage

H$_2$ end uses

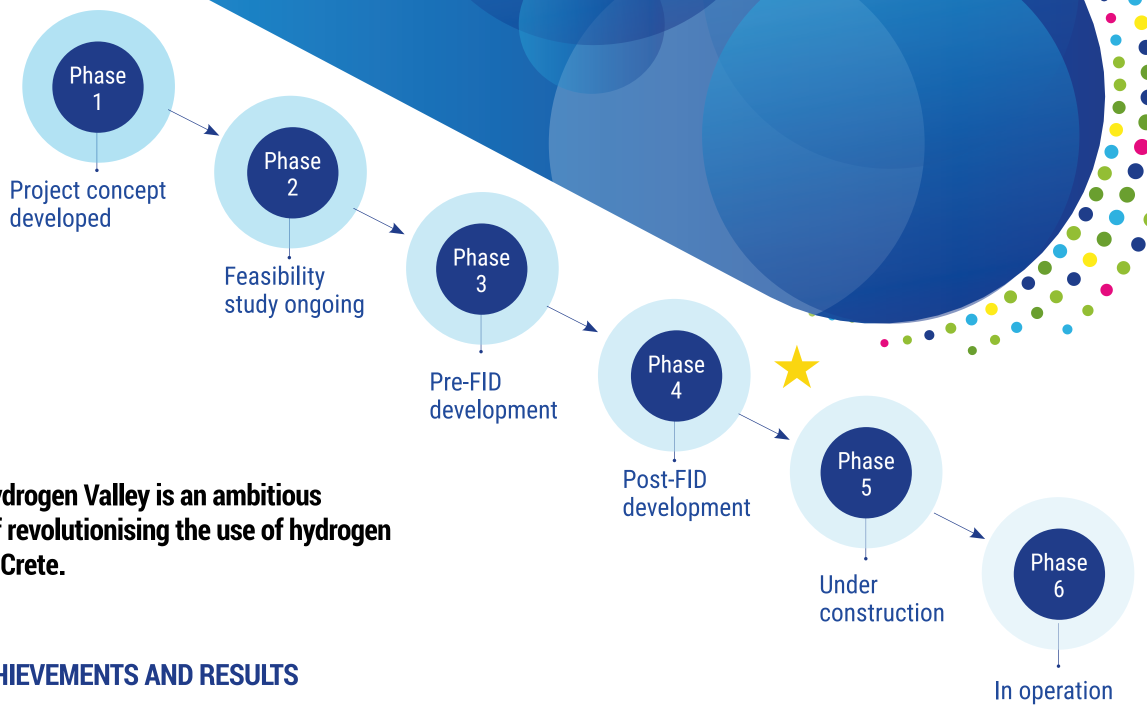
Energy
Stationary Fuel Cells

Transport
Coach Buses

Industry
Industry and other uses



PROJECT TIMELINE



The Cretan-Aegean Hydrogen Valley is an ambitious project with the aim of revolutionising the use of hydrogen on the Greek island of Crete.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

H_2 PRODUCTION PLANT

- Safety Plan prepared and submitted.
- Regulatory and licensing frameworks are being dddressed.
- Greek authorities were engaged to align hydrogen regulations.

INFRASTRUCTURE PROGRESS

- Preliminary environmental and infrastructure assessments were conducted.
- Preliminary layout and technical specs for all system components were developed.
- Alternative hydrogen distribution and storage methods were assessed.

TECHNOLOGIES DEVELOPMENT

- A 4 MW alkaline water electrolyser was designed.
- a hydrogen-powered fuel cell (FC) facility was designed.
- Technical specifications for a hydrogen coach bus were created.
- A hydrogen utilization plan was developed and is continuously updated.

OTHER

- Built strong relationships with policymakers, local authorities, and energy cooperatives.
- Participation in EU and national hydrogen events.
- Development and maintenance of the Crave-H_2 website and social media.
- Participation in key events like the Conference on Hydrocarbons and the European Hydrogen Valleys Investment Forum 2024, as well as EU and national hydrogen events
- Publishing of 2 peer-reviewed research papers in open-access journals.

FUTURE STEPS AND PLANS

- Finalise site design and permitting for hydrogen production and storage.
- Construct and install the hydrogen production and storage system.
- Complete permitting for the fuel cell plant.
- Construct and install the stationary FC plant.
- Select and commission a hydrogen FC bus supplier/manufacturer.
- Deliver and commission the hydrogen FC bus.
- Analyse alternative uses of hydrogen (e.g., in power plants, industry, maritime).
- Create and distribute promotional materials (posters, infographics, etc.).
- Produce the first project video.
- Participate in conferences, workshops, and seminars.
- Publish additional project results in scientific journals.
- Organize open discussions with local island residents.

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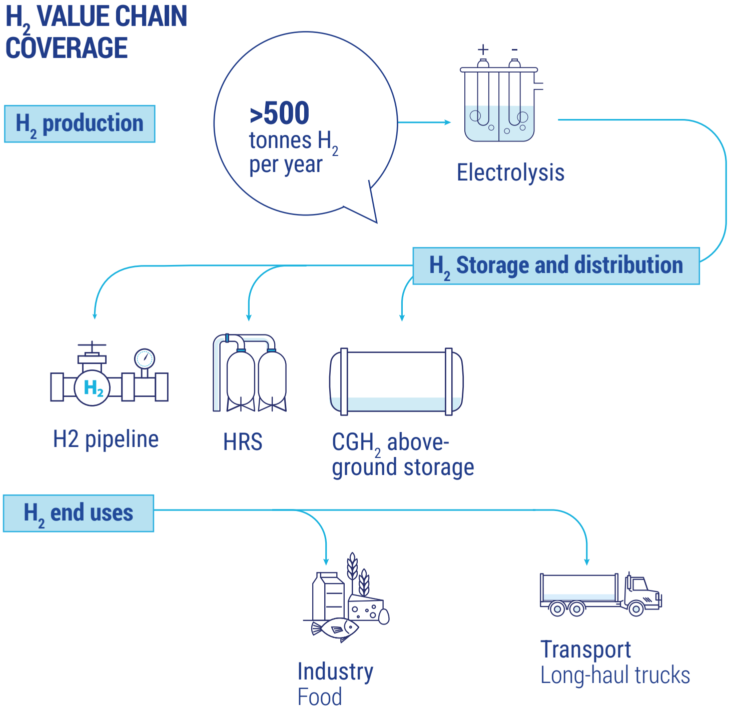
CONVEY

nordiC hydrOgen eNergy VallEY

Project ID	101137581
PRR 2025	Pillar 6 – H_2 Valleys
Call Topic	HORIZON-JTI-CLEANH2-2023-06-02
Coordinator Beneficiary	NORWEGIAN HYDROGEN AS, NO
Project Period	01-03-2024 - 28-02-2029
Location	Denmark



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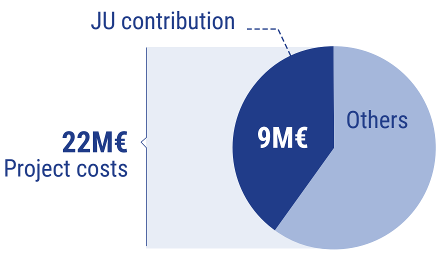

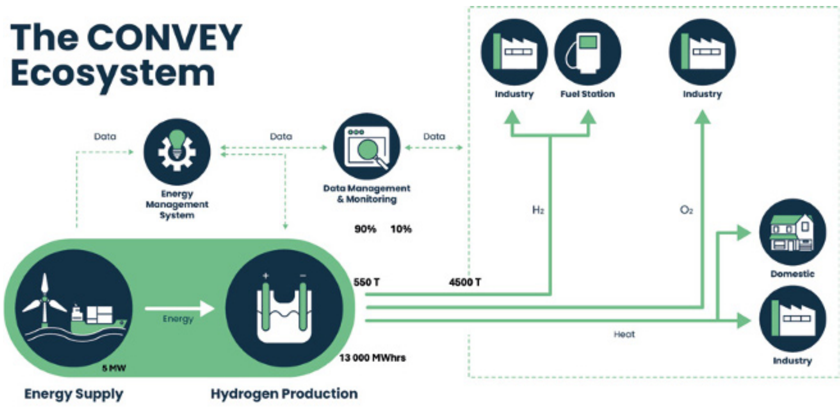

https://convey.energy/

PROJECT TIMELINE

Phase 1 — Project concept developed

Phase 2 — Feasibility study ongoing

Phase 3 — Pre-FID development ★

Phase 4 — Post-FID development

Phase 5 — Under construction

Phase 6 — In operation

The CONVEY project is based at Port of Hirtshals in Northern Denmark, where the consortium is developing and building a closed-loop ecosystem powered by green hydrogen. The aim is to leverage local renewable resources—in this case, wind energy—to create a sustainable cycle of production, use, and by-product integration that can benefit the port and the surrounding community.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

- A techno-economical model for the CONVEY ecosystem was developed and used to assess use cases and guide partners' investments.
- The model serves as the foundation for a future energy management tool, to be developed alongside infrastructure.
- Partners selected technologies for hydrogen and by-product production and usage, supporting engineering and permitting efforts.
- Dissemination and communication activities included stakeholder engagement, networking, a podcast series, newsletter, website, and social media.
- Replication efforts have begun, including identifying other ports where the CONVEY concept could be applied.

FUTURE STEPS AND PLANS

CONVEY is moving towards individual investment decisions on equipment for the Hydrogen Valley. The CONVEY ecosystem will be built, commissioned, and launched over the next two years.

- Progress is being made on:
  - ➤ Detailed engineering and permitting.
  - ➤ Contracts with customers for hydrogen and by-product offtake.
  - ➤ Beginning the construction phase.
- In parallel, the consortium is working on:
  - ➤ Business model development.
  - ➤ Raising awareness of the green hydrogen ecosystem through communication and dissemination.
  - ➤ Strengthening efforts for replication and scale-up.

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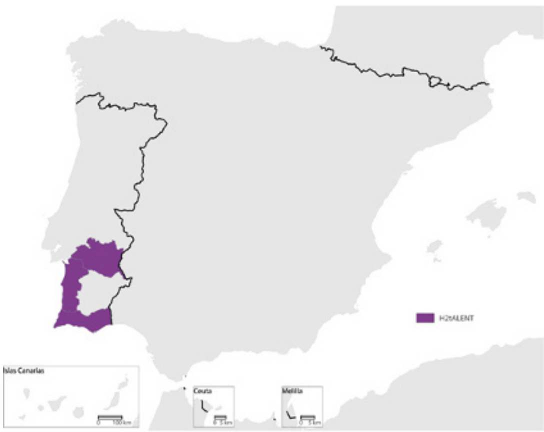
H_2tALENT

Alentejo Green Hydrogen Valley delivering integrated full-chain sustainable hydrogen ecosystem with technical, economic, social and environmental benefits and superior upscaling/replicability.

Project ID	101137611
PRR 2025	Pillar 6 – H_2 Valleys
Call Topic	HORIZON-JTI-CLEANH2-2023-06-02
Coordinator Beneficiary	UNIVERSIDADE DE EVORA, PT
Project Period	01-03-2024 - 28-02-2029
Location	Portugal



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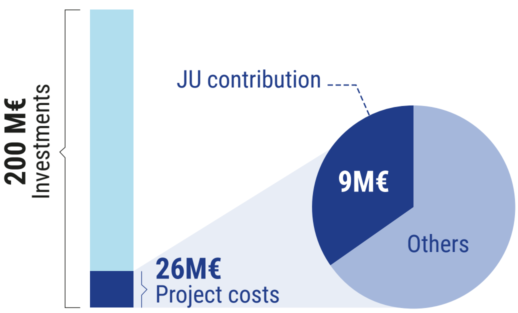
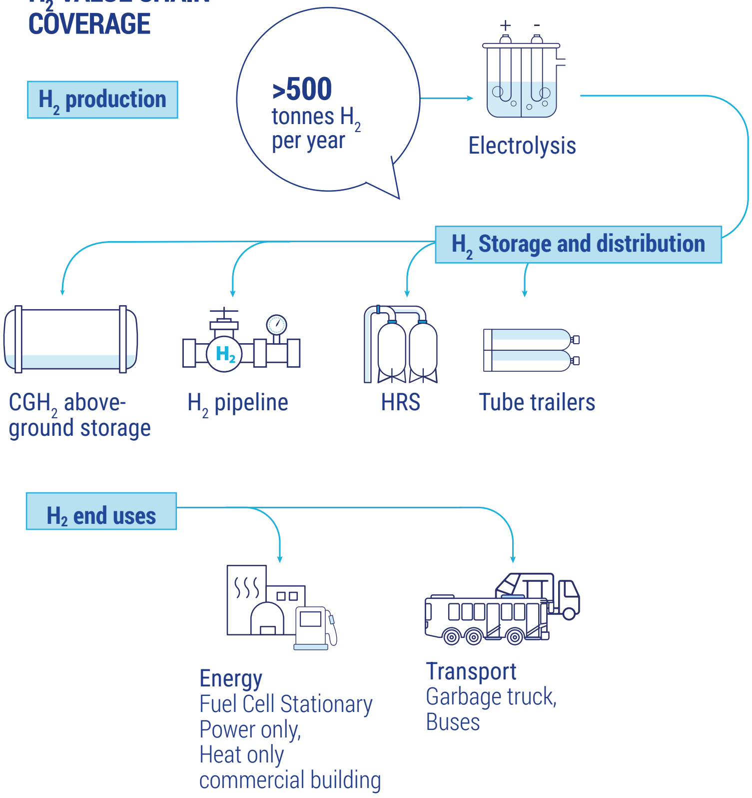
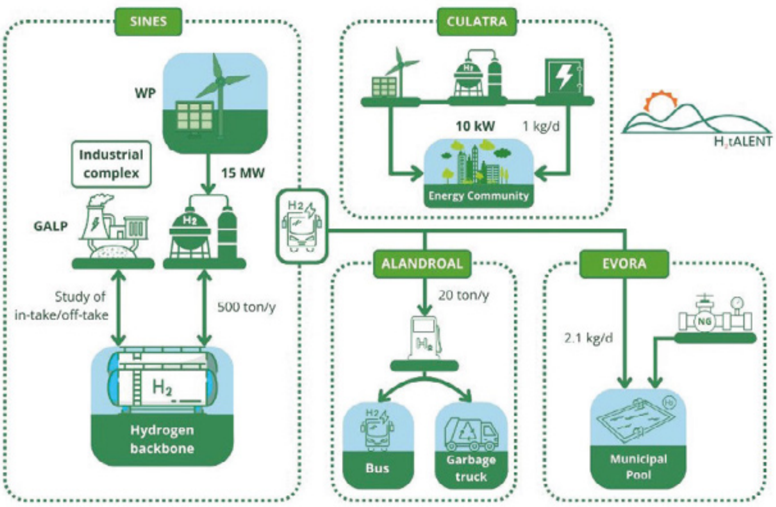


https://h2talent.eu/

H_2 VALUE CHAIN COVERAGE





PROJECT TIMELINE

Phase 1 — Project concept developed

Phase 2 — Feasibility study ongoing

Phase 3 — Pre-FID development

Phase 4 — Post-FID development

Phase 5 — Under construction

Phase 6 — In operation

H_2tALENT is creating a Hydrogen Valley in Alentejo, integrating “green” hydrogen into industry, mobility, and public infrastructure. The project aims to decarbonize key sectors, optimize hydrogen logistics, and establish models for hydrogen adoption in Europe.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

- The project governance structure to ensure consortium cohesion was established.
- Preliminary hydrogen safety measures were developed.
- The project management and data management plans were submitted.
- Progress was made in the hydrogen logistics and system integration strategies.

FUTURE STEPS AND PLANS

- Implementation of hydrogen demonstrators in Évora, Alandroal and Culatra island, integration with the Sines hydrogen backbone, finalization of regulatory and safety assessments, optimization of hydrogen logistics and expansion of international collaboration for replication in other regions.

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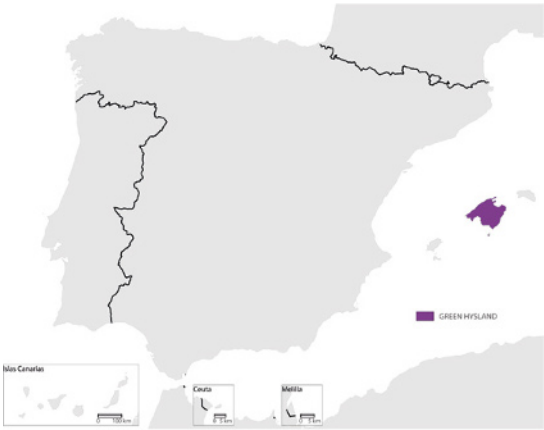
GREEN HYSLAND

DEPLOYMENT OF A H_2 ECOSYSTEM ON THE ISLAND OF MALLORCA

Project ID	101007201
PRR 2025	Pillar 6 – H_2 Valleys
Call Topic	FCH-03-2-2020
Coordinator Beneficiary	ENAGAS RENOVABLE SA, ES
Project Period	01-01-2021 - 31-12-2025
Location	Spain



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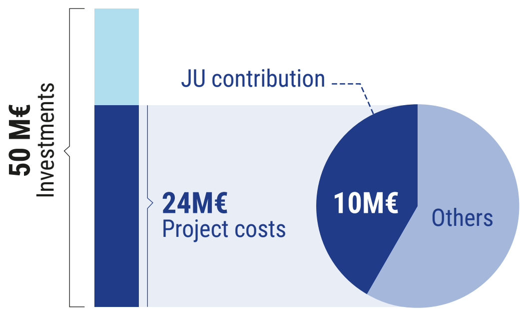
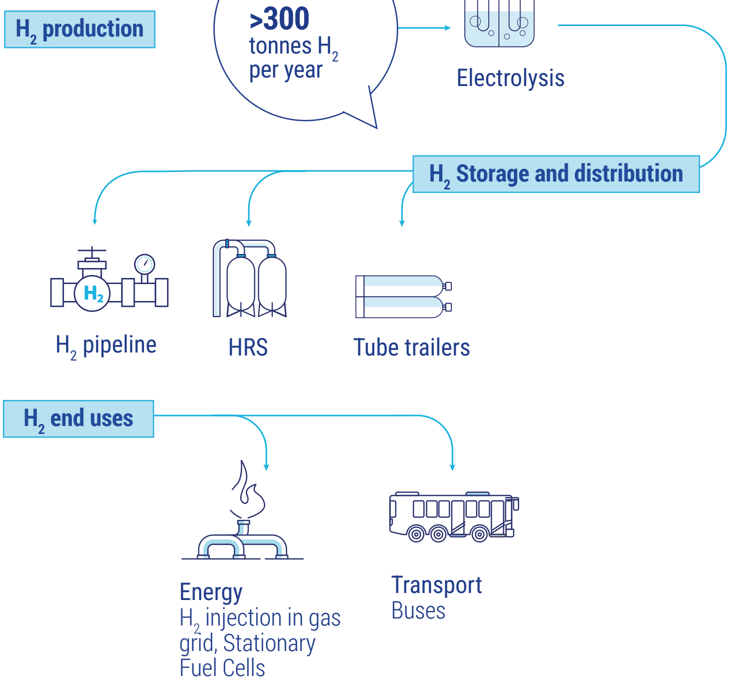
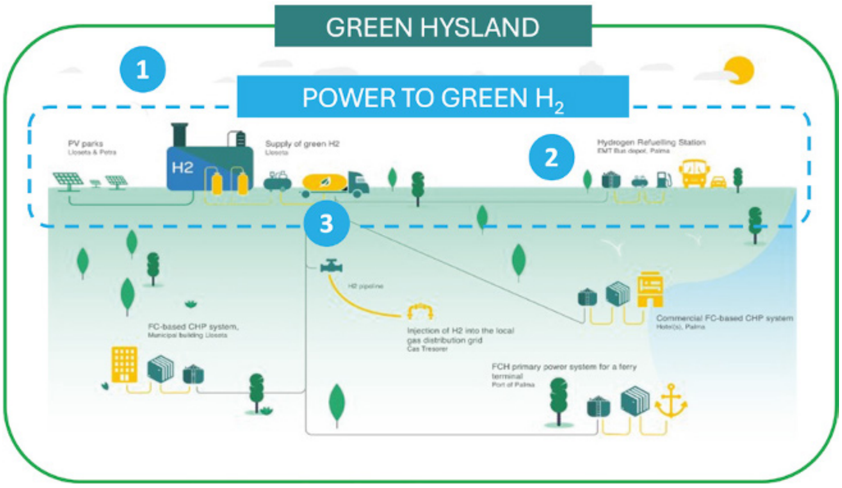


http://www.greenhysland.eu

H_2 VALUE CHAIN COVERAGE





PROJECT TIMELINE

- **2019** – Project concept developed
- **2020** – Grant Agreement Signature + Project Start
- **2021** – H_2 Value Chain Deployment preparation + Engineering
- **2022** – Permitting + Acquisition assets + Deployment & start construction
- **2023** – End of Civil works + End of deployment + FAT
- **2024-2025** – SAT + Start operation (H_2 Plant; Injection point & H_2 Buses)

The Green Hysland project aims to deploy a fully integrated and functioning H_2 ecosystem in the island of Mallorca, Spain.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

H_2 PRODUCTION PLANT

- Site Acceptance Tests (SAT) began in May 2024 and were completed in July 2024.
- Plant resumed operations in September 2024 to finalize the testing phase, successfully producing hydrogen molecules.
- Registered on the "Guarantees of Origin" platform in August 2024. Meanwhile, it has started industrial operation.

INFRASTRUCTURE PROGRESS

- Civil works for H_2 pipeline and blending station completed. Both are currently operational.
- First hydrogen injection into the grid occurred in September 2024.
- SATs for tube trailers completed; they are now fully operational.

FUEL CELL (FC) DEVELOPMENTS

- FC tender at Port of Palma awarded in November 2024 (11-month contract); design phase in progress.
- For Palma Hotel Iberostar:
  - ➤ FAT (Factory Acceptance Tests) of the FC stack conducted in July 2024.
  - ➤ Main stack equipment received in November 2024.
  - ➤ Civil works initiated in the first week of November 2024.
- Tourist and local survey data collection completed.
- Full Green Hysland project modeled in PERSEE, ready for simulations, optimization, and evaluation.
- Substantial progress has been made in drafting and researching a roadmap for hydrogen deployment in the Balearic Islands by 2050.

FUTURE STEPS

- Temporary H_2 portable dispenser for EMT bus depot was deployed in 2024 and EMT buses are now operating.
- Ongoing efforts to resolve the HRS (Hydrogen Refueling Station) situation; alternative solutions under evaluation.
- Fuel Cell at Iberostar Hotel is expected to be operational by end of 2025.
- SAT and training for Fuel Cell at Port of Palma scheduled for autumn 2025.
- Ongoing discussions to find a third party to join the project for vehicle deployment and operation.

Clean Hydrogen Partnership

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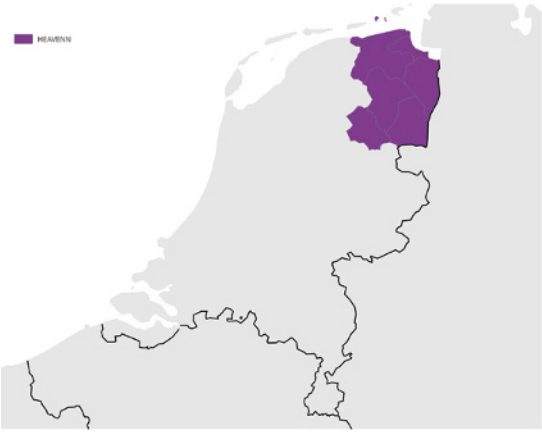
HEAVENN

HYDROGEN ENERGY APPLICATIONS FOR VALLEY ENVIRONMENTS IN NORTHERN NETHERLANDS

Project ID	875090
PRR 2025	Pillar 6 – H_2 Valleys
Call Topic	FCH-03-1-2019
Coordinator Beneficiary	STICHTING NEW ENERGY COALITION, NL
Project Period	01-01-2020 - 31-12-2027
Location	The Netherlands



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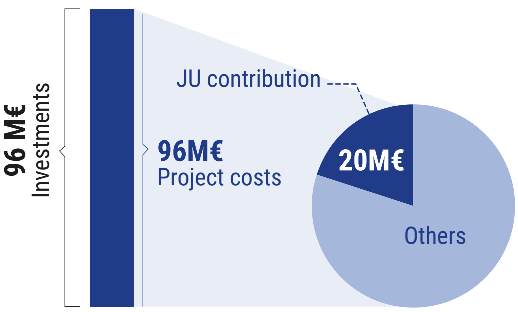
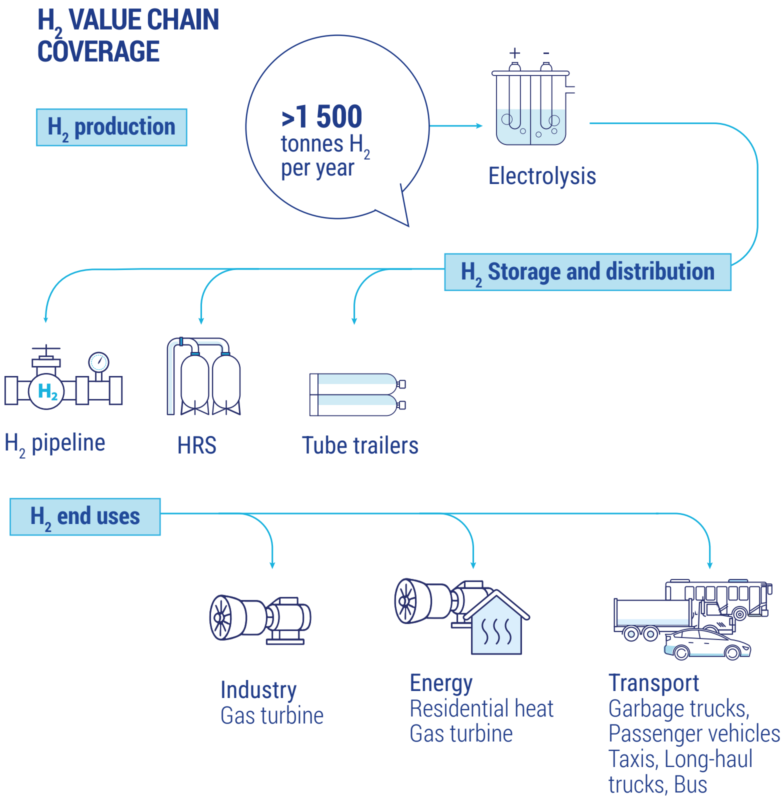
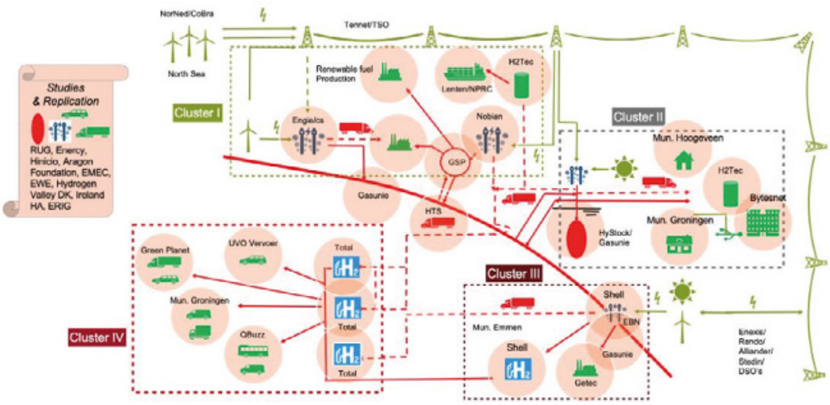


http://www.heavenn.org





PROJECT TIMELINE

- Phase 1: Project concept developed
- Phase 2: Feasibility study ongoing
- Phase 3: Pre-FID development
- Phase 4: Post-FID development
- Phase 5: Under construction
- Phase 6: In operation

HEAVENN is a large-scale demonstration project bringing together core elements production, distribution, storage and local end use of H_2 into a fully integrated and functioning hydrogen valley that can serve as a blueprint for replication across Europe and beyond.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

HYDROGEN APPLICATIONS

- Salt barge hull is currently sailing in the Netherlands using a container swap solution for hydrogen refuelling.
- Vehicles have been ordered or purchased and will be delivered this year.
- In Hoogeveen, construction has started on hydrogen-powered housing.
- The data centre hydrogen project is evaluating the best fuel cell type and size for its energy needs.

STORAGE AND DISTRIBUTION

- Salt cavern testing is ongoing and is being successful
- First static tests were successfully performed by Gasunie, showing that hydrogen can be safely stored in salt caverns.
- Designs and layout plans for future H_2 caverns are in progress.
- The Hydrogen Refueling Station (HRS) is operational and in use by partner UVO.
- The Emmen EMMHY pipeline is installed and ready to begin using hydrogen.

MARKETABILITY PROGRESS

- The connections specification study is complete, exploring market scenarios and design scalability; results include a plot plan and capacity-range definition.
- In Eemshaven, efforts are ongoing to matchmake for the pipeline, seeking customers and purchase agreements.
- The HyCC factory is progressing toward a Final Investment Decision (FID).
- The Hydrogen Hub is applying for a final co-financing subsidy and will proceed to FID after approval.

FUTURE STEPS AND PLANS

- A critical assessment of deliverables is planned.
- Tasks and deliverables will be reassessed and updated due to changes since the grant agreement.
- A few partners are awaiting cofounding; if secured, they plan to accelerate all actions.
- The consortium has been awarded a definitive extension, which aid partners in closing their business case and proceeding to FID.
- Significant effort will be made to connect hydrogen valley projects, focusing on:
  - Sharing experiences and lessons learned;
  - Creating synergies;
  - Mutual strengthening of projects.

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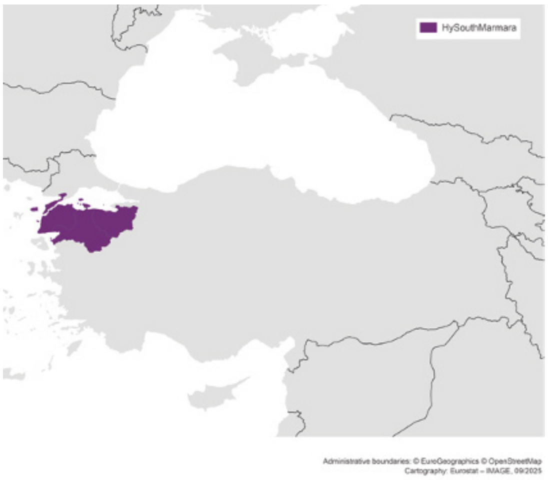
HYSouthMarmara

SOUTH MARMARA HYDROGEN SHORE

Project ID	101112054
PRR 2025	Pillar 6 – H_2 Valleys
Call Topic	HORIZON-JTI-CLEANH2-2022-06-02
Coordinator Beneficiary	GUNEY MARMARA KALKINMA AJANSI, TR
Project Period	01-07-2023 - 30-06-2028
Location	Türkiye



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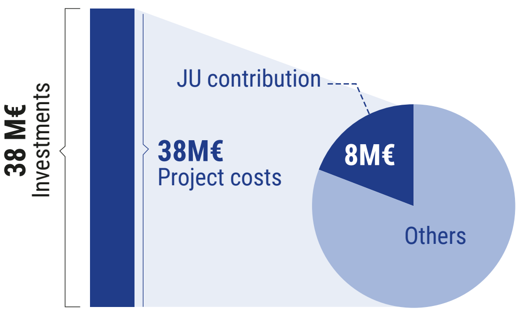
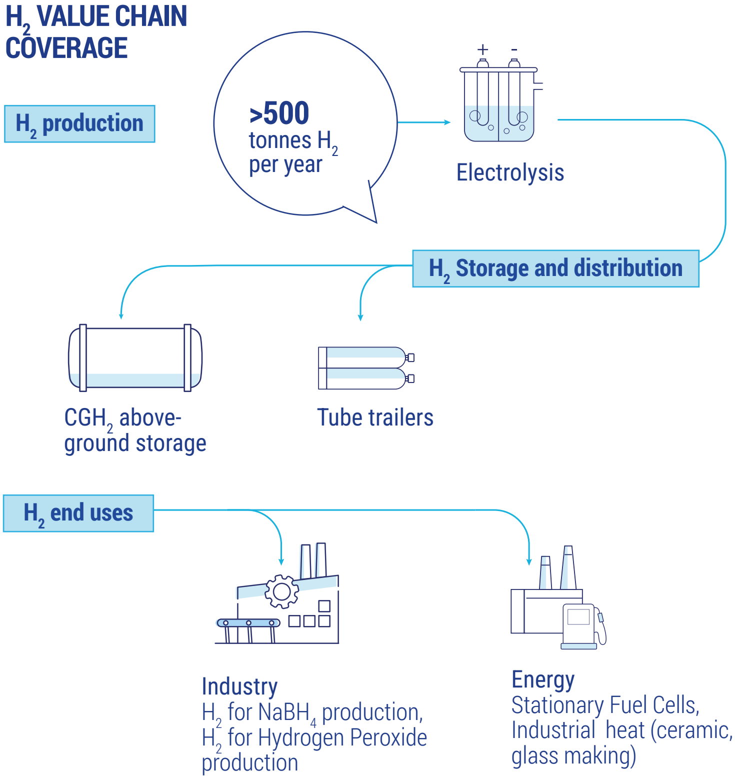
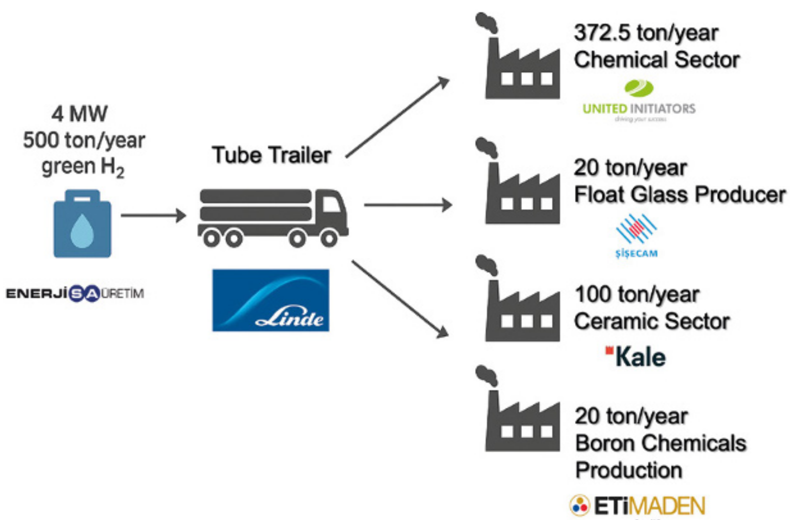


https://hysouthmarmara.org/en

H_2 VALUE CHAIN COVERAGE





PROJECT TIMELINE

HYSouthMarmara Valley Project will be the first solid step to ramp-up the hydrogen market and to boost hydrogen economy in the region, focusing on green hydrogen as well as liquid and solid derivatives such as ammonia, methanol and boron-hydrogen compounds.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

- The technical specifications for services related to the ***South Marmara Hydrogen Roadmap*** has been finalized.
- Contract signed for the tender process conducted by GMKA according to public procurement regulations.
- The Feasibility reports for a 50 000 tonnes/year green methanol plant and a 100 000 tonnes/year green ammonia plant are completed.
- Feasibility report for a 4 MW green hydrogen plant (including storage and transport) is completed.
- Final Investment Decision (FID) phase for work packages 2 and 3 is in progress.
- The technical design and specifications finalized for kiln components is underway:
  - ➤ General layout of kiln and pre-kiln.
  - ➤ Dampers' number/position and firing zone section insulation details.
  - ➤ Module lining drawings and list of refractory/insulating materials.
  - ➤ Specifications for rollers, fans, drivers, and electric control board.
- The first phase (tri-methyl metaborate production) of Sodium Borohydride Pilot Plant is completed.
- Stakeholder engagement through meetings and site visits for feedback and collaboration.
- A Hydrogen Valleys Workshop was organized with public, private, and academic participation to discuss green hydrogen's future in Türkiye and the EU.

FUTURE STEPS AND PLANS

- The ***South Marmara Hydrogen Roadmap*** is expected to be finalized by end of 2025, laying the groundwork for the region's strategic hydrogen development.
- Development of the Strategic Business Model for South Marmara.
- For work packages 2 and 3, FID will be taken.
- Use of green hydrogen in chemical and glass industries of the regions.
- Construction design of the hybrid kiln will be finalized and construction phase of the kiln will be initiated.
- Efficiency improvement studies for Sodium BoroHydride (SBH) will be completed in the laboratory and Eti Maden will move to the phase of procurement of equipments and installation of the facility for SBH plant.
- HYSouthMarmara has implemented a Learn and Teach strategy within the project, which includes site visits to both mature and early-stage valleys. Those site visits, along with in-person meetings, will be conducted in the future.
- The consortium will go on participating in national and international organizations to introduce Turkiye's first Hydrogen Valley Project.

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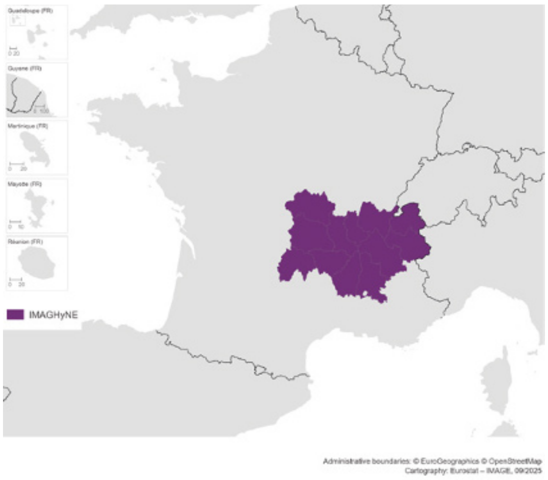
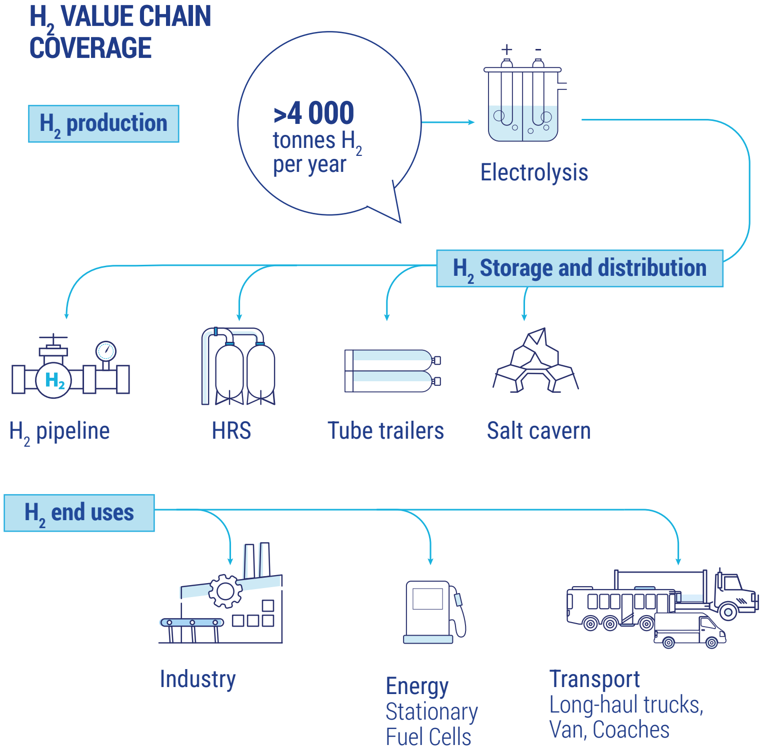
IMAGHyNE

IMAGHYNE: INVESTMENT TO MAXIMISE THE AMBITION FOR GREEN HYDROGEN IN EUROPE

Project ID	101137586
PRR 2025	Pillar 6 – H_2 Valleys
Call Topic	HORIZON-JTI-CLEANH2-2023-06-01
Coordinator Beneficiary	REGION AUVERGNE RHONE ALPES, FR
Project Period	01-01-2024 - 31-12-2029
Location	France



H_2 VALUE CHAIN COVERAGE



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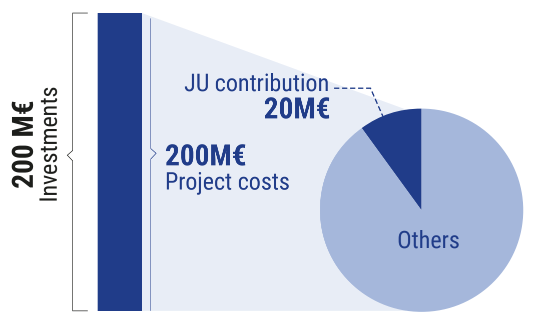

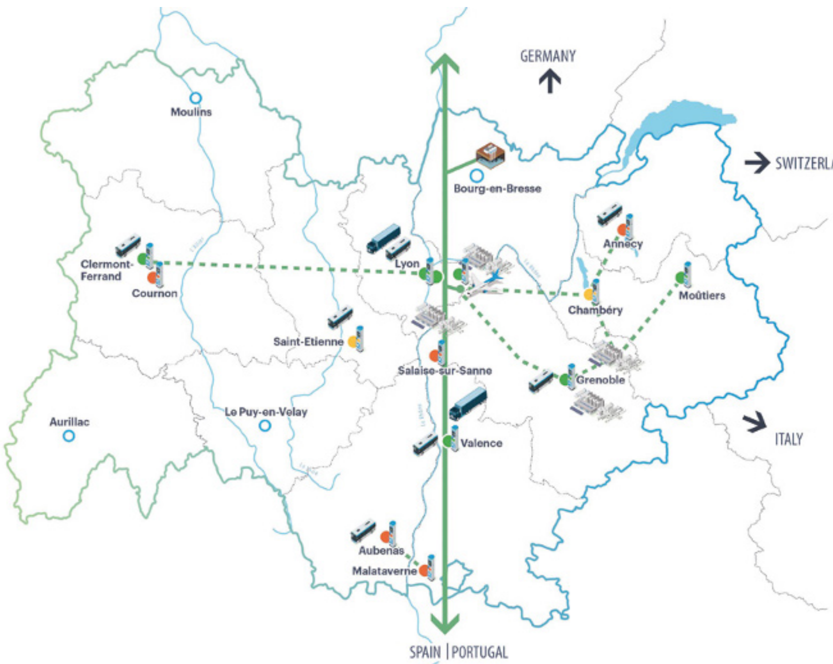

www.imaghyne.eu

IMAGHyNE will pave the way for the deployment of a large-scale renewable hydrogen (H_2) economy in the Auvergne-Rhône-Alpes region, fully integrated in the energy system and addressing the needs of high emitting sectors.

OBJECTIVES

- Strengthen the robustness of the overall energy and hydrogen supply chain by integrating a flexible industrial player in the ecosystem.
- Design an efficient pipeline-based multi-user hydrogen system and provide evidence to help settle on the optimum hydrogen transport and storage technology choice(s) for wider rollouts.
- Prepare for additional large-scale deployment as part of the Valley extension and its replication in Europe and beyond.
- Disseminate and communicate the results of the project to technical and institutional stakeholders, as well as general public to foster a faster adoption of hydrogen technologies at European level.

Clean Hydrogen Partnership
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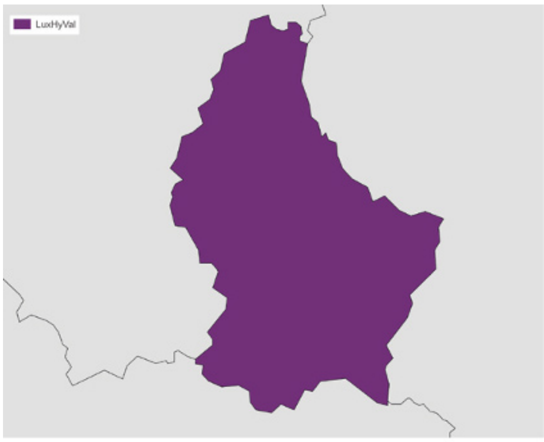
LuxHyVal

Luxembourg Hydrogen Valley delivering integrated full-chain sustainable hydrogen ecosystem with technical, economic, social and environmental benefits and superior replicability.

Project ID	101111984
PRR 2025	Pillar 6 – H_2 Valleys
Call Topic	HORIZON-JTI-CLEANH2-2022-06-02
Coordinator Beneficiary	UNIVERSITE DU LUXEMBOURG, LU
Project Period	01-11-2023 - 31-01-2029
Location	Luxembourg



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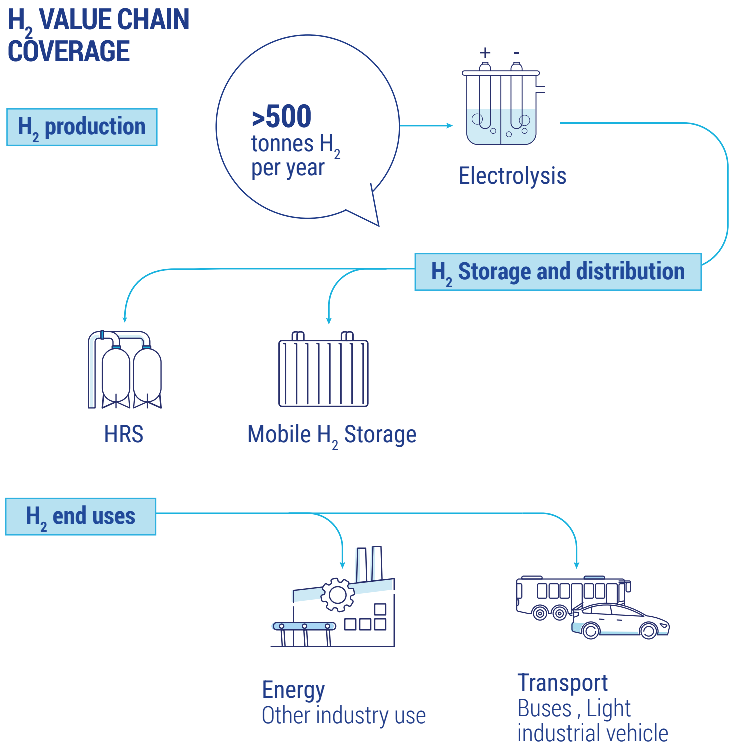

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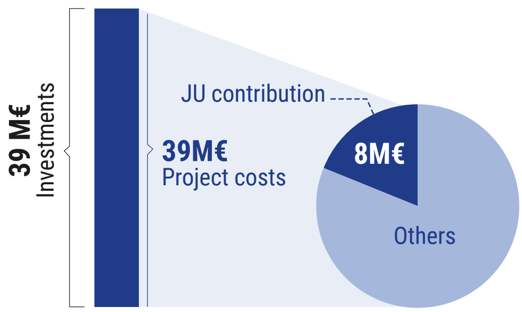

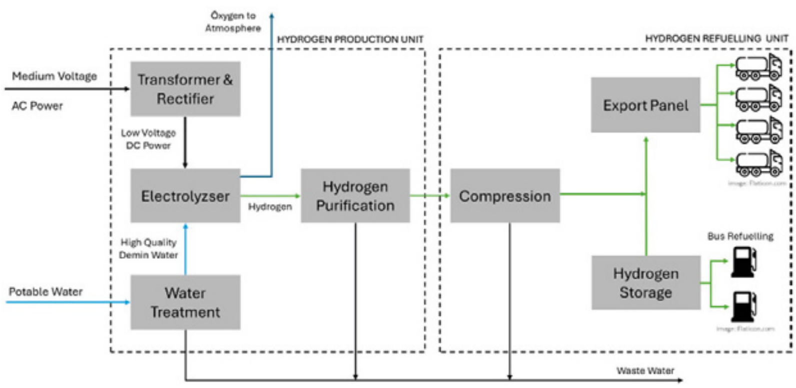

https://luxhyval.eu/

PROJECT TIMELINE

- **2021** – Feasibility study with national support
- **2023** – **Nov.** official CHP-funded project start
- **2024** – National call for pilot-scale H_2 production
- **2025** – **May.** allocation of national funding; **June.** Procurement step 1 (qualification); **Aug.** Procurement step 2 (three complete EPC contractor bids) + Negotiations/selected contractor, award Contract (effectively FID)
- **2026** – Construction phase
- **2027** – Q1 First deliveries
- **2027 - 2028** – Phase 2, additional off-take and PPAs + Ramp to 500+ tonnes/annum
- **2029** – **Feb.** completion of CHP-funded EU project
- **2037** – Completion of first ten years operation with nationally-funded production subsidy

LuxHyVal launches a flagship hydrogen valley in Luxembourg to boost the penetration of hydrogen by deploying green hydrogen initiatives across the entire value chain from local production to utilisation, including storage and distribution for a range of applications targeting industry and mobility, while also aiming to connect with existing/planned infrastructures.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

PROJECT MANAGEMENT, COMMUNICATION AND DISSEMINATION

- Tailored and implemented project management practices, including communication platform, templates and the organization of three general assemblies.
- Developed and executed a communication and dissemination strategy, including a project identity, website, social media, launch event, press release, and participation in conferences, workshops and roundtable discussions.

PUBLIC PERCEPTION AND ACCEPTANCE OF H_2 TECHNOLOGIES

- Ongoing analysis of hydrogen technologies perception and acceptance, to establish baseline understanding and identify gaps in H_2 technology perception:
  - ➤ Stakeholder analysis was conducted, and results are being analysed.
  - ➤ Social assessment and perception analysis for H_2 technologies are in progress.
  - ➤ Methodology for data collection through a national survey in 4 languages (for Luxembourgish residents) has been developed.

BUSINESS MODELS

- Tailored business models for key products and services are completed, focusing on electrolyser, storage, and HRS (Hydrogen Refuelling Station), CAPEX, OPEX and electricity procurement.

PLANNING AND DESIGN OF INFRASTRUCTURE

- Detailed technical design and safety plan are under development.

FUTURE STEPS

- Continued focus on enhancing project communication and visibility.
- Ongoing work on planning and technical design of the infrastructure.
- Start deployment and commissioning of the plant and related infrastructure.
- Focus on the production, storage, distribution, and use-cases of the system.
- Evaluate the project's life cycle (Project Life Cycle Assessment (LCA)) and overall performance.
- Conduct an assessment to extract lessons learned and areas for improvement.
- Develop a digital twin for optimizing, replicating, and scaling the valley project.
- Continue to work on exploitation of ERs (Energy Resources or related elements).

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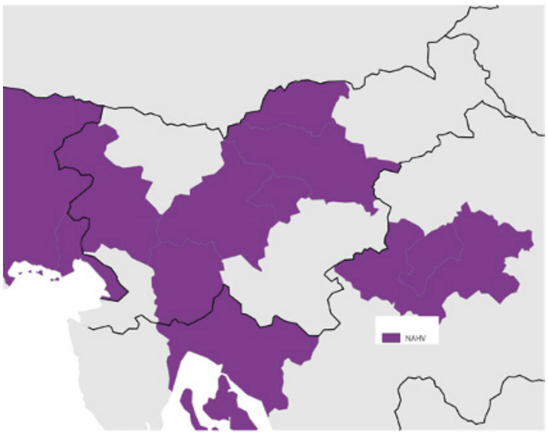
NAHV

NORTH ADRIATIC HYDROGEN VALLEY

Project ID	101111927
PRR 2025	Pillar 6 – H_2 Valleys
Call Topic	HORIZON-JTI-CLEANH2-2022-06-01
Coordinator Beneficiary	HOLDING SLOVENSKE ELEKTRARNE (HSE), SI
Project Period	01-09-2023 - 31-08-2029
Location	Crossborder Italy – Croatia – Slovenia



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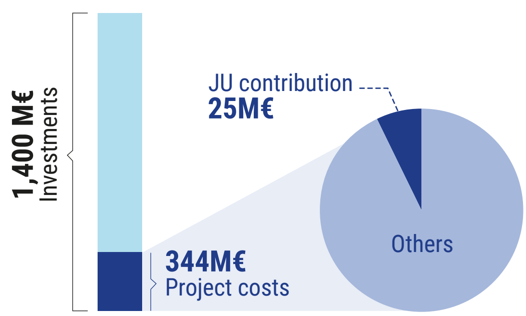
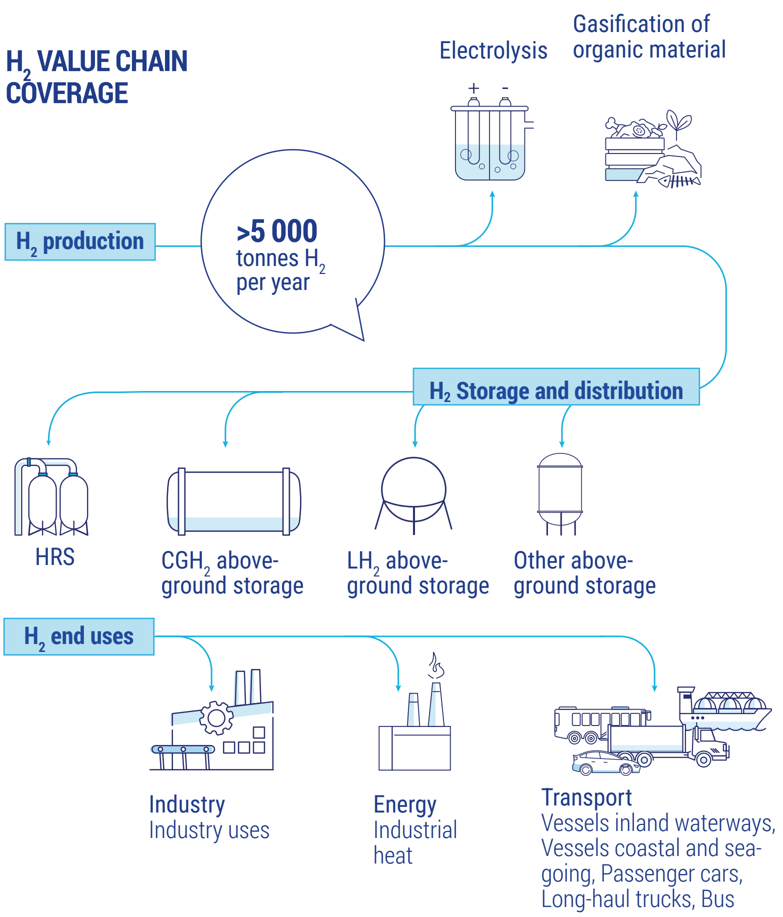
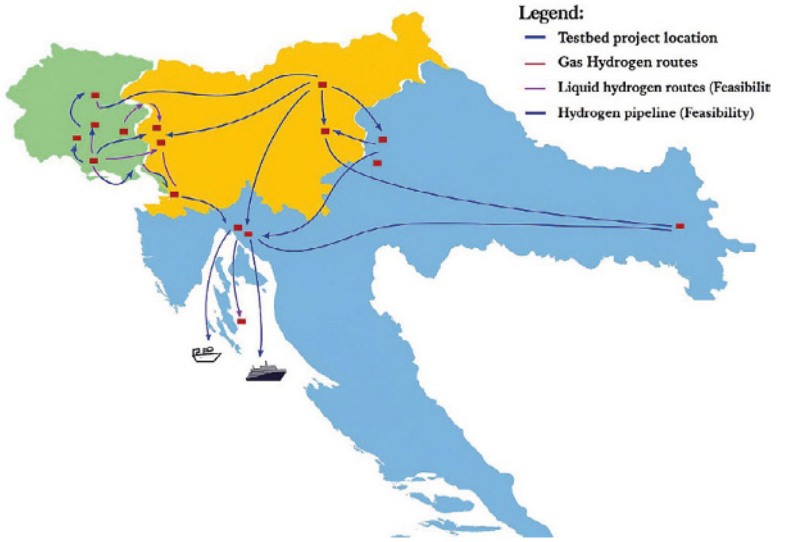
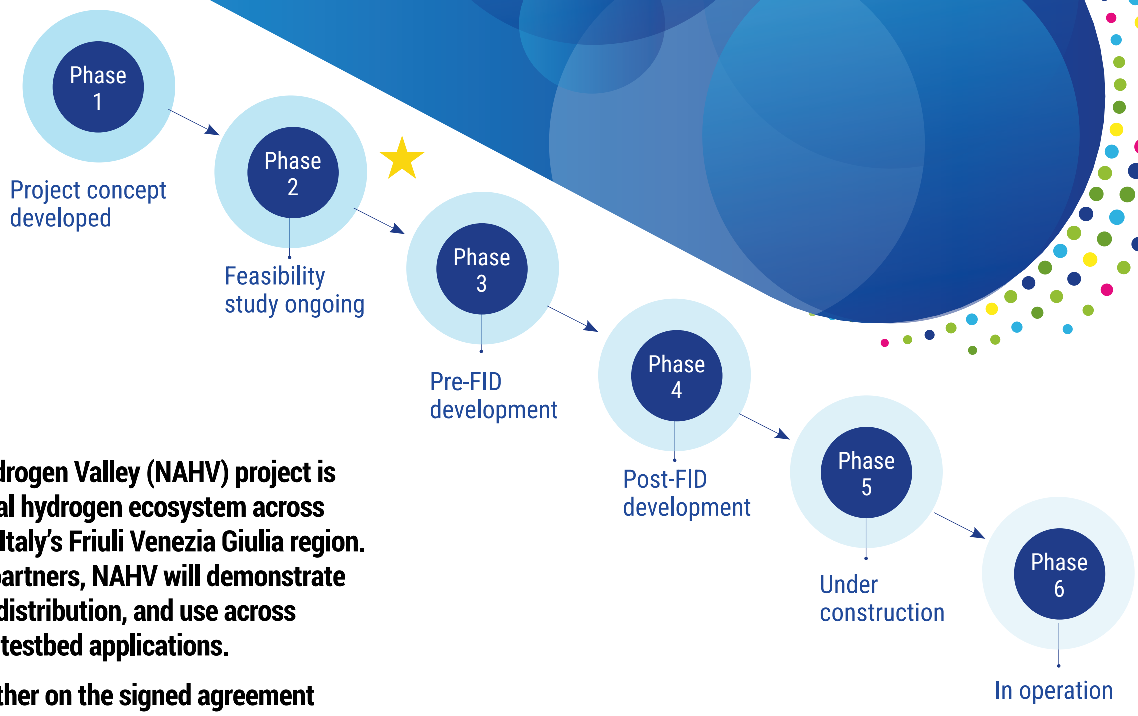


https://www.nahv.eu/





PROJECT TIMELINE



The North Adriatic Hydrogen Valley (NAHV) project is building a transnational hydrogen ecosystem across Slovenia, Croatia, and Italy's Friuli Venezia Giulia region. Bringing together 37 partners, NAHV will demonstrate hydrogen production, distribution, and use across industries, piloting 17 testbed applications.

This project builds further on the signed agreement between the Slovenian State Secretary of the Ministry of Infrastructure, the Croatian State Secretary of the Ministry of Economy and Sustainable Development, and the President of the Friuli Venezia Giulia Autonomous Region, recognizing the relevance of regional cooperation and a cross-border hydrogen valley in boosting energy transition and promoting sectorial integration between transport, hard-to-abate industries, and end users in an integrated ecosystem.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

PROJECT MANAGEMENT AND FINANCING

- The establishment of an Association Internationale Sans But Lucratif (AISBL) under Belgian Law is underway, including preparing the formal documentation, definition of the business plan and organizational model, and determination of financial needs and ways to source for additional funding. The NAHV AISBL will be supported by the 3 involved countries, and it will become the governing body of the NAHV ecosystem, going far beyond the NAHV project.
- A Stakeholders Advisory Forum (SAF), including over 47 organizations from business, academia, civil society, and policy institutions, has been formed to ensure local voices influence the project. This participatory model strengthens transparency, equity, and local engagement.
- 17 pilot projects to demonstrate hydrogen applications across different sectors have been launched. These projects serve as real-world testbeds, helping to increase the technology readiness level of the technologies involved in the project:

➤ In Croatia, a hydrogen-powered kiln in Dilj, Vinkovci, is expected to reduce CO_2 emissions by more than 20% and energy consumption by over 10%.

➤ In Trieste, Italy, ACEGAS has launched a hydrogen production initiative for logistics and public transport, with an expected annual output of 370 tonnes.

➤ In Slovenia, the cement industry in Anhovo is utilizing hydrogen to fuel transport trucks, with an estimated production of 50 tonnes per year.

➤ HSE in Ljubljana has deployed a 3 MW PEM electrolyser with an initial hydrogen production capacity of 300 tonnes per year, with plans to scale up to 30 MW and 3 000 tonnes annually.

FUTURE STEPS AND PLANS

Future steps will focus on:

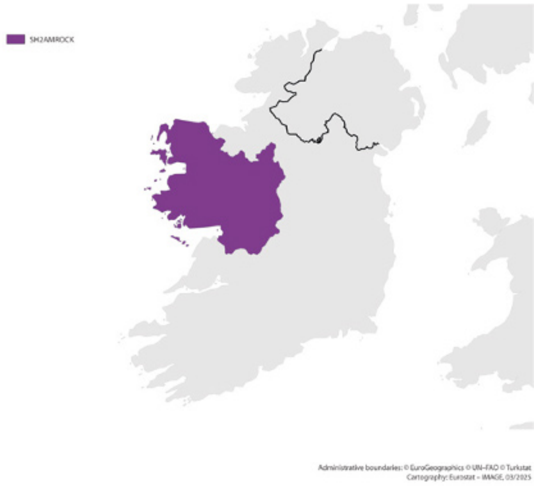
- Scaling up hydrogen production.
- Finalizing regulatory frameworks, by tackling the challenge of regulatory fragmentation in hydrogen policy in the participation countries: the project is piloting regulatory sandboxes, developing certification schemes, and proposing roadmaps for policy alignment.
- Encouraging further private sector investment: The established AISBL will help particular beneficiaries to find missing public funding and/or try to allocate a particular testbed or project task within the territory to allow for further funding.
- Developing and testing a model for mutualization of hydrogen production, distribution and storage that can be replicated in other hydrogen valleys.

Clean Hydrogen Partnership
Co-funded by the European Union

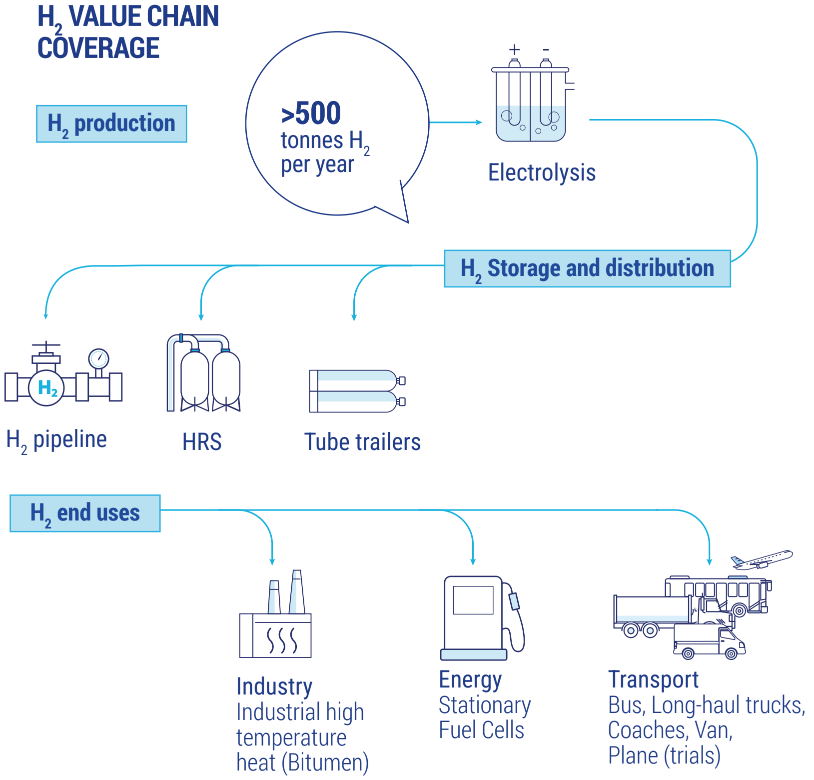
$SH_2AMROCK$

SOURCING HYDROGEN FOR ALTERNATIVE MOBILITY, REALISING OPPORTUNITIES AND CREATING KNOW HOW IN IRELAND

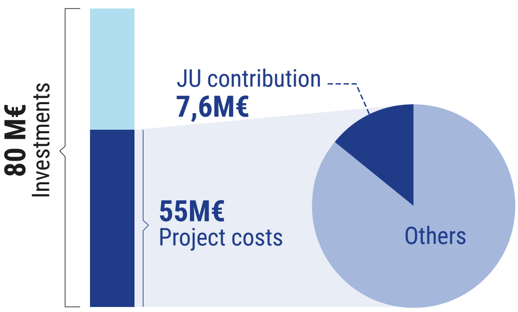
Project ID	101112039
PRR 2025	Pillar 6 – H_2 Valleys
Call Topic	HORIZON-JTI-CLEANH2-2022-06-02
Coordinator Beneficiary	UNIVERSITY OF GALWAY, IE
Project Period	01-01-2024 - 31-12-2028
Location	Ireland



H_2 VALUE CHAIN COVERAGE



Finances



https://www.sh2amrock.eu/

PROJECT TIMELINE

Phase 1 — Project concept developed
Hydrogen transport & dispensing

Phase 2 — Feasibility study ongoing
Hydrogen end users

Phase 3 — Pre-FID development
Hydrogen production & compression

Phase 4 — Post-FID development

Phase 5 — Under construction

Phase 6 — In operation

$SH_2AMROCK$ will deploy green hydrogen across key hard-to-abate sectors across the island of Ireland - including key infrastructure to enable the production, distribution, and use of green hydrogen.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

PROJECT MANAGEMENT AND FINANCING

- Project management team set in place and 1st General Assembly held in December 2024.
- Efforts have been focused on setting up and organising the project's operational and management structure. The Governance structure has been set up and 11 Steering Committee meetings & 3 General Assembly (GA) meetings held to date.
- Efforts to source additional funding are underway, including with the Irish Department of Environment and Climate Action and Department of Transport and other potential national funders.

INFRASTRUCTURE PROGRESS:

- Planning permission complete for Hydrogen Production Site.
- Detailed engineering design completes.
- Design concept for use site under development.

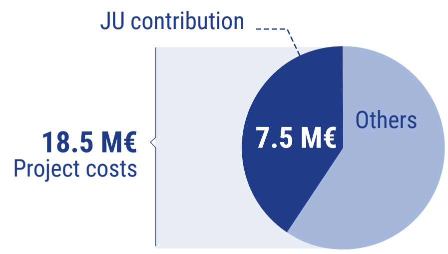
Clean Hydrogen Partnership
Co-funded by the European Union

TH$_2$ICINO

Towards H$_2$ydrogen Integrated eConomies In NOrthern Italy

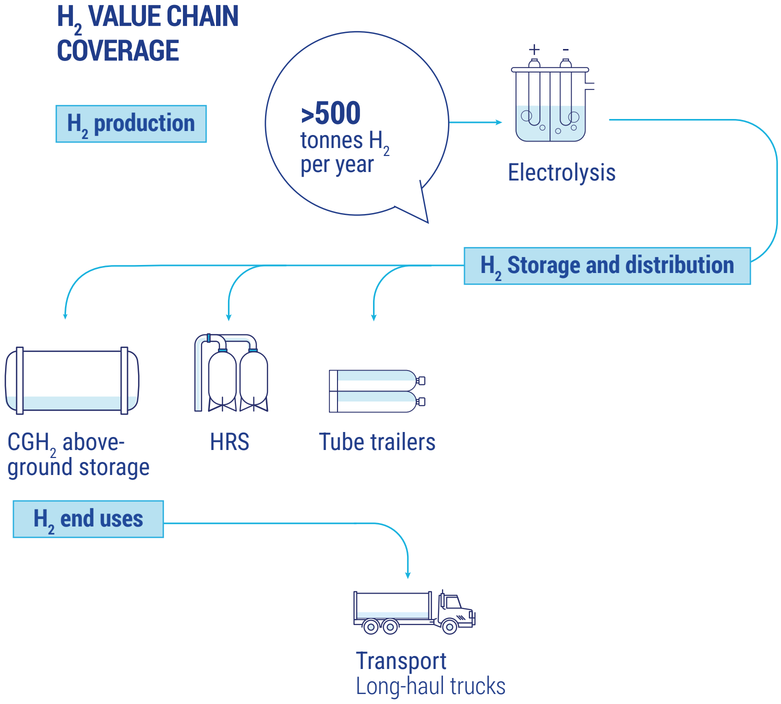
Project ID	101112098
PRR 2025	Pillar 6 – H$_2$ Valleys
Call Topic	HORIZON-JTI-CLEANH2-2022-06-02
Coordinator Beneficiary	RINA CONSULTING, IT
Project Period	01-09-2023 - 31-08-2027
Location	Italy

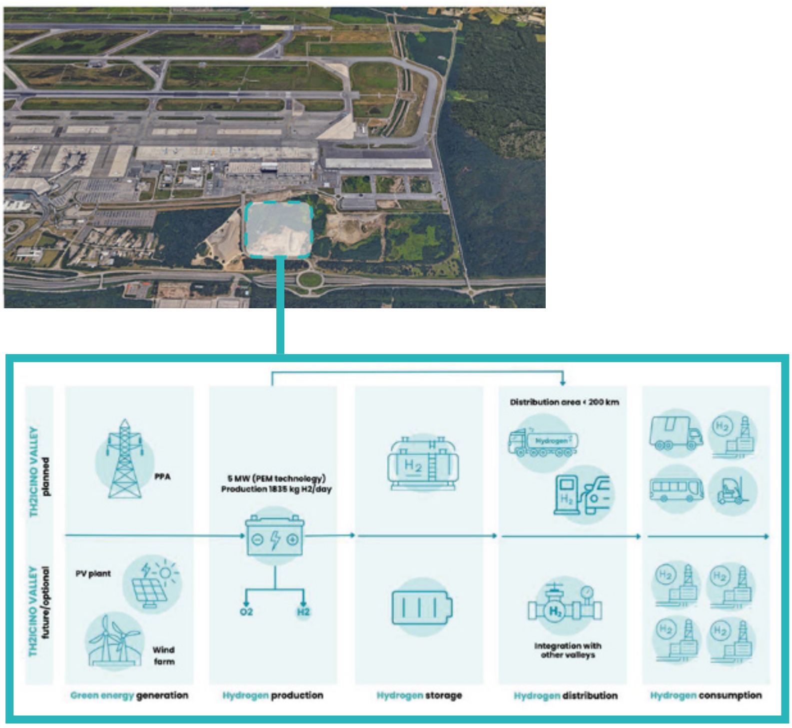
Finances



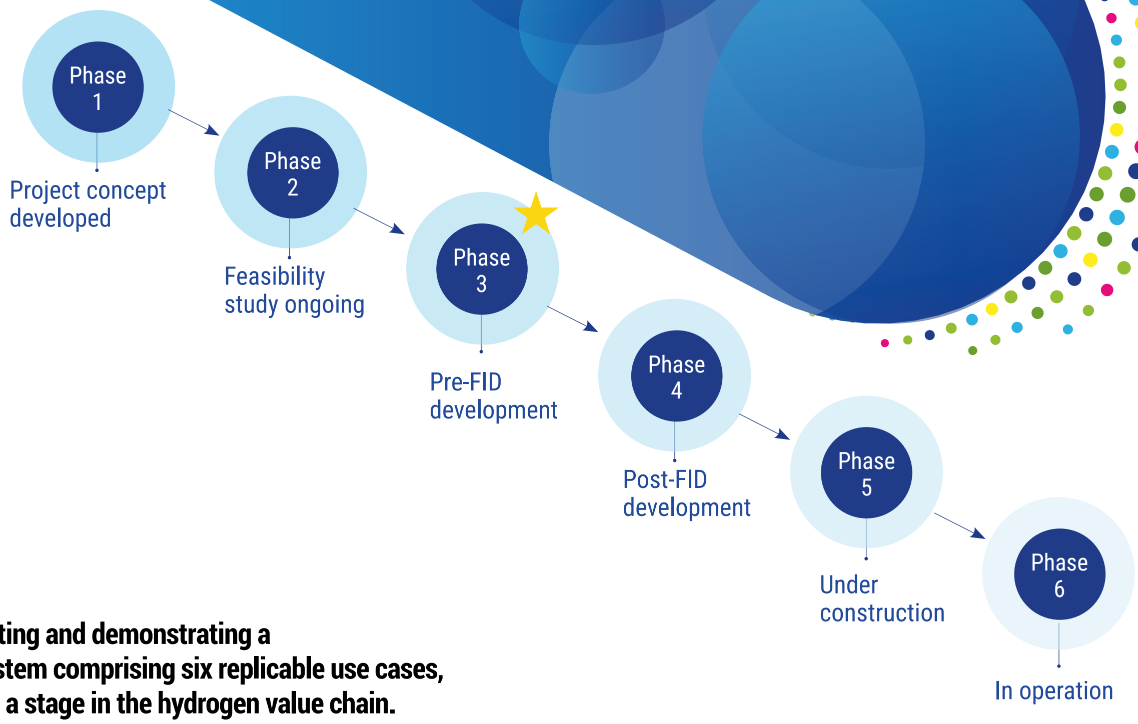
http://th2icino.eu

H$_2$ VALUE CHAIN COVERAGE





PROJECT TIMELINE



TH_2ICINO aims at creating and demonstrating a comprehensive ecosystem comprising six replicable use cases, each corresponding to a stage in the hydrogen value chain. The project's outcomes will involve the validation and testing of a Master Planning Tool (MPT). The project's primary focus is to establish a hydrogen valley in northern Italy, concentrating on four key areas of the hydrogen value chain: hydrogen production, storage, distribution and consumption.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

COMMUNICATION AND DISSEMINATION

- A dissemination and communication strategy has been prepared, to engage stakeholders, raise awareness about hydrogen technologies, and disseminate project updates; materials such as brochures, flyers, social media content and newsletters.

SAFETY AND RISK ASSESSMENT

- Initial steps have been taken to outline the hydrogen safety planning framework, ensuring adherence to stringent safety standards and protocols throughout the project lifecycle.
- Safety protocols and risk assessment procedures have been developed to mitigate potential hazards associated with hydrogen production, storage, and transportation.

MODELLING

- The modelling phase for the extended valley has begun, aiming to simulate and optimize various aspects of the hydrogen ecosystem, including production, distribution, and utilization.

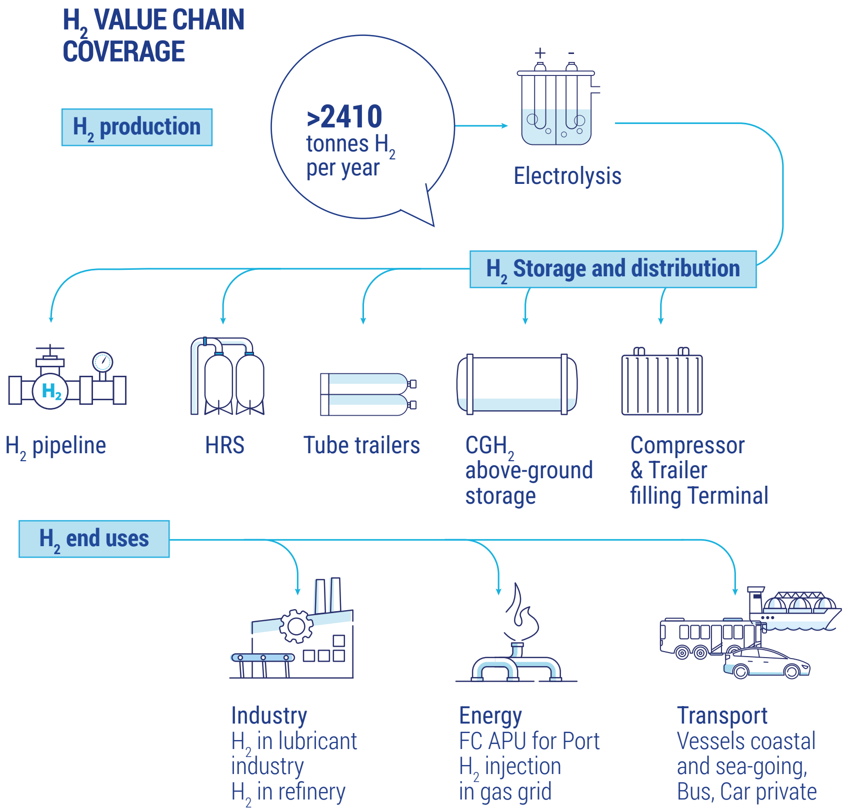
FUTURE STEPS AND PLANS

- Continuing collaboration with off-takers (started March 2024) to refine project strategies and align objectives with off-taker. Engaging with off-takers will enable the refinement of project strategies, alignment of objectives, and validation of technological solutions tailored to meet end-users' needs.

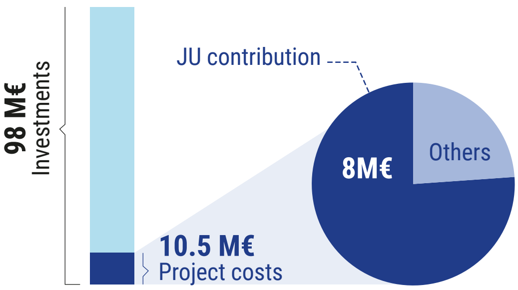
TRIERES

Towards the development of a hydRogen valley demonstratIng applications in an intEgRated EcoSystem in Greece

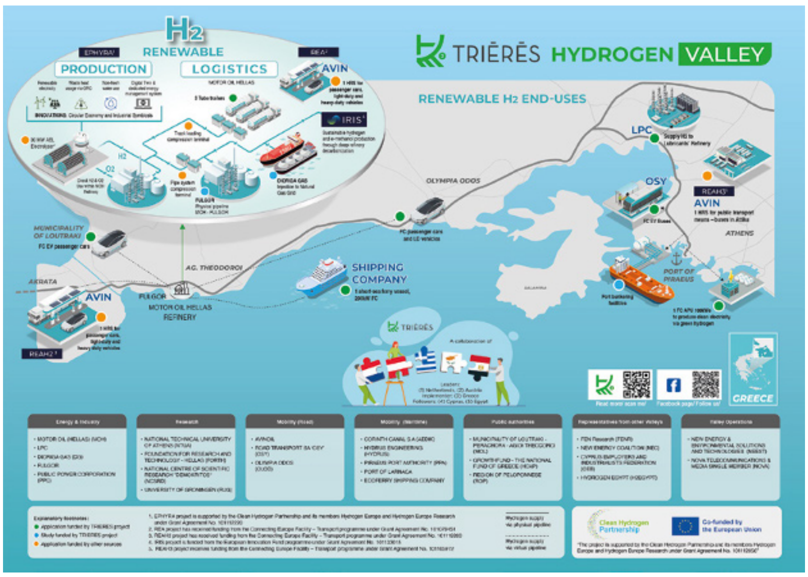
Project ID	101112056
PRR 2025	Pillar 6 – H_2 Valleys
Call Topic	HORIZON-JTI-CLEANH2-2022-06-02
Coordinator Beneficiary	MOTOR OIL, EL
Project Period	01-07-2023 - 30-04-2028
Location	Greece



Finances



https://www.trieres-h2.eu/



PROJECT TIMELINE

- Phase 1 – Project concept developed
- Phase 2 – Feasibility study ongoing ★
- Phase 3 – Pre-FID development
- Phase 4 – Post-FID development
- Phase 5 – Under construction
- Phase 6 – In operation

TRIĒRĒS Hydrogen Valley represents Greece's first integrated hydrogen initiative, anchoring the country's entry into the global clean hydrogen economy. Centered around the Motor Oil Corinth Refinery, the project aims to establish a full hydrogen value chain—from production to end-use applications—and to position Greece as a regional hub for hydrogen in the Balkans, Southeastern Europe, and the Eastern Mediterranean, with a particular focus on Crete and Cyprus.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

SAFETY AND SUPPLY

- Preliminary Safety framework for the Corinth Hydrogen Valley completed.
- Green hydrogen supply to be initiated according to schedule.
- Open access publication of a scientific paper on alternative green hydrogen production technologies from biomass.
- HAZOP study for electrolyser and tube trailers completed.
- HAZOP study and QRA for 1st HRS of AVINOIL (subsidiary of Motor Oil) in Agioi Theodoroi completed.

HYDROGEN LOGISTICS AND DISTRIBUTION

- Four Tube trailers for virtual pipelines acquired (~990 kg H_2 at 380 bar) (3 co-funded by the project and 1 by Motor Oil's own resources).
- Scheduling and distribution optimization underway for road-based hydrogen transport (virtual pipeline).

INFRASTRUCTURE DEVELOPMENT

- Following a positive FID, the EPHYRA electrolysis unit will be upscaled to 50 MW under the RRF, including ancillary construction works for renewable hydrogen supply and distribution, with first green hydrogen expected to flow in 2026.
- One Hydrogen Refuelling Station (HRS) operational in Agioi Theodoroi Corinth, constructed with co-funding of CEF-Transport; one HRS under preparation of tendering procedure for public buses depot; three more planned.
- One hydrogen car under tender procedure by the Municipality of Loutraki-Perachora-Agioi Theodoroi with possibility now to load fuel from Agioi Theodoroi HRS.
- Technical specs completed for three hydrogen buses (OSY) to be co-funded by the project and 50 more hydrogen-powered buses expected to be funded by secured Modernisation Fund resources.
- Preparation of tender documents/specifications under way for 100kWe FC APU in Port of Piraeus.
- Feasibility studies launched for:
  - ➤ Hydrogen-powered ferry (short-sea distance case);
  - ➤ Hydrogen pipeline to FULGOR (pre-feasibility study);
  - ➤ Hydrogen use in lubricant production (LPC).

COLLABORATION & KNOWLEDGE SHARING:

- Participation in international forums
- Strengthened ties with Austria's Hydrogen Valley ("WIVA P & G HyWest") through study visit, workshops and reports; Another study visit in North Netherlands Hydrogen Valley ("HEAVENN") by consortium scheduled for October 2025.
- Promotion of hydrogen innovation for regional growth through a high impact workshop focused on Peloponnese case for enhancing mobility and local value chains with over 90 participants in person and more than 60 online attendees from 28 countries, representing EU institutions, industry, academia, and public bodies.
- Fostering knowledge sharing and new skills gained on hydrogen mobility and safety during the co-organisation of the 3rd JIVE Roadshow across Greece and the Balkans.
- Emphasis on cross-border cooperation, including emerging markets like Crete, Cyprus and Egypt.

OUTREACH & COMMUNICATION:

- Project website launched for public access to updates and findings.
- Variety of social media activated to reach different target groups.
- Scientific publications and conference participations at national and international level to increase TRI R S' visibility.
- Honored with the prestigious Hydrogen Valley of the Year 2024 award, granted by the Clean Hydrogen Partnership in collaboration with the European Commission, demonstrating its substantial progress in hydrogen technology and highlighting its potential to transform the energy sector.

Clean Hydrogen Partnership

Co-funded by the European Union

XVI. PILLAR 7: SUPPLY CHAIN

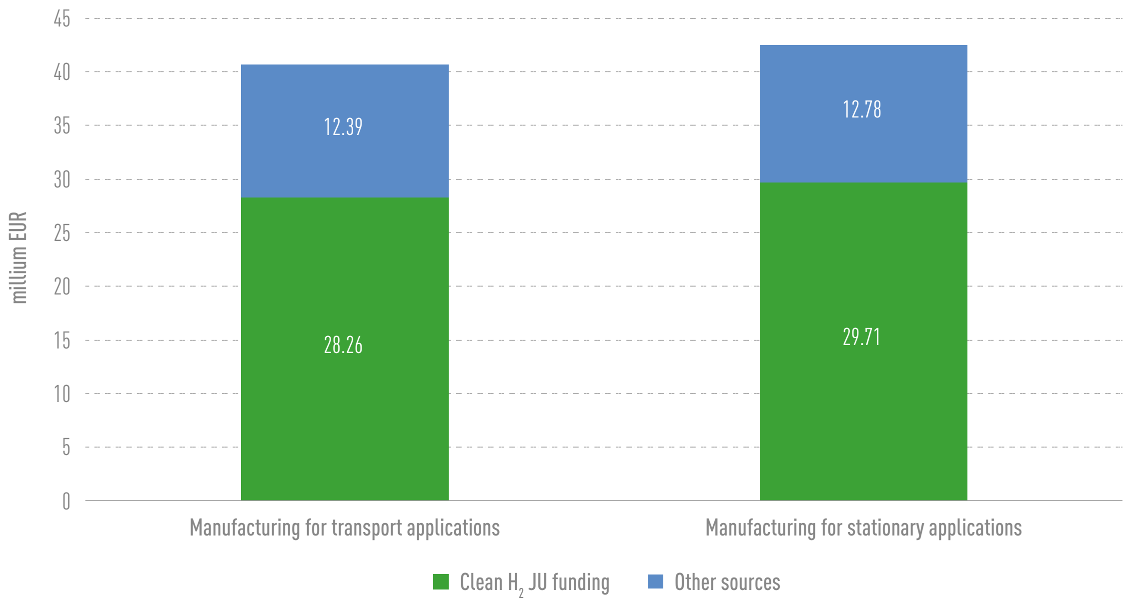
OBJECTIVES: The objective of pillar 7, as indicated in the SRIA, is to define and support the activities needed to strengthen the overall supply chain related to hydrogen technologies, recently identified by the European Commission as a strategic value chain for Europe. The overall goal of projects in this research area is to enable efficient large-scale manufacturing of PEM and solid oxide fuel cell technologies, while reducing production costs and improving fuel cell performance and environmental impact.

Pillar 7 is a relatively new Pillar, benchmarking supply chain activities in three research areas:

- **Manufacturing for stationary applications**: optimisation of materials and/or BoP components and architectures design to meet stationary application needs.
- **Manufacturing for transport applications**: addressing optimisation of BoP components and architectures design to meet transport application needs.
- **Critical raw materials**: addressing critical raw materials issues.

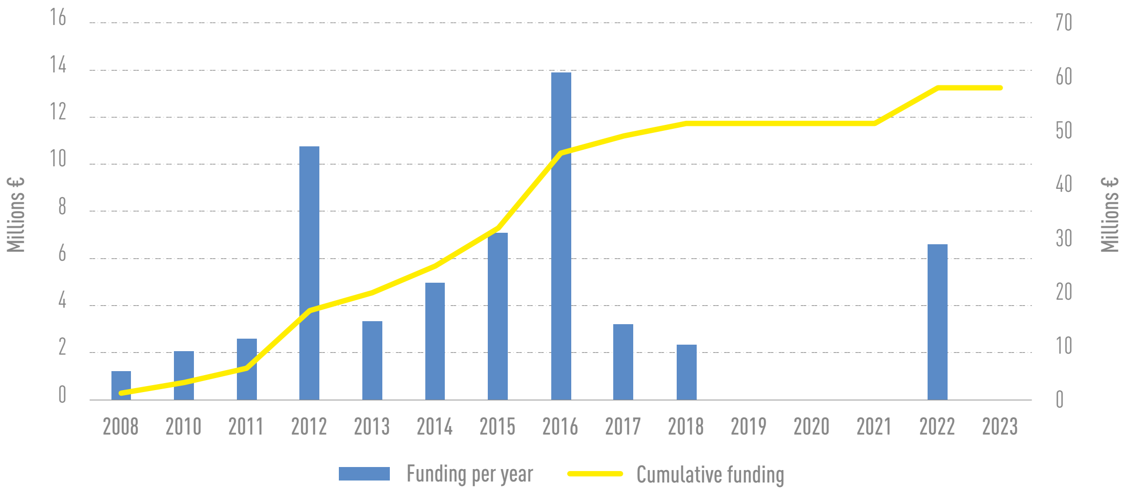
OPERATIONAL BUDGET: In Pillar 7, funding was distributed almost equally between the two main research areas: manufacturing for transport applications and manufacturing for stationary applications (Figure 72). Between 2008 and 2024, a total of 18 projects were supported under this pillar, with the Clean Hydrogen JU contributing over EUR 58 million in funding (Figure 73).

Figure 72: Funding per research area for Pillar 7 projects from 2008 to 2024



Source: Clean Hydrogen Joint Undertaking

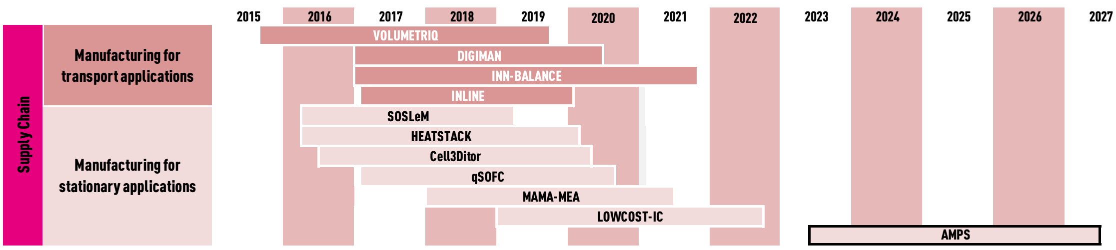
Figure 73: Funding (per year in pink/left axis and cumulative in grey/right axis) for Pillar 7 projects from 2008 till 2024



Source: Clean Hydrogen Joint Undertaking

PILLAR IN BRIEF: The projects included in Pillar 7 are shown in Figure 74, with the one currently ongoing highlighted in black.

Figure 74: Project timelines of Pillar 7 – Supply chain



Source: Clean Hydrogen Joint Undertaking

The collaboration among project partners, including cross-country partnerships spanning six EU member states, is illustrated in Figure 75 and Figure 76, highlighting a particularly strong connection between Finland, Estonia, Italy, and the Czech Republic. While other projects across various pillars address different supply chain challenges, the single project under review this year demonstrates a well-balanced collaboration among four distinct organisation types (a higher education institution, a research institution, a private company, and an SME) each contributing equally, as shown in Figure 77. The leading institutions involved in the project are listed in Table 3. Finally, one peer-reviewed publication was published in 2025.

Figure 75: Pillar 7: Collaboration network of EU countries (1 project)

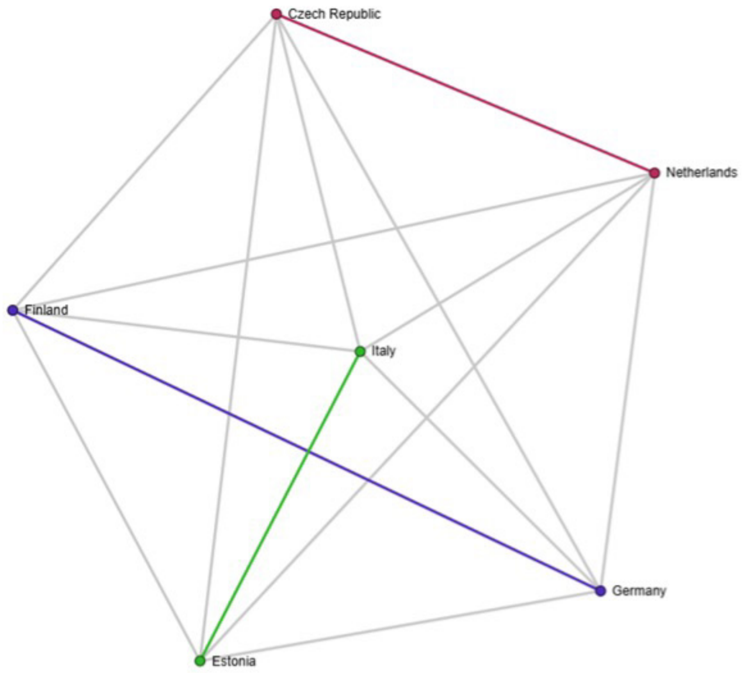


Figure 76: Pillar 7: Breakdown of projects by participating entity type

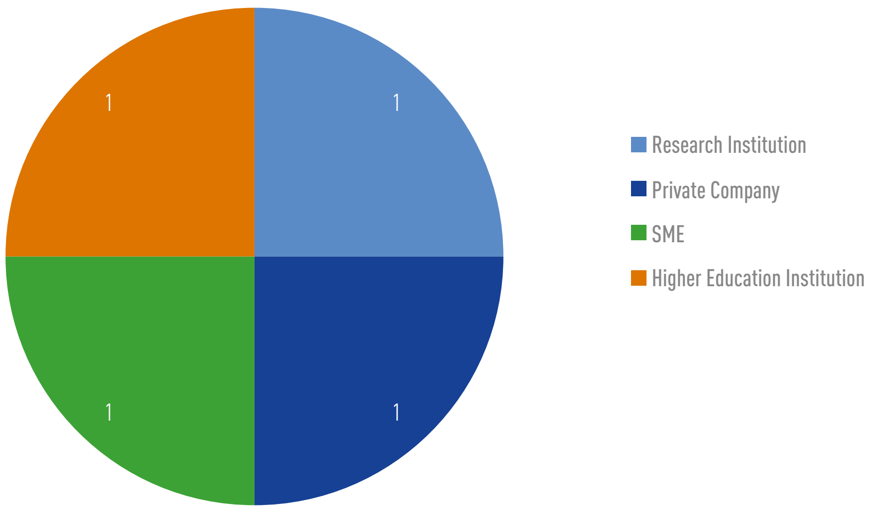


Figure 77: Pillar 7: Collaboration network of top participating institutions

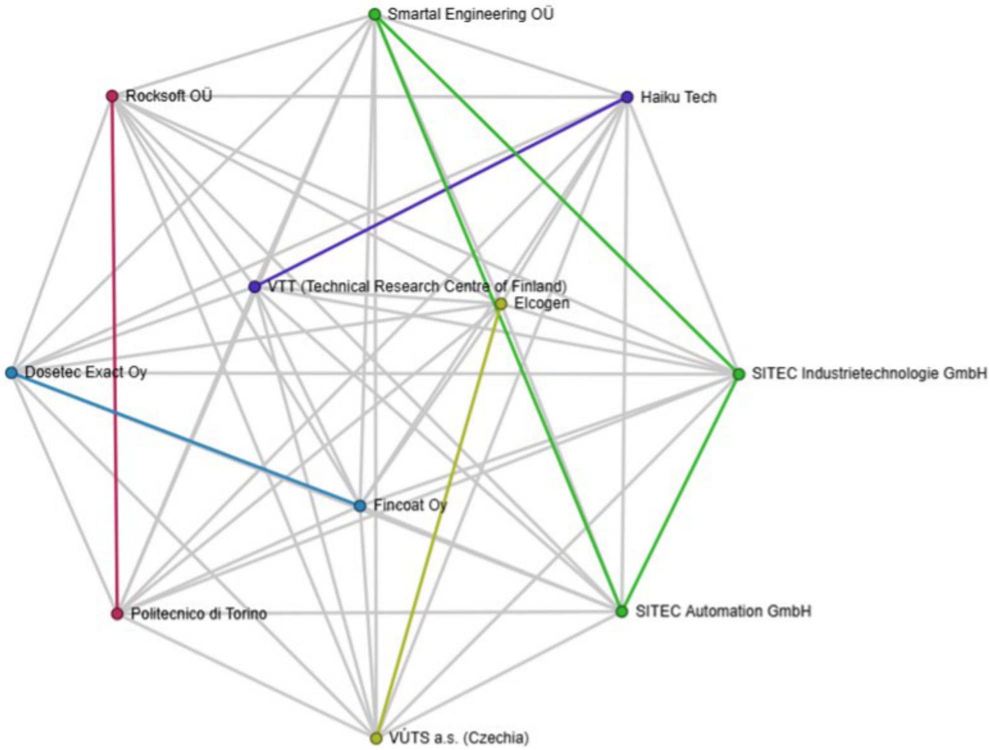


Table 3: Pillar 7: Institutions involved in Pillar 7 (1 project)

Entity name
Smartal Engineering OÜ
VÚTS a.s. (Czechia)
Fincoat Oy
Politecnico di Torino
SITEC Industrietechnologie GmbH
Rocksoft OÜ
VTT (Technical Research Centre of Finland)
Dosetec Exact Oy
Elcogen
Haiku Tech
SITEC Automation GmbH

PROJECTS FACTSHEETS

AMPS

AMPS

AUTOMATED MASS PRODUCTION OF SOC STACKS

Project ID	101111882
PRR 2025	Pillar 7 - Supply Chain
Call Topic	HORIZON-JTI-CLEANH$_2$-2022-04-01
Project Total Costs	8 711 520.00
Clean H$_2$ JU Max. Contribution	6 606 098.26
Project Period	01-06-2023 - 31-05-2027
Coordinator Beneficiary	TEKNOLOGIAN TUTKIMUSKESKUS VTT OY, FI
Beneficiaries	ROCKSOFT OU, DOSETEC EXACT OY, SMARTAL ENGINEERING OU, SITEC AUTOMATION GMBH, SITEC INDUSTRIETECHNOLOGIE GMBH, HAIKU TECH EUROPE BV, ELCOGEN OY, FINCOAT OY, AKTSIASELTS ELCOGEN, VUTS AS, POLITECNICO DI TORINO

https://www.amps-project.eu/

PROJECT AND GENERAL OBJECTIVES

AMPS project brings together the leading European companies across the Solid Oxide Fuel Cell and Solid Oxide Electrolyser manufacturing value chain. The project includes automation companies and manufacturing equipment producers as well as a cell manufacturer and a stack manufacturer. The project is motivated by their strong commitment to develop their products and services and commence real mass-manufacturing.

AMPS has the following objectives:

- Automated high-speed cell production with integrated quality control.
- Automated high-speed interconnect plate production and coating with integrated quality control.
- Automated high-speed stack assembly with integrated quality control.
- Complete component tracking and optimised mass-manufacturing by using virtual twins.
- Assessment and demonstration of target stack manufacturing cost of < EUR 800 /kWel at a production volume of 100 MW/year.
- Establishment of a European supply chain of solid oxide cell manufacturing equipment.
- AMPS advances beyond the state-of-the-art by developing several automated manufacturing solutions that significantly reduce cycle times, enabling the scale-up of stack production to exceed 100 MW per year.

NON-QUANTITATIVE OBJECTIVES

- To target the main barrier currently slowing down large-scale deployment of solid oxide fuel cells/ solid oxide electrolyser technologies.
- To develop, demonstrate and validate in actual production lines mass-manufacturing and quality control methods to produce solid oxide cell components and stacks at low cost and high volumes.
- To perform circularity and life cycle assessments of the developed technologies, processes and methods.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

Preparation of “Project Quality Management Plan PQMP”, “Ethics Plan”, and “Project Data Management Plan PDMP” which provide a solid base for future technical and scientific work.

- Development of a method to recycle cell production waste.
- Design of automated raw material handling for nickel oxide.
- Design of automatic cell heat treatment process for mass production.
- Specification and requirements for the interconnect laser welding process.
- First draft of the “Hydrogen Safety Planning”.
- Preliminary validation of cell production waste reduction method; additional tests will be done to achieve a stack production of 100 MW/year.

FUTURE STEPS AND PLANS

The next steps are the validation of automated raw material handling in cell production and the definition of methods for automated handling of stack components.

PROJECT TARGETS

Target source	Parameter	Unit	Target	Achieved to date by the project	Target achieved?
Project's own objectives	Automated high-speed cell production with integrated quality control.	Yield-%	> 95	75	
	Automated high-speed bipolar/ interconnect plate production and coating with integrated quality control.	Degree of automation-%	90	75	
	Automated high-speed stack assembly with integrated quality control.	Reduction of stack assembly time-%	> 80	20	
	Complete component tracking and optimised mass-manufacturing by using virtual twins.	Component tracking accuracy-%	> 99	N/A	
	Stack manufacturing cost.	€/kW	800	N/A	

Clean Hydrogen Partnership
Co-funded by the European Union

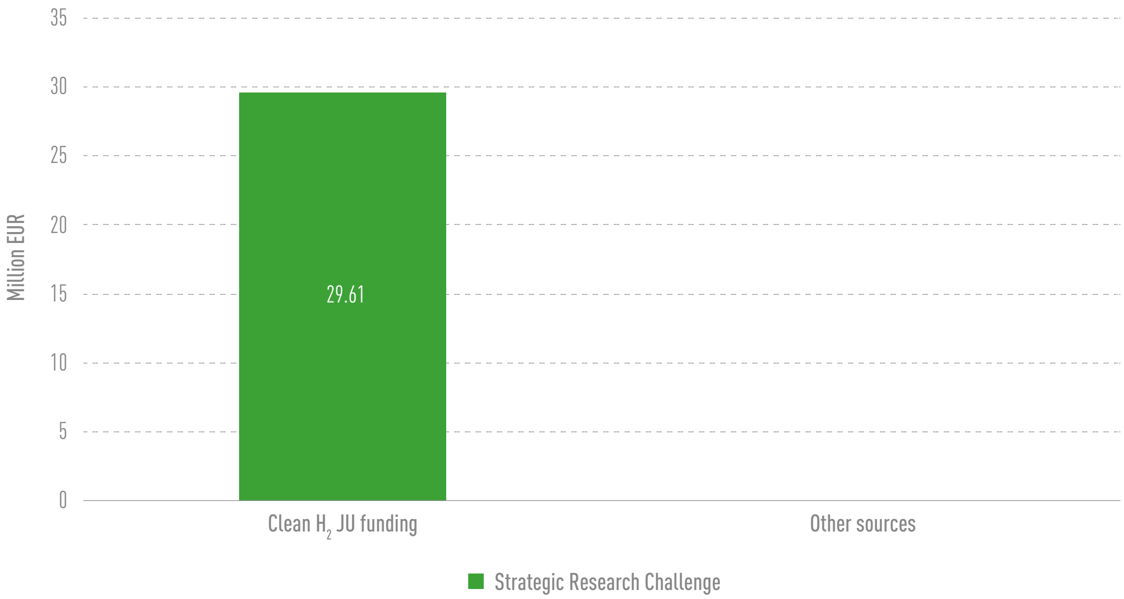
XVII. PILLAR 8: STRATEGIC RESEARCH CHALLENGES

OBJECTIVES: The objective of this pillar is to sustain a steady flow of early-stage scientific knowledge, something that conventional three-year research projects may struggle to deliver consistently. Previous roadmaps have identified three most significant research challenges:

- Reducing the use of materials that are critical, such as PGMs, or unsustainable, such as PFAS, in electrolysers and fuel cells;
- Advancing materials and processes for hydrogen storage;
- Enhancing the understanding of the performance and durability mechanisms of electrolysers and fuel cells.

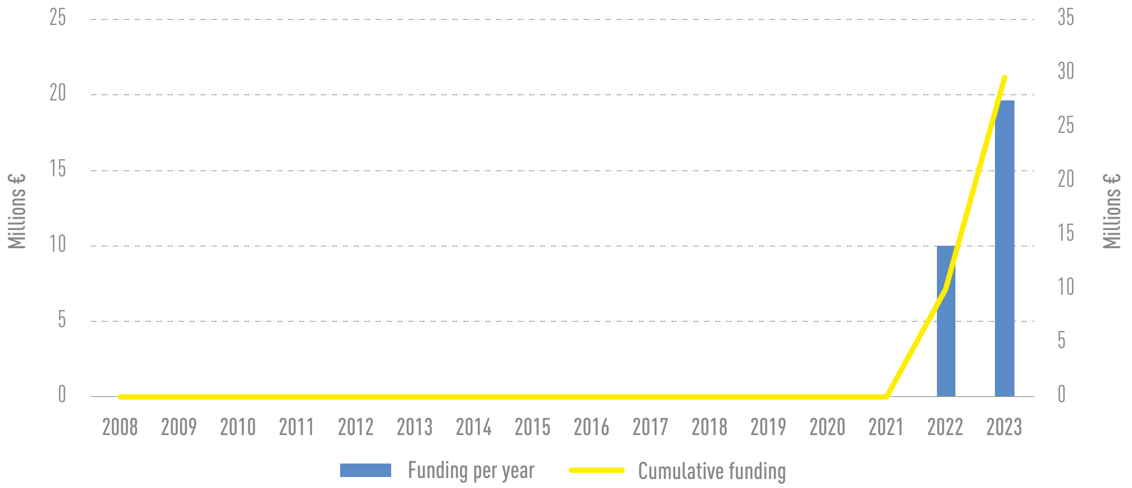
OPERATIONAL BUDGET: For this pillar, approximately EUR 30 million have been funded by the Clean Hydrogen JU so far (Figure 78), with an initial allocation of EUR 10 million in 2023, followed by a doubling of this amount to EUR 20 million in 2024 (Figure 79).

Figure 78: Funding per research area for Pillar 8 projects from 2008 to 2024



Source: Clean Hydrogen Joint Undertaking

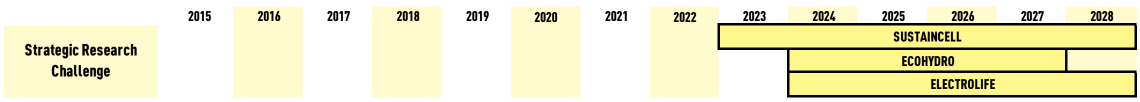
Figure 79: **Funding (per year in light yellow/left axis and cumulative in grey/right axis) for Pillar 8 projects from 2008 to 2024**



Source: Clean Hydrogen Joint Undertaking

PILLAR IN BRIEF: Three projects have been funded for each of the most significant research challenges, shown in Figure 80.

Figure 80: **Project timelines of Pillar 8 – Strategic Research Challenges**



Source: Clean Hydrogen Joint Undertaking

Three projects have been funded under this pillar so far (Figure 81), with France and Germany showing the highest participation, being involved in all three projects (Figure 82). Italy, Denmark, Spain, and Finland each contributed to two projects, while Poland, Belgium, Luxembourg, Portugal, the Netherlands, Estonia, and Austria participated in one project each. The collaboration network (Figure 83) highlights strong cross-country cooperation, with France, Germany, and Italy serving as central hubs. These projects feature a balanced mix of organisation types, including research institutions, higher education institutions, private companies, and SMEs (Figure 84). Most activity occurred in 2024, with all entity types represented. The Sankey diagram (Figure 85) shows that higher education institutions and research institutions were involved in projects during 2023 and 2024, whereas SMEs and private companies participated only in 2024, reflecting a recent diversification of industry engagement alongside academia. Across the three Pillar 8 projects, only Forschungszentrum Jülich (FZ Jülich) participated in two projects, with all remaining organisations involved in a single project. Finally, pillar 8 generated 4 scientific publications published in 2024 and 2025, all of them being peer-reviewed.

Figure 81: Pillar 8: Trend in number of projects per year

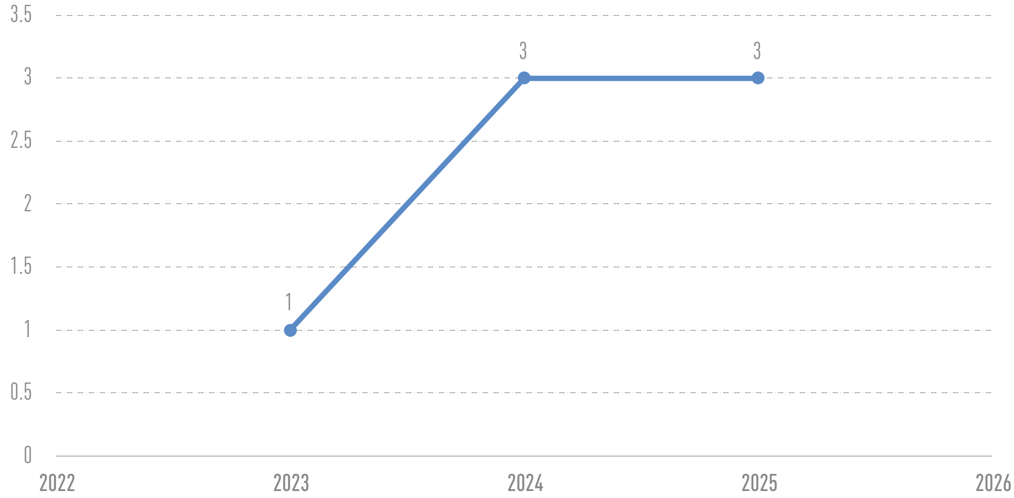


Figure 82: Pillar 8: Project participation by EU country

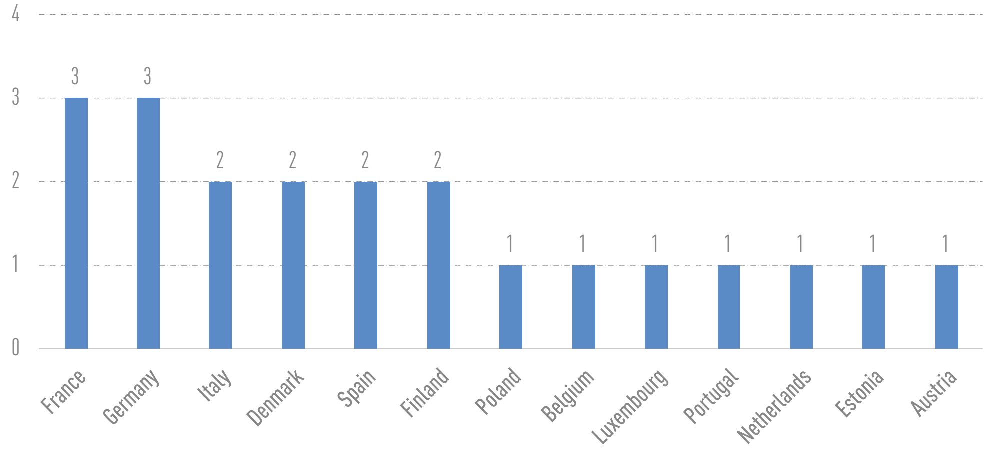


Figure 83: Pillar 8: Collaboration network of EU countries

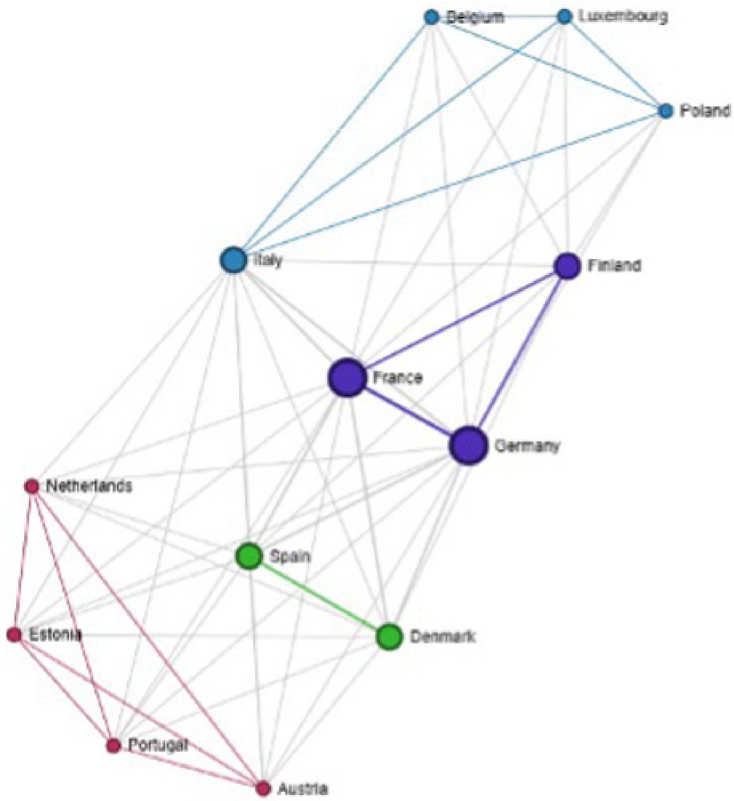


Figure 84: Pillar 8: Breakdown of projects by participating entity type

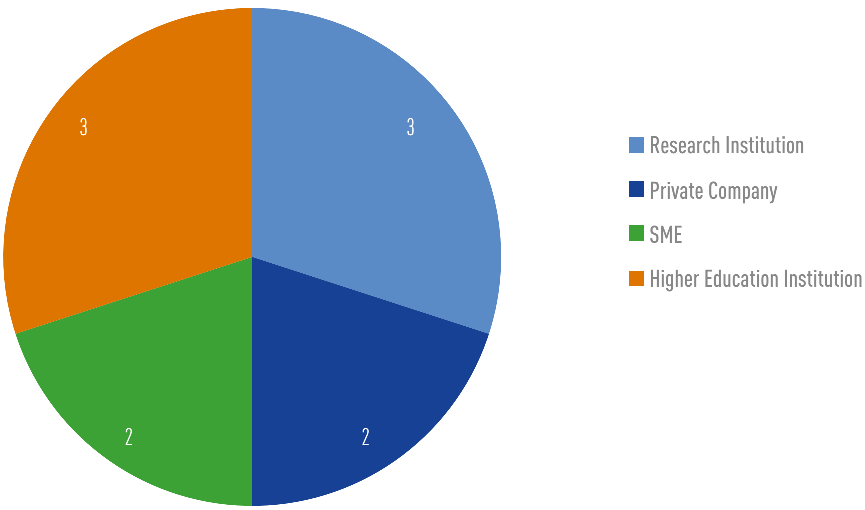


Figure 85: Pillar 8: Participation by organisation type across years

PROJECTS FACTSHEETS

ECOHYDRO

ECONOMIC MANUFACTURING PROCESS OF RECYCLABLE COMPOSITE MATERIALS FOR DURABLE HYDROGEN STORAGE

Project ID	101138008
PRR 2025	Pillar 8 - Strategic Research Challenge
Call Topic	HORIZON-JTI-CLEANH$_2$-2023-07-01
Project Total Costs	9 617 290.00
Clean H$_2$ JU Max. Contribution	9 617 290.00
Project Period	01-01-2024 - 31-12-2027
Coordinator Beneficiary	INSTITUT MINES-TELECOM, FR
Beneficiaries	HAESAERTS FOR HYDROGEN, ELECTRA COMMERCIAL VEHICLES LIMITED, BASALTEX NV, FEV TR OTOMOTIV VE ENERJI ARASTIRMAVE MUHENDISLIK LIMITED SIRKETI, LUXEMBOURG INSTITUTE OF SCIENCE AND TECHNOLOGY, MAHYTEC SARL, PROMAT RESEARCH AND TECHNOLOGY CENTRE, TEMSA SKODA SABANCI ULASIM ARACLARI ANONIM SIRKETI, M.D.P. MATERIALS DESIGN AND PROCESSING SRL, CENTRE TECHNOLOGIQUE NOUVELLE-AQUITAINE COMPOSITES and MATERIAUX AVANCES, ARKEMA FRANCE SA, POLITECHNIKA WROCLAWSKA, AIRBUS, KATHOLIEKE UNIVERSITEIT LEUVEN

https://ecohydro-project.eu/

PROJECT AND GENERAL OBJECTIVES

ECOHYDRO's global objective is to ensure an economic process for manufacturing recyclable composite materials for durable hydrogen tanks through the usage of high-strength carbon fibre, low-viscosity thermoplastic liquid resin and instant in-situ photopolymerisation for composite pressure vessels.

ECOHYDRO has six ambitious general objectives:

- Identify and develop multi-functional sustainable materials enabling a circular design and reducing the whole life cost of hydrogen storage solutions.
- Develop standardised inspection and repair methods that improve safety aspects of hydrogen storage and increase the lifetime of hydrogen storage solutions.
- Develop smart solutions that allow for cross-application uses of hydrogen storage to reduce the total number of storage tanks produced.
- Demonstrate increased storage size and reduced capital cost for aboveground storage of hydrogen.
- Demonstrate increased tube trailer payload, reduced capital cost and increased operating pressure for road transport of hydrogen.
- Demonstrate increased gravimetric capacity, conformability, reduced capital costs and increased tank gravimetric efficiency for onboard storage of hydrogen in heavy-duty truck and aviation applications.

NON-QUANTITATIVE OBJECTIVES

- Increase of public acceptance of hydrogen technologies by improving the safety aspects of hydrogen storage in tanks.
- Improvement of public perception of composite material solutions by developing new recycling technologies.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

Testing of various initiators for polymerising acrylic resin through photopolymerisation, thermal polymerisation, and dual polymerisation.

- Modification of acrylic resin with phosphorus comonomers for fire resistance.
- addition of special fillers to enhance thermal insulation while optimising the balance with resin viscosity.
- Creation of self-healing acrylic resin to repair cracks at the fiber/matrix interface.
- Impregnation of different fiber rovings with acrylic resin.
- Optimisation of winding parameters.
- Analysis of microstructures and mechanical properties of the composites, revealing good properties for carbon fiber composites but lower for basalt fiber due to defects.
- Numerical modelling for the filament winding process as well as simulations for resin flow and fiber deformation.
- Finalisation of preliminary designs for four hydrogen storage demonstrators, focusing on various storage types.
- Start with thermal and mechanical modelling for the aviation demonstrator, along with multi-scale damage modelling and the development of a digital twin for monitoring hydrogen tank lifecycle.
- Initial work on hybrid and physico-chemical recycling and development of a life cycle analysis model.

FUTURE STEPS AND PLANS

- Mechanical and thermal characterisation (including cryogenic tests, hydrogen permeation, etc.) of newly developed functional materials.
- Optimisation of manufacturing process in terms of process defects and energy consumption.

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- Modelling of manufacturing process and damage analysis.
- Process monitoring and structural health monitoring by sensor integration and data analysis by an artificial intelligence algorithm.
- Optimisation of recycling process and life cycle analysis of the new materials and manufacturing process.
- Improvement of the preliminary design of demonstrators.

PROJECT TARGETS

Target source	Parameter	Unit	Target	Achieved to date by the project	Target achieved?	SoA result achieved to date (by others)	Year for reported SoA result
Project's own objectives	Storage size (Above ground storage)	tonnes	20	5		1.1	2020
	Cost reduced (Above ground storage)	€/kg	600	700		750	2020
	Trailer payload (Road transport of hydrogen (Gaseous H_2))	kg	1 500	700		850	2020
	Trailer capital cost (Road transport of hydrogen (Gaseous H_2))	€/kg	350	450		650	2020
	Operating pressure (Road transport of hydrogen (Gaseous H_2))	bar	700	500		300	2020
	Storage tank capital cost (Onboard storage of hydrogen in heavy duty truck applications (Gaseous H_2))	€/kg H_2	300	500		600	2020
	Increase in gravimetric capacity (Onboard storage of hydrogen in heavy duty truck applications (Gaseous H_2))	%	7	6.5		6	2020
	Tank gravimetric efficiency (Onboard storage of hydrogen for aviation applications (LH_2))	% weight	35	15		12	2020
	Increase of the number of safe cycles before replacement (Safety and lifetime of hydrogen storage)	Number of cycles	7 500	5 000		5 000	2020
	Life cost reduction (Life cost of hydrogen storage solutions)	%	50	50		N/A	2020

ELECTROLIFE

ENHANCE KNOWLEDGE ON COMPREHENSIVE ELECTROLYSERS TECHNOLOGIES DEGRADATION THROUGH MODELING, TESTING AND LIFETIME PREVISION, TOWARD INDUSTRIAL IMPLEMENTATION

Project ID	101137802
PRR 2025	Pillar 8 - Strategic Research Challenge
Call Topic	HORIZON-JTI-CLEANH$_2$-2023-07-02
Project Total Costs	9 995 705.00
Clean H$_2$ JU Max. Contribution	9 995 705.00
Project Period	01-01-2024 - 31-12-2028
Coordinator Beneficiary	POLITECNICO DI TORINO, IT
Beneficiaries	STARGATE HYDROGEN SOLUTIONS OU, VOLYTICA DIAGNOSTICS GMBH, 1S1 ENERGY PORTUGAL UNIPESSOAL LDA, OU STARGATE HYDROGEN SOLUTIONS, UNIVERSITE DE LILLE, KERIONICS S.L., HYTER SRL, PIETRO FIORENTINI SPA, SOLYDERA SPA, ENEL GREEN POWER SPA, AEA s.r.l., UNIRESEARCH BV, AALBORG UNIVERSITET, TECHNISCHE UNIVERSITAET GRAZ, CONSIGLIO NAZIONALE DELLE RICERCHE, FORSCHUNGSZENTRUM JULICH GMBH, FRIEDRICH-ALEXANDER-UNIVERSITAET ERLANGEN-NUERNBERG

https://electrolife-project.eu/

PROJECT AND GENERAL OBJECTIVES

ELECTROLIFE aims to comprehend the fundamental mechanisms and causal relationships underlying aging processes of electrolysers to mitigate the limited understanding of degradation phenomena. This understanding will enable the development of models and daily operational strategies to prolong the lifespan of electrolysers. Therefore, ELECTROLIFE integrates advanced modeling techniques, diagnostic tools, next-generation stacks, standardised test benches, testing protocols, and post-mortem analysis.

ELECTROLIFE addresses the scalability challenges of electrolyser technologies by extending their lifespan, enabling operation at higher current densities with reduced overpotentials, and incorporating innovative materials to minimise the reliance on critical raw materials and precious group metals. Thus, ELECTROLIFE contributes to the sustainable development and scaling-up of electrolysis technologies.

NON-QUANTITATIVE OBJECTIVES

- Advancement of electrolyser degradation modelling through the implementation of standardised testing methods.
- Development of dedicated diagnostic tools for precise state of health assessment.
- Development of tailored testing and diagnostic instruments to suit ELECTROLIFE requirements.
- Refinement of operational strategies to enhance efficiency and effectiveness.
- Establishment of guidelines for next-generation robust stacks, diagnostic tools, and optimised operational strategies to extend the lifetime of electrolysers.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

Discussions on the preliminary design of testing instruments and protocols for all electrolyser technologies.

- Establishment of benchmarks for ongoing development by sharing existing models.
- Preliminary single-cell testing of electrolysis components has been initiated to assess beginning-of-life performance.
- Conduction of accelerated stress tests.
- Analysis of the current state-of-the-art knowledge on degradation mechanisms for electrolysers, including the influence of renewable energy sources.

FUTURE STEPS AND PLANS

ELECTROLIFE will:

Undertake testing on individual cells and short stacks.

- Develop and validate models integrating degradation mechanisms.
- Validate use of functional materials at the stack level through dedicated testing, diagnostic instruments, and online data analysis.

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PROJECT TARGETS

Target source	Parameter	Unit	Target	Achieved to date by the project	Target achieved?
Project's own objectives	Data collection from previous or ongoing projects and/or data available at electrolysis manufacturers.	% Data Completeness Index = (Total amount of data collected / Total amount of data expected*) x 100. *(at least 1 set of data for each electrolysis technology, 100% EU funded projects analysed; >100 publications analysed)	> 90	100	✓
	Identification of degradation mechanisms and effects of their superposition by modelling and simulation activities validated by relevant experimental data.	% Number of models Index = (Total amount of models developed / Total amount of data expected*) x 100. *(#5 models)	100	20	
	Evaluate the impact of RES electrical profile on electrolysers durability in terms of the dynamic operating conditions.	% Number of RES profiles Index = (Total amount of RES profiles made available / Total amount of RES profiles expected*) x 100. *(#4 RES profiles)	100	10	
	Modelling of degradation resulting from different degradation phenomena and operating conditions, including RES operation models, should be validated by experimental data.	% Degradation Modelling Accuracy Index = (1 - |Predicted degradation - Actual degradation| / Actual degradation) x 100.	> 90	10	
	With the support of dynamic modelling, simulation of the transient electrical and thermal behaviour in view of the impacts on degradation effects.	% Degradation Modelling Accuracy Index = (1 - |Predicted degradation - Actual degradation| / Actual degradation) x 100	DMAI > 80	-	
	Development of lifetime prediction models based on the degradation modelling proposals may include verification testing for such models for selected technologies defining predictive modelling of state-of-health / state-of-life for given operation.	% Lifetime Prediction Tool Accuracy Index = (1 - |Predicted lifetime - Actual lifetime| / Actual lifetime) x 100	> 90	-	
	Development of operation solutions diminishing the degradation in stationary or transient operations (e.g. novel operating and control strategies, diagnostics etc.)	% Operating strategies Index = (Total amount of deliverables on operating strategies made available / Total amount of operating strategies expected) x 100	100	-	
	Adaptation or improvement of advanced characterisation methods for deeper understanding by in situ, ex-situ or in-operando analyses.	% Testing procedures Index = (Total amount of deliverables on testing procedures made available / Total amount of testing procedures expected) x 100	100	25	
	Validation of novel solutions in short stack level (minimum 5 repeating units) for at least 10 000 hours by meeting degradation rate while keeping similar level of performance (current density, hydrogen production rate) or in accelerated stress tests.	% SRIA Targets Achievement Index = (Total amount of 2030 SRIA Targets achieved / Total amount of 2030 SRIA Targets considered*) x 100. *(#4: degradation rate, current density, OPEX and CAPEX).	100% for AEL and PEM, 75% for SOEL, and at least 50% for AEMEL, and PCCEL.	-	
	Development of uniform data formats that can potentially be used for machine learning and big data processing to identify and correlate cause and effect of degradation phenomena.	% Data Standardization Index = (Total amount of datapoint included in the standard dataset / Total number of variables available) x 100.	80	-	
	Assessment of the improved durability on the lifecycle impact of the selected technologies.	% Lifecycle impact analysis Index = (Total amount of LCA performed in the project / Total number LCA expected*) x 100. * (#5)	100	-	

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SUSTAINCELL

SUSTAINCELL: DURABLE AND SUSTAINABLE COMPONENT SUPPLY CHAIN FOR HIGH PERFORMANCE FUEL CELLS AND ELECTROLYSERS

Project ID	101101479
PRR 2025	Pillar 8 - Strategic Research Challenge
Call Topic	HORIZON-JTI-CLEANH$_2$-2022-07-01
Project Total Costs	9 993 652.00
Clean H$_2$ JU Max. Contribution	9 993 652.00
Project Period	01-01-2023 - 31-12-2028
Coordinator Beneficiary	SINTEF AS, NO
Beneficiaries	UNIVERSITE DE MONTPELLIER, TEKNOLOGIAN TUTKIMUSKESKUS VTT OY, HAUTE ECOLE SPECIALISEE DE SUISSE OCCIDENTALE, FUNDACION TECNALIA RESEARCH and INNOVATION, ECOLE POLYTECHNIQUE FEDERALE DE LAUSANNE, FORSCHUNGSZENTRUM JULICH GMBH, DEUTSCHES ZENTRUM FUR LUFT - UND RAUMFAHRT EV, DANMARKS TEKNISKE UNIVERSITET, COMMISSARIAT A L ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES, CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS

https://sustaincell.eu/

PROJECT AND GENERAL OBJECTIVES

SUSTAINCELL aims to support European industry in developing next-generation electrolyser and fuel cell technologies by developing a sustainable European supply chain of materials, components and cells. This will be based on scientific breakthrough innovations, eco-design guidelines and environmentally-friendly manufacturing routes.

SUSTAINCELL focuses on developing new critical-raw-material (CRM)-lean and/or CRM-free materials and architectures, aiming to maximise functionalities and durability while decreasing CRM content per unit cell. The new flexible and scalable processing routes will exhibit higher productivity, reduced utilities consumption and reduced greenhouse gas emissions. The project will also develop enhanced recovery and treatment processes for optimising recovery and reuse of platinum group metals / CRMs and ionomers extracted from end-of-life stacks and production processes.

NON-QUANTITATIVE OBJECTIVES

- Harvesting and expanding European knowledge and know-how on the identification, substitution, recovery and recycling strategies and value chains, of critical raw materials.
- Ensuring the replacement and/or reduction of critical raw materials per unit cell using eco-friendly processing methods.
- Increasing the yield of ionomer and critical raw materials recovered from used cells and membrane electrode assemblies and from scrap and waste, by recycling.
- Contributing to the development of EU harmonised protocols.
- Validating new solutions in terms of gain in performance and durability at single cell level.
- Demonstrating the sustainability of at least three innovative solutions for each technology.
- Maximising the impact, uptake and acceptance of SUSTAINCELL results by developing strategies for dissemination to, communication with and exploitation by academia, industries, policy makers, non-governmental organisations and the public.
- Establishing a suitable toolbox for efficient risk management and knowledge sharing between partners.

PROGRESS, MAIN ACHIEVEMENTS AND RESULTS

Materials and processes for critical raw material reduction in high temperature electrolysers:

- Thinned Ni-3YSZ electrodes with 50% less NiO using $MgAl_2O_4$ and Al_2O_3 additives showing increased mechanical strength.
- Ni-free, REE-lean perovskite electrodes (LST and LSCM) showing comparable performance to Ni-based cermets.
- LSF-based electrodes with YSZ backbones showing improved polarisation resistance (ca 50%).
- PBSCF nanofiber electrodes for PCCELs showing reduced Co/REE use and improved porosity and performance (ca 93–97%).
- Exploration of photonic annealing for rapid electrode sintering.

CRM Reduction in LT Electrolysers:

- Novel AEMs and CEMs developed showing stable performance and good conductivity (up to 0.07 S/cm).
- pPIM ionomers showing higher oxygen diffusion and PEMFC performance versus Nafion.
- Ni@C-N HOR catalysts and Ni-MOF based HER catalysts showing optimised activity and stability.

Innovation & Testing:

- A robotic catalyst discovery platform was built at DTU using ML-guided synthesis and testing.
- Round-robin testing protocols were harmonised among partners for AEMEL cells.

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- Photonic annealing, flame spray pyrolysis, and dip-coating enabled scalable electrode production.

Recycling & Sustainability:

- Testing of critical raw materials separation from end-of-life high temperature cells through physical disintegration methods (ball milling, hydrogen decrepitation).
- Life cycle analysis and techno-economic assessments identified environmental hotspots and critical raw material use across even electrolysis/FC technologies.
- A benchmark report mapped critical raw materials usage, with outreach to industry and RTD groups.

FUTURE STEPS AND PLANS

- Amplify interaction with external stakeholders and dissemination activities through setting up the advisory board of the project.
- Organise joint seminars and workshops with European and international projects addressing similar research topics and/or focusing on the development of SUSTAINCELL technologies.
- Pursue research activities and validate performance of new materials and components at cell level.

PROJECT TARGETS

Target source	Parameter	Unit	Target	Target achieved?
Project's own objectives	CAPEX	€/kW	@ 100 MW [AEL 400 €/kW, AEMEL 300 €/kW, PEMEL 500 €/kW, SOEL 520 €/kW], @ 500 kWe, PEMFC 900 €/kW]	
	PEMFC electrical efficiency, non-recoverable CRM loading, degradation rate	%	~56% (% LHV H_2), 0.01 mg/Wel, 0.2%/1 000 h	

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