Clean Hydrogen Partnership

PROGRAMME REVIEW REPORT 2023

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PROGRAMME REVIEW
REPORT 2023

EUROPEAN PARTNERSHIP

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LIST OF ACRONYMS

AEL	Alkaline Electrolysis/Electrolyser
AEMEL	Anion Exchange Membrane Electrolysis/Electrolyser
AFIR	Regulation on Deployment of Alternative Fuel Infrastructure
APR	Aqueous Phase Reforming
APU	Auxiliary Power Unit
ASR	Area Specific Resistance
AST	Accelerated Stress Tests
AWP	Annual Working Plan
BEV	Battery Electric Vehicle
BoP	Balance of Plant
BoL	Begin of Life
BT	Benzyltoluene
CEN	The European Committee for Standardisation
CENELEC	The European Committee for Electrotechnical Standardisation
CCM	Catalyst Coated Membrane
CHP	Combined heat and power
CMSM	Carbon Molecular Sieve Membranes
CMR	Catalytic Membrane Reactor
CRM	Critical Raw Materials
CSP	Concentrating Solar Power
DBT	Dibenzyltoluene
EHP	Electrochemical Hydrogen Purification
EHSP	European Hydrogen Safety Panel
EIS	Electrochemical Impedance Spectroscopy
ETS	EU Emission Trade System
EU	European Union
FC/FCS	Fuel Cell/Fuel Cell System
FCB	Fuel Cell Bus
FCT	Fuel Cell Truck
FCEV	Fuel Cell Electric Vehicle
FCHO	Fuel Cells and Hydrogen Observatory
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).
FP7	EU's 7th framework programme
GHG	Greenhouse Gases
H2020	Horizon 2020
HE	Horizon Europe
HHV	Higher Heating Value
HDV	Heavy-duty Vehicle

HRS	Hydrogen Refuelling Station
HT	High Temperature
HMT	Hydro-Metallurgical Technology
HTT	Hydrothermal Treatment
HTP	Hydrogen Territories Platform
ICT	Information Communication Technology
IEA	International Energy Agency
IEC	International Electrotechnical Commission
IPCEI	Important Projects of Common European Interest
IPHE	International Partnership for Hydrogen and Fuel Cells in the Economy
IRENA	International Renewable Energy Agency
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
LHV	Lower Heating Value
LOHC	Liquid Organic Hydrogen Carrier
LT	Low Temperature
m-CHP	micro-CHP
MAIP	FCH JU's Multi-Annual Implementation Plan (2008-2013)
MAWP	FCH 2 JU's Multi-Annual Work Plan (2014-2020)
MDPC	Monitoring, Diagnostic, Prognostic and Control Tool
MEA	Membrane Electrode Assembly
MHV	Materials handling vehicles
MOF	Metal Organic Framework
MRL	Manufacturing Readiness Level
NG	Natural gas
OEM	Original equipment manufacturer
OSR	Oxidative Steam Reformer
PCC	Proton Conducting Ceramic Electrochemical Cells
PCCEL	Proton Conducting Ceramic Electrolysis/Electrolyser
PCD	Porous Current Distributors
PDA	Project Development Assistance
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
PRD	Programme Review Days
PSA	Pressure Swing Adsorption
PTL	Porous Transfer Layer
PTX	Power to X
PV	Photovoltaic
R&I	Research and Innovation
R&D	Research and Development
RCS	Regulations, Codes and Standards
RES	Renewable Energy Sources
rSOC	Reversible Solid Oxide Cell
SBA	Single Basic Act
SET	Strategic Energy Technology
SME	Small and medium-sized enterprise
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
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 relevant environment (industrially relevant environment in the case of key enabling technologies) TRL 6 – technology demonstrated in 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
TSA	Temperature Swing Absorption
VPS	Vacuum Plasma Spray Systems

EXECUTIVE SUMMARY

The EU has continued to support research and innovation on hydrogen for many years. The Clean Hydrogen Joint Undertaking (Clean Hydrogen JU), following the legacy of the successful Fuel Cell and Hydrogen JUs (FCH JU and FCH 2 JU), under the EU's 7th Framework Programme (FP7) and Horizon 2020 (H2020) respectively, aims to ensure the development of a full hydrogen supply chain to serve the European economy. The research and innovation activities of the Clean Hydrogen JU are related primarily to the production of clean hydrogen and the distribution, storage and end use applications of low carbon hydrogen in hard to abate sectors of the European economy.

The purpose of the periodic Programme Review is to ensure that the Clean Hydrogen JU Programme is aligned with the strategy and objectives set out in its founding Regulation, as further elaborated in its Strategic Research and Innovation Agenda (SRIA) for 2021-2027. The Joint Research Centre of the European Commission (JRC) was entrusted with the Programme Assessment based on the data collection from projects carried out by the Programme Office (mainly through the TRUST Platform and the Project Fiches). Since 2022, the scope of the Programme Review has broadened, however, the Annual Programme Technical Assessment performed by the JRC, together with the annual event, the EU Research Days (previously Programme Review Days) and the publication of the Clean Hydrogen JU project posters, remain at the core of the Programme Review.

The Annual Programme Technical Assessment covers 81 projects active between January 2022 - March 2023. In line with the new programme structure of the Clean Hydrogen JU, the reviewed projects have been assigned to 7 "Review Pillars": Hydrogen Production, Hydrogen Storage and Distribution, Hydrogen End Uses – Transport, Hydrogen End Uses – Clean Heat and Power, Cross-Cutting Issues, Hydrogen Valleys and Hydrogen Supply Chains. Each Pillar consists of a set of Research Areas which group projects covering similar and/or related topics. The programme assessment is performed for each Research Area.

Hydrogen Production (Pillar 1), with 19 projects reviewed, shows great progress towards achieving cost-competitive, large-scale clean hydrogen production. Projects in Alkaline (AEL) and Proton Exchange Membrane Electrolysis (PEMEL) are paving the way towards improvement of the low-temperature technologies, while Anion Exchange Membrane Electrolyser (AEMEL) projects are pushing low-TRL technology higher. Solid Oxide Electrolysis (SOEL) remains the main high-temperature electrolysis technology covered by the reviewed projects, showing progress against most of the technical KPIs, together with one project working on the Proton Conducting Ceramic Electrolysis (PCCEL). Finally, solar thermochemical hydrogen production is the only non-electrolytic renewable hydrogen production technology, represented by one reviewed project.

Hydrogen Storage and Distribution (Pillar 2) plays a vital role in the renewable hydrogen uptake; 9 projects are being reviewed in the areas of above ground and underground storage, hydrogen in the gas grid, Liquid hydrogen carriers, HRSs, compression, purification and metering solutions. The funding is gradually increasing, in an effort to close the gap between the numerous technical objectives and the number of projects.

Hydrogen End Uses in Transport (Pillar 3) reflects the significant effort to develop, validate and demonstrate technologies for FC material handling vehicles, FC buses and FCEV passenger cars that can be considered ready for market deployment, reviewing 25 projects in total. This area consists of research and demonstration activities distributed in 7 areas: Building blocks, heavy duty vehicles, waterborne, rail and aeronautic applications, buses and coaches, and cars.

Hydrogen End Uses in Clean Heat and Power (Pillar 4) can provide the necessary capacity to efficiently combine the output coming from intermittent renewable energy sources with the fluctuating demand. The Research Areas cover a large variety of renewable and flexible heat and power generation systems for different end users: m-CHP, commercial and industrial size systems, off-grid gensets and other research areas; 12 projects have been reviewed.

Cross-Cutting Issues (Pillar 5) contains specific supporting activities which play an enabler role to reinforce Europe's leadership position, accelerate mass-market adoption and maximise contribution to decarbonisation targets. It includes 3 Research Areas, currently represented by 11 reviewed projects, on sustainability, LCSA, recycling, eco-design, education, public awareness, safety, PNR and RCS.

Hydrogen Valleys (Pillar 6) has gained momentum and is now one of the main priorities of the European Commission for scaling-up hydrogen deployments and creating interconnected hydrogen ecosystems across Europe. The 3 projects reviewed are likely to have a high impact due to their high visibility and will make significant progress towards reaching the SRIA goals for Hydrogen Valleys, despite the significant challenges they are facing.

Also, Supply Chains (Pillar 7), currently represented by only 1 reviewed project, aims to define and support the activities needed to strength the overall supply chain related to hydrogen technologies, recently identified by the European Commission as a strategic value chain for Europe. A considerable increase of qualified companies is required along the supply chain to support the massive hydrogen production targeted in the next years.

In addition to the funded projects, the Clean Hydrogen JU undertook additional activities aiming to strengthen the knowledge and capacity of scientific and industrial actors along the Union's hydrogen value chain and increase public and private awareness, acceptance and uptake of clean hydrogen solutions.

In terms of studies, it published two studies on hydrogen in ports and industrial coastal areas aiming to allow port authorities and other port-related stakeholders to navigate easily through the relevant considerations for hydrogen (carriers) related activities of interest to them. The first report studies the role port ecosystems are expected to play in the expansion of the European hydrogen market through to 2050. The second one informs stakeholders and policymakers on the areas of priority for overcoming technological, safety and non-technical (policy, regulatory, governance, strategic) gaps for the timely development of hydrogen related activities and infrastructure in EU port areas. Moreover, it published a report on the results of a public opinion survey conducted in autumn 2022 in 27 EU countries to analyse and assess European citizens' attitudes towards and level of knowledge and awareness of hydrogen technologies and determine a baseline for monitoring changes in public opinion over time.

The above studies were complemented with two technical workshops, one on Hydrogen Valleys and one on H2 powered aviation, and the relaunch of both the European Hydrogen Observatory and the Hydrogen Valley Platform. As part of the relaunch of the latter, an update to its survey on barriers and best practices to hydrogen deployment was performed, confirming that regulation issues affect projects worldwide evenly, while finding secure public and private funding and the building of a de-risked financial model constitute a major issue for the deployment of hydrogen.

Concluding the Programme Review, the Clean Hydrogen JU continues to contribute to the development of hydrogen technologies, including their cost-efficiency, scaling up and demonstration. All the projects reviewed this year come from the previous programme, whereas new projects of the Call 2022 will be reviewed next year, highlighting the need to continue research, address cross cutting issues and support the further deployment of hydrogen technologies.

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.

1. INTRODUCTION

Hydrogen is expected to play an important role in achieving EU objectives to reduce greenhouse gas emissions by a minimum of 55% by 2030 and reach net zero emissions by 2050. Hydrogen is already being used as a feedstock but can also be used as an energy carrier and as a fuel. Its consumption does not emit CO_2 and when used it generates almost no air pollution. Clean hydrogen use (hydrogen produced using either renewable or low-carbon energy) can help decarbonise not only energy-intensive industries (such as steel, chemicals and cement) and the transport sector (e.g. heavy-duty vehicles, rail and maritime), but also the power sector.

The EU has been supporting research and innovation on hydrogen technologies for two decades, initially through traditional collaborative projects, and subsequently, mainly with the FCH JU and its successors. These efforts have enabled several technologies to come close to maturity[1], alongside the development of high-profile projects in promising applications[2], and to achieve EU global leadership for future technologies, notably on electrolysers, hydrogen refuelling stations and megawatt-scale fuel cells. 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.

To ensure that a full hydrogen supply chain will be available to support the European economy, further research and innovation efforts are required. In this direction, the EU has planned a number of actions, including:

- Support through Horizon Europe (HE)[3] – EU's key funding programme for research and innovation;
- Supporting the EU Emission Trade System (ETS) Innovation Fund[4] ;
- Supporting the integration of hydrogen in the Strategic Energy Technology (SET) Plan[5] activities;
- Co-leading the Clean Hydrogen Mission[6] launched under Mission Innovation; and
- Targeted support through dedicated instruments (e.g. InnovFin Energy Demonstration Projects, InvestEU).

These actions are guided to a large extent by the EU's Hydrogen Strategy[7] and the policy developments in this context, contributing to its implementation.

The founding of the Clean Hydrogen Joint Undertaking (JU)[8] served as a strong message for the continuing support of the EU Research and Innovation (R&I) activities in clean hydrogen solutions and technologies, under Horizon Europe, in synergy with other EU initiatives and programmes. The Clean Hydrogen JU is the continuation of the successful Fuel Cell and Hydrogen JUs (FCH JU and FCH 2 JU) under the FP7 and H2020 programmes respectively.

The multi-annual programme of the Clean Hydrogen JU is described in its Strategic Research and Innovation Agenda[9]. Compared to the past JU Programmes, the SRIA describes 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

1 E.g. buses, passenger cars, vans, material-handling vehicles, and refuelling stations.

2 E.g. e-fuels for aviation, hydrogen in rail, and the maritime sector.

3 Regulation (EU) 2021/695 establishing Horizon Europe – the Framework Programme for Research and Innovation, OJ L 170, 12.5.2021, p. 1–68.

4 https://single-market-economy.ec.europa.eu/industry/strategy/hydrogen/funding-guide/eu-programmes-funds/innovation-fund_en

5 https://energy.ec.europa.eu/topics/research-and-technology/strategic-energy-technology-plan_en

6 http://mission-innovation.net/missions/hydrogen/

7 COM(2020) 301 final, A Hydrogen Strategy for a climate neutral Europe.

8 Council Regulation (EU) 2021/2085 of 19 November 2021 establishing the Joint Undertakings under Horizon Europe

9 SRIA, Clean Hydrogen JU webiste

end-uses. Simultaneously, with many more research Programmes targeting the deployment of hydrogen technologies, 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 Union scientific capacity to accelerate the development and improvement of advanced clean hydrogen market ready applications.

The Clean Hydrogen JU's budget has been significantly increased compared to its predecessor, with EUR 1 billion[10] for the period 2021-2027, complemented by at least an equivalent amount of private investment from the private members of the JU. On top of that, the EU allocated an additional EUR 200 million aiming to double Hydrogen Valleys across Europe, as part of REPowerEU.

10 Plus 200 million for Hydrogen Valleys, as mentioned in the European Commissions' Communication "*REPower EU Plan*", COM(2022) 230

2. PURPOSE AND SCOPE OF PROGRAMME REVIEW 2023

The purpose of the periodic Programme Review is to ensure that the Clean Hydrogen JU Programme is aligned with the strategy and objectives set out in the SBA, further elaborated in its SRIA for 2021-2027. It is performed in a similar manner as its predecessors, FCH JU and FCH 2 JU, and their respective founding Regulations and multi-annual work plans: Multi-Annual Implementation Plan (MAIP)[11] for 2008-2013 under FP7 and Multi-Annual Work Plan (MAWP)[12] for 2014-2020 under H2020.

The Programme Review is an exercise dating back to 2011. Initially, between 2011 and 2016, it was carried out by external experts from research and industry, both European and non-European, as well as by members of the FCH 2 JU Scientific Committee. The main objective was to focus on the progress towards research objectives[13], the Programme Review focused on assessing the progress against the multi-annual targets for fuel cells and hydrogen technologies in Europe in the form of specific and quantitative key performance indicators (KPIs) described in the multi-annual plans, covering parameters such as cost, durability and performance.

As a follow-up to a recommendation[14] made by the Internal Audit Service of the Commission, the 2017 Programme Review was performed following a different procedure to that which was applied in previous years. Upon proposal by the Programme Office and following endorsement by the Governing Board, the JRC was entrusted with the 2017 Programme Review as part of its activities under the multiannual Framework Contract signed between the FCH 2 JU and the JRC. The data collection of relevant information from projects was carried out by the Programme Office using multiple sources, including the TRUST (Technology Reporting Using Structured Templates)[15] platform, project deliverables and a dedicated EU-Survey. After the signature of a Declaration of Confidentiality and Conflict of Interest, the assessment of the Programme was performed by the JRC that prepared a detailed report with observations on the projects' major accomplishments, and the difficulties encountered, and evaluated the performance of the Programme against the KPIs.

Starting with the 2022 Programme Review, the scope of the Programme Review has broadened compared to previous years. The Annual Programme Technical Assessment performed by the JRC[16] remains at the core of the Programme Review, together with the annual event, the EU Research Days (previously called Programme Review Days) and the publication of the Clean Hydrogen JU project fiches (previously called posters). Focusing on the JRC assessment, its scope is to review the annual progress of the Clean Hydrogen JU Programme towards its multi-annual research targets, as reflected by the SRIA technology KPIs, while also identifying gaps in the Programme and providing recommendations on how to better meet its multiannual programme objectives and targets.

The JRC recommendations are then complemented by the independent opinions of the wider scientific community, as foreseen in Article 82 (d) of the Single Basic Act[17] (SBA), gathered through the Wider Scientific Community

11 MAIP, Clean Hydrogen JU website

12 MAWP, Clean Hydrogen JU website

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

14 Final Audit Report on Performance management of the FCH 2 JU activities (Internal Audit Service Report: IAS.A2-2016-FCH 2 JU-003)

15 https://trust.fch.europa.eu/ui/projects

16 A summary of the JRC Programme Technical Assessment per Pillar can be found in the second part of this report, as introductory information for each Pillar.

17 Regulation (EU) 2021/2085 - adopted by the Council of the European Union on 19 November 2021 - concerning the establishment of Joint Undertakings under Horizon Europe.

Survey 2023 that performed between 9 June and 31 July 2023. In addition, the Programme Review reports on possible relevant studies commissioned by the JU and certain major reports published by international bodies and selected international developments, providing a more holistic picture on the wider developments in the hydrogen sector and how the Clean Hydrogen JU activities fit within this wider context. Moreover, the Program Review concludes by summarising observed technological, economic and societal barriers to market entry, tasked to the JU by the SBA Article 74 (a).

The inclusion of all these topics in the Programme Review Report allow it to go beyond the simple act of monitoring the Programme, providing important input for the next Annual Work Programmes (AWPs) and the identification of research areas and topics for the forthcoming Calls.

3. JRC'S ANNUAL PROGRAMME TECHNICAL ASSESSMENT 2023 OVERVIEW

The Annual Programme Technical Assessment has included all projects up to the 2020 Calls for Proposals that were ongoing[18] in the period January 2022 to March 2023. The current Annual Programme Technical Assessment therefore covers 81 projects, of which 1 began under FP7 and 80, under H2020. Projects under the 2022 Calls[19], initiated from 2023 onwards, are expected to be reviewed for the first time in 2024. In this respect, all projects considered for this year's assessment have run for more than 18 months, resulting in the assessment between projects being considered more correct and fairer compared to previous years, where projects with a shorter running life were also considered. This implies that the findings of the review are representative of all projects.

In line with the new programme structure of the new Clean Hydrogen JU, explained in the SRIA, the reviewed projects have been assigned to 7 "Review Pillars"[20]:

- Pillar 1: Hydrogen Production
- Pillar 2: Hydrogen Storage and Distribution
- Pillar 3: Hydrogen End Uses - Transport
- Pillar 4: Hydrogen End Uses - Clean Heat and Power
- Pillar 5: Cross-Cutting Issues
- Pillar 6: Hydrogen Valleys
- Pillar 7: Hydrogen Supply Chains

Each Pillar is characterised by a wide range in scope, activities and applications of the included projects. Therefore, each Pillar consists of a set of Research Areas which group projects covering similar, related topics. The programme assessment is performed for each Research Area. This split is presented in Table 1 below.

18 "Ongoing" means between project start date and project end date.

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

20 There are currently no reviewed projects under the horizontal activity "Strategic Research Challenges", so the related review pillar is not considered for this Programme Review.

Table 1: Research Areas and Topics per Pillar for the 2023 Programme Review

PILLARS	RESEARCH AREAS	RESEARCH TOPICS
1) Hydrogen Production	1 - Low temperature electrolysis	Projects targeting AEL, PEMEL and AEMEL
	2 - High-temperature electrolysis (incl. co-electrolysis)	Projects targeting SOEL and PCCEL
	3 - Other hydrogen production methods	Projects covering reformer development for distributed hydrogen production and thermochemical hydrogen production are covered in this review
2) Hydrogen storage and distribution	4 - Aboveground storage	Projects addressing optimisation and deployment of large-scale solid state storage solution
	5 - Underground storage	Projects targeting the feasibility, risks and impact of H_2 underground storage
	6 - H_2 in the natural gas grid	Projects assessing the effect of H_2 on transmission (High pressure) Natural Gas (NG) pipeline
	7 - Liquid H_2 carriers	Projects focusing on the improvement of the roundtrip efficiency of conversion and system cost
	8 - Compression, purification and metering solutions	Projects demonstrating feasibility of direct separation of H_2 from NG and material research on proton conducting ceramic electrochemical cells (PCC)
	9 - H_2 refuelling stations	Projects addressing reliability and availability issues indicated by operation of existing Hydrogen Refuelling Stations (HRS)
	10- Hydrogen transportation (pipelines, road transport and shipping)	*currently not covered by any projects*
	11 - Hydrogen distribution (pipelines)	*currently not covered by any projects*
3) Hydrogen end uses - transport	12 - Building Blocks	Projects focusing on material, design and system optimisation for LT and HT PEMFC
	13 - Heavy Duty Vehicles	Projects addressing optimisation of BoP components and architectures design to meet Heavy-Duty Vehicles (HDV) needs
	14 - Waterborne Applications	Projects focusing on improving access to the market for hydrogen, its derivatives and FCs, initially on smaller vessels
	15 - Rail Applications	Projects with the objective of enabling hydrogen to be recognised as the leading option for trains on non-electrified or partially electrified routes

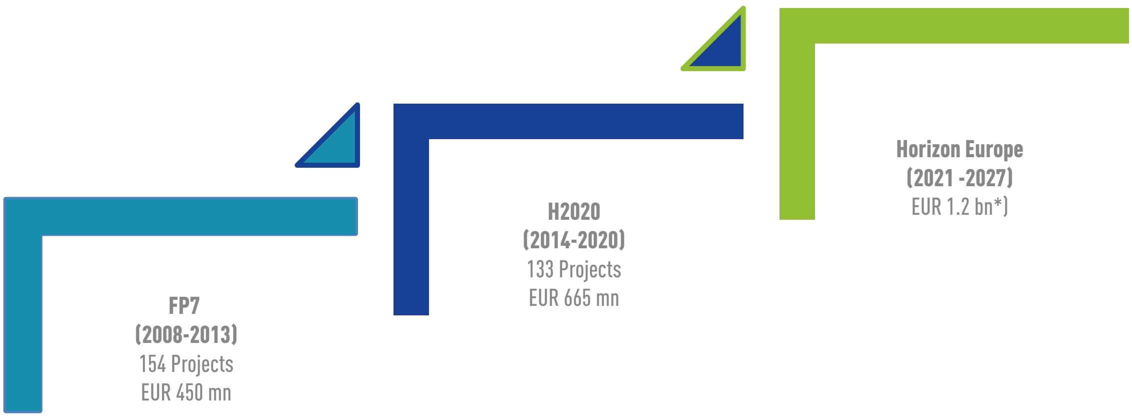
PILLARS	RESEARCH AREAS	RESEARCH TOPICS
	16 – Aviation Applications	Projects addressing optimisation of Balance of Plant (BoP) components and architectures design to meet aviation needs
	17 – Bus/Coaches	Projects with the objective of improving the deployment of hydrogen in this segment
	18 - Cars	Projects with the objective of improving the deployment of hydrogen in this segment
4) Hydrogen end uses – Energy	19 - m-CHP	Project exploring the deployment of PEMFC and SOFC for micro-Cogeneration
	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	Demonstration projects exploring the application of Proton Exchange Membrane (PEM), Solid Oxide and Alkaline hydrogen technologies (FC and electrolysers)
	23 – Next generation degradation and performance & Diagnostic	Exploration projects for utilisation of biogas fed with a SOFC CHP system and use of Electrochemical Impedance Spectroscopy (EIS) technology for monitoring and diagnostic purposes
5) Cross-cutting topics	24 - Sustainability, Life Cycle Sustainability Assessment, recycling and eco-design	Projects addressing needs to define guidelines for sustainability assessment
	25 - Education and Public Awareness	Projects aiming to increase the knowledge on hydrogen technology at educational level (schools / universities)
	26 - Safety, Pre-Normative Research and Regulations, Codes and Standards	Projects focusing on improving knowledge on hydrogen risk of utilisation and definition of protocol for permitting
6) Hydrogen Valleys	27 – H_2 Valley	Projects aiming to develop a hydrogen integrated system when favourable conditions at industrial or geographical point of view
7) Hydrogen Supply Chains	28 – Manufacturing for stationary applications	Projects addressing optimisation of materials and/or BoP components and architecture design to meet stationary application needs
	29 – Manufacturing for transport applications	*currently not covered by any projects*
	30 – Critical Raw Materials (CRM)	*currently not covered by any projects*

4. BUDGET

The Clean Hydrogen JU succeeded the FCH 2 JU, under the Horizon Europe Programme, inheriting the technological achievements and funding expenditures of the previous Programmes for continuing the legacy of its predecessor(s). Before the current Horizon Europe Programme and the establishment of the Clean Hydrogen JU, the cumulative budget invested in Hydrogen technology projects reached the total amount of EUR 1.07 billion.

In line with the ambition and the objectives set for the Clean Hydrogen JU, the overall programme funding will be reaching EUR 1 billion[21]. Moreover, to double the number of Hydrogen Valleys under the REPowerEU Plan, the Commission will provide additional funding of EUR 200 million to top-up the overall budget for the Clean Hydrogen JU goal.

Figure 1: Implementation of MAIP 2008-2013, MAWP 2014-2020 and SRIA 2021-2027



**including foreseen funding for hydrogen valleys from the REPowerEU Plan*
Source: Clean Hydrogen JU

In the year 2022, there was still 1 ongoing project from FP7 and 80 more from H2020, with a total budget of EUR 454.4 million. Moreover, the Clean Hydrogen Partnership has launched its first two Calls for Proposals under Horizon Europe: Call 2022 on 31 March 2022 and the second one - Call 2023 - on 17 January 2023. Following the evaluation results of Call 2022[22], 50 grant agreements were signed for funding under Horizon Europe[23], with a budget of EUR 322.8 million[24]. Table 2 presents the distribution of the projects that were on-going during the current Programme Review period, to the 8 Review Pillars.

21 This amount is to be complemented by at least an equivalent amount of private investment (from the private members of the partnership), raising the total budget to above EUR 2 billion.

22 https://www.clean-hydrogen.europa.eu/about-us/key-documents/annual-work-programmes_en

23 Including EUR 33 million for 2 Hydrogen Valleys to be funded via REPowerEU.

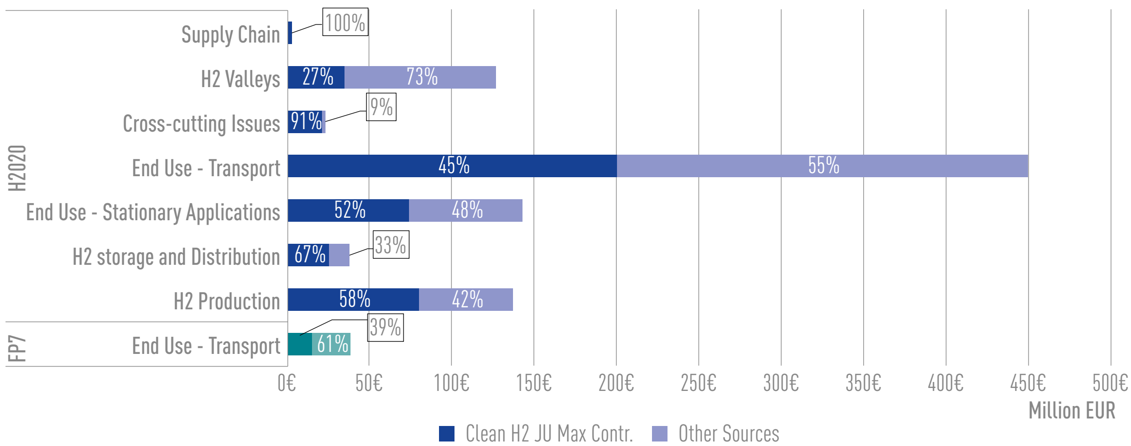
24 There are still 3 successful projects of Call 2022 in the final stages of grant preparation, two of which Hydrogen Valleys to be funded via REPowerEU, but which are not included in the figures above.

Table 2: MAWP/SRIA Pillars reviewed

Programme	SRIA Panel	No. of projects	Total JU funding in M€
FP7 1 Project & 15 M€	Pillar 3 - H2 End Uses - Transport	1	15
H2020 80 Projects & 439.4 M€	Pillar 1 - H2 Production	19	80.25
	Pillar 2 - H2 Storage and Distribution	9	25.35
	Pillar 3 - H2 End Uses - Transport	25	201.48
	Pillar 4 - H2 End Uses - Stationary Applications	12	74.22
	Pillar 5 - Cross-cutting	11	20.8
	Pillar 6 - H2 Valleys	3	35
	Pillar 7 - Supply Chain	1	2.34
Horizon Europe 50 Projects & 322.8M €	Pillar 1 - H2 Production	13	68.3
	Pillar 2 - H2 Storage and Distribution	11	38.9
	Pillar 3 - H2 End Uses - Transport	9	91.5
	Pillar 4 - H2 End Uses - Stationary Applications	4	17.7
	Pillar 5 - Cross-cutting	5	8.5
	Pillar 6 - H2 Valleys	6	81.4
	Pillar 7 - Supply Chain	1	6.6
	Pillar 8 - Strategic Research Challenge	1	10

Focusing on the on-going legacy projects from FP7 and H2020, the split between the funding provided from the Clean Hydrogen JU and other (private) sources is presented in Figure 2 below.

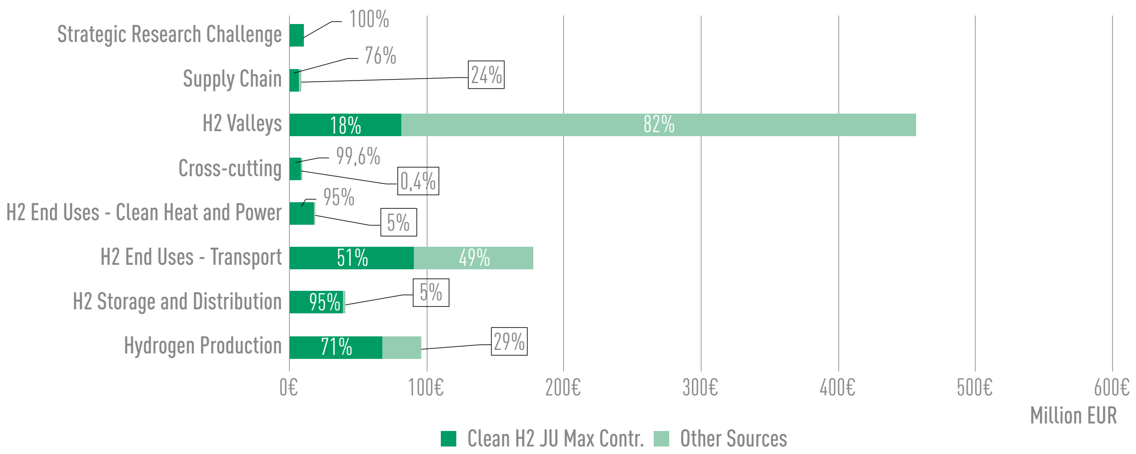
Figure 2: Source of funding for ongoing legacy projects in 2022



Source: Clean Hydrogen JU

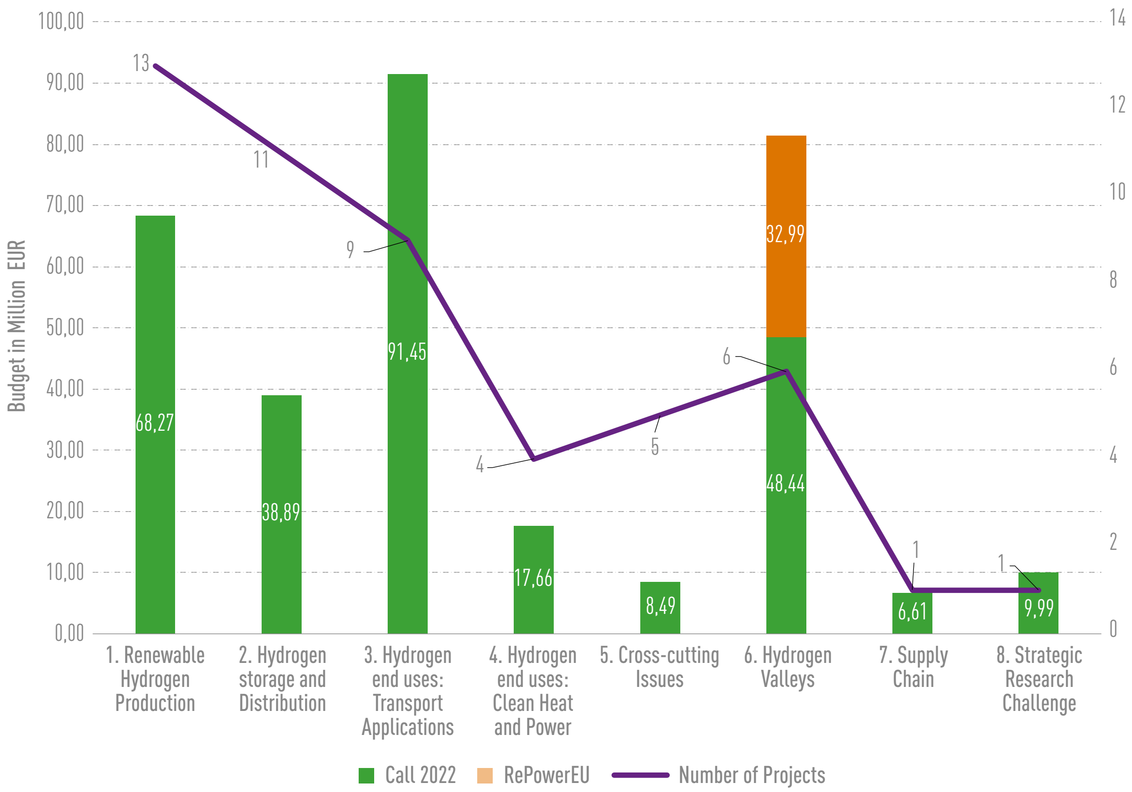
For the successful projects from Call 2022, the split between the funding to be provided from the Clean Hydrogen JU and from other sources is presented in Figure 3 below, while Figure 4 depicts the funding contribution and number of projects per Review Pillar.

Figure 3: Clean Hydrogen JU Call 2022 source of funding



Source: Clean Hydrogen JU

Figure 4: Clean Hydrogen JU funding contribution and number of projects per Review Pillar for Call 2022



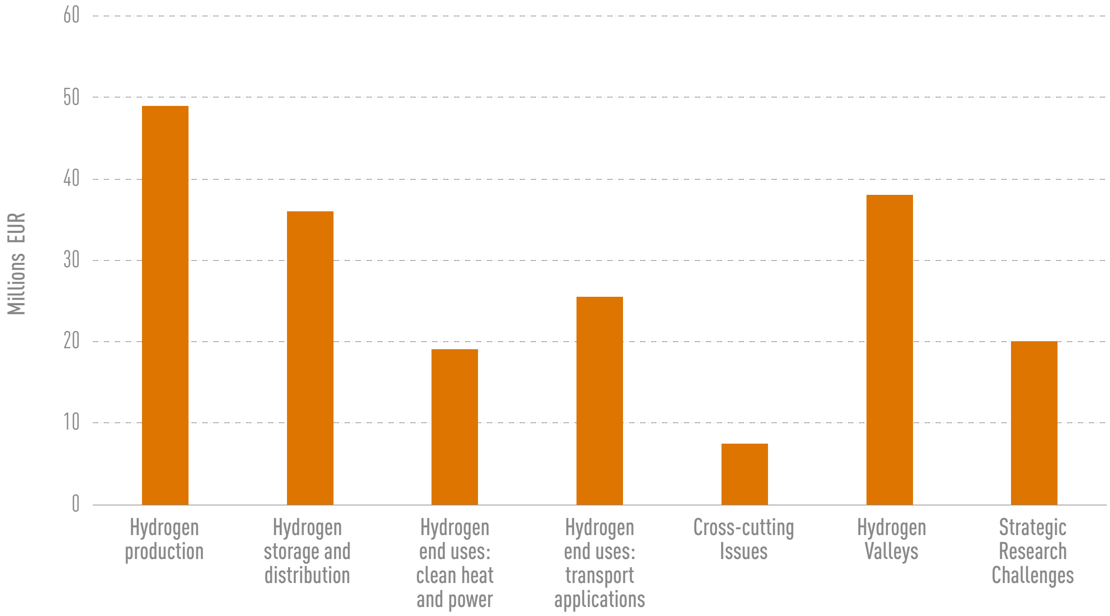
Source: Clean Hydrogen JU

In January 2023, a new Call for Proposals was published with an indicative total budget of EUR 195 million covering 26 research and innovation topics across the whole hydrogen value chain, including:

- 7 topics for Renewable Hydrogen Production;
- 5 topics for Hydrogen Storage and Distribution;
- 3 topics for Transport;
- 4 topics for Heat and Power; and
- 3 topics' projects will support Cross-cutting Issues.

The Call also included 2 Hydrogen Valleys and 2 Strategic Research Challenge topics. The foreseen total budget of EUR 195 million for the Call 2023[25] can be allocated per Review Pillar as presented in Figure 5 below, although the final allocation will depend on the final list of successful projects that will sign a grant agreement with the Clean Hydrogen JU.

Figure 5: Clean Hydrogen JU Call 2023 maximum budget allocation per SRIA Pillar



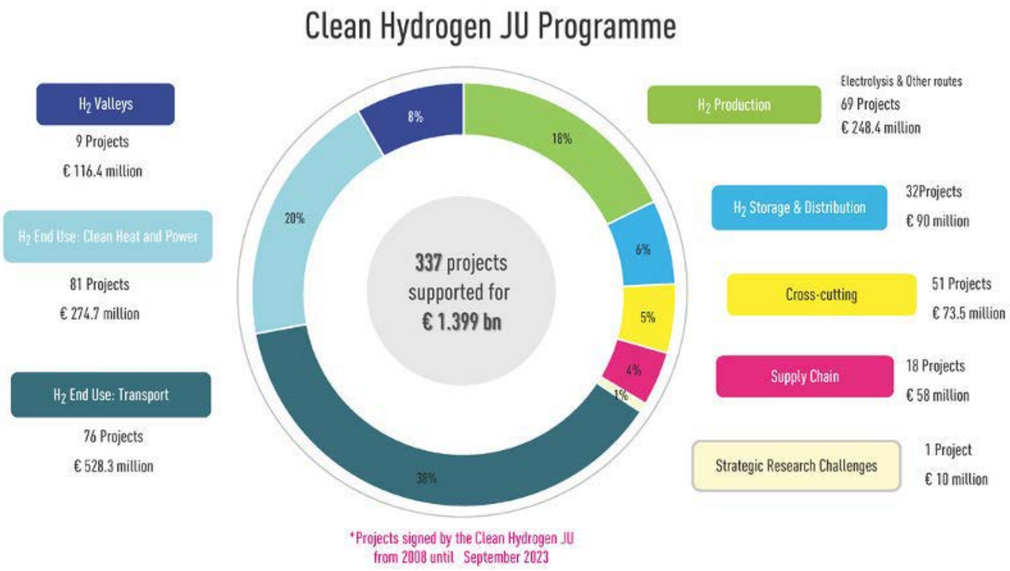
Source: Clean Hydrogen JU

Finally, the overview of the overall split of the Clean Hydrogen JU funding[26] is portrayed in Figure 6

25 https://www.clean-hydrogen.europa.eu/document/download/3aca5d27-2002-4100-813f-d0edf89b2911_en?filename=Clean%20Hydrogen%20JU%20AWP%202023_0.pdf

26 Only for signed grants until September 2023.

Figure 6: Overview of the Clean Hydrogen JU programme per Pillar (2008 – 2023)



Source: Clean Hydrogen JU

5. PILLARS REVIEW

5.1. PILLAR 1 - HYDROGEN PRODUCTION

The vast majority of hydrogen produced and used in the EU (and globally) comes from fossil fuels. There is an increasing urgency to decarbonise hydrogen production, to produce hydrogen through sustainable methods on a large scale, in order for hydrogen to take its place in the energy mix of a decarbonised society. SRIA[27] dictates that in order for hydrogen technologies to scale up, renewable hydrogen needs to become cost competitive. In transport applications, a cost of around 5 €/kg at the pump must be achieved for cost parity with conventional fuels. In industry, renewable hydrogen as a feedstock must reach levels between 2-3 €/kg to achieve cost parity with fossil-based inputs, once the cost of carbon is included in the feedstock cost.

The projects in Pillar 1 contribute towards achieving the techno-economic objective of making hydrogen production from renewables competitive and enabling the scale-up of these technologies. In particular, improvements in efficiency and cost reduction are required across all hydrogen production routes.

Overview of Research Areas

Low-Temperature Electrolysis: The focus area currently consists of 9 projects, including 3 on alkaline electrolysis (**DEMO4GRID, DJEWELS, OYSTER**), 3 on PEM electrolysis (**REFHYNE, HAEOLUS, NEPTUNE**), and 3 on anion exchange membrane electrolysis (**ANIONE, CHANNEL, NEWELY**).

Looking the historical achievements of the JU in this research area, the R&I projects funded by the JU have contributed to improving a number of techno-economic parameters of the low temperature electrolysers, most importantly reaching the majority of the MAWP 2020 targets for PEM electrolysers. In terms of CAPEX (EUR/kW), there is a trend in PEM towards lower values with more than one project achieving the SRIA 2024 cost target.

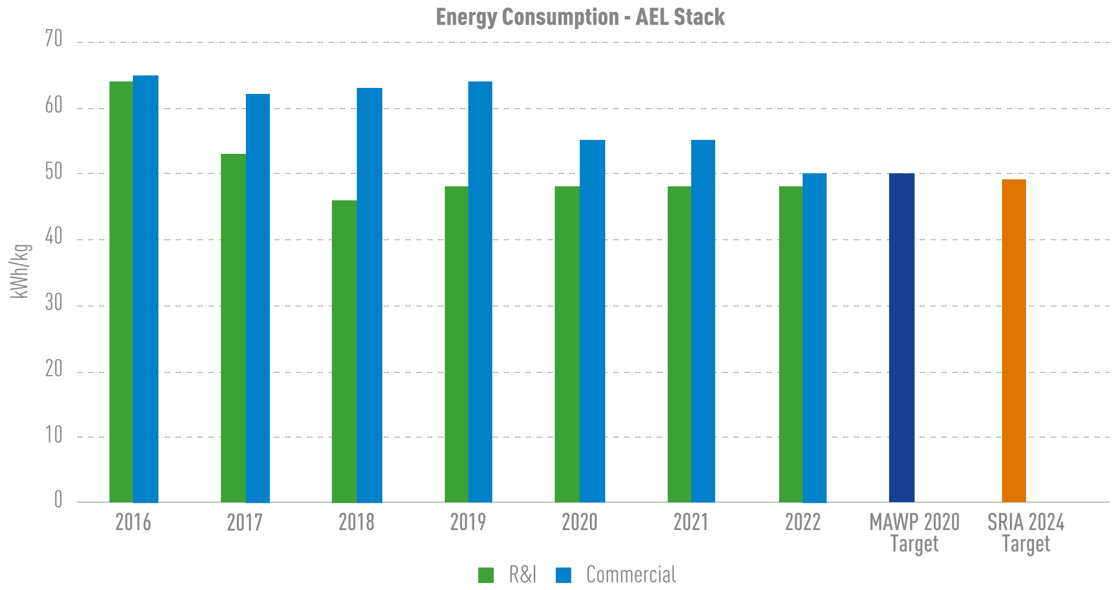
PEM electrolysers has also achieved most of the MAWP KPIs. The target for the electrolyser footprint has been achieved by far since 2015, with the average footprint reported in 2022 being 13.75 m^2/kW, less than half the average value of 2015. Also, one KPI related to the Critical Raw Materials (Iridium) has shown considerable decrease from an average of around 0.74 mg/kW in the years 2015-2020 to around 0.16 mg/kW in 2022. Finally in 2022, both degradation rate (0.13%/1000h) and current density (2.7 A/cm^2) are considered to have met the 2024 SRIA target.

The improvement in terms of energy consumption per kg H_2, both for AEL and PEMEL, is depicted in Figure 7 below, as well as the comparison of the annual achievements of the R&I electrolysers versus the commercial ones, which are the ones used in the HRS projects.[28] Additional effort is necessary to achieve the 2024 SRIA target.

27 Before the observed increase in energy prices.

28 Commercial projects refer to data coming from transport projects using commercial electrolysers for the production of hydrogen for their HRS. The bars indicate the best values reported per year (not the best value up until that year). Note also that almost in all cases there were better values than the ones depicted in the graphs, but which cannot be reported due to confidentiality reasons. Finally, in some cases the values do not come from one project, but are the result of averaging, to respect the confidentiality aspects.

Figure 7: Energy consumption between R&I and Commercial projects of both Alkaline and PEM electrolysers



Source: Clean Hydrogen JU

AEMEL is currently at a low TRL level, however the 3 projects currently supported by the Clean Hydrogen JU, namely CHANNEL, ANIONE and NEWELY, seem to be progressing well towards reaching the SRIA 2024 targets. Only one manufacturer of AEMEL (Enapter) currently exists on the market.

High-Temperature Electrolysis: This Research Area mainly covers the SOEL technology. This Research Area covers the Solid Oxide Electrolyser projects **SWITCH, NEWSOC, GRINHY2.0, MULTIPLHY, REFLEX, MEGASYN, PROMETEO** and **REACTT** as well as the single PCCEL project **GAMER**. It should be noted that several of these projects are at a relatively early stage and are being presented in the Programme Technical Assessment for the first time (MEGASYN, NEWSOC, PROMETEO, REACTT).

There have been fewer projects at higher TRL levels, as the technology is less advanced than AEL or PEMEL. Therefore, most of these KPIs have been achieved by only one or two projects (with the exception of production loss where a number of projects achieved the 2020 target).

Significant progress against most technical KPIs has been made in the previous Programme. The System CAPEX KPI was significantly overachieved in terms of the MAWP 2020 target and therefore the SoA in SRIA for 2020 was reduced to 3 550 EUR/(kg/day). Already the SRIA 2024 target of 2 000 EUR/kW has been achieved by the average project reporting in 2022. Over time, the average values reported decreased in 2022, which can be considered a significant improvement. In terms of reversible capacity (around 27% on average) and production loss rates (around 0.28%/1000h), projects have shown considerable improvement.

Significant progress against most technical KPIs appears to have been made in the previous programme. Several projects are currently at a relatively early stage, but the Clean Hydrogen JU overall funding in HT electrolysis compared to the number of installed R&I MW is decreasing, indicating the progress that has already been made.

Reversibility of SOEL technology is technically interesting; when renewable energy is available, the system produces green hydrogen as an electrolyser, but can also generate electricity in a reverse fuel cell (SOFC) mode (project SWITCH). It can also contribute to the improvement of energy efficiency using the waste heat in industrial processes (GrInHy2.0, MULTIPLHY). However, reversibility does not seem to be fully justified so far by the use cases.

Also, PCCEL (Proton Conducting Ceramic Electrolyser) technology is presented by the project GAMER. It has advanced tubular PCEL technology and is currently building a 10kW system, however the high degradation rates have prevented the scaling up so far. The project published its findings in Nature Materials[29].

Other Routes of Renewable Hydrogen Production: Compared to electrolysis, all other renewable hydrogen production technologies are of lower TRL. The JU is supporting alternative routes to electrolysis for renewable hydrogen production, for example project **HYDROSOL-BEYOND** in demonstrating solar thermochemical hydrogen production, that is facing a number of technical challenges regarding the durability and stability of the materials operating at temperature over 1,000°C.

Highlights

The currently on-going Clean Hydrogen JU projects considered in this review have installed more than 16 MW of electrolysers, or they are planning to deploy them, demonstrating not only the potential and scalability of the technology, but also business cases suitable for different type of industries (refineries, steel making etc) and ancillary services:

- A 3.2 MW pressurised AEL in Austria, at the MPREIS industrial bakery is commercially setup and has been operating since March 2022 under the project **DEMO4GRID**[30] to provide hydrogen (for heavy-duty vehicles), heat and grid balancing services. The project has received many awards, such as the Tirol Change Award and the Energy Globe Award Austria.
- A 10 MW PEM electrolyser from ITM has been operating since the beginning of 2022 in the Shell Rhineland Refinery in Wesseling, Germany, by the project **REFHYNE**. It supplies the refinery with 4,000 kg of green hydrogen a day (at 20 bar pressure). Based on the gained experience, a new 100 MW installation is being considered.
- A 2.5 MW PEMEL, directly connected with a 45 MW wind farm in a remote area of Norway, has been operating since June 2022. The **HAEOLUS** project can produce up to 1 tonne of hydrogen a day (at 30 bar and 60°C) and is combined with a storage tank and a 120 kW fuel cell for re-electrification. The project achieved its own targets for electrolyser efficiency and cost per kW.
- Considerable progress has been made in low-TRL AEMEL technology through the projects CHANNEL, ANIONE and NEWELY. In general, the projects have managed to achieve promising data on novel membranes, electrocatalysts and combined as Membrane Electrode Assemblies. **CHANNEL** demonstrated a 2KW prototype with non-PGM reaction catalysts achieving the performance targets set for the cell and the catalysts, while **ANIONE** has successfully developed two membranes and managed to integrate large-area membranes delivering 25 large-area MEAs (>100 cm^2). Finally, **NEWELY** developed PSEBS membrane with characteristics successfully reaching the project's targets, having completed several publications and submitted 2 patent applications.
- **SWITCH** has demonstrated a reversible system (rSOC) of 25 kW (SOFC) / 75 kW (SOEC), able to operate in SOEC and SOFC mode, that achieved a conversion efficiency of 80% and a SOEC mode to SOFC mode switchover time of 15 minutes, which is half the target value.
- **NewSOC** has identified an optimum SOE cell configuration, offering low ASR and high mechanical strength. It succeeded in improving the SoA of Ni/YSZ fuel electrodes aided by modelling. Robust and high performing electrodes, namely titanate doped Ni/GDC and LCr fuel electrodes and CO-free oxygen electrodes for intermediate temperature operation (650-700°C), were developed and tested with promising results comparable or superior to SoA.
- The world's biggest HT SOEL at a capacity of 720 kW was demonstrated in August 2021 by the project **GrInHy2.0.** The installation uses steam coming from industrial waste heat at a Salzgitter steel mill. By project end, the system operated for more than 14,000 hours, injecting more than 100 tons of hydrogen into the grid, having also achieved the target of 84.6% of lower heating value (LHV) efficiency.

29 Vøllestad, E., Strandbakke, R., Tarach, M. *et al.* Mixed proton and electron conducting double perovskite anodes for stable and efficient tubular proton ceramic electrolysers. *Nat. Mater.* **18**, 752–759 (2019). https://doi.org/10.1038/s41563-019-0388-2.

30 It is building on the outcomes of the ELYGRID and ELYNTEGRATION projects.

Gap Analysis – Main JRC Recommendations

As mentioned earlier, there is currently a pressing need to produce hydrogen on a mass scale in a sustainable way. The work that has taken place to date under the Clean Hydrogen JU has established a solid basis for advancing technological performance, particularly in the areas of PEMEL and SOEL. Research projects on AEMEL show good progress when it comes to the development of components but should consider the potential for mass-manufacturing at an earlier stage in the project. Large-scale deployment can be expected under programs such as the hydrogen IPCEI, so the Clean Hydrogen JU will need to focus on areas of clear added value. This should include both lower TRL research that will develop the next generation of hydrogen production technologies, and selected demonstrations, that should focus on a first-of-a-kind deployment in applications that can assist the rapid deployment in industrial settings. Especially industry-relevant projects will have to make greater efforts in cross-sectorial dissemination and reaching out to non-expert, less technically oriented audiences in order to better explore the developed technologies' potential.

LT Electrolysis: Despite an increasing number of planned and ongoing large-scale electrolyser deployment projects incorporating AEL and PEMEL across the world, there are still demonstration areas where the Clean Hydrogen JU will be able to play a valuable role. Identifying or anticipating gaps and bottlenecks arising from large projects in such programmes as the hydrogen IPCEI, the Clean Hydrogen JU could make a considerable impact in the development of novel manufacturing methods for the automation of electrolyser production, a great deal of which is currently carried out manually. This should also benefit from the outcome of fuel cell manufacturing projects.

Also, as mentioned in the SRIA, the focus on new technologies for seawater electrolysis could become increasingly important for the future. As water related issues attract more attention from policymakers, an assessment of water needs and water efficiency issues at the component and system level would be essential for the projects. Finally, the outcomes of previous projects on diagnostics and monitoring should be better valorised. If there are commercial products as outcomes, this should be well publicised.

The use of critical raw materials must be significantly reduced in cases where high current densities without the use of platinum group metals (PGM), in particular iridium in PEMEL, cannot be achieved, a greater focus on recycling methods could be applied. Also, in view of the discussions related to the banning of PFAs[31], alternatives to membranes and ionomers using them should be explored.

Predictive modelling and rapid screening methods along with advanced computational methods, including upcoming AI approaches, should be engaged in. Objectives include the search of both viable alternative eco-friendly materials and feasible synthesis and processing routes to bring them into eventual existence.

For AEMEL, the current projects are developing stacks up to the size of 2 kW. The existing projects seem to be highly successful in developing novel materials and components so the next focus should be on the scaling up to more practical stack and system sizes.

Research related to the use of seawater for hydrogen production could be of interest, both at the component and at the system level, such as new components for direct sea water electrolysis or activities related to the integration of desalination and thermal management components into the electrolysis system. The tracking and reporting on water-related parameters such as water consumption or more efficient cooling designs, reducing the need for water-based cooling systems, should also be considered.

Additional effort is required concerning the automation of manufacturing processes and methods and the assessment of the capacity for the newly developed material and/or components to be manufactured and processed at a higher volume rate. Coating processes (catalytic inks application, decal method), membrane cutting technologies, and roll-to-roll processes, among other techniques, could benefit from an increased research focus. This could also include the development of innovative tools for components' handling, thus reducing the risk of damages done to components and materials when the production rate increases.

31 Perfluoroalkyl and Polyfluoroalkyl Substances

HT Electrolysis: With SOEL being at a lower TRL level (and system scale) than PEMEL and AEL, some opportunities for larger scale demonstrations and integration in industrial settings within the Clean Hydrogen JU programme will certainly remain. There is still considerable room for improvement in both technical and economic KPIs associated with the technology.

At the lower TRL level, focus can include the reduction in use of those heavy and light rare earth metals which are listed by the European Commission as critical raw materials. The economic and ecological impact of the expanded use of these materials should be considered. Also, additional efforts should be made into lowering the operating temperature and increasing the output pressure of the hydrogen produced.

Additional resources to improve durability of SOEL coupled to intermittent RES could be allocated if considered of more added value compared to the focus on reversible electrolysis, for which it is not clear if it corresponds to industry and customer needs.

Alternative Methods of Hydrogen Production: The experience from HYDROSOL projects shows that there is are still high risks making difficult the advance of the technology to TRL 6. Although most of the advancements will be at component or even plant design level, these are to be tested in the field. It is proposed to fund a new study, comparing the various alternative hydrogen production methods in terms of cost and environmental impacts. In addition, the current TRL of each route should be assessed carefully. This could be an update of the study funded by the JU in 2015, which analysed 11 different pathways.

More info on the Pillar, the related Research Areas and the projects can be found in the Annex, under PILLAR 1 - HYDROGEN PRODUCTION.

5.2. PILLAR 2 - HYDROGEN STORAGE AND DISTRIBUTION

The REPowerEU plan and the European Hydrogen Strategy recognise the important role that hydrogen storage and distribution play in order to further the penetration of renewable hydrogen in Europe. The REPowerEU plan envisions the import of 10 million tonnes of hydrogen by 2030. The Hydrogen Strategy also mentions that a logistical infrastructure must be developed in order to transport hydrogen from areas with large renewable potential to demand centres across Europe. There are various options to transport and store hydrogen, that can serve as building blocks for an EU-wide logistical infrastructure in its multifaceted complexity. The SRIA calls for a pluralistic approach in respect of these technologies to be investigated and supported.

Overview of Research Areas

Aboveground Storage: Hydrogen can be stored as compressed gas in aboveground pipelines or other types of pressure vessels[32]. Solid state hydrogen storage is one of the technologies funded by the Clean Hydrogen JU (SSH2S, HYPER, BOR4STORE, EDEN) which has certain advantages for aboveground storage. Metal or chemical hydrides allow hydrogen storage at high volumetric and gravimetric density at low pressures. There has been a lot of research effort, also by many projects funded through other programmes at (inter)national and EU level, to identify and develop solid-state storage materials with the right characteristics for this purpose. Cyclability, a suitable heat supply, and thermal management have proven to be particularly challenging.

This Research Area currently consists of 1 finished project, **HYCARE**, focusing on solid state storage. The HYCARE project is targeting the upscaling of a solid-state hydrogen storage system based on metal hydrides, albeit at a much smaller scale (44 kg H2 reversibly stored) than the SRIA target of 5 tonnes for 2024.

Underground Hydrogen Storage: Underground storage[33] offers the potential to deploy large amounts of gas storage at a relatively low cost. Flows of large amounts of hydrogen derived from renewable sources will need

32 Since mid-1960s, the two largest liquefied hydrogen storage tanks (around 212 tonnes of liquefied hydrogen each) have been operating at NASA facilities.

33 There are salt caverns commercially operating for the storage of hydrogen in the U.K. and U.S. In Teeside, U.K. three smaller caverns of 70 000 m^3 capacity are owned by Sabic Petrochemicals. In Texas, three larger caverns, with capacity over 560 000 m3 each are supplying hydrogen to the petrochemical industry (operated by Praxair, Air Liquide and ConocoPhillips).

to be coupled with low-cost bulk storage solutions, able to even out and buffer any temporal mismatch between hydrogen production capacity and hydrogen consumption. As large-scale hydrogen underground storage in salt caverns is at a higher TRL, the SRIA's main aim for this topic is to reduce costs and identify best practices and business cases for coupling renewable hydrogen production with underground storage. In addition, more fundamental research is needed in order to investigate hydrogen compatibility with porous rock media and improve associated designs.

The 3 projects (**HYPSTER, HYSTORIES** and **HyUsPRe**) funded by the Clean Hydrogen JU on this topic can build on the findings of several nationally funded projects and exploit synergies with several other initiatives. Many other projects are investigating the field. The Underground Sun Storage[34] and HyINTEGER[35] projects performed testing on steels and rubbers and on materials compatibility and durability of cement mixtures for use in porous rock hydrogen storage facilities. H2Store[36] had a focus on micro-biological interactions with hydrogen, which are a concern in porous rock formations. The German project HYPOS H2 UGS has paved the way for the construction of a research salt cavern in eastern Germany, which is to supply hydrogen to the surrounding chemical plants. The Dutch project HYSTOREREACT is investigating the potential effects of geo- and biochemical reactions of hydrogen with storage media. HYSTOCK is going to develop and test a salt cavern for hydrogen storage in proximity of an industrial centre in the north of the Netherlands. This will be linked to the future hydrogen transmission grid and used as a template for future storage sites across the country. The British HYSTORPOR is also investigating interactions between the stored hydrogen gas and fundamental microbiological and geological processes. The Polish HESTOR project aims at investigating salt cavern options for hydrogen storage.

In addition, Task 42 of the IEA Hydrogen TCP is bringing together experts working with underground hydrogen storage. There are also many other fora, or public and private initiatives at European and international level which can support, complement or exploit the know-how generated by the CH JU financed projects.

Hydrogen in the natural gas grid: Several research and demonstration pathways are being explored to decarbonise the natural gas grid and to distribute hydrogen. This Research Area focuses on admixture of hydrogen to natural gas and repurposing of natural gas pipelines for the transmission and distribution of 100% hydrogen.

Many projects in Europe (particularly in Germany[37]) have conducted research on how much hydrogen can be safely added to the natural gas system, and on whether the existing infrastructure can be used. According to the ENTSOG hydrogen project visualisation platform[38], more than 70 projects are dealing with repurposing infrastructure in Europe[39]. According to the outcomes of these projects, hydrogen can be added up to 20% of volume to the natural gas distribution grid without causing significant issues[40]. Also, repurposing of existing pipelines to transport 100% hydrogen is already ongoing, and there are research efforts underway in order to

34 Underground Sun Storage (underground-sun-storage.at)

35 https://www.gfz-potsdam.de/en/section/geomicrobiology/projects/hyinteger

36 H2STORE: GFZ (gfz-potsdam.de)

37 DVGW Website: Power to Gas

38 ENTSOG - Hydrogen project visualisation platform

39 In France, the GRHYD demonstration project ran until 2020. Hydrogen was injected into the natural gas distribution network with a concentration up to 20 vol%. In the United Kingdom, the HYDEPLOY project is a demonstration on the use of blended hydrogen in the U.K. gas grid. The HyNTS project evaluated the costs and opportunities to repurpose the existing compression equipment and investigated the compatibility of typical National Transmission System (NTS) components. There are also plans for repurposing the existing infrastructure to 100% hydrogen (H21, H100). At EU level, the HYREADY project has produced a set of engineering guidelines on how to identify and quantify the effects of hydrogen addition to natural gas in a specific network and to propose feasible mitigating measures if needed. The GERG (European Gas Research Group) Hydrogen in Pipeline Systems (HIPS) project had looked into the impact of hydrogen on the gas grid and issued a number of recommendations. It is followed up by the HIPS-NET project with a similar objective. Repurposing of steel pipelines has been tested in initiatives led by Transmission System Operators (TSO), for example in the Netherlands by Gasunie, and in Germany by RWE. TSOs have joined to present the European Hydrogen Backbone report, which shows plans for an extensive hydrogen pipeline infrastructure covering 21 countries, with two thirds of the pipelines being repurposed. In the U.S., the HyBlend project aims to address technical barriers for blending hydrogen in natural gas pipelines, including materials compatibility R&D, techno-economic analysis, and life cycle analysis.

40 For higher hydrogen concentrations there are knowledge gaps as well as known problems, for which solutions need to be identified.

safely enable this[41]. Also, there is still uncertainty on the amount of hydrogen that might leak from repurposed natural gas pipelines[42].

Project **HIGGS**, aiming to increase the knowledge on the effects of hydrogen on the high-pressure natural gas infrastructure, has been reviewed under this Research Area.

Liquid Hydrogen carriers: Hydrogen delivery at large scales and over long distances is deemed challenging, due to the low energy density of hydrogen. Transfer over distances of 3 000 km with pipelines is likely to be a less economic option than shipping of compressed or liquid hydrogen, or shipping of chemical carriers. Apart from Liquid Hydrogen (LH_2)[43], hydrogen carriers are an important component for establishing a hydrogen delivery chain. The chemical carriers being considered by stakeholders are ammonia, methanol and Liquid Organic Hydrogen Carriers (LOHC). Ammonia production (with fossil fuels) and transport can be considered established technologies, but there is not much experience yet with its cracking (hydrogen release) at scale. Unlike methanol, LOHC does not release CO_2 during hydrogen release and in addition, it has the advantage that existing infrastructure such as oil tankers can be reused. A critical parameter for the delivery of hydrogen with chemical carriers is the energy needed for dehydrogenation[44]. Internationally, the LOHC delivery chain has been demonstrated on a large scale in a project transporting hydrogen from Brunei to Japan; the Japanese SPERA Hydrogen project[45].

The Clean Hydrogen JU project **SHERLOHCK** under review investigates this area, by developing a novel catalytic system architecture, with active and selective catalysts with partial or total substitution of platinum group metal.

Compression, purification and metering solutions: Depending on the source of hydrogen, hydrogen may need to be either separated from a gas mixture or further purified. Separation and purification of hydrogen can be carried out through Pressure Swing Adsorption (PSA), membrane separation, cryogenic separation and partial condensation, electrochemical separation or hybrid solutions[46]. Diffusion based techniques utilising membranes (polymer, ceramic, carbon or metal) offer lower energy demand and higher recovery rates (up to 99%) but are currently better suited to smaller scale installations. Electrochemical compression technology allows simultaneous separation and purification of hydrogen gas present in a (mixed) gas stream with potentially low energy demand. A more novel approach is based on proton conducting ceramic membranes based on rare earth-doped ceria oxides. These membranes exhibit protonic conductivity at high temperatures between 700 °C and 1000 °C and low hydrogen permeability.

41 The transmission network is operated at high pressures (around 80 bar), and it is not yet clear how hydrogen will affect the various components under these conditions. Some components will need to be adapted or replaced.

42 Pneumatic emissions will cease to exist in repurposed pipelines thanks to the replacement of pneumatic actuators by electrical actuators. Fugitive hydrogen emissions are expected to be 1.25 to 3 times the methane ones depending on the dynamics of the flow. Overall, Air Liquide estimates that the amount of hydrogen released will be less than 1% of the hydrogen transported According to SNAM (the main operator for the transport and dispatching of natural gas in Italy) all of their existing pipelines are ready to transport 100% hydrogen, most of which (70%) with no or limited reductions on the maximum operating pressure. However, there is concern within the scientific community for hydrogen damage and catastrophic failure, particularly for old-aged gas pipelines, after long-term service. Even small volume percentage of gaseous hydrogen in a mixture (1%) can lead to serious pipeline material deterioration and hydrogen embrittlement when combined with stress concentration conditions.

43 LH_2, due to its high gravimetric and volumetric density is a promising option for hydrogen transport, but there are still numerous technical issues to be overcome, such as reducing the energy demand for liquefaction and boil off management.

44 By 2024, the energy demand for liquefaction should be reduced to 8-10 kWh/kg H_2 (from 10-12 kWh/kg H_2 as current SoA), and the energy needed for dehydrogenation of chemical carriers should be 17 kWh/kg H_2, compared to 20 kWh/kg H_2 at present. The EU still has some catching up to do, as Japan seems to have advanced LOHC delivery to a higher TRL.

45 The chemical carrier used was the toluene / Methylcyclohexane (MCH) system. Using ISO tank containers mounted on ships and trailers, the MCH was transported to Japan, where it was extracted at a dehydrogenation plant. In June 2020, the SPERA Hydrogen demonstration was successfully concluded with the transport of toluene from Japan to Brunei where it was recombined with hydrogen to form MCH. This was the world's first international hydrogen delivery, and the project confirmed that with the LOHC based method developed by Chiyoda Corporation, toluene can be hydrogenated to form MCH with yields over 99%, while hydrogen could be produced from the same MCH with yields over 98% via the dehydrogenation process.

46 Research is being conducted to improve processes for both the purification and separation of hydrogen, mainly in terms of energy efficiency and costs. One of the objectives is the separation of hydrogen from hydrogen and natural gas blends with low hydrogen content (up to 20%). For large hydrogen volumes, Pressure Swing Adsorption (PSA) is typically used. This process can produce purities up to 99.999% hydrogen, but this may entail low hydrogen recovery rates (up to 65-90%), depending on the feed pressure.

Compressors are critical for the delivery of hydrogen, with pressures above 700 bar required for refuelling and up to 100 bar for injection into pipelines. Higher reliability of the compressors must be achieved, especially for HRS; work in this area is ongoing in the COSMHYC XL and COSMHYC DEMO projects[47]. Excluding these two projects, reviewed in the next section, the only project reviewed in this Research Area is **WINNER.**

Hydrogen Refuelling Stations: The deployment of HRS is expanding globally. In 2022, 130 new HRS went into operation worldwide; 45 new HRS were opened in Europe (more than ever before), 73 in Asia, and 11 in North America. Similarly to 2021, South Korea was the country adding the largest number of new stations. In total, 814 HRS were in operation worldwide at the end of 2022, of which 455 were in Asia, 89 in North America and 254 in Europe. Germany is the country with the most operating stations in Europe (105), followed by France (44), the UK and The Netherlands (both with 17), and Switzerland (14)[48].

The geographical coverage of hydrogen refuelling infrastructure continues to expand, supporting the increasing number of FCEVs deployed. The EU HRS availability system, an initiative funded by the Clean Hydrogen JU, offers a portal providing live-status information regarding each HRS in Europe[49]. Currently, 177 hydrogen-refuelling stations are sending live data.

The Clean Hydrogen JU has funded the installation of 113 HRS up to date (planned, deployed and decommissioned units). The 2 projects being assessed, **COSMHYC XL** and **COSMHYC DEMO**, are based on the innovative scalar and modular hybrid compression solution developed under the COSMHYC project[50].

Highlights

Many of the projects under this Pillar are demonstrating significant advances in different areas of research and innovation.

- **HyCARE** has started the testing of a small-scale prototype hydrogen storage tank based on solid state storage solutions, aiming to couple the storage system with an electrolyser and a fuel cell. It follows the optimisation and the production of the selected metal hydride material (a titanium-iron-manganese alloy) at scale, the finalisation of the full storage design and the completion of the qualification process.
- **HYSTORIES** has collated publicly available data of different types of potential porous media in Europe into a geological database. This will help to identify how many of the gas fields in Europe are likely to be suitable for hydrogen storage, paving the way, together with HYSPER, for future large demonstrations.
- **HIGGS** has completed dynamic and static tests for blends of 20 vol% hydrogen in natural gas, assessing the sensitivity to hydrogen and gas tightness of API 5L steels, valves, fittings and equipment present in NG European transmission grids, with promising results. Additional campaigns are planned with injections of 30 vol% hydrogen in natural gas, and 100% hydrogen.
- **SHERLOCK** achieved the hydrogen productivity in dehydrogenation target (3g H2/g catalyst/min), reaching a productivity of 5.3 g H2/g catalyst/min. The addition of 0.5 wt% Co over Pt-based catalyst with low metal content (0.5 wt% Pt) resulted in an increase in the dehydrogenation productivity, cutting the amount of this noble metal in half.

Gap Analysis – Main JRC Recommendations

There is a mismatch between the high number of KPI targets for Pillar 2 in the SRIA and the current number of projects. However, it is positive to see the increased funding for this topic and that there are new projects.

Underground Storage: For porous rock storage the findings of HYSTORIES and HYUSPRE may not be easily transferable to other potential sites, due to geological and microbial differences. It is therefore very positive that

47 See also the following section on HRS.

48 https://www.h2stations.org/press-release-2023-another-record-addition-of-european-hydrogen-refuelling-stations-in-2022/

49 https://h2-map.eu/

50 If successfully deployed this original technology, combining a metal hydride compressor with a mechanical compressor, will enable lower CAPEX and OPEX, reduced noise, increased Availability and higher hydrogen delivery efficiency.

the project HYSTORIES has collated publicly available data of different types of potential porous media in Europe into a geological database. This will help to identify how many of the gas fields in Europe are likely to be suitable for hydrogen storage.

A study is recommended to determine the amount of large-scale storage that will be needed in the EU in the future, with regards to hydrogen imports. Analysing the interactions between port infrastructures, hydrogen imports and underground storage sites could be part of a future Call.

Hydrogen in the NG grid: There has been progress towards an understanding of an acceptable hydrogen concentration in the natural gas system at European level. However, a key challenge remains; the hydrogen concentration limit for steel tanks for CNG vehicles. This issue should be at least followed by the Clean Hydrogen JU's RCS SC task force. In general, the programme should carefully evaluate if hydrogen blending with NG should be pursued. Despite some natural synergies, it might make more sense to put all effort into 100% hydrogen pipelines, whether conversion of NG pipelines or dedicated new hydrogen pipelines, rather than focusing on blending. There is also the need to develop a PIMS (Pipeline Integrated Management System) for hydrogen-transmission lines. This is a complex set of inspection measures and preventive maintenance procedures aiming to guarantee safety and reliability, preventing incidents and maintaining the operation license. For both 100% hydrogen pipelines and blending, the Clean Hydrogen JU should closely follow the work of the standard CEN/TC234 in order to be updated on eventual pre-normative research needs.

Liquid H_2 carriers: More research on other hydrogen carriers than LOHC (namely liquid hydrogen, methanol, ammonia, and methane) is needed. Potential aspects to investigate are infrastructure needs and potential repurposing of existing infrastructure, and potential environmental impacts from the delivery chain (e.g. leakage of the hydrogen carrier, water consumption, raw material use). Road transport of LH2 is currently not covered by any projects or call topics, except from a safety perspective (Pillar 5, PRESLHY, AWP 2022 call topic). This is a concern, and it would be important for the Clean Hydrogen Partnership to prioritise these topics in the next Calls.

Compression, purification and metering: The proton conducting ceramic technology is a low-TRL technology and WINNER is the only project setting up the SoA, mainly exploiting the results of the GAMER project. More emphasis should be put on the techno-economic potential of the PCC cells with respect to the compression and purification stage of traditional systems in order for it to be better assessed.

Hydrogen Refuelling Stations: H2ME's emerging conclusions report has outlined the main issues with car HRS and helps identify the key problems, however, a dedicated study could be useful, gathering the information from the operation of HRS at EU level. Research being undertaken into novel compression technologies by projects such as COSMHYC XL and COSMHYC DEMO can help to overcome the average station's high energy demand, increasing the cost of the dispensed hydrogen. Also, it is positive that the AWP 2022 had a call topic on refuelling for maritime or inland shipping applications.

Further analysis of hydrogen chillers causing downtime in hydrogen refuelling stations is recommended. In addition, as larger flows of hydrogen are dispensed for truck fuelling operations, funding a project on developing innovative and efficient cooling for dispensed hydrogen should be considered.

More info on the Pillar, the related Research Areas and the projects can be found in the Annex, under PILLAR 2 - HYDROGEN STORAGE AND DISTRIBUTION.

5.3. PILLAR 3: HYDROGEN END-USES: TRANSPORT

The predecessor of the Clean Hydrogen JU, the FCH JU, aiming at advancing the adoption of hydrogen and fuel cell technologies in the transport sector, dedicated significant effort to develop, validate and demonstrate technologies for FC material handling vehicles, FC buses and FCEV passenger cars that can be considered ready for market deployment. Still, solutions in sectors such as heavy-duty vehicles, off-road and industrial vehicles, trains, shipping and aviation need further development and demonstration.

Overview of Research Areas

Heavy Duty Vehicles (Building Blocks) - Fuel cell stack and fuel cell system technology: This Research Area includes 8 projects on FC system technologies (**FURTHER-FC, CAMELOT, GAIA, Virtual-FCS, IMMORTAL, DOLPHIN, MORELIFE** and **STASHH**).

Although there are currently available commercial PEM FC systems for transport and stationary applications with satisfactory performance, their durability requires further development. Loss of performance of FC systems is still a bottleneck in wide dissemination of hydrogen fuel cells in industry and transport. Low-TRL projects (DOLPHIN, MORELIFE and IMMORTAL) reported that the durability of their systems meets the SRIA targets, but experimental data are obtained at a small scale. Another difficulty constraining broad application of PEM FC technology corresponds to the usage of expensive and rare materials, mainly PGM metals. There is a continuous challenge to maintain satisfactory performance and degradation rate of FC stack with minimising the use of PGM materials.

Heavy Duty Vehicles (Building Blocks) - On-board vehicle hydrogen storage: 3 projects on on-board vehicle hydrogen storage are assessed within this Research Area, namely **TAHYA, THOR** and the recently started **SHA2PED**.

Compressed hydrogen storage on-board vehicle technology is already well established. State-of-the-art compressed hydrogen storage systems are made up of carbon fibre composite reinforced vessels. A key question is the decrease of tank's costs by reducing the amount of carbon fibre used while keeping the storage's performance and safety. An important technological progress is the development of conformable tanks, which will allow optimising the volume of hydrogen stored by adapting the tank shapes to the available free space in the vehicle. Liquid cryogenic hydrogen is envisaged as a solution to store large amounts of hydrogen in heavy duty vehicles and maritime vessels as well as in future rail and aeronautic applications.

Heavy duty vehicles: Fuel cell hydrogen trucks (FCET) are considered one of the best options to decarbonise heavy duty road freight transport. FCETs are potentially best suited for longer-range missions and the heaviest goods, enabling connectivity to more remote areas than other solutions such as battery or catenary trucks[51]. Demonstration activities on heavy-duty trucks started in 2018 with the project **REVIVE** and grew in 2019 with the project **H2HAUL**. These 2 projects will deploy 29 fuel cell trucks and bin-lorries at 13 sites in 7 European countries; see Figure 8.

51 Decarbonisation of heavy duty transport: zero emissions heavy goods vehicles, JRC, 2021

Figure 8: Geographical distribution of heavy-duty vehicles from Clean Hydrogen JU projects

Source: Clean Hydrogen JU

Worldwide, there are already some demonstration initiatives of prototype FCETs[52]. This will allow the development of the FCET technology towards series manufacturing of the vehicles by Daimler Trucks, Iveco Group and Volvo Group. The trucks to be deployed in the first stage are expected to be either 4x2 or 6x2 wheel, with up to 44 tonne capacity, using either 700 bar or liquid hydrogen, and having a range of at least 600 km. H2Accelerate TRUCKS is co-financed by the Clean Hydrogen JU and the Connecting Europe Facility respectively, funding the deployment of vehicles and infrastructure[53].

Waterborne applications: The Research Area waterborne applications covers 2 projects on the development of fuel cells for maritime applications (**MARANDA** and **SHIPFC**) and 3 projects deploying zero-emission fuel cell ships and hydrogen in maritime ports (**FLAGSHIPS, HYSHIP** and **H2PORTS**).

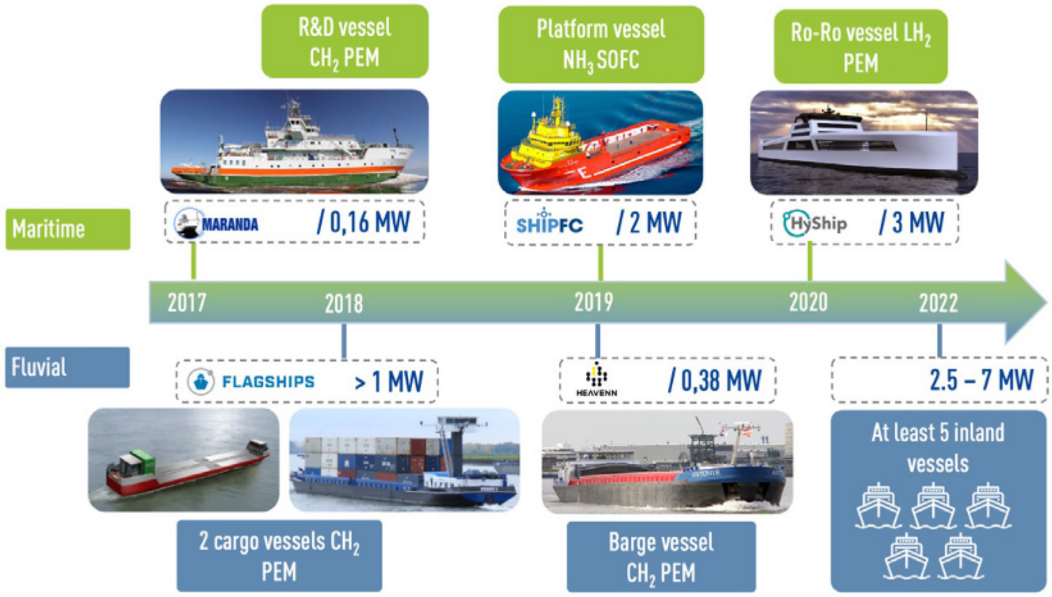
In Europe, there are several ongoing projects that aim to demonstrate fuel cell powered vessels. Bunkering of hydrogen (or ammonia) is to be developed together with fuel cell ships. The bunkering technology must be adapted to both liquid and compressed hydrogen and some pilot initiatives for hydrogen supply in ports and offshore have been launched. There is a strong trend towards larger vessels and hydrogen delivery by ships, as shown in Figure 9. Demonstration projects are important to speed up standards for waterborne applications. In addition, the Clean Hydrogen JU has contracted a “Study on hydrogen in ports and industrial coastal areas” to assess the hydrogen demand in ports and industrial coastal areas, enabling the creation of a “European Hydrogen Ports Roadmap”[54]. The study provides new directions for research and innovation, guidance for regulation, codes and standards, and proposals on policy and regulation to boost hydrogen applications in ports (for more information see Section 8).

52 The most well known FCETs initiative in Europe is the deployment of a fleet of 140 Hyundai Xcient trucks in Switzerland, expected to grow by another 1 600 trucks by 2025. The Hyundai Xcient trucks have 2×90 kW FC stacks and a 72 kWh battery for a power of 350 kW/ 20237 Nm torque and a range of 1 000 km (350 bar hydrogen, 31 kg stored on board). In the autumn of 2022, there were 47 trucks operating at 23 Swiss companies in logistics, distribution and supermarket supply missions. Also, the project “Large scale deployment project to accelerate the uptake of Hydrogen Trucks in Europe - H2Accelerate TRUCKS” will deploy 150 hydrogen trucks and eight8 heavy duty hydrogen refuelling stations across Europe.

53 https://h2accelerate.eu/the-h2accelerate-collaboration-announces-acquisition-of-funding-to-enable-deployment-of-150-hydrogen-trucks-and-8-heavy-duty-hydrogen-refuelling-stations/

54 https://www.clean-hydrogen.europa.eu/media/publications/study-hydrogen-ports-and-industrial-coastal-areas_en

Figure 9: Clean Hydrogen Partnership projects on maritime applications



Source: Clean Hydrogen JU

Class societies are gaining experience with certification of fuel cell systems for waterborne applications and in the last year several systems have received their approval. Still, the approval of the vessels and the permit of hydrogen infrastructure on ports is a challenge. Even though projects in this area are working closely with approval authorities the lack of regulations and suitable standards makes the process lengthy.

Projects are building knowledge on hydrogen safety, hazard, and risk assessments, for instance, FLAGSHIPS is developing e-tools (publicly accessible from HYRESPONDER E-laboratory repository[55]) to support the safety assessment of a design choice specific to waterborne/maritime fuel cells and hydrogen application. FLAGSHIPS has also held several safety workshops with the consortium members and is contributing to the development of safety approval practices. This knowledge built by waterborne projects should be consolidated by the E-SHYIPS project (Pillar 5).

Rail applications: The only project under this Research Area is **FCH2RAIL**. The hydrogen and fuel cell technology for rail applications has been trialled across Europe, Asia, North America, the Middle East, Africa, and the Caribbean, since 2005[56]. Although those trials show that FCH technology can meet the requirement for rail applications, there are few demonstration projects of hydrogen train prototypes[57].

55 https://hyresponder.eu/e-platform/e-laboratory/

56 Study on the use of fuel cells and hydrogen in the railway environment, FCH 2 JU, 2019

57 The most advanced is the Alstom Coradia iLint, which has a 400 kW FC, has a speed of 140 km/h and a max range of 1 000 km (350 bar hydrogen, 260 kg stored on board) and can accommodate up to 300 passengers. The Coradia iLint has been tested in passenger service in Lower Saxony, Germany. From 2018 to 2022 it has accumulated more than 200 000 km. A milestone was reached in September 2022 when the train travelled 1175 km without refuelling. Regular service of the Alstom Coradia started in summer 2022, with 14 FCH trains in operating in a German commercial route. Those trains are refuelling at the Bremervörde HRS, which is the first HRS for trains in Germany. It was built by Linde and started operation also in summer 2022.Siemens has developed Mireo Plus H fuel cell and hydrogen train. It can achieve ranges of up to 600 km as a two-part train, and from 800 to 1 000 km as a three-part train, depending on the line profile and mode of operation. The Siemens Mireo Plus H is powered by a 1700 kW Ballard fuel cell with a target service life of 34000 hours of operation. This will provide a maximum speed of 160 km/h with an acceleration of 1.1 m/s. It will be tested in Germany in 2023.

Aeronautic applications: HYCARUS and SUAV were pioneer JU projects integrating hydrogen and fuel cells in aeronautic applications. HYCARUS developed a PEMFC and hydrogen storage as APU for non-essential applications, which passed performance and qualification tests in a demonstrator. Starting from HYCARUS's experience, the Clean Hydrogen JU project **FLHYSAFE** aims to design and demonstrate the feasibility of using a PEMFC system as an Emergency Power Unit.

Substantial progress was realised thanks to the strong industry interest and public support. In **HEAVEN**, the first partially hydrogen powered aircraft flying tests have been already carried out by ZeroAvia and shortly after, in early 2023, Universal Hydrogen (a US based startup working on hydrogen-electric propulsion systems for planes) has successfully completed a 15 minute test flight on a 50 seat hybrid aircraft retrofitted with 1 hydrogen engine and a liquid hydrogen storage system. The "Hydrogen powered aviation" study[58] published in 2020 concluded that hydrogen – as a primary energy source for propulsion, either for fuel cells, direct burning in thermal (gas turbine) engines, or as a building block for synthetic liquid fuels – could feasibly power aircraft with entry into service by 2035 for short-range aircraft. The "Hydrogen-Powered Aviation Research and Innovation" technical workshop took place in April 2023 with the objective of discussing the year 2024 priorities for the Clean Aviation and Clean Hydrogen programmes (for more information see Section 8).

Moreover, 3 projects on aeronautic applications, from the 2022 Clean Hydrogen JU Call for proposals, have started in 2023:

- Project BRAVA (Breakthrough Fuel Cell Technologies for Aviation) is developing a 300kW fuel cell stack;
- NIMPHEA (Next generation of improved High Temperature Membrane Electrode Assembly for Aviation) will study and develop suitable high temperature fuel cells for aviation application; and
- COCOLIH2T will develop a conformable liquid hydrogen storage system for aeronautic application.

Buses and cars: Hydrogen fuel cell buses represent a solution to decarbonise public transport and reduce air pollution. At the end of 2021, there were over 4 700 fuel cell buses in operation worldwide, mostly in China, which accounts for over 85% of global deployment[59]. Europe as a whole had 219 fuel cell buses in operation at the end of 2021, being one of the most active regions deploying hydrogen buses. This technology requires investment in infrastructure and maintenance, a factor that slows down its growth. China is still the leading manufacturer of fuel cell buses. After China, European countries have the largest number of fuel cell bus manufacturers, an indicator of technological progress and innovation[60]. This is partly due to the significant contribution of Clean Hydrogen JU demo projects (CHIC, HIGHVLOCITY, HYTRANSIT, 3EMOTION, JIVE and JIVE2), focusing on the large-scale demonstration of fuel cell buses in Europe since 2010. Additionally, these bus demos have improved the public acceptance of fuel cell buses in Europe. Whereas fuel cell buses are established for urban use, there is the need to advance the technology for longer distances in order to cover interurban and regional routes.

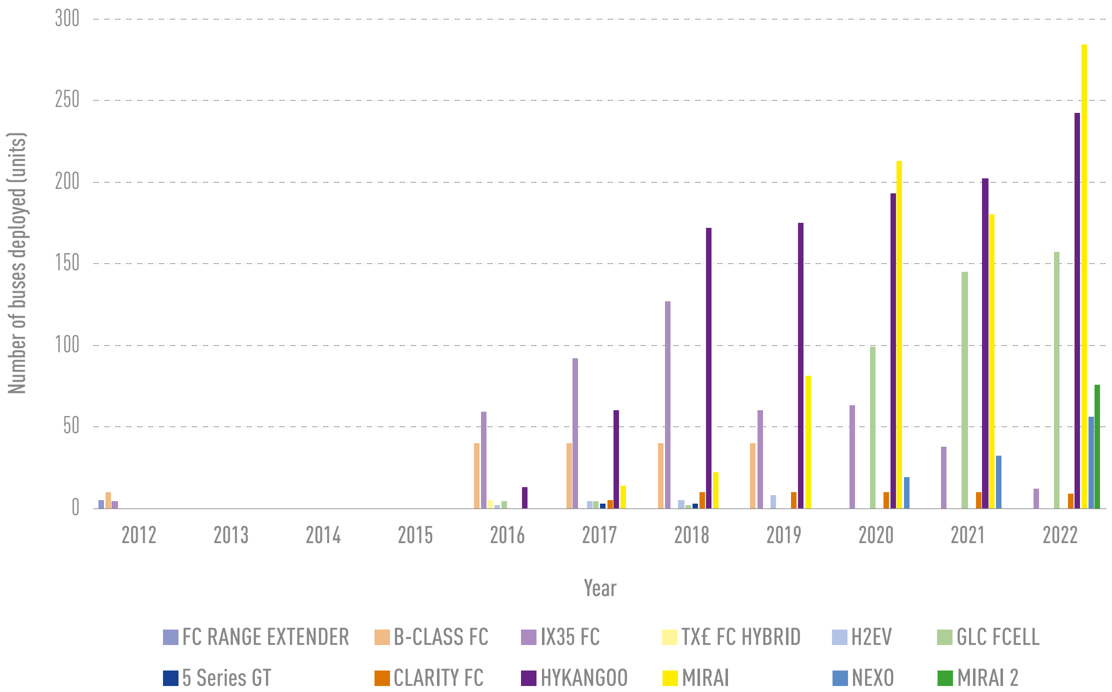
Focusing on the reviewed projects this year, i.e. **3EMOTION, JIVE** and **JIVE2**, there were 258 Clean Hydrogen JU buses in operation and reporting data throughout 2022 in 17 cities. Considering the bus demonstration projects that were reporting in TRUST between 2016 and 2022, a total distance of over 14.8 million km was accumulated, with almost 6.9 million km accumulated in 2022 alone. In the last 6 years, over 1.4 million tonnes of hydrogen have been consumed, of which 44% were consumed in 2022.

58 Fuel Cells and Hydrogen 2 Joint Undertaking, *Hydrogen-powered aviation – A fact-based study of hydrogen technology, economics, and climate impact by 2050*, Publications Office, 2020, https://data.europa.eu/doi/10.2843/471510

59 Other regions such as South Korea, Japan, the United States, and Europe are also developing fuel cell bus fleets, although at a slower pace. South Korea (129) and Japan (110) follow China in second and third place.

60 https://fuelcellbuses.eu/suppliers#29

Figure 10: **Number of deployed vehicles in operation reporting data from each model versus year**



Source: Clean Hydrogen JU

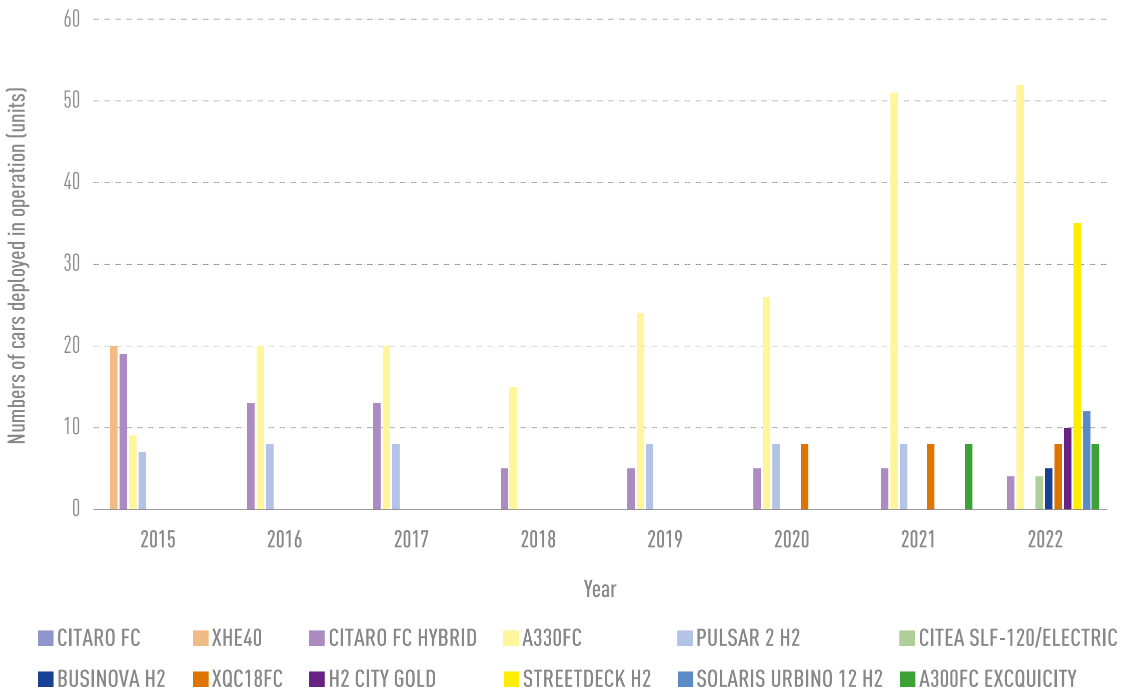
Fuel cell car deployment has noted steady growth in recent years. According to recent data from the International Energy Agency, the worldwide fleet of fuel cell cars has surpassed 42 000 units by the end of 2021[61]. South Korea is leading the deployment of hydrogen vehicles with 38% of the worldwide fleet, followed by the US (24%), China (16%) and Japan (13%). When comparing continents, Asia takes the lead with 67.4 % of the fleet, followed by North America (24.5%) and Europe (7.7%)[62]. The technical specifications of the vehicles (fuel cell power capability, storage capacity, range, and hydrogen consumption) have improved globally over the last few years.

A major contribution of the Clean Hydrogen JU projects is the achievement of a large scale deployment of fuel cells cars in Europe. Figure 11 shows details of the fuel cell car models deployed within the projects over the years. It is noticed that the early deployments that started with the H2MOVES SCANDINAVIA, HYTEC, SWARM and HYFIVE projects have seen an exponential growth with the H2ME initiative (H2ME and H2ME2) and the ZEFER project. In 2022 (data from 2021), 594 FCEVs were in operation and reporting data from H2ME, H2ME2 and ZEFER projects in Europe. The deployment data from 2022 are presented in detail in the Annex. It is worth mentioning that the gap observed between 2013 and 2015 is an artificial one due to the lack of data reporting during that period. HYTEC, SWARM and HYFIVE projects were deploying vehicles over the 2013-2015 period, and we can observe the cumulative deployment from these projects in 2016.

61 Samsun, R.C., M. Rex, L. Antoni, and D. Stolten, 'Deployment of Fuel Cell Vehicles and Hydrogen Refueling Station Infrastructure: A Global Overview and Perspectives', Energies, Vol. 15, No. 14, 2022 https://www.mdpi.com/1996-1073/15/14/4975

62 South Korea and Japan are the two largest manufacturers of commercial fuel cell passenger cars. The Asian region has surpassed the European market, and the currently available makers and models (Toyota Mirai II, Hyundai Nexo) are dominating the global market taking up 89,52% of all FCEV production (commercially available). Looking at fuel cell engine manufacturing, Japanese and Korean manufacturers are the leading players again, with China taking the second position with less than 4% of the production and installation of the above mentioned two countries.

Figure 11: Number of deployed vehicles in operation reporting data from each model versus year



Source: Clean Hydrogen JU

Demonstration projects are recurrently suffering from the local authorities' lack of experience, as well as from the absence of standardised processes for reviewing and approving HRS permit authorisation. However, difficulties encountered when requesting permits for HRS are diminishing, with lead-time for commissioning an HRS in Germany decreasing to 12 months from the previous 24. The Clean Hydrogen JU funded project MultHyFuel, reviewed under Pillar 5, is contributing to ease HRS permitting issues.

Highlights

The Clean Hydrogen JU projects under Pillar 3 have significant results to show in the last 18 months, as detailed below.

- **HEAVEN** managed to deliver the Hy4 prototype, fuelled with liquid hydrogen. It is the world's first ever flight completed on a passenger plane using liquid hydrogen as fuel on a fuel cell powertrain. It managed to double the flight range (1500 km) with a tank capacity of 16kg of LH_2, doubling a previous flight made using gaseous H_2. Its first 4 test flights were completed on 7th September 2023.
- **GAIA** managed to deliver a high Beginning of Life (BoL) power density of 1.80 W/cm2 at 0.6 V without increasing platinum loading, reducing the Pt-specific power density from 0.45 g Pt/kW (e.g., VOLUMETRIQ) to 0.25 g Pt/kW. GAIA was given the best success story award during the Programme Review Days 2022.
- **THOR** project has brought out several innovations, such as the integration of optical fibres in the tank wrapping, the design optimisation of the winding pattern and boss, as well as the leak-before-burst technology. The use of embedded optical fibres, for monitoring both tank temperature in filling and tank's remaining strength, will open the discussion for the reduction of small safety factor[63] in type-approval

63 Small safety factor means that it will be possible to optimise the composite wrapping thickness, hence reducing the amount of carbon fibre and resins.

regulations. This knowledge is as very valuable for liquid hydrogen storage vessels and shall be preserved and transferred to future on-board vehicle storage projects.

- Six refuse FCETs (out of 14) from project **REVIVE** are already in operation. The HRSs in Gothenburg and Groningen started operation in 2021 while Breda and Antwerp HRSs opened in April and May 2022 respectively.
- **3EMOTION** has deployed all 29 FCBs: 10 buses in London, 6 in Rotterdam and the South Holland province, 7 in Versailles, 3 in Pau and 3 in Aalborg, demonstrating the operability of buses from **4** different manufacturers with 2 different fuel cells systems. The buses of in some sites of **3EMOTION** met the targets on Hydrogen Consumption (average of 8 kg H_2/100 km), Warranty Time (15 000 h) and Bus Cost (< 850 000 EUR).
- Combined **JIVE** and **JIVE 2** are deploying over 300 FCBs in 22 cities across Europe, the largest deployment programme in Europe to date. JIVE has ordered all the 142 planned buses and 132 are in operation, while JIVE 2 has ordered 122 buses out of 156 originally planned, has 98 buses in operation and expects to have the committed fleet delivered by mid-2024.
- The H2ME initiative (**H2ME** and **H2ME2** projects) is the largest European deployment to date for hydrogen mobility, planning to deploy more than 1100 vehicles in 10 countries and 50 HRS from 10 suppliers in 6 countries. The project H2ME 2 alone has deployed 759 vehicles and 15 new HRSs.
- The 180 FCEVs in operation (60 in Paris, 60 in London and 60 in Copenhagen) under project **ZEFER** are demonstrating viable business cases for captive fleets of FCEVs (taxi, private hire and police services).
- Based on data collected in TRUST on the performance of 727 vehicles running in 2022 (FCEVs and plug-in hybrids), the deployed FCEVs (472) drove over 8 million km with a reported consumption of 91.7 tonnes of hydrogen. The 2022 figures have continued the upward trend from the figures of 2021 where 405 FCEVs drove 6.4 million km with a consumption of 71.7 tonnes of hydrogen. This shows the growing usage of FCEVs after the easing of restrictions. In total, Clean Hydrogen JU-funded vehicles have now driven a total of almost 38.7 million km and consumed over 518.3 tonnes of hydrogen since 2016, avoiding emissions of about 1420 tonnes of CO_2.
- Clean Hydrogen JU funded 112 HRS [64] including cars, buses and MHVs demo projects (planned, deployed, and discontinued units). In 2022, 83 HRSs had already been deployed.

Gap Analysis – Main JRC Recommendations

In general, the absence of a well-established RCS framework for permitting and approvals for field tests remains an important impediment to most of the initiatives. Local Authorities are gaining experience with hydrogen technologies and the time taken to grant permits is decreasing in the countries leading participation in demo projects (Germany and France). However, new regions setting off demonstrations of hydrogen fuelled vehicles still suffer from lengthy permitting procedures. Experience from running projects should be shared with future Clean Hydrogen initiatives.

Building Blocks: The use of non-PGM for electro-catalysis is studied in the projects with encouraging results and is providing the basis to potentially reduce the use of EU defined critical raw materials. Several projects (i.e. IMMORTAL, DOLPHIN, MORELIFE, FURTHER-FC are also developing knowledge and tools to improve fuel cell designs and adapt their features to fit the requirements of automotive applications, both light and heavy duty. Also, recyclability of compressed hydrogen storage tanks is addressed.

The successful approach taken by the projects of Autostack, Autostack-Core and Autostack Industrie for the development and manufacture of automotive MEAs and eventually of FC stacks should be taken as best practices to develop MEAs and stacks for use in heavy-duty applications, aligning also with successful developments in other initiatives (e.g. IPCEIs projects on fuel cells) to obtain mutual benefits. Synergies between pilot manufacturing, materials research and fit-for-purpose testing, should be better exploited to facilitate innovative FC designs ready for scale up.

64 Including 2 deployed and discontinued stations.

Heavy Duty Vehicles: Some transport demo projects stand out for their relationships and interactions with other European, national, and regional programmes. H2HAUL will further demonstrate the truck deployed by Interreg project H2Share.

At present, homologation is granted following individual vehicle approval process. The overall certification process of the hydrogen vehicles is very detailed and is a source of delay in the project execution. Also, the requirements to obtain a registration plate (matriculation) for hydrogen trucks varies from Member State to Member State. Projects H2Haul and REVIVE should document their experiences to help future Clean Hydrogen JU initiatives demonstrating heavy duty vehicles.

Maritime Applications: Lack of regulations and suitable standards makes the approval of the vessels and the permit of hydrogen infrastructure on ports difficult. Experience from running projects should be shared with future Clean Hydrogen JU maritime applications initiatives. Also, supply chain of fuel cells is not yet established. Fuel cells are being produced on customers' demand by few available manufacturers with long delivery times.

In addition, liquid hydrogen supply chain is non-existent. There are few production facilities in Europe and the liquid hydrogen is already dedicated to other end uses.

Aeronautics Applications: Cryogenic supply chain is still limited. The workshop resulted in the need to address the following topics in particular: Large-scale LH2 storage tanks, ground-based supply system for LH2 distribution, technology and protocols for ground based LH2 refuelling, lack of suitable liquid hydrogen testing facilities, new standards and safety and certification (for all items above).

Buses and Cars demonstration: The potential of fuel cell and hydrogen coaches to contribute to decarbonisation of road passenger transport is high. COACHYFIED is a first step, but a larger initiative will be beneficial for the technology's progress, as it has been for the fuel cell buses. However, FCEBs encounter difficulties competing against the cheaper costs of battery electric buses, mainly because of the increased hydrogen at the pump triggered by the energy crisis, affecting the financial viability of the projects.

There is a lack of validated Well-to-Wheel data, specially adapted to the most recent models of fuel cell and hydrogen cars, buses and trucks. In addition, there is a weak supply chain of components for hydrogen mobility applications in general. The main issue is that manufacturers tend to follow demand and there is little flexibility to increase the stock of spare parts. Furthermore, the increase of manufacturing capacity and cost optimisation are limited.

More info on the Pillar, the related Research Areas and the projects can be found in the Annex, under PILLAR 3 - H_2 END USES - TRANSPORT.

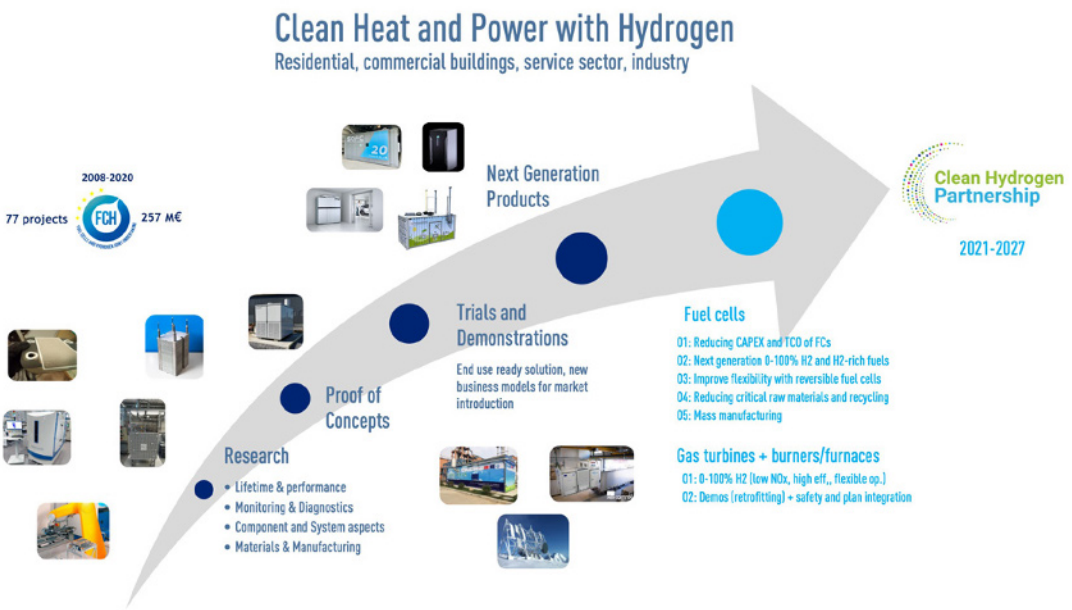
5.4. PILLAR 4: HYDROGEN END-USES: CLEAN HEAT AND POWER

To cope with the increasing mismatch between the output coming from variable renewable energy sources on the one hand and fluctuating demand on the other hand, additional response capacity is recommended in the SRIA. Such capacity could be stationary fuel cells up to the 10 MWe scale and use of gas turbines for applications above 50 MWe. A technology-neutral approach is considered, where either 100 % hydrogen fuel cells or turbines or a combination of both could be favoured.

The overall goal of this Pillar is the development of renewable and flexible heat and power generation systems for different end users – from domestic systems to large-scale power generation plants. Although preferential funding is given to systems using 100% hydrogen, hydrogen mixture solutions in gas grid of up to 20% are also proposed for support in the SRIA during the transition phase. Such solutions can be stationary fuel cells, gas turbines, boilers and burners. Turbines, boilers and burners are new elements in SRIA, not being considered in the FCH 2 JU MAWP[65].

65 The first Research Innovation Action topic related to gas turbines was published in 2022. The 2 projects funded under this topic started in early 2023 (FLEX4GRID, HELIOS) and therefore, are not included in this report.

Figure 12: Clean Heat and Power Applications supported by the Clean Hydrogen JU



Source: Clean Hydrogen JU

The FCH JU MAWP objectives of the former energy Pillar were to accelerate the commercialisation of FCH technologies for stationary fuel cells, in particular increasing the efficiency and the durability of fuel cells for sustainable power production, while reducing costs. The widespread deployment of competitive FCH technologies can deliver substantial benefits in terms of energy efficiency, emissions and security, while simultaneously enabling the integration of renewables into the energy systems.

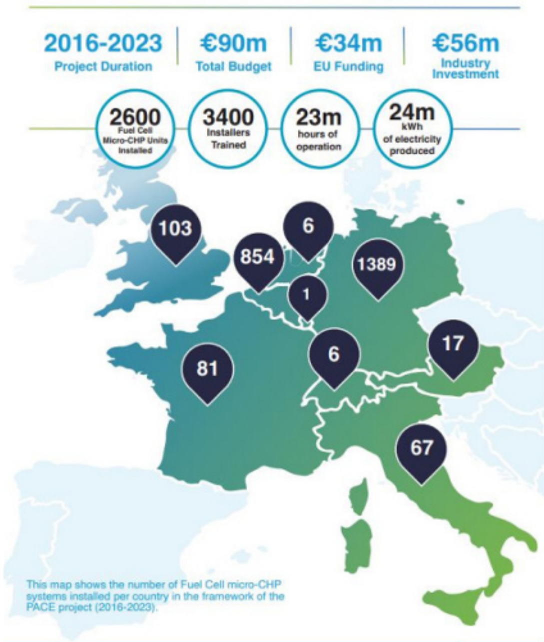
Overview of Research Areas

The Research Areas relevant to Pillar 4 are:

m-CHP: Project **PACE** represents this area, exploring the possibility to deploy both PEMFC and SOFC fuelled with natural gas for fuel cell micro-Cogeneration for small stationary applications. PACE is a m-CHP deployment initiative involving six leading European fuel cell manufacturers, a follow-up of the FCH 2 JU project ENEFIELD. Between 2016-2023, the project has deployed more than 2.600 new fuel cell micro-CHP units with real customers and monitor them for an extended period (Figure 13).

The PACE project showed the potential of the fuel cell micro-cogeneration as a feasible technology allowing the production of heat and electricity for a small business or house from a single fuel. It demonstrated that fuel cells can operate seamlessly for a long periods of time: 5 years operational time was already demonstrated while - 15 years projected system lifetime could be expected (5 years more than the initially planned 10 years). Although the technology is proven and ready for the market, there are still a number of barriers to overcome. The main barriers identified for market uptake were lack of adequate standards and regulations, financial incentives, electricity tariffs, administrative barriers for grid connection, building standards and customer perception and understanding of the technology in addition to achieving robust supply chains for the OEMs.

Figure 13: Achievements of the PACE project



Source: PACE

Commercial Size Systems: This research area contains 2 demonstration projects focused on fuel cell-based systems for power and heat solutions in the mid-sized power ranges of up to 100 kW, namely **ComSos** and **E2P2**, both exploring SOFC technology. Three other projects look at the next generation systems: **SO-FREE** and **CH2P** using SOFC technology, **EMPOWER** using high temperature PEMFC technology.

Industrial Size Systems: Industrial size CHP RA includes projects dealing with large scale, usually in the MW scale, represented by project **GRASSHOPPER** addressing the challenge of setting up a cost-effective and flexible power plant, powered by MW-size FC.

Off grid/back up/gensets: This Research Area contains the demonstration projects focused on off-grid applications, both in remote locations as well as in temporarily powered event areas. The current assessment period includes 3 projects: **REMOTE, ROREPOWER** and **EVERYWH2ERE**. The projects are exploring the application of PEM, SO and Alkaline hydrogen technologies (FC and electrolysers) for off-grid applications, but also for urban areas.

Other research areas: Two projects, **WASTE2WATTS** and **RUBY**, dedicated to the use of biogas for SOFC-CHP system and the use of advanced diagnostic, monitoring and controls for fuel cells (SOFC and PEMFC).

Although the Research Areas are split in terms of application size, it is more interesting to examine the technology progress and state of the art in terms of the two stationary fuel cells technologies (PEMFC and SOFC).

PEMFC technology: Between 2011 and 2022, 14 projects of this pillar are classified as contributing to the development of PEMFC technology. In general MAWP 2020 KPI targets have been reached to a significant extent or are close to be reached within the short term. It is noteworthy that the SRIA target 2024 regarding Electrical Efficiency for the use of hydrogen as fuel could be revised to higher values for all considered device sizes in the near term. Looking at the CAPEX targets, on average micro-PEMFC projects have met the MAWP 2020 target, while there are also projects meeting already the SRIA KPI 2024 targets. For larger size PEMFC, the MAWP 2020 and SRIA SoA targets have been met, while there is further progress indicating that also the 2024 SRIA target can be met.

SOFC technology: Between 2011 and 2022, 13 projects of this pillar were classified as contributing to the development of SOFC technology. Similar to PEMFC, the former 2020 MAWP targets have been reached to a significant extent or are close to be reachable within the Clean Hydrogen JU programme. The MAWP 2020 **CAPEX** target for µ-SOFC is achieved in the best case, but not on project average. On the other hand, for mid- and large-size SOFC, this target is achieved also on project average and, in contrast to µ-SOFC, looks feasible to reach the SRIA 2024 targets. Again, similar to PEMFC, in the case of electrical efficiency the best-case deployments already exceed the SRIA 2024 target. Improved efficiencies could compensate the user for a CAPEX that could be higher than for competing technologies by providing a lower TCO.

HIGHLIGHTS

A number of important achievements of Clean Hydrogen JU projects under Pillar 4 are reported below.

- Project **PACE** accomplished excellent results in comparison to SoA; 3 091 units were sold and installed out of which 2 502 units are commissioned, demonstrating already 5 years of operational time, and 15 years system lifetime must be expected with > 50% reduction in stack replacement or no stack replacement during a 10-year service plan, and high availability of 96-99%.
- Project **ComSos** has already achieved 2 MAWP targets, namely Electrical Efficiency of more than 50% and NOx emission of less than 40 mg/kWh. CAPEX target can be achieved through the automated mass production (more than 100 units a year per manufacturer).
- **EVERYWH2ERE** manage to successfully demonstrate a 25 kW and a 100 kW container "plug and play" gensets, suitable for use in construction sites, music festivals and urban public events. The project managed to obtain CE marking for the gensets, facilitating the local operating permits processes.
- The standardisation of the interface of stack modules and systems by project **SO-FREE** can accelerate the use and acceptance of the SOC technology, its market penetration as well as cost competitiveness. By integrating activities carried out in different European states, the project contributes to strengthening the European industries in this area.
- **RoRePower** project managed to install 41 off-grid units at sites located in remote areas with harsh climate conditions (from -40 to +50°C) able to give demonstration data. It has achieved several AWP targets, such as electrical efficiency of > 35% (up to 53% measured in some cases), operation in harsh conditions at -40°C, and long-term desulphurisation of 15 month.

Overall, projects under Pillar 4 help manufacturers to significantly increase manufacturing capacities and move towards product industrialisation and fostered market development at national level (e.g. PACE project) and increased the competitiveness internationally, brining innovation and reduced cost (COMSOS project). Also, despite all regulatory and standardisation difficulties, PACE also helped to train a large number of now highly skilled workers. All in all, these are excellent results.

Gap analysis – Main JRC Recommendations

The following topics may be considered as meriting funding in the future JU calls:

- Developing concepts for reversible cells with improved round trip efficiency (> 50%) at a range of scales.
- Research on the use of ammonia for fuel cells, taking into account the outcomes of the JU funded projects on this topic (NH34POWER, TOWERPOWER).
- Using existing gas turbines and the use of low-carbon hydrogen[66] in burners and boilers.
- Development of commercial/industrial scale CHP unit and/or prime power units by European suppliers (100 kWe – several MWe scale).

66 Low-carbon hydrogen: hydrogen that is made in a way that creates little to no greenhouse gas emissions.

- For industrial heat and power development, work on prototypes for the smart cogeneration of industrial heat and electricity by FC CHP at 1, 10 and 100 MW scales, specifically targeting selected industrial environment.
- More attention should be given to methods on eliminating contaminants which might significantly affect the durability of large stacks.

More info on the Pillar, the related Research Areas and the projects can be found in the Annex, under PILLAR 4 - H_2 END USES – CLEAN HEAT AND POWER.

5.5. PILLAR 5: CROSS-CUTTING TOPICS

This Pillar contains specific supporting activities which play an enabler role in reinforcing Europe's leadership position, accelerating mass-market adoption and maximising contribution to decarbonisation targets. The cross-cutting activity area is structured around three Research Areas with the following overarching objectives.

Overview of Research Areas

Sustainability, LCSA, recycling and eco-design: One of the concluded projects, HYTECHCYCLING (2016-2019), which studied recycling and dismantling strategies applied to the whole fuel cell and hydrogen technology chains, used the methodology defined in the FC-HyGUIDE LCA guidelines and performed a full "cradle-to-grave" LCA to assess the material flow along the hydrogen supply chain, dedicating particular attention to the critical materials in water electrolysers (alkaline and PEM) and fuel cells (PEMFC and SOFC). The analysis performed in 2020 by the FCH 2 JU on the sustainability dimension of all projects identified priorities for a new momentum in this area and allowed the design of 3 topics in the AWP2020, which generated the 3 projects included in the Programme Review 2023: **SH2E, BEST4HY** and **GHOST**.

Education and public awareness: The 2 projects included in this report, **TEACHY** and **HYRESPONDER**, are the last of a multi-annual series of projects dedicated to training and education. From a historical perspective, it could be concluded that at the end of the H2020 Framework Programme, this area has produced a complete range of tools to train and educate all stakeholders and players along the technology value chain. A recent example is project NET-TOOLS (2017-2020) which developed an e-learning platform for scientific training purposes, and KNOWHY (2014-2018) which offers trainings for technicians and workers. Part of their achievements have been a useful starting base for TEACHY, which also plans to use NET-TOOLS online platform to publish its deliverables. Project FCHGO represent a recent effort to broaden the audience by reaching out to pupils. The continuous availability and update of all these tools will be challenging.

In the area of education and awareness the FCH Observatory[67] (FCHO) also plays a role. This knowledge management tool has become a reference provider of structured data and indicators for stakeholders, professional operators and general public[68]. It also provides a list of courses and training materials[69]. The Clean Hydrogen JU re-launched the platform as the European Hydrogen Observatory in September 2023 (for more information see Section 8).

Safety, PNR and RCS: This area is composed of 6 projects, **AD ASTRA, PRHYDE, THYGA, HYTUNNEL-CS, e-SHYIP** and **MULTHYFUEL**. They have all a strong pre-normative research dimension and their outcomes will contribute to new or improved standards. Some of them are specifically focussed on safety-related topics, others on performance and degradations of hydrogen systems.

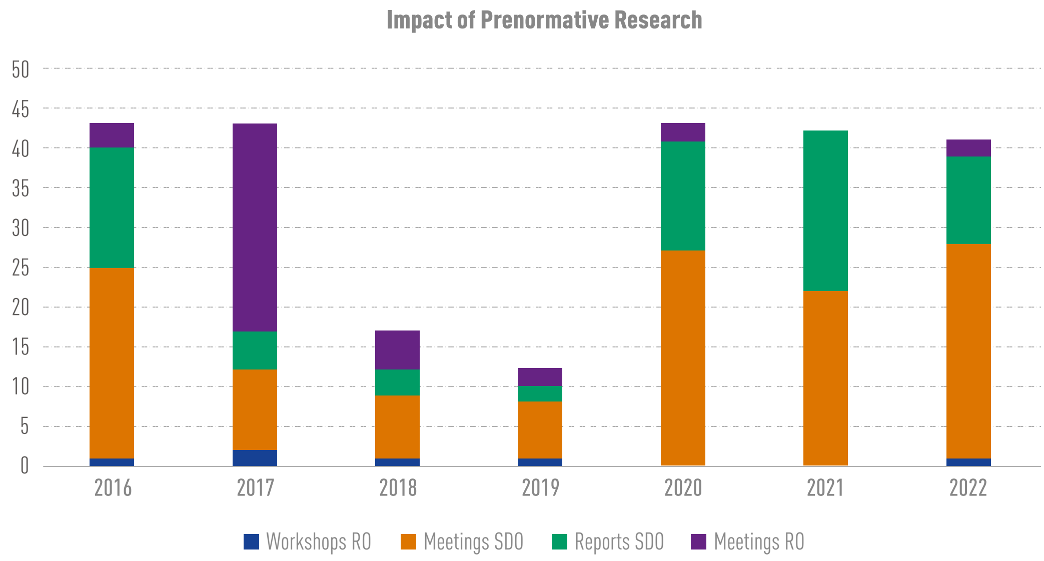
67 https://www.fchobservatory.eu/observatory

68 For example, by gathering and rationalising results and data of projects, it overcomes their fragmentation caused by individual project websites and platforms.

69 The list contains not only the achievements of JU projects, such as **HYRESPONDER**, but also materials delivered by other training providers, such as the JESS (Joint European Summer School on Fuel Cell, Electrolyser and Battery Technologies).

The Research Areas is characterised by a high degree of publicly available outputs and of inter-projects collaborations. Figure 14 shows the various categories of impact of the Research Areas Safety, PNR and RCS.

Figure 14: Overviews of the various categories of impact of the Research Areas Safety, PNR and RCS



Source: Clean Hydrogen JU

Highlights

Clean Hydrogen JU projects under Pillar 5 managed to demonstrate a number of important achievements as listed below.

- **BEST4HY** already delivered some promising laboratory results: Pt recovery of more than 90%, an anode recovery for SOFC of more than 80%, and a La and Co recovery of more than 80%.
- **AD ASTRA** has produced a set of validated models able to predict the degradation of SOC and the Remaining Useful Life of the cell, keeping a record of 20 peer-reviewed publications.
- **THYGA** experts contributed to revisions of the existing standards and/or drafting of new standards based on PNR results. The affected standards are part of the European RCS framework covered by the Gas Appliances Regulation 2016/426. For example, one of them is the standard EN 437 Test gases – Test pressures – Appliance categories, which needs substantial modification before being used for certifying gas appliances when working at high hydrogen concentrations.
- **HYTUNNEL-CS** has concluded to 3 sets of recommendations: (a) recommendations for intervention strategies and tactics for first responders, related to the scope of the HyResponder project, (b) recommendations for inherently safer use of hydrogen vehicles in underground transportation systems, targeting local and national administration and stakeholders; (c) recommendations for standardisation bodies.

Table 3: Standardisation impacts of PNR/RCS/Safety projects

RCS/PNR project	RCS body/document addressed	Impact on RCS framework
AD ASTRA	IEC/TC 105, AHG1, working towards a NWIP for a standard on AST protocols for SOFC and PEMFC	The project has published protocols for SOFC degradation assessment, which can be used by IEC/TC 105. A partner is member of AHG11 and responsible for the integration of project results into an IEC TR document. The expected NWIP was not submitted because the group concluded that it is too early for an international standardisation of testing procedures. The SOFC and SOEC technology still requires widespread acceptance. Nevertheless, AHF11 will further exist, collecting new evidence and paving the way to a future standard.
PRHYDE	New ISO 19885-3 Gaseous hydrogen — Fuelling protocols for hydrogen-fuelled vehicles — Part 3: High flow hydrogen fuelling protocols for heavy duty road vehicles	PRHYDE has provided results to ISO/AWI 19885-3 which is under preparation by the ISO/TC 197 WG24, led by one of the PRHYDE partners.
THYGA	Gas Appliances Regulation 2016/426. Its harmonised standards are under the mandate of several CEN/TC: TC238 / Gas appliances: TC48, TC49, TC58, TC62, TC106, TC109, TC131, TC180, TC299	Assessment of the applicability of the GAR regulation to H_2NG blends. Recommendations to modify EN 437 and review several related harmonised standards mentioned by the Gas Appliances Regulation.
HYTUNNEL-CS	UN-ECE GTR13; CEN/CENELEC JTC6 WG 3 “Safety”; ISO TC 197; First responders Standardisation bodies Local/national stakeholders	Three important sets of recommendations report have been issued on hydrogen behaviour in parking garages and accessing tunnels and underpasses. These recommendations targets standardisation bodies, stakeholders and first responders. There is, however, no engagement with specific standardisation bodies.
e-SHYIP	IMO IGF code, guidelines for hydrogen storage on ship	Recommendations to be considered by IMO, in updating the IGF Code. However, the project still does not have a convincing way to intervene at IMO MEPC level in place and this reduces the potentially high impact.
MULTHYFUEL	Guidelines for the design and construction of multi-fuels refuelling stations	The work will facilitate the permitting process for multi-fuels stations. Updating HyLaw which is a repository of applicable administrative and legal permitting rules.
HyRESPONDER	Not yet identified European standardisation body	The project is checking the possibility to transform the European Emergency Response Guide into a standard.

Gap analysis – Main JRC Recommendations

Sustainability, LCSA, recycling and eco-design: The overall progress of the programme must be linked to the development of methodologies, measurement and assessment tools as well as the collection of data. All projects will have to embed sustainability and circularity principles in designing their products and their activities. The life cycle assessment must become the reference tool to measure and rank the available technology options.

Also, research on quantifying and mitigating the life cycle impact of hydrogen use on environmental categories other than climate change, such as water consumption, is needed. Ideally, the impact on the 16 environmental categories recommended by the Environmental Footprint method should be covered.

Education and public awareness: The audience required seems to have been partially reached by the projects in this area. In general, investment in skills and knowledge is happening in the field, however, a more thorough analysis on how much the projects have contributed is necessary.

Safety, PNR and RCS: On PNR, when dealing with pre-normative research and RCS activities dedicated to handling large hydrogen quantities, there is a clear difficulty related to the need for larger facilities and more funds and the limitation of the R&I programme. For instance, to understand the behaviour of liquid hydrogen transfer, laboratory-scale experiments will not deliver the knowledge and the data required to fully understand large transfers phenomena and risks, which is something we need to take into consideration towards the scale up of the hydrogen economy.

In terms of the maritime sector's standards, when dealing with hydrogen solution for ships, it is critical to develop a strong relationship with IMO, to inject the findings of the projects over hydrogen solutions applicable to ships in its works. This would allow magnifying the projects' impact and achievements.

Finally, due to the complexity of the topics covered, several projects included in this report have made it clear that follow ups are required to help reduce the knowledge gaps.

More info on the Pillar, the related Research Areas and the projects can be found in the Annex, under PILLAR 5 – CROSS – CUTTING TOPICS.

5.6. PILLAR 6: HYDROGEN VALLEYS

The Hydrogen Valley concept has gained momentum and is now one of the priorities of the European Commission for scaling-up hydrogen deployments and creating interconnected hydrogen ecosystems across Europe. This is evidenced in the REPowerEU Plan[70] where it was announced that the Clean Hydrogen JU would receive an additional EUR 200 million budget to support the acceleration of Hydrogen Valleys in Europe. In particular the "REPowerEU" plan aims to double the number of Hydrogen Valleys across Europe by 2025.

Three projects are contributing to this Research Area, namely **BIG HIT, HEAVENN** and **GREEN HYSLAND**. The projects are covering the period between 2016 and 2022.

In 2023, the Clean Hydrogen JU has selected 9 Hydrogen Valley projects for funding (in total EUR 105.4 million), following its first Call Proposals (2022). The projects should be able to mobilise additional private and public investments of at least 5 times the amount of funding provided by the EU[71].

In addition to the support via its Call for Proposals, the JU is helping to create a pipeline of hydrogen projects (including Hydrogen Valleys) via its dedicated Project Development Assistance (PDA) initiative. The PDA I initiative, concluded in June 2021, supported 11 selected regions to develop detailed work plans for the implementation of hydrogen projects. The report[72] contains summaries of the project plans and the work undertaken in each of

70. https://www.clean-hydrogen.europa.eu/system/files/2022-05/COM_2022_230_1_EN_ACT_part1_v5.pdf
71. https://hydrogeneurope.eu/clean-hydrogen-partnership-invests-e105-4m-in-9-h2-valleys/
72. https://www.clean-hydrogen.europa.eu/get-involved/regions-hub/clean-hydrogen-ju-pda-regions_en

the selected regions, as well as the next steps after the end of the PDA support period. Building on the success of the pilot PDA initiative, the JU AWP 2022 included a procurement for the implementation of the "Project Development Assistance (PDA) for Regions II" with a clear focus on countries targeted by the Cohesion Fund, outermost regions and islands. The Call for tenders was published in December and was awarded in Q1 2022. Following an Expression of Interest, in January 2023, the Clean Hydrogen Partnership selected 15 regions which are now receiving support in the framework of the latest PDA II initiative and working in the development of hydrogen projects'

In 2021, as a result of a public procurement contract, the JU released the Hydrogen Valley Platform[73] under the umbrella of the Mission Innovation's 'Renewable and clean hydrogen' innovation challenge. It is aimed primarily at project developers, but it is also raising awareness among policymakers and is intended to inspire others willing to replicate similar projects. The platform was launched publicly on 19 January 2021, featuring 30+ global Hydrogen Valleys with a cumulative investment volume of over EUR 30 billion. An accompanying report[74] summarised the findings and presented identified best practices for successful project development as well as recommendations for policy makers on how to provide a favourable policy environment that paves the way to reach the Hydrogen Valleys' full potential as enablers of the global hydrogen economy. As of May 2023, following the relaunch of the platform, there are 81 valleys globally, 60 of these are in Europe out of which 16 are in Germany, representing an investment of EUR 84.978 million[75].

Once the projects have reached their maximum build-out scale around 8.5 MtH_2 will be produced, by a mix of PEM and alkaline electrolysis (3% other sources). 80% of projects intend to target mobility end use, 60% industrial off-takers and 53% energy end use[76]. This represents an investment of over EUR 90 million.

Gap analysis – Main JRC Recommendations

All 3 projects are likely to have a high impact due to their high visibility and will make significant progress towards reaching the SRIA goals for Hydrogen Valleys. However, the projects are facing a number of challenges causing delays and will likely need to adapt their plans. The recent sharp increase in electricity prices has meant that business cases have become more tenuous and operational strategies of the hydrogen production plants had to be changed.

A clear definition of a Hydrogen Valley is necessary, with a list of basic requirements. As recommended by the HEAVENN project, this could be anchored in EU legislation such as the gas market package.

Additional funding for Hydrogen Valleys is necessary to sustain a business case well after the end of the JU funding period. This should even be considered from the project's inception phase to avoid possible dismantling after conclusion. The lack of additional funding creates uncertainties and delays and is perceived as the most important hurdle during the planning phase. The recently announced Hydrogen Bank and efforts being made to create synergies between JU funding and other national/regional funding sources via e.g. "Seal of Excellence" and JU Technical Assistance to MS are steps in the right direction.

Furthermore, support for the Valleys is needed from the legal perspective, in order to de-risk them and to allow the attraction of the necessary private financing. Attracting the necessary funding is a key barrier that causes delays for the parties seeking to launch a Hydrogen Valley (see Figure 4). Overspending is also common. It is recommended that while business cases are still tenuous, the share of public funding is increased. This would create more stability and reduce the necessity of combining many different funding sources.

The European Hydrogen strategy recognises the importance of Hydrogen Valleys, which, as it proposes, will develop particularly around local hydrogen production facilities. However, the presence of hydrogen consumers in the area is also a key factor for the success of a Valley.

73. https://h2v.eu/
74. https://h2v.eu/media/7/download
75. The majority of projects still awaiting final investment decision (https://h2v.eu/)
76. https://www.clean-hydrogen.europa.eu/system/files/2023-05/20230508_Relaunch%20event_Full%20presentation_vFinal%20II_Update.pdf

Hydrogen Valleys should also be located close to TEN-T corridors. In general, they should also be located in proximity to suitable geological formations for hydrogen storage, and near newly built RES. The resulting possible locations based on the combination of all these constraints (most importantly the presence of several hydrogen consumers) should be studied further for the EU.

More info on the Pillar, the related Research Areas and the projects can be found in the Annex, under PILLAR 6 – HYDROGEN VALLEYS.

5.7. PILLAR 7: SUPPLY CHAIN

As indicated in the SRIA, Pillar 7 aims 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. A considerable increase of qualified companies is required along the supply chain to support the massive hydrogen production targeted in the next years. Supply chain includes everything from processing the raw materials into specialised materials (e.g. electro-catalysts), the production of components and sub-system to system integration. The supply chain is also complemented by the wider view of the value chain approach vis-à-vis creation of jobs and added value to economy and industry competitiveness.

According to the SRIA, the overall goal of the projects in this Research Area is to enable efficient manufacturing of large volumes of PEM and SO fuel cell technologies with improvements in respect to current production costs, FC performances and environmental impact. Noticeable improvements have been made by FC products obtained with innovative manufacturing methods. Even if improvements can be detected for many KPIs linked with performance, such as Efficiency, FC stack durability, FC module availability, Minimum Pt, CRMs/PGMs recycled from scraps and wastes, it seems that CAPEX is a crucial parameter still far away from the expected values.

The R&D priorities are addressing early stage development, development research actions and demonstration actions. The early-stage development is mostly focused on new manufacturing technologies and production processes. The development research actions are mostly focusing on bottlenecks along the hydrogen supply chain (e.g. critical components and sub-systems supply), training and skills on manufacturing, integration of new manufacturing technologies, use of artificial intelligence etc. As for demonstration actions, they should address the development of medium and large manufacturing capacity as well as development of pan European technology (testing) platforms based on the gap analysis of the study of the supply and value chains.

The supply chain of hydrogen-based technologies is still under development and consists mainly of relatively small organisations. About 300 European companies contribute to the development of hydrogen technologies and many more are involved in various steps of the hydrogen supply chain. European companies and research organisations are leaders in many segments along the hydrogen supply chain, which gives Europe a competitive advantage along with other key players such as Japan, South Korea, the USA and more recently, China. This leadership should be preserved by constant effort to keep up with R&I actions able to fill existing gaps and mitigate vulnerabilities and remain competitive at a global level.

- Project **LOWCOST-IC** managed to increase robustness by improving the mechanical contact between the SOFC and the interconnect, while low cost (> 80% cost reduction for raw materials used) is realised. The project developed novel robust contact layers based on Mn-Co and Mn-Cu spinels. Especially Mn-Cu spinels possess exceptionally high mechanical robustness (in the best case 15 times higher robustness than SoA). The project is progressing well towards achievement of its target of reducing the Ohmic resistance across the interconnect to < 15mΩcm2 at 750°C and < 20 mΩcm2 at 850°C (evaluated after 3,000 h). Demonstration of stable operation for > 3000 hours and 50 cycles with the new contact layers and coated interconnects in multiple 1 kW stacks were done.
- The main European SO stack manufacturers (Sunfire, Haldor Topsoe, Elcogen and Ceres Power (in the C2Fuel project) are currently using the model developed by LOWCOST-IC. The project opens a new way to reduce SOFC cost with a deep investigation on new and cheaper materials. State-of-the-art large-scale roll-to-roll manufacturing methods are used for both interconnect coating and shaping, and a fast drop-on-demand (DoD) printing technology - for application of the contact layer. In addition, the

diagnostic tools to investigate material degradation processes developed by LOWCOST-IC project can be implemented in commercial products.

Gap analysis – Main JRC Recommendations

Currently SOC technology is upscaling and enjoys rather high attention and involvement of industrial/commercial actors. However, durability of the technology can still be considerably improved and is essential for its future success. Therefore, more focus in materials research is still needed for the SOC technology. Also, more effort should be done towards open access research data (e.g. publishing in the Open Research Europe platform).

European manufacturers must cover the main segments of the supply chain, including the production of specialised and advanced materials, components and equipment, despite the efforts made under this Pillar. In addition, more effort is necessary in addressing the circular approach as a central part of the hydrogen supply chain, dealing with recovery and recycling of by-products and wastes during manufacturing. Finally, cost reduction will be achieved through automation; developing adequate tools, machines and robots.

More info on the Pillar, the related Research Areas and the projects can be found in the Annex, under PILLAR 7 – SUPPLY CHAIN.

6. GENERAL JRC RECOMMENDATIONS

The JRC performs the Annual Assessment of the Programme as a formal part of the regular improvement cycle of the Clean Hydrogen JU. Its main purpose is to provide feedback to the members of the Programme Office of the JU on the performance of the Research Areas directly in their remits. It also informs the decisions of future Annual Work Plans, by identifying gaps and possible improvement actions. Over a multi-annual timescale, it assesses the practical fit-for-purpose of the adopted key performance indicators and their targets, gathering improvement elements useful for their future updates. It also provides a fact-check basis which can be used by other Programme Technical Assessments (for example the mid-term and the ex-post assessments). Finally, the data collection performed annually supports the assessment of long-term, historical progress of specific hydrogen technologies.

In general, it can be concluded that the Clean Hydrogen JU activities have quickly and successfully aligned to the recent R&I policy priorities expressed in the Green Deal and the REPowerEU action. Although the projects forming the base of the Programme Technical Assessment 2023 have been designed and funded still by the old FCH 2 JU, the expected stronger attention to renewable hydrogen production and selected end-use sectors has already emerged clearly. This is an excellent demonstration of structural flexibility and capacity to align quickly to the European Commission's policy requirements. For example, since the new programme should be led by sustainability principles, the current projects are developing life-cycle sustainability assessment methodologies and approaches which can be applied to all future projects. In line with the policy expectation regarding the role of hydrogen for the decarbonisation of hard-to-abate sectors, the fuel cells development effort has shifted focus to solutions for long-haul, high-power transport sectors. Another effort worth mentioning is the strong focus on the coupling between electrolysers and variable renewable energy sources, in term of performance optimisation, durability and safety.

As for the data collection, the newly introduced Project fiches (that replaced the EU Survey annual exercise) represent an improvement of the data collection process in several ways; by containing data previously dispersed across several sources and by being a living document where progress achieved through the years by projects can be traced. Nevertheless, to become a successful data collection tool, the willingness of the project coordinators to thoroughly fill in and frequently update each Project fiche is vital. This observation is even more important for information that cannot be shared in the project deliverables. This remains one of the main goals that the Programme Office aims to achieve through the Knowledge Hub[77], the new platform planned to be developed in 2024.

Project reporting in TRUST is of rather inconsistent quality and much of the data submitted is labelled as confidential. In many cases, data is marked as confidential, even if the same information is publicly available from other sources. A quick check on 2022 TRUST data shows that roughly half of the reported KPI data are marked as confidential and certain amount of the data are blank or zero. This implies that the efforts made by the JU to convince projects on making their data available should continue.

In addition, it should be very clear which sections contain Public information and which sections Confidential information, as the issue of confidentiality is hindering the publication of programme achievements. Even for the current KPI tables, it is not clear whether this information can be included in all cases within a public report, especially in Research Areas where there are few projects.

77. The tender is on-going: https://etendering.ted.europa.eu/cft/cft-display.html?cftId=15172

KPIs need to be extracted on a yearly basis and tracked. As the SRIA KPIs are now well identified within TRUST, this made the work much easier. Also, the transition from MAWP to SRIA targets should be discussed. Although many projects were still funded under the previous framework programme, the programme as a whole should achieve the SRIA targets.

It has been observed that in some projects the step from the laboratory to the demonstration stage is not successful. Two stages per project can be foreseen, a shorter duration project with and lower budget for building the prototype, with focus on materials and components, and if successful, followed by a second stage for operation of the prototype.

Third parties should verify LCAs performed by major JU funded projects. This aspect could be one of the tasks of the sustainability panel. The sustainability panel could also play a role in deciding in which cases verification of the LCAs is warranted, or even play a more direct role in corroborating the outcomes.

In order to improve the dissemination of project results, stricter requirements for project web sites should be introduced for new call topics, for example making it mandatory that all public deliverables, papers and presentations are readily available and that websites are regularly updated throughout the life of the project. The Knowledge Hub is expected to provide an alternative dissemination path, making the public deliverables of the projects directly accessible.

7. VIEWS OF THE WIDER SCIENTIFIC COMMUNITY (2023)

The Clean Hydrogen JU is trying to progress on the objectives reflected in the SRIA, by involving as many of the stakeholders of the hydrogen technologies sector as possible. Actions undertaken by the Clean Hydrogen JU should take into account not only the views of its public and private members, the recommendations coming from the JRC, reflected in its Programme Annual Assessment and summarised above, but also the views of the wider scientific community[78]. In this context, the JU has conducted a survey addressing the wider scientific community to gather feedback on the SRIA topics, in view also of the upcoming SRIA revision, and implementation through the AWP 2022 and AWP 2023.

The Wider Scientific Community Survey 2023 (WSC Survey) was conducted by the Clean Hydrogen JU, between 9 June and 31 July 2023. Based on the findings, a number of areas have been highlighted where SRIA could contribute further according to the respondents:

- Address the cross-cutting challenges of RCS and education/training.
- Increase public awareness of the benefits of hydrogen technologies.
- Ensure the availability of resources and components in Europe.
- Further support the deployment of hydrogen valleys.
- Continue working on next generation technologies.
- The need to achieve synergies between the JU's SRIA and other national and European programmes.

In terms of priority, specific areas of intervention are suggested by the respondents, as summarised below per Pillar.

A. **Hydrogen Production**

- Research and development of more efficient and cost-effective methods for producing hydrogen from renewable energy sources. This could involve:
  - Improving mature production technologies (Alkaline and PEM electrolysers), by developing new catalysts for water electrolysis or improving the efficiency of solar-powered hydrogen production.
  - New methods need to be further investigated and developed, such as solar thermochemical hydrogen production and electrochemical water splitting.
- Development of new technologies for producing hydrogen from biomass and other waste materials.
- More research on the safety and environmental impact of hydrogen production.

B. **Hydrogen Storage & Distribution**

- Additional efficient and safe ways to store hydrogen must be investigated.

78. According to SBA Article 82 (d), the Governing Board of the JU must ensure that independent opinions and advice of the wider scientific community on its SRIA, work programmes and developments in adjacent sectors are gathered through an independent scientific advisory workshop as part of the European Clean Hydrogen partnership forum.

- Development of new materials for hydrogen storage such as metal hydrides and carbon nanotubes.
- Development of new materials and techniques for building and maintaining hydrogen pipelines.
- Hydrogen refuelling stations (HRSs), to develop new designs that are more efficient and cost-effective.
- Development of liquid organic hydrogen carriers (LOHC).
- Further research on the infrastructure needed for hydrogen storage and distribution, including the efficiency of hydrogen compression.

C. **Hydrogen End-Uses: Transport**

- Need to develop more efficient and affordable fuel cell vehicles.
- Need to develop hydrogen-powered aircrafts and ships.
- More research on the safety of hydrogen in transportation applications.

D. **Hydrogen End-Uses: Clean Heat & Power**

- Need to develop hydrogen based heating and cooling systems.
- Widespread use of hydrogen as a fuel for power generation.
- Further research on the economics of hydrogen uses in heat and power applications.
- Use of hydrogen in industrial processes as a fuel.
- Need to investigate other uses of hydrogen e.g. in agriculture or manufacturing.

E. **Cross-Cutting Topics**

- Stringent safety standards for hydrogen production, storage, and use.
- More comprehensive and coordinated research on hydrogen.
- Increase public awareness of the benefits of hydrogen.

F. **Hydrogen Valleys**

- Hydrogen valleys can successfully demonstrate the benefits of hydrogen.
- Need to develop more case studies and best practices for developing hydrogen valleys.

G. **Supply Chain**

- Need to develop a more robust and efficient hydrogen supply chain.
- Need to develop more innovative solutions for transporting and distributing hydrogen.

Also, priority in the next AWPs should be given to interdisciplinary research analysing the hydrogen supply chain.

In addition, respondents highlighted financial, legal, and policy synergies to support the research and deployment of hydrogen technologies:

- The use of carbon pricing mechanisms to make hydrogen production more competitive.
- The provision of government subsidies and grants to support hydrogen research and development.
- The development of financial instruments, such as green bonds, to finance hydrogen projects.
- The development of clear and harmonised regulations for hydrogen production, storage, and distribution.

- The removal of barriers to trade in hydrogen technologies.
- The protection of intellectual property rights in hydrogen technologies.
- The development of national and regional hydrogen strategies.
- The coordination of hydrogen policies between different European countries.
- The promotion of international cooperation not only on hydrogen research and development, but also on developing common RCS.

Overall, many of the comments and recommendations made by the respondents in the survey are considered to be adequately addressed by the SRIA already. The fact that only a few recommendations could be considered during the upcoming SRIA revision confirms that the Programme is updated and well-positioned to address the main challenges towards research, development and deployment the hydrogen technologies.

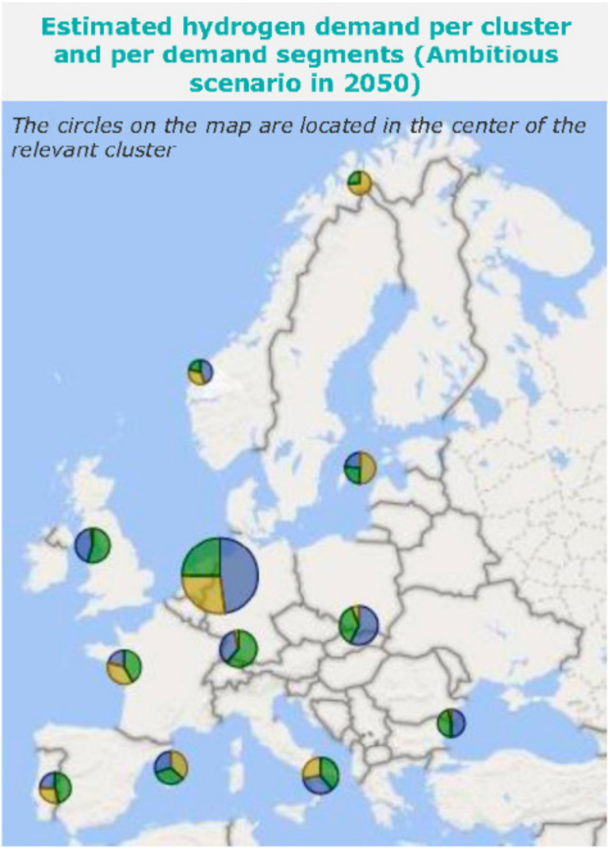
8. STUDIES ON HYDROGEN

In this section the JRC assessment and recommendations, as well as the views of the wider scientific community, are complemented by interesting results of studies following the developments in the hydrogen sector. These studies were published between the end of 2022 until September 2023 and were either procured by the JU or performed by international organisations.

In January 2023 the Clean Hydrogen JU published its annual edition of Success Stories[79]. The Success Stories provide a comprehensive overview of our projects' and initiatives' impact and explains how the Clean Hydrogen Partnership is making fuel cells and hydrogen an everyday reality in Europe. This edition covered topics in relation to hydrogen production from solid oxide electrolysers, the advances in hydrogen distribution, hydrogen car and buses deployment in transport, improving fuel cell membrane technology, the shift to gigawatt-scale fuel cell manufacturing and the important contributions to the development of safety regulations.

In March 2023[80] a study on hydrogen in ports and industrial coastal areas was published by the Clean Hydrogen JU. This is the first report of a series of 3 reports studying the role port ecosystems are expected to play in the expansion of the European hydrogen market through to 2050.

Figure 15: Estimated Hydrogen Demand in ports



Source: Clean Hydrogen JU, Deloitte

79. https://www.clean-hydrogen.europa.eu/media/publications/2022-success-stories_en
80. https://www.clean-hydrogen.europa.eu/media/publications/study-hydrogen-ports-and-industrial-coastal-areas_en

- Using a scenario-based approach, the study provides detailed outlooks of the potential hydrogen demand and supply in European ports and coastal areas in 2030, 2040 and 2050, along with the required hydrogen value chain infrastructure and a no-regrets investment roadmap for the development of hydrogen activities and infrastructure in the vicinity of ports. The report also provides an overview of the various possible roles that a port could fulfil in Europe's future hydrogen economy.
- The key message of the study is that achieving REPowerEU's ambitious target and continuing to expand the European hydrogen market through 2050 requires accelerated investment in dedicated infrastructure in port areas to deliver hydrogen to multiple end-users in the wider port areas and/or into the hinterland. Up to 42% (22 Mt, or 730 TWh) of total hydrogen demand in the EU in 2050 could be located in port areas.

In September 2023[81], the second report in this series was published, informing stakeholders and policymakers on the areas of priority for overcoming technological, safety and non-technical (policy, regulatory, governance, strategic) gaps for the timely development of hydrogen related activities and infrastructure in EU port areas. Although the transformations expected in ports as a result of the emergence of a European hydrogen economy are specific to each port, with different implications expected for sea and inland ports, the recommendations on strategic actions for port authorities and other port-related stakeholders outlined in the report are intended to encompass the entire European port ecosystem, and are therefore not tailored to any particular port archetype (e.g., seaport or inland port, logistics and transport, urban, industrial, or bunkering).

In July 2023[82] the Clean Hydrogen JU published a report based on a public opinion survey conducted in 27 EU countries, with the goal to analyse and assess European citizens' attitudes towards, and level of knowledge of, hydrogen technologies and determine a baseline for monitoring changes in public opinion over time. The survey explored a range of issues, including knowledge and awareness of energy in general and of hydrogen energy in particular. Among its key findings, the report found that:

- Over 8 in 10 respondents were aware of hydrogen energy; 7 in 10 would be interested in receiving (even) more information about it;
- Hydrogen has a positive image in terms of environmental impact;
- Half of the respondents using gasoline or diesel cars said they would likely switch to a car powered by an alternative fuel, 10% of which mentioning hydrogen as their preferred choice;
- Cost is the main obstacle for switching to cleaner energy sources; still, 60% of respondents would be willing to pay more for cleaner energy for their personal needs;
- Hydrogen is also seen as a safe source by 6 in 10 respondents, although 2 in 10 felt oppositely and the remaining felt there is a gap in information about this topic; and
- Finally, 1 in 10 respondents said that they had experienced energy in some form of its application.

In 2023 the JRC published 2 technical reports, carried out under the Framework Contract between the JRC and the JU, related to harmonised testing procedures of electrolysers:

a) EU harmonised testing procedure: Determination of water electrolyser energy performance[83], January 2023

b) EU harmonised testing protocols for high-temperature steam electrolysis[84], May 2023

The first report presents a testing procedure for establishing the energy performance of water (steam) electrolyser systems, whether grid-connected or off-grid, and individual water electrolysers/high-temperature electrolysers for the generation of hydrogen by water/steam electrolysis. The second report presents testing protocols for

81. https://www.clean-hydrogen.europa.eu/media/news/press-release-second-report-study-hydrogen-ports-and-industrial-coastal-areas-now-published-2023-09-20_en
82. https://www.clean-hydrogen.europa.eu/media/publications/awareness-hydrogen-technologies-survey-report_en
83. https://publications.jrc.ec.europa.eu/repository/handle/JRC128292
84. https://publications.jrc.ec.europa.eu/repository/handle/JRC129387

establishing the performance and durability of high-temperature electrolyser stacks and high-temperature steam electrolysis systems for the generation of bulk amounts of hydrogen by the electrolysis of steam (water vapour) using electricity mostly from variable renewable energy sources.

In addition to the above studies, it is also important to mention 4 more activities of the Clean Hydrogen JU complementing its other activities and the reporting of the developments in the (European) hydrogen sector:

1. Workshop "Towards an EU Roadmap for Hydrogen Valleys"[85] in March 2023

The Clean Hydrogen Partnership, the European Hydrogen Valleys Partnership and the Northern Netherlands region organised the workshop "Towards an EU Roadmap for Hydrogen Valleys – Regional actors and their role: double the number of valleys by 2025 and build-up skills". The purpose of this 2 day workshop was for the regional and local actors to discuss current opportunities and challenges in rolling-out and scaling-up Hydrogen Valleys in Europe. More than 150 people attended the workshop on each day, highlighting the increasing interest towards the topic. The outcomes of the workshop were summarised in a report in May[86].

2. The Clean Aviation and Clean Hydrogen joint technical workshop on H2-powered aviation[87] in April 2023

Considering the Strategic Research and Innovation Agendas of the Clean Aviation and Clean Hydrogen Joint Undertakings, along with the hydrogen-powered aviation roadmap, participants identified potential gaps and barriers within the roadmap. This resulted in a set of key recommendations, including to accelerate the H2 technology maturation, integration and demonstration, increase alignment between the two partnerships and Horizon Europe Cluster 5 Work Programme, and gain more understanding on the climate impact of H2-powered aviation emissions (non-CO2 emissions).

3. The relaunch of the Hydrogen Valley Platform[88] in May 2023

The Hydrogen Valley platform is a global collaboration platform for all information on large scale hydrogen flagship projects and aims to facilitate a clean energy transition by promoting the emergence of integrated hydrogen projects along the value chain as well as by raising awareness among policy makers. In May 2023 the platform was revamped and an extensive data collection of primary data from the projects was performed, in order for the platform to provide comprehensive insights into the most advanced and ambitious Hydrogen Valleys around the globe.

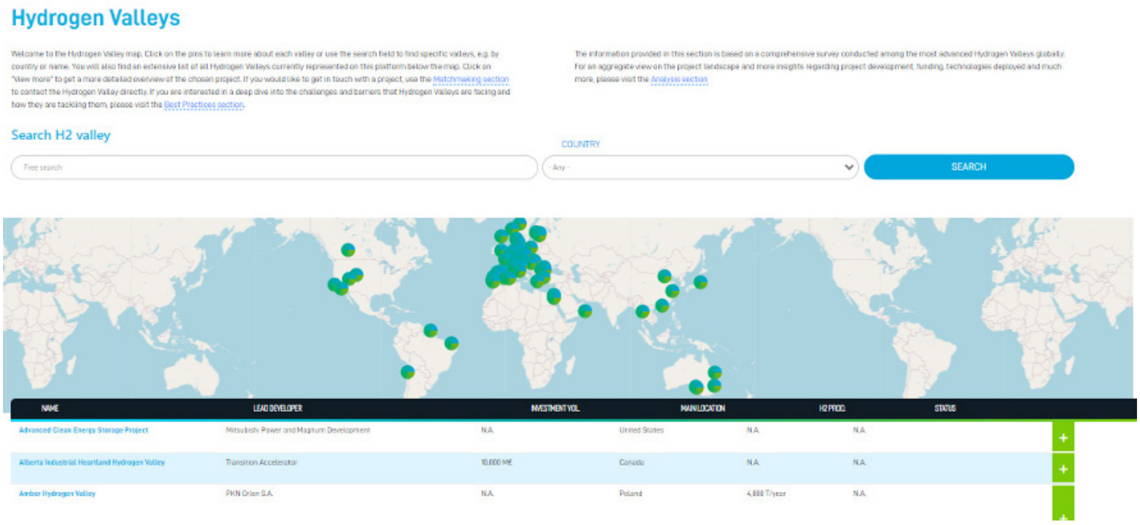
85 https://www.clean-hydrogen.europa.eu/media/news/interested-hydrogen-valleys-presentations-workshop-towards-eu-roadmap-hydrogen-valleys-are-now-2023-03-15_en

86 https://www.clean-hydrogen.europa.eu/system/files/2023-05/H2%20Valleys%20Workshop%20Outcomes.pdf

87 https://www.clean-hydrogen.europa.eu/media/news/key-recommendations-clean-aviation-and-clean-hydrogen-joint-workshop-h2-powered-aviation-2023-07-12_en

88 https://h2v.eu/

Figure 16: The relaunched Hydrogen Valleys Platform



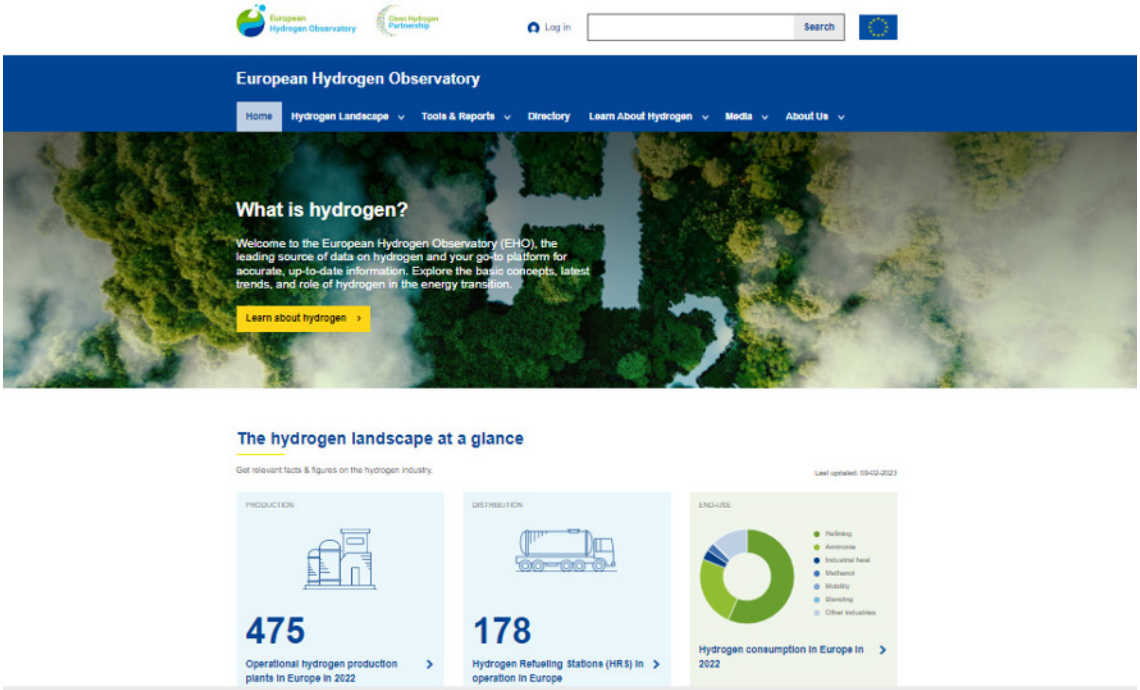
Source: Hydrogen Valley Platform

4. The relaunch of the European Hydrogen Observatory[89] in September 2023

The European Hydrogen Observatory (EHO) is an open platform providing data and up to date information about the entire hydrogen sector, aiming to address the lack of data publicly available at EU and national level concerning the uptake of fuel cell and hydrogen technologies on the EU market and the absence of a coordinated methodology on how to monitor their market evolution. EHO was officially launched on 15 September 2020 under the original name of Fuel Cell and Hydrogen Observatory (FCHO). After the relaunch, it was renamed to European Hydrogen Observatory, with an improved design and visualisations, enhanced data services and additional tools.

89 https://observatory.clean-hydrogen.europa.eu/

Figure 17: The relaunched European Hydrogen Observatory



Source: European Hydrogen Observatory

On the international stage, International Energy Agency (IEA) published its annual Global Hydrogen Review 2023[90] 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 included a special focus on demand creation for low-emission hydrogen, because although global hydrogen use is increasing, demand remains so far concentrated in traditional uses in refining and the chemical industry and mostly met by hydrogen produced from unabated fossil fuels.

An important message coming from the report is that although the number of announced for low-emission hydrogen production is rapidly expanding[91], only 4% of this potential production has at least taken a final investment decision (reaching nearly 2 Mt). In particular, to meet climate ambitions, there is an urgent need to switch hydrogen use in existing applications to low-emission hydrogen and to expand use to new applications in heavy industry or long-distance transport. But measures to stimulate low-emission hydrogen use have only recently started to attract policy attention and are still not sufficient to meet climate ambitions.

In parallel, IEA finds that end-use technologies, in sectors where emissions are hard to abate and hydrogen is expected to play a more important role for decarbonisation, are much less mature and innovation is taking place at a slower pace. Therefore research, innovation and development are critical to demonstrate the viability of these technologies and to support continued cost reduction of technologies that are nearing commercialisation. Nevertheless, there are some positive signs of progress, such as in industry, where R&D in the use of hydrogen for high temperature heat in ancillary processes moved forward last year.

In January 2023 IEA combined its expertise with the European Patent Office to address the innovation trends related to hydrogen in the report entitled "Hydrogen patents for a clean energy future"[92]. The report showcases

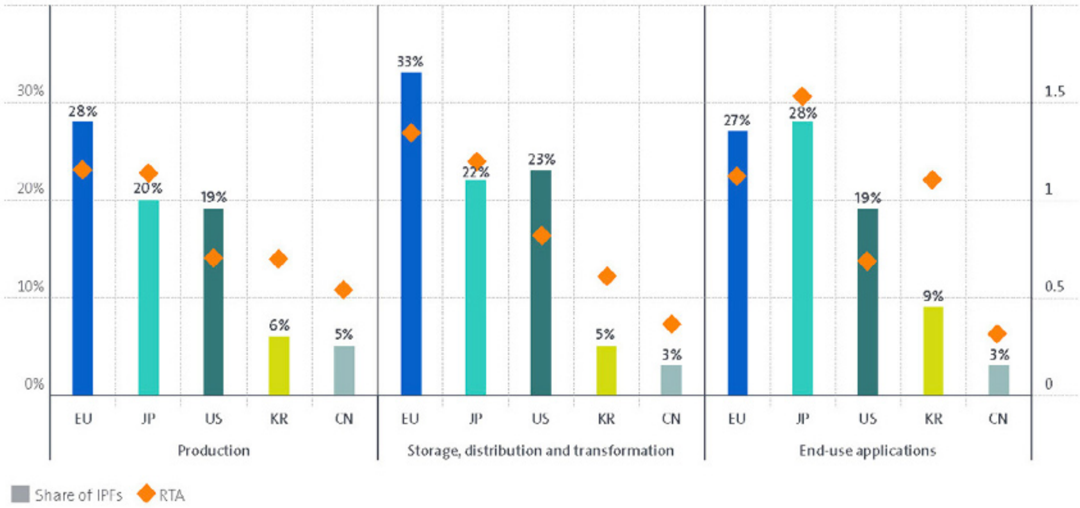
90 https://www.iea.org/reports/global-hydrogen-review-2023

91 The potential production by 2030 from announced projects to date is 50% larger than it was at the time of the release of the IEA's Global Hydrogen Review 2022.

92 https://iea.blob.core.windows.net/assets/1b7ab289-ecbc-4ec2-a238-f7d4f022d60f/Hydrogenpatentsforacleanenergyfuture.pdf

that competition in hydrogen innovation is intensifying and has the potential to drive commercialisation. The results reveal encouraging transition patterns across countries and industry sectors, including Europe's major contribution to the emergence of new hydrogen technologies. Although the chemical industry dominated innovation in the past, companies in automotive and chemical sectors are now focusing on electrolysis and fuel cell technologies. The report also highlights the contribution of start-ups to hydrogen innovation, and their strong reliance on patents to bring new technology to market. However, activity remains concentrated in a small number of regions and is uneven across technologies, indicating the need for policy action to address this.

Figure 18: Share of international patenting



Source: IEA

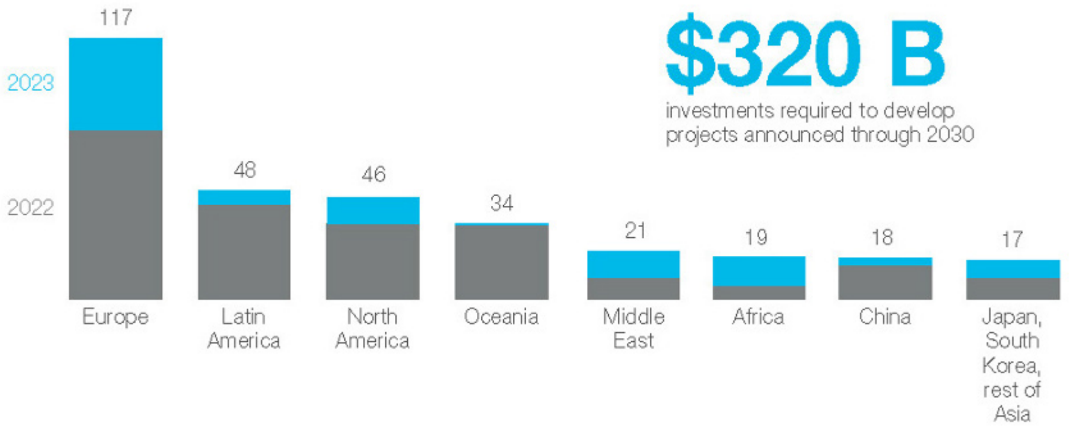
The Hydrogen Technology Collaboration Programme (Hydrogen TCP), established under IEA, published 2 task reports[93]; one in April 2023, a Technology Monitoring Report on Underground Hydrogen Storage and another in June 2023, the Final Report on analysis and modelling of hydrogen technologies. The first report formulates several key actions and recommendations for a safe and responsible implementation of underground hydrogen storage projects in the coming years. The second report aims to help better integrate hydrogen into a broad range of energy models, by providing guidelines for different types of models, while also identifying the bigger challenges in this effort.

Focusing more on deployment, the Hydrogen Council released its H_2 Insights 2023 report[94], summarising the current state of the global hydrogen sector and actual hydrogen deployment, with a deep dive into North America. According to this report, there is a pipeline of hydrogen projects that is growing continuously, with more than 1040 projects announced globally, worth USD 320 billion, growing from 240 billion in the previous year, however, actual deployment though is lagging. Europe is in the lead in terms of proposed investments, but China is the one leading on actual deployment of electrolysers and Japan and South Korea in fuel cells.

93 https://www.ieahydrogen.org/tasks-reports/

94 https://hydrogencouncil.com/en/hydrogen-insights-2023/

Figure 19: Announced hydrogen projects per region of the world



Source: Hydrogen Council

Finally, the emerging global hydrogen economy, with the increasing demand especially for renewable or low carbon hydrogen, requires advancing quickly on the aspects of hydrogen certification. Three important reports were published on this topic in 2023:

- In January 2023, IRENA published the report “Creating a global hydrogen market: Certification to enable trade”[95];
- In April 2023, IEA published the report “Towards hydrogen definitions based on their emissions intensity”[96]; and
- In August 2023, Hydrogen Council published the report “Hydrogen Certification 101”[97].

All reports emphasise the importance of these certification schemes, identify their critical elements and provide recommendations and design principles for them. They all highlight the need for harmonisation, noting the risk that lack of alignment of the several certification schemes or regulatory frameworks currently developed may lead to market fragmentation.

95 https://www.irena.org/Publications/2023/Jan/Creating-a-global-hydrogen-market-Certification-to-enable-trade

96 https://www.iea.org/reports/towards-hydrogen-definitions-based-on-their-emissions-intensity

97 https://hydrogencouncil.com/en/hydrogen-certification-101/

9. BARRIERS TO ENTRY IN HYDROGEN MARKETS

The Clean Hydrogen JU has been tasked in its founding Regulation[98] to assess and monitor technological, economic and societal barriers to market entry, including in emerging hydrogen markets. This is a difficult task, considering that hydrogen is both an energy carrier with multiple applications and production methods, as well as a feedstock. Moreover, with mature hydrogen applications only now entering the market, many of these barriers have only become known recently. In order to identify such barriers, one should look on large scale hydrogen flagship projects, addressing production and consumption in multiple sectors of the economy. Hydrogen Valleys thus constitute an ideal source for such information. The Hydrogen Valleys platform collects such information, separating the barriers in 3 different categories[99]:

- Regulation: Inadequate hydrogen legal framework, as well as the lack of experience of permitting authorities with hydrogen projects.
- Project development - preparation: Barriers related to securing funding, developing a sound business case, obtaining permits, and finding experienced staff.
- Project development - financing: Barriers related to securing public financial support and customer commitments.

The results from the surveys so far[100] are presented below, per category.

9.1. MAIN BARRIERS - REGULATION

This question provides insights into the main regulatory hurdles of Hydrogen Valleys displaying both the number of Valleys as well as the share of all Valleys[101] that identified the respective hurdle. Please note that the Hydrogen Valleys were able to choose multiple answers.

Comparing the replies at global level and in Europe, one sees that the missing procedure and lack of hydrogen experience of permitting authorities have roughly the same share, close to 60% and 80% respectively. The existence of missing or strict regulations and the tax levies on electricity from RES, also appear as approximately the same barrier both in Europe and globally.

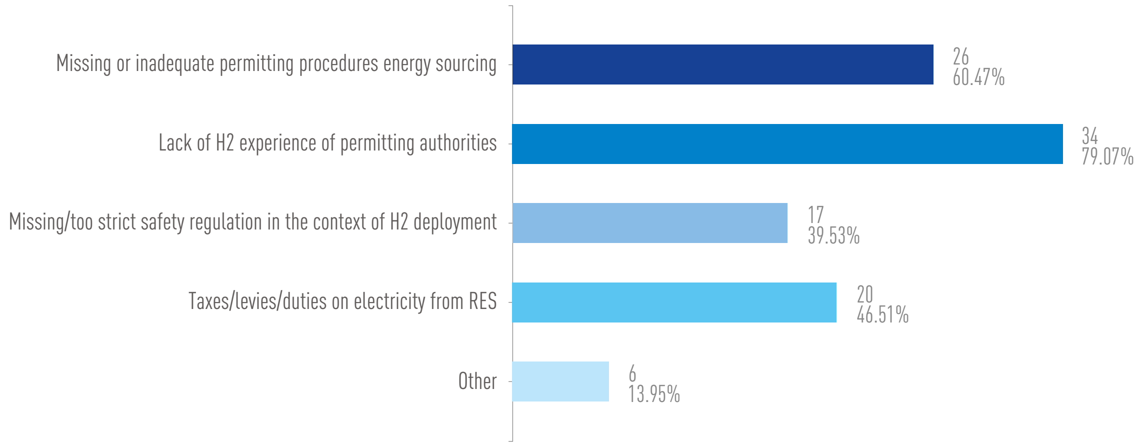
98 SBA Article 74 (a)

99 https://h2v.eu/analysis/barriers/regulation

100 Concerning 38 Valleys at the time of the drafting of the text.

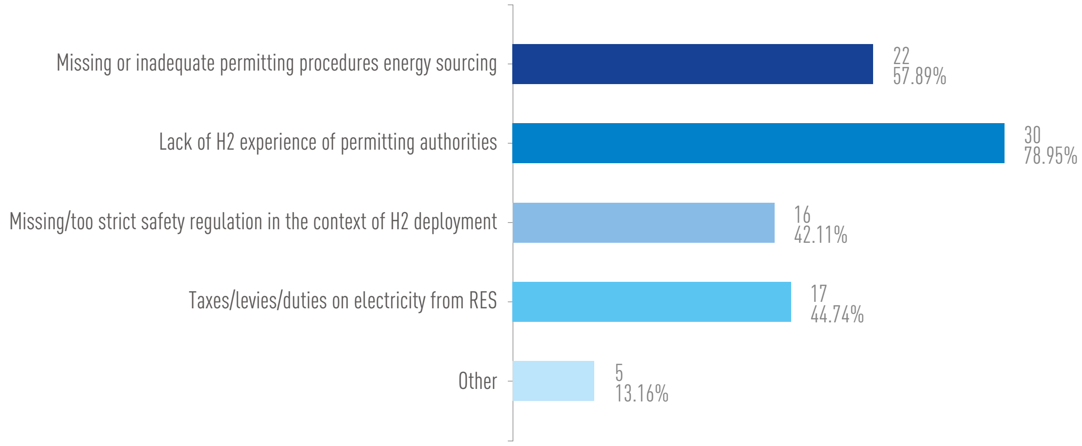
101 38 Valleys in total, 13 of which outside Europe.

Figure 20: Main Regulatory Barriers - Global



Source: Hydrogen Valley Platform

Figure 21: Main Regulatory Barriers - Europe



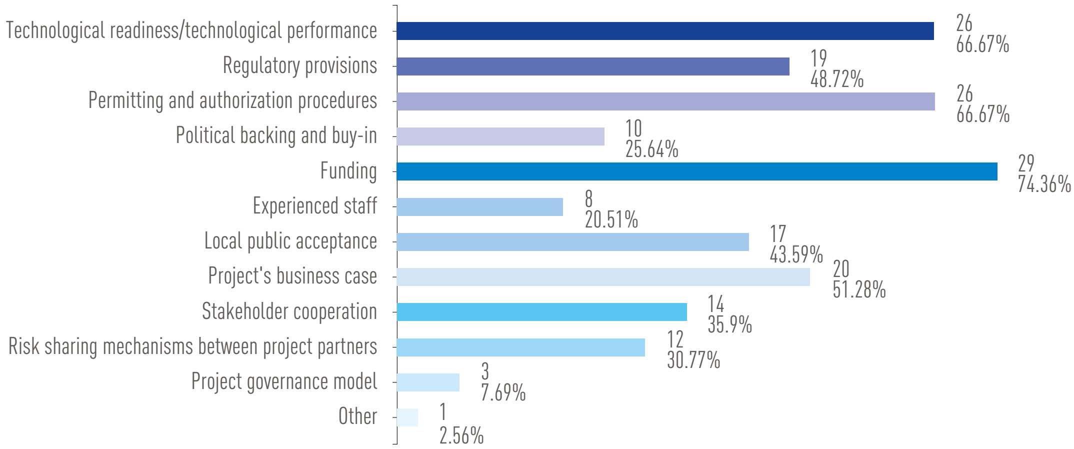
Source: Hydrogen Valley Platform

9.2. MAIN BARRIERS – PROJECT DEVELOPMENT - PREPARATION

This question provides insights into the main hurdles and barriers for Hydrogen Valleys in the preparation phase displaying both the number of Valleys as well as the share of all Valleys that identified the respective hurdle. Please note that the Hydrogen Valleys were able to choose multiple answers.

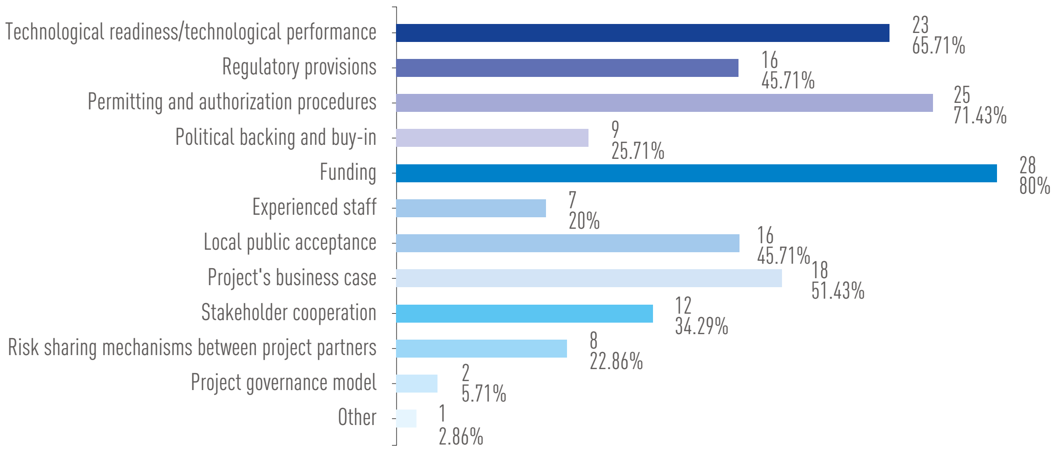
Comparing the replies at global level and in Europe, one sees that in Europe, funding and permitting barriers have slightly greater impact, while finding experienced staff is a common barrier both globally and in Europe, as is political backing and local public acceptance.

Figure 22: Main Project Preparation Barriers - Global



Source: Hydrogen Valley Platform

Figure 23: Main Project Preparation Barriers - Europe



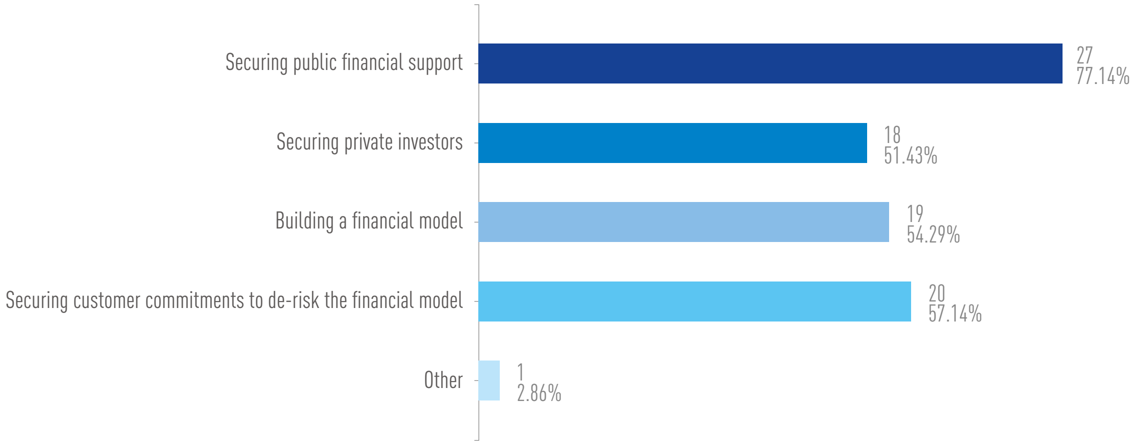
Source: Hydrogen Valley Platform

9.3. MAIN BARRIERS – PROJECT DEVELOPMENT - FINANCING

This question provides insights into the main hurdles and barriers for Hydrogen Valleys in the commercial and financing phase displaying both the number of Valleys as well as the share of all Valleys that identified the respective hurdle. Please note that the Hydrogen Valleys were able to choose multiple answers.

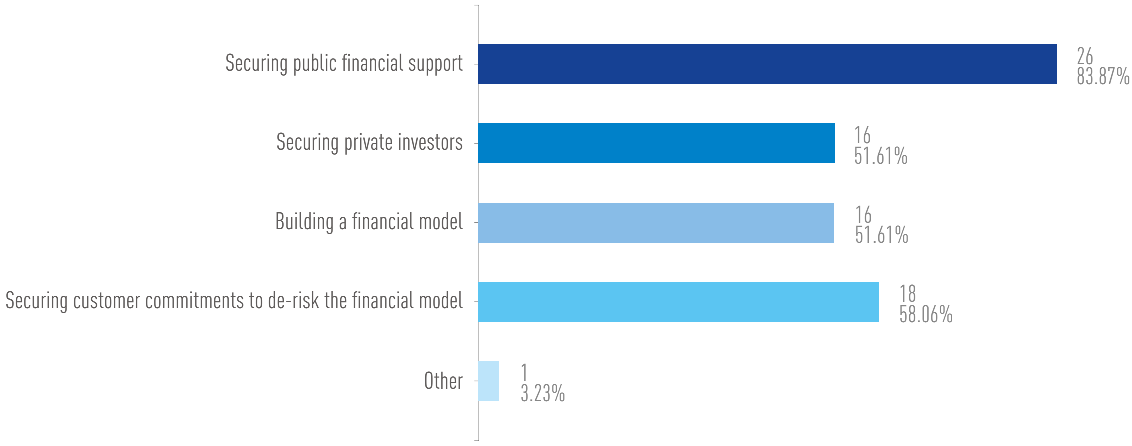
The answers to the questionnaire support the findings in the preparation questionnaire, that securing the public financial support has greater impact in Europe than globally. Nevertheless, in both cases, securing private investors and customer commitments to de-risk the financial model are the main barriers both globally and in Europe.

Figure 24: Main Project Financing Barriers - Global



Source: Hydrogen Valley Platform

Figure 25: Main Project Financing Barriers - Europe



Source: Hydrogen Valley Platform

Overall, the results of the surveys suggest that the challenges to hydrogen deployment are similar in Europe and globally, closing the gap noticed last year. Regulation issues remain and affect projects worldwide evenly, while finding secure public and private funding and the building of a de-risked financial model constitute a major issue for the deployment of hydrogen.

10. CONCLUSIONS AND NEXT STEPS

The Clean Hydrogen JU is expected to contribute to the European climate neutrality goal by producing noticeable, quantifiable results towards the development and scaling up of hydrogen production, storage, distribution and end use applications. This will help develop a number of hydrogen technologies, which are currently either not competitive or have a low technology readiness level but are expected to contribute to the 2030 energy and climate targets and most importantly to the climate neutrality goal by 2050. The final goal is to contribute to a sustainable, decarbonised and fully integrated EU energy system, and to the EU's Hydrogen Strategy, playing an important role in the implementation of its roadmap towards climate neutrality.

This report presents the review of 81 projects still active during 2022, that the Clean Hydrogen JU inherited from the preceding programmes under the FCH JU and the FCH 2 JU. As presented in Section 5, a number of have shown interesting results, especially those near conclusion or already concluded within 2022, while other promising projects are still ongoing – especially those that started in 2021. Significant progress has been made in electrolysis, both in AEL and PEMEL with the large demonstration projects, but also in SOEL and the rest of the low TRL technologies. In storage and distribution, projects demonstrated promising results, while in end uses large demonstrations are showing the potential of hydrogen technologies, also increasing visibility and public acceptance. Cross-cutting projects are paving the way to facilitate hydrogen uptake by the authorities and supply chain prepares the way towards atomisation of the spare parts production. Finally, Hydrogen Valleys is gaining all the more visibility, accelerating the deployment of hydrogen technologies in whole areas.

The gap analysis and recommendations of the JRC, together with the feedback from the wider scientific community, indicate that further improvements are required especially in cost reduction and efficiency increase for a variety of renewable hydrogen production routes, despite the effort and the achievements in the field so far. Water electrolysis will be the main supported technology, covering high technology readiness level (TRL) types - Alkaline Electrolysis (AEL), Proton Exchange Membrane Electrolysis (PEMEL), Solid Oxide Electrolysis (SOEL) - and less mature types - Anion Exchange Membrane Electrolysis (AEMEL) and Proton Conducting Ceramic Electrolysis (PCCEL). Also, alternative routes exploiting direct sunlight such as thermal dissociation of water using concentrated solar energy or through photocatalysis, biomass/biogas or other biological routes will be eligible.

In storage and distribution, a pluralistic approach with respect to the technologies that will be investigated and supported is envisaged, to have a complete set of technologies that can serve as building blocks of the EU wide logistical infrastructure. Compressed and liquefied hydrogen solutions, and especially compressed hydrogen pipelines, are considered cost-effective for the European territory distances. Also, the repurposing of existing natural gas pipelines for hydrogen use is expected to significantly lower the delivery cost, making the pipeline option even more competitive in the future.

Hydrogen-based transportation will benefit from the research and innovation actions in order to drive the Total Cost of Ownership (TCO) of the FC vehicles down, especially for the road heavy-duty transport segment. Also, maritime and aviation applications will continue to be further investigated. In regards to clean heat and power, although support will be preferential for solutions running on 100% hydrogen, there is still room to support solutions running on a hydrogen mixture in the gas grid during the transition phase. For gas turbines, support for actions running with different hydrogen admixtures are likely to be required to facilitate the development process and to achieve the final goal of 100% hydrogen turbines.

Cross-cutting activities are expected to focus on the recurring observation of stakeholders to invest further in all related fields, especially in RCS and green hydrogen skills. Also, a set of actions aiming at strengthening the overall supply chain of hydrogen technologies, from processing the raw materials to specialised materials (e.g. electro-catalysts), the production of components and sub-system to system integration. The supply chain is complemented by the wider view of the value chain approach vis-à-vis creation of jobs, added value to economy and industry competitiveness.

Hydrogen Valleys can demonstrate how all the different parts of the hydrogen value chain fit together in an integrated system approach. A key objective will be to progressively set up hydrogen local ecosystems which will accelerate the development of an EU hydrogen economy, interconnecting them step by step, and building on local renewable energy resources including mixing them to produce renewable hydrogen.

Finally, to ensure a continuous generation of early-stage research knowledge, the following strategic research challenges appear the most relevant: Low or free platinum group metal (PGM) catalysts, including safe and sustainable use of all materials, advanced materials for hydrogen storage and advanced understanding of the performance and durability mechanisms of electrolysers and fuel cells.

Clean Hydrogen Partnership

ANNEX: PROJECTS REVIEW & POSTERS

I. PILLAR 1 - HYDROGEN PRODUCTION

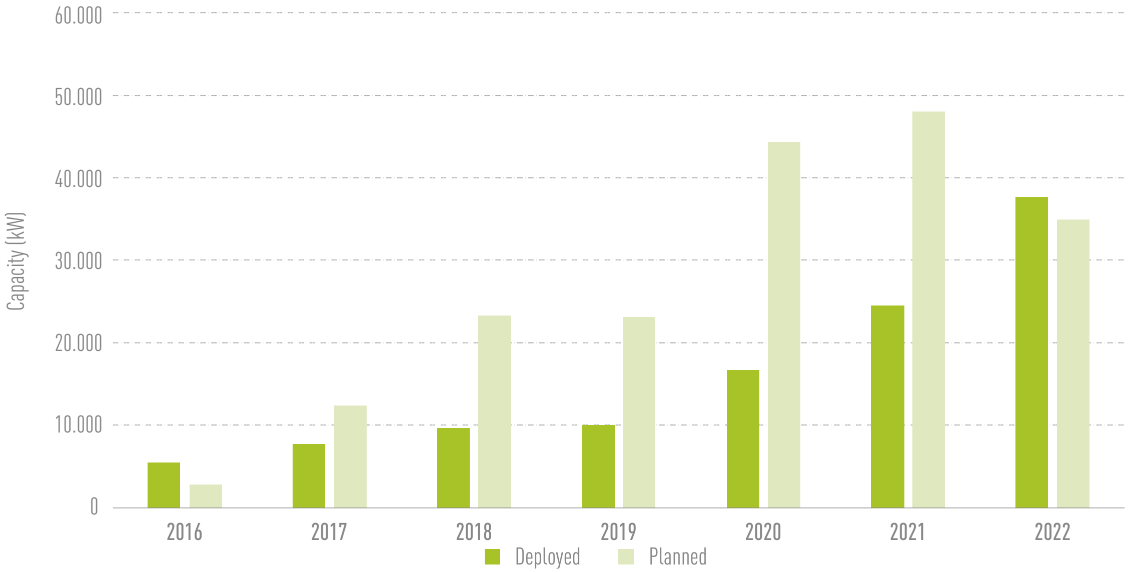
Objectives: The main technology funded under this Pillar is electrolysis. Higher-TRL technologies such as Alkaline Electrolysers (AEL), Proton Exchange Membrane Electrolysers (PEMEL) and Solid Oxide Electrolysers (SOEL) are supported, along with newer lower-TRL technologies Anion Exchange Membrane Electrolysers (AEMEL) and Proton Conducting Ceramic Electrolysers (PCCEL). The alternative hydrogen production technology funded under this Pillar is thermo-chemical cycles with concentrated solar energy. Other production processes such as photoelectrochemical water splitting or hydrogen production from biomass or waste have been supported in previous years and covered in the SRIA.

For Pillar 1, three Research Areas were defined for this year's assessment:

- low temperature electrolysis including AEL, PEMEL and AEMEL;
- high-temperature electrolysis (incl. co-electrolysis) and including SOEL and PCCEL;
- other hydrogen production methods (thermo-chemical hydrogen production).

Figure 26 shows the installed and planned electrolyser capacity of JU projects for each year until 2021. A marked increase in planned capacity can be noted starting from 2020, with the deployment of more than 40 MW. The time lag between planning announcements and deployment is notable.

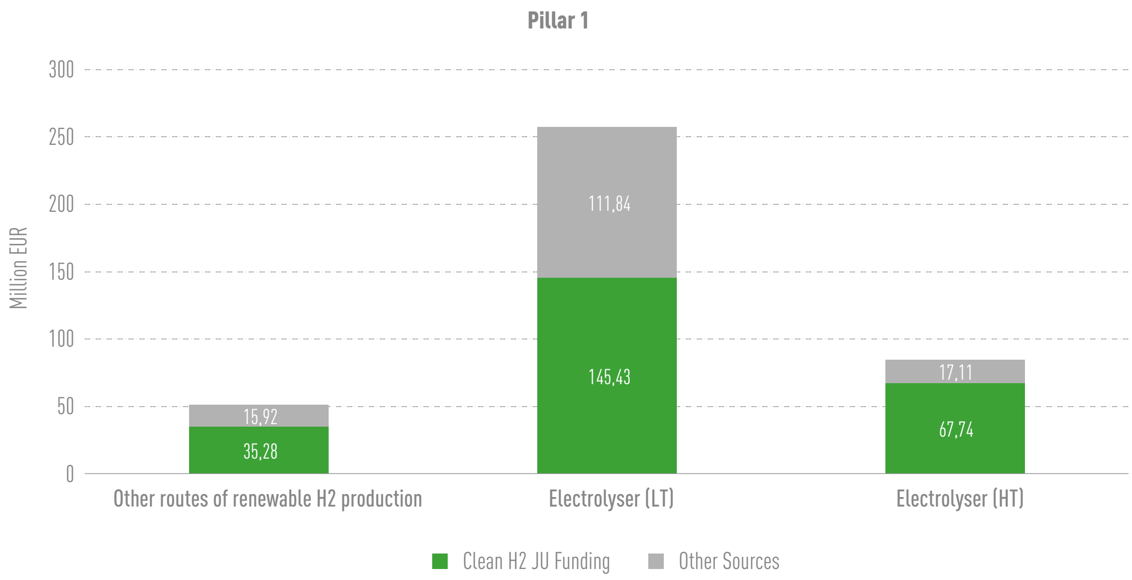
Figure 26: Clean Hydrogen JU projects deployed and planned electrolyser capacity in kW per year



Source: Clean Hydrogen JU

Budget: Following the calls between 2008 and 2020, the Clean Hydrogen JU has supported 56 projects relevant to this Pillar with a total Clean Hydrogen JU contribution of EUR 180.2 million and a contribution from partners of EUR 298.8 million. The distribution of funding over the three Research Areas considered in this Pillar is shown in Figure 27.

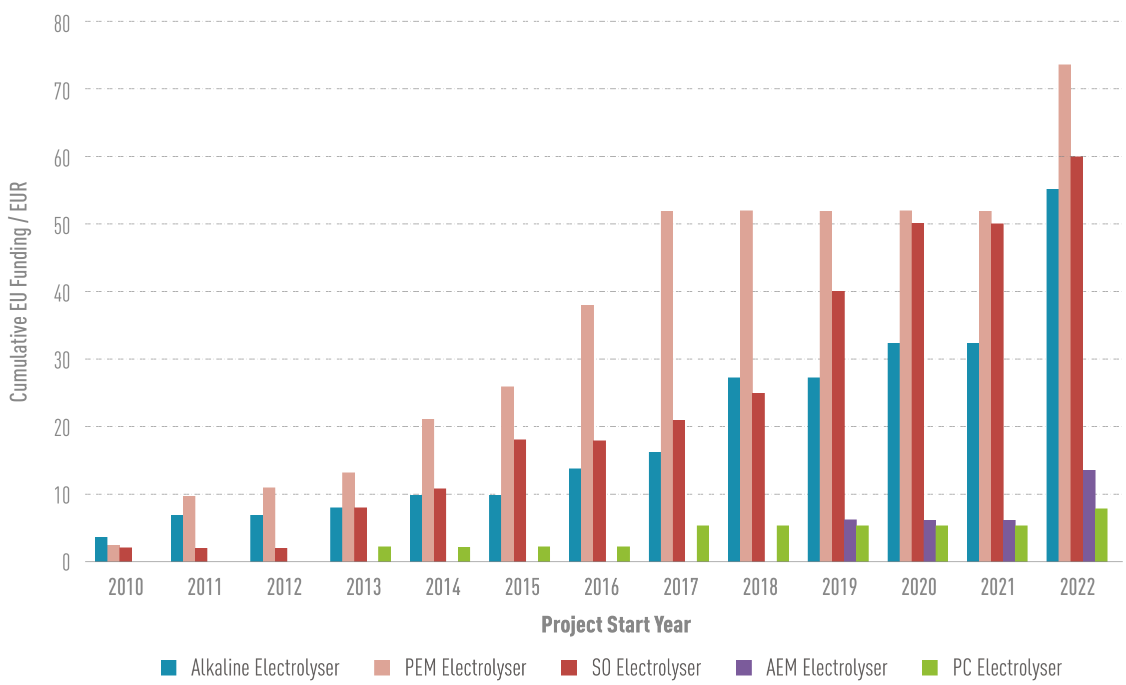
Figure 27: Funding for Pillar 1 projects (2008-2022)



Source: Clean Hydrogen JU

Figure 28 shows the cumulative contribution to projects working on various electrolyser technologies from 2010 onwards. PEM electrolysis has received the highest share of the funding, but support to SOEL development is increasing steadily and could reach similar levels in the future, should this trend continue.

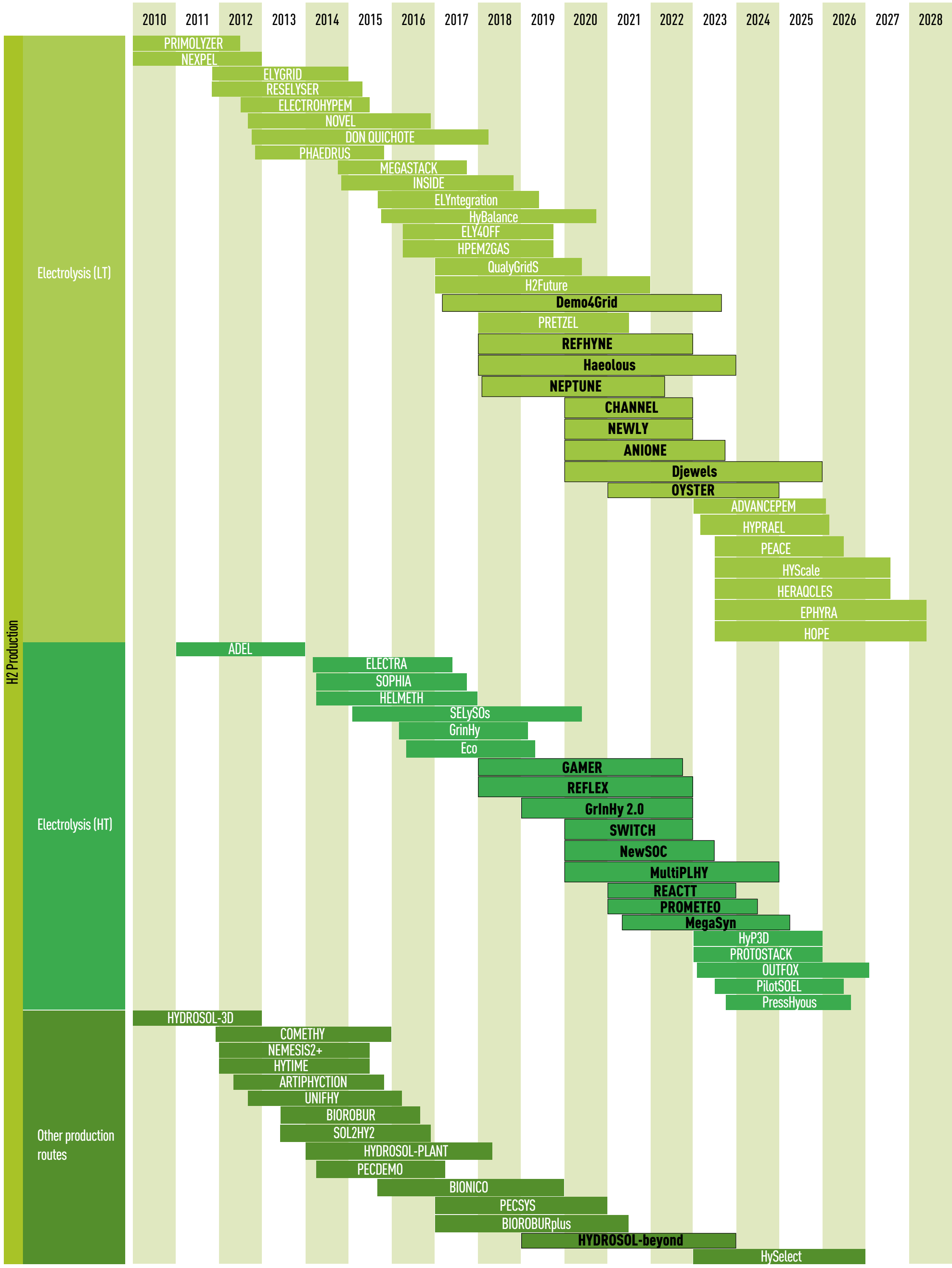
Figure 28: Cumulative level of EU Funding Contribution for projects



Source: Clean Hydrogen JU

Projects: The majority of projects in this Pillar are part of the Research Areas 1 and 2 and are devoted to the development and demonstration of low and high-temperature electrolysis (18 of 19 projects in this Pillar). The full list of all projects reviewed under 2022 annual review are highlighted in black font in Figure 29.

Figure 29: Project timelines of Pillar 1 - Hydrogen Production



Source: Clean Hydrogen JU
NB. Projects highlighted in black were considered for the 2023 Programme Review.

Figure 30 presents the connection between the partners present in the 22 projects reviewed within this Pillar. Apart from DJEWELS project (top left cluster) and Demo4Grid (bottom left cluster), participants in the rest projects seem to be connected[102]. The key participants in this panel (i.e. those present in the most projects) are dominated by research institutes (CEA, CERTH, SINTEF and DLR) along with the SOEL company, Sunfire, and the Ecole Polytechnique Federale de Lausanne. This is well displayed in the TIM plot below (Figure 30). France, Germany and Italy are once again the EU member states represented in the most projects relating to low temperature electrolysis. Of the non-EU states, Switzerland is present in the most low-temperature electrolyser projects (4).

Figure 30: TIM Plot showing the participants in the 22 projects reviewed

Participant	Number of Projects
CEA	7
ECOLE POLYTECHNIQUE FEDERALE DE LAUSANNE	4
STIFTELSEN SINTEF	4

Source: TIM, JRC – June 2023

LOW-TEMPERATURE ELECTROLYSIS

Alkaline Electrolysis (AEL) Projects

In general, the AEL projects must further enhance their progress against the steady state performance KPI outlined in the previous MAWP and the current SRIA. For the facilities already in operation, it is likely that not all relevant data is being submitted due to commercial sensitivity reasons.

The project **DEMO4GRID** is, as of March 2023, officially operating a 3.2 MW pressurised alkaline electrolyser at the MPREIS industrial bakery[103]. The project aims to show a viable business case for operating a large electrolyser adapted to specific local conditions, meeting the requirements for providing grid-balancing services and also providing heat up to 300 °C (through a dual fuel burner/boiler combination) for the industrial bakery. Furthermore, it will supply hydrogen for fuel cell trucks (not as part of the current project), through a multi-fuel refuelling station implemented by BREIS. The electrolyser has achieved a power consumption of 51 kWh/kg H2 and it produces 600 Nm^3 H2/h at 30 bar, and 99.8% of purity. The expected lifetime of the electrolyser is 10 years[104]. LCA assessment showed that the main environmental hotspots derive from the use of electricity in the electrolyser in operation stage. The project's testing phase is now underway.

The project **DJEWELS** plans to deploy a novel, high current density 20 MW AEL that can operate flexibly (3-100% of nominal power) at a low degradation rate (less than 1%/year). And the hydrogen would be used to

102 The size of the node (circle) represents the number of projects a partner is involved in; the thickness of the lines linking the nodes represents the number of projects two partners have in common.

103 It is building on the outcomes of the ELYGRID and ELYNTEGRATION projects.

104 DEMO4GRID deliverable D6.6 (public)

produce green methanol. The business plan also includes the delivery of balancing products to reduce costs. The electrolyser design foresees a system energy consumption of less than 52.9 kW/kgH2, which would be a significant contribution towards reaching the MAWP 2024 targets. The design of the plant has been completed and the project has already received an environmental and construction permit. In 2022, testing of the 1MW modules commenced. An investment decision still has to be made, which not only depends on the outcome of these tests and the regulatory environment that is expected to define the investment decision, but also as further clarifications are needed on whether renewable methanol will meet the RED II/III criteria. There is also uncertainty regarding Fit for 55, as well as the definition of Renewable Fuels of Non-Biological Origin (RNFBOs) and blending mandates. This means that the expected revenues are uncertain, putting the business case at risk. In 2023, DJEWELS held a workshop on the effect of the delegated act on PtX projects.

The project **OYSTER**, which began on January 1, 2021, aims to develop and demonstrate an electrolyser suitable for fully integrated deployment with an offshore wind turbine, based on a shoreside pilot project. Conditions are not usually met by other land-based electolysers, such as high salinity, periods with no electricity generation, accelerations and deformations (physical motion of the offshore platform) and transportation to the site of use. The targets of the project have been adjusted during this reporting period; the cost targets became more ambitious (from 28 to 20 €/(kg.yr) for OPEX and from 950 to 800 €/(kg/day) for CAPEX), while targets related to the system performance drastically decreased (current density changed from 3 to 0.2-0.4 A/cm2; target for footprint increased from 20 to 50 m2/MW).The project was forced to change from PEM to AEL technology following the departure of ITM Power and its replacement by the company Stiesdal that will develop and deploy a marinised 3MW AEL. Also, the project decided to change the dedicated location of the trial from Grimsby, United Kingdom to Zeeland, Netherlands. A shore side trial and data collection are expected to start in 2024.

Proton Exchange Membrane Electrolysis (PEMEL) Projects

PEM electrolysis projects are targeting different TRL and applications. As well as several large-scale demonstration projects, there are also efforts underway to develop the next generation of stacks. In the section, relating to Hydrogen Valleys (Pillar 6), more projects deploying multi-MW electrolysers are described.

The **REFHYNE** project is aiming to validate the business model for supplying electrolytic hydrogen to refineries[105]. Since the beginning of 2022 it is operating a 10 MW PEMEL from ITM to supply 4,000 kg of green hydrogen a day (at 20 bar pressure) to the Shell Rhineland Refinery in Wesseling, Germany. The business case is based on the provision of balancing services and production of hydrogen. The project will gather data on market conditions during its operation and has already contributed an assessment on policy implications. Additionally, the project performed a detailed design study for a 100MW electrolyser (REFHYNE 2).

The **HAEOLUS** project has deployed a 1t/day electrolyser in a difficult to access area of Norway, north of the polar circle. The official opening of the site took place on June 15, 2022. The project has met its own targets in terms of CAPEX and efficiency, with reported costs of 2.3 MEUR/t/d and 53.8 kWh/kg H2. Other targets have not been achieved (Cold and Warm Start; Degradation Rate). The electrolyser will be integrated with the Raggovidda wind farm which cannot be expanded due to grid constraints. The objectives of the project include demonstrating different strategies and algorithms for energy storage, isolated grid operation and fuel production in order to optimise the techno-economic performance of the system. Due to the remoteness of the site, the project will use a remote monitoring and control system to operate the plant without personnel on site. Apart from the potential off-takers for the hydrogen produced, steps have been made towards establishing a Hydrogen Valley in the region, and major investments are planned by Varanger Kraft. Future developments in the area depend on receiving support from the Norwegian government and plans include a project for 100 MW of electrolysers to produce ammonia for export and to enable the HAEOLUS plant to supply filling stations serving the Varanger area.

The **NEPTUNE**, considered as a game changer PEM electrolyser project, is a follow-up to HPEM2GAS, and ended in December 2022. The aim of the project was to increase hydrogen output pressure to 100 bar (based on pressure differentiation) and current densities to over 4 A/cm^2 for the nominal base load. The project included developments at cell, stack and system level, and aimed for a final system demonstration at 48 kW capacity.

105 Refineries need hydrogen for upgrading fuels and removal of sulphur components.

The project improved the understanding of the aging process and associated loss of performance of Aquivion membranes reinforced with expanded polytetrafluoroethylene (e-PTFE) fibres, compared to the extruded membrane used as reference. The novel MEAs were tested at varying temperatures and pressures. The extruded membranes showed performance slightly missing the target at 4 A.cm^{-2}, with a cell voltage reaching 1.86 V (with a target at 1.75 V). Overall, the project provided important insight related to the use and the scaling up of Aquivion membranes operating under high temperature and pressure conditions, although a proper assessment of the reinforced membranes at industrial scale needs to be performed.

Anion Exchange Membrane Electrolysis (AEMEL) Projects

In addition to the 2 main low temperature electrolyser technologies (alkaline and PEM electrolysis), recent years have seen the development of Anion Exchange Membrane electrolysers (AEMEL). AEMEL operate in alkaline media but use a solid electrolyte. In principle, this means they can combine the use of non-platinum group metal catalysts with the production of high-purity hydrogen due to the presence of the solid electrolyte. However, this technology is currently at a low TRL level and cannot achieve the performance and durability of other water electrolysis technologies as of now.

With this in mind, the Clean Hydrogen JU launched a call topic in 2019 (FCH-02-4-2019 "New Anion Exchange Membrane Electrolysers") aiming to provide the material and design breakthroughs necessary for this technology to fulfil its full technical potential. Projects should develop new components (membranes, ionomers and electrocatalysts) and produce at minimum a 1 kW stack with more than 5 cells and a performance of 2V @ 1 A/cm^2 Current Density. The projects should include an industrial partner capable of scale up and the projects should move the technology from TRL 2 to TRL 3. Three projects were approved and funded: CHANNEL, ANIONE and NEWELY.

The objective of the **CHANNEL** project is to develop a 2kW prototype low-cost electrolyser stack and associated Balance of Plant (BoP), using low-cost materials, non-PGM catalysts, state of the art anion exchange membranes and ionomers, along with low-cost transport layers, current collectors and bipolar plates. The project has developed active non-PGM hydrogen (HER) and oxygen (OER) evolution reaction catalysts for use in the 2 kW prototype. The single cell performance target of 1.85 V at 1 A/cm2 using non-PGM electro-catalyst has been achieved. The project also achieved its targets in terms of catalysts performance (reaching 237 mV over-potential at 1M KOH and 270 mV at 0.1 M KOH on OER catalyst; 60 mV in 1 M KOH and 120 mV in 0.1 M KOH on HER catalyst). However, the stability of both catalysts did not reach the targets. Some issues with dissolution of the novel OER catalysts have been experienced in long term (>1000 hour) tests. The 2-kW stack prototype built on this latest design has not been tested yet. The project hired two PhD students and 3 scientific articles are currently under review.

The objectives of the **ANIONE** project are similar. The project is developing non-CRM catalysts and novel membranes for application at TRL 4 for a validated 2 kW electrolyser. The project has successfully developed 2 membranes for AEM water electrolysis. The first is a perfluorinated Aquivion®-type backbone reinforced with reasonable mechanical properties, low crossover and conductivity in the range of 50 mS/cm, which achieved promising performance of 0.9 A/cm2 at 2.2 V at 90°C with voltage efficiency approaching 70 %. The second is a highly conductive and chemically stable hydrocarbon ionomer/membrane with conductivity values above 100 mS/cm (higher than benchmarked AEM membrane at 50 mS/cm). Large-area membranes (with an active area >100 cm^2)[106] were successfully produced. The project also developed high performance, electrochemically stable NiFe oxide, oxygen evolution electrocatalysts. Subsequently, it has been able to prepare enhanced catalyst coated membrane electrode assemblies[107]. This has demonstrated a performance of 1.8 V at 1 A.cm^{-2} and 50°C, plus stable performance during 2000 hrs steady state and 1000 hrs cycled (2 V at 1 A.cm^{-2}) operations[108]. The project successfully integrated the large-area membranes and delivered 25 large-area MEAs (>100 cm^2)[109]. The design and engineering of the balance of plant of the AEM stack test system is completed and a full 2-kW stack

106 ANIONE – Publishable Summary
107 ANIONE – Publishable Summary
108 ANIONE – Publishable Summary
109 ANIONE – Publishable Summary

prototype based on the developed membrane-electrode assembly will be tested in M42-M45[110]. The project is now ready to conduct performance tests at a larger scale and prepare for the integration of the MEAs in an AEM stack test system.

The third project in this grouping is **NEWELY** that also has similar goals. The project successfully developed PSEBS membrane with characteristics successfully reaching the project's targets (energy consumption at 53.6 kWh/kg @ 3.6 W/cm^2 corresponding to 2 V @1.8 A/cm2, membrane conductivity at 62 mS/cm and area specific resistance at 0.065 Ω.cm^2) in 0.1M KOH at 25°C, lower than other AEM projects operating at 1 M KOH. The project has also completed several publications and submitted 2 patent applications. The project will conduct a 2000-hour cross-comparison test to validate the components developed for NEWELY in comparison to commercially available CENmat components. It is important that it achieves the final milestone of scaling up to the 2 kW stack test, in particular because this project intends to utilise its own novel hydraulic high-pressure stack design. In addition, NEWELY successfully provided a techno-economic assessment and a life cycle assessment of the developed membrane electrolyser assembly. An update including the latest data retrieved from the tests is expected in 2023.

In general, the projects have managed to achieve the majority of their goals at the component level, with promising data on novel membranes, electrocatalysts and combined as Membrane Electrode Assemblies. These low TRL projects need to demonstrate whether the materials developed can show enhanced performance and durability when functioning in the short-stack format. The future challenges for these low TRL projects lie in their capacity to scale up manufacturing while maintaining performance obtained at lab-scale, and to develop a clear exploitation programme for their novel systems.

HIGH-TEMPERATURE ELECTROLYSIS PROJECTS

This Research Area covers the Solid Oxide Electrolyser projects SWITCH, NEWSOC, GRINHY2.0, MULTIPLHY, REFLEX, MEGASYN, PROMETEO and REACTT as well as the single Proton Conducting Electrolyser project, GAMER.

Solid Oxide Electrolyser Projects (SOEL)

The increase in capacity to the MW scale is a very promising development, which helps to further establish SOEL as a competitor for the large-scale production of green hydrogen. Moreover, there are projects working on a more fundamental level, improving components to improve durability of SOEL, which seems to be one of the key remaining challenges. Finally, the reversibility of SOEL technology is technically interesting.

GrInHy2.0: The project demonstrated the world's biggest HT electrolyser at a capacity of 720 kW, with a nominal hydrogen production rate of 200 Nm³/h. By project end, the system had operated for more than 14,000 hours, injecting more than 100 tons of hydrogen into the grid – reaching 2 more project goals. Also, the availability of the HTE was increased to 94 % in its second year of operation. Analysis of CO_2 avoidance potential of hydrogen for the entire European iron and steel industry by Salzgitter, showed that with shifting from coal-based BF-BOF to gas-based DR-EAF along with hydrogen as reducing gas, CO2 emissions can be reduced by more than 90% (approx. 150 Mio. t CO2/year avoided). However, CAPEX requirements are high, and operation is only sustainable and economically viable where cheap green energy is available.

The **SWITCH** project is developing a reversible system (rSOC), able to operate in SOEC and SOFC mode, with a capacity of 25 kW (SOFC) / 75 kW (SOEC). The system can produce green hydrogen when renewable energy is available, but also operate in a reverse fuel cell (SOFC) mode. In SOFC mode, other feedstock sources such as methane and bio-methane can be used. The prototype system consists of 1 rSOC-unit developed in the SWITCH project and 2 SOFC-units developed in the CH2P project. The SOEC mode has already been tested at single stack level and the target capacities have been achieved. SWITCH achieved a conversion efficiency of 80%, in parity with the GrinHy and GrinHy 2.0 projects being SoA as of 2021, while the project's own target was 85%. In addition, it had a SOEC mode to SOFC mode switchover time of 15 minutes, which is half the target value. In addition, a

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transient model was developed and validated for a 1000 h durability test with daily switches between SOFC and SOE mode.

The **NewSOC** project, which started in January 2020, aims to produce high performing and stable solid oxide cell (SOC) electrodes, which are to be validated as part of large cells with > 50 cm2 active area and short stacks. The project has identified an optimum cell configuration, offering low ASR and high mechanical strength. The highest Current Density has been obtained for the case of 10Sc1CeSZ based cells, ranging from 0.75 to 1.2 A·cm-2 (at 1.5 V, 850°C), with ASR values of 0.4-0.6 Ω·cm2 and 0.45-0.7 Ω·cm2 for steam and co-electrolysis respectively. NewSOC succeeded in improving the SoA of Ni/YSZ fuel electrodes aided by modelling. Work included integration of an improved deposition of barrier layer between the oxygen electrode and electrolyte to reach a 25% increase of the applicable electrolysis current at degradation rates of 0.3-0.5 %/kh @ 1.2 A/cm2 (vs 1.2 %/kh FCH 2 JU MAWP 2024 target) and a 25% ASR reduction. Robust and high performing electrodes, namely titanate doped Ni/GDC and LCr fuel electrodes and CO-free oxygen electrodes for intermediate temperature operation (650-700°C), were developed and tested with promising results comparable or superior to SoA. Further achievements relate to interconnect coating improvement, development of deposition methodology, and 3D printing of a large cell for planned integration into commercial cells.

MULTIPLHY: The project builds on the outcomes of the GRINHY and GRINHY2.0 projects, aiming to install and operate a 2.4 MW high-temperature electrolyser system able to produce 60kg H2/h at a biofuels refinery in Rotterdam to produce hydrogen for the refinery processes. The installation in Rotterdam is ongoing, with commissioning scheduled for 2023. The hydrogen processing unit has been manufactured and installed. The project has also contributed, together with DJEWELS, to the analysis of the implications of the REDII, issuing a position paper to the Dutch government. Regarding the issuance of hydrogen guarantees of origin (GOs) through the CertifHy platform, the project is working on developing a methodology for the renewable origin and GHG footprint of the steam supply to SOEC. If successful, it will advance SOEC based high-temperature electrolyser from TRL 7 to 8.

REFLEX: Following a similar concept to the SWITCH project, this project is also targeting reversible Solid Oxide Cell technology, and focuses on improving rSOC components (cells, stacks, power electronics, heat exchangers). The efficiency targets for the system are > 80% HHV in SOEC mode, and > 55% LHV in SOFC mode with CH4 fuel supply.

MEGASYN: This project had planned to install a novel co-electrolyser system in a refinery by OMV but is currently suspended as the consortium is reconsidering the project's business plan. The 1MW plant was to produce syngas, which could then be used for e-fuels or other products. The project has designed and built a new reformer reactor and several experiments were performed with varying parameters such as operating temperature and gas composition, in order to determine the best operating conditions. It was found that temperatures higher than 700°C were advantageous.

PROMETEO: This project has a novel approach to combining heat from Concentrating Solar Power (CSP) systems with Thermal Energy Storage (TES) to supply solar heat to a SOEL. Solar heat will be collected and stored in thermal oil or Molten Salt mixtures to balance out the fluctuation of renewable heat sources. A fully integrated and optimised system will be developed, to increase electrical efficiency higher than 85% LHV. A modular 25 kWe SOEL prototype will be designed, built, and connected to representative external power/heat sources and validated through tests for 1,000 hours. The project will focus on part load operation and hot standby periods. Techno-economic and LCA studies will be performed. PROMETEO defined end users' cases, created preliminary process flow diagrams, identified and validated TES system and developed process modelling tools. Due to infrastructure restrictions at EPFL, the 25 kWel stack tower manufactured will also be tested by SolydEra (formerly SolidPower).

REACTT: This project is developing a Monitoring, Diagnostic, Prognostic and Control Tool (MDPC) for SOEL and rSOC stacks and systems[111]. The control unit will be used to ensure optimal operation of the system, thereby

111 Electrolyser operating modes with high current and transients could cause degradation. In order to mitigate eventual performances, a monitoring tool containing an excitation module to probe the stack with a PRBS (pseudo-random binary signal) and a control coordination unit.

increasing reliability and extending stack lifetime. The project aims to test the tool on an SOEL system and on an rSOC system. The development of the hardware platform and embedded diagnostics and prognostics algorithms is currently under way. According to their published paper[112], the project developed a dynamic physically based model to reveal the relationships between SoC response and electrode reactions. A good agreement between experimental and simulated data was found.

Proton Conducting Ceramic Electrolyser Projects (PCCEL) Project

The project **GAMER** has advanced tubular PCCEL technology. The objective was to design a 10 kW electrolysis system, demonstrating an electrical efficiency higher than 75% Higher Heating Value (HHV), to be operated in a methanol plant with efficient thermal integration, producing pure dry pressurised hydrogen at 30 bars. The project achieved a Faradaic efficiency of the Single Engineering Unit[113] (SEU) of 95%, both at 3 bar and 10 bar, beyond the target set of > 85%[114] (at 3 bar at 0.1 mA/cm2 at 600 °C). A containerised pilot plant rated for 10 kW and 30 bar operation has been designed and commissioned. A second rack with 16 SEU was tested at 3 different temperatures (600-575-550 °C, 1 bar). GAMER has also developed a tool for assessing energy efficiency and dimensioning of components, which has been selected as a key innovation by the European Commission Innovation Radar. The project is considered successful, despite the technical challenges met during scaling up. It is positive that the containerised pilot plant will be used by the follow up PROTOSTACK project (started January 2023). The WINNER project on PCCEL (started 01/01/2018) is described in Pillar 2. Increasing the current density is a key development need to reach the economic objectives of the SRIA (for SOE, as PCCEL does not have KPIs). The WINNER project is addressing this issue.

A new project, SUSTAINCELL (January 2023), will focus on sustainable value chains and also cover PCCEL technology. Funded through national sources, low TRL research activities on PCCEL will be conducted in the new Centre for Excellence in Norway “FME HYDROGEN” (started July 2022).

OTHER ROUTES OF RENEWABLE H_2 PRODUCTION

Apart from electrolysis, any other technologies are of very low TRL and only a couple of existing or recently ended projects are exploring the possibilities to progress. Many technical challenges are still pending regarding the durability and stability of the materials operating at a temperature of over 1,000ºC of the reactor in thermo-chemical hydrogen production.

Thermo-chemical hydrogen production

The **HYDROSOL-BEYOND** project aims to demonstrate solar thermochemical hydrogen production with a solar-to-hydrogen efficiency > 5%, using the existing 750kWth platform in Almeria. Tests will be carried out in 2023, following the experimental campaign carried out with Synlight at the high flux solar simulator in Juelich. There, a qualification of the solar cavity reactor was carried out. The reactor was integrated with heat exchangers to recover heat from the product gases. Testing was performed according to the so called swing strategy, with temperatures of 1400°C for the reduction cycle, and 1100°C for the oxidation step. Higher temperatures lead to higher hydrogen yield, but the harsh conditions are a major challenge regarding materials and component degradation. This is an issue that had been encountered already by predecessor projects like HYDROSOL-PLANT. Maximum hydrogen yield per cycle was 8.8 gr, which is a good achievement but still far less than the 13.9 gr theoretical maximum[21]. The project attributes the lower output to the non homogeneous temperature distribution inside the receiver. The reactor did not reach 1400 °C everywhere due to the temperature drop from absorber frontside to backside[21]. It is not clear how the results of the project will be utilised in the future. Call 2023 contained a topic on Photo(electro)chemical (PEC) and/or Photocatalytic (PC) production of hydrogen.

112 doi 10.1149/10301.0893ecst

113 The SEU is a tubular cell constituting the smallest electrolysis unit.

114 AWP 2017 efficiency target above 75% based on higher heating value.

ANIONE

ANION EXCHANGE MEMBRANE ELECTROLYSIS FOR RENEWABLE HYDROGEN PRODUCTION ON A WIDE-SCALE

Project ID:	875024
PRD 2023:	Panel 1 – H2 production
Call topic:	FCH-02-4-2019: New anion exchange membrane electrolysers
Project total costs:	EUR 1 999 995
Clean H_2 JU max. contribution:	EUR 1 999 995
Project period:	1.1.2020–31.12.2022
Coordinator:	Consiglio Nazionale delle Ricerche, Italy
Beneficiaries:	Hydrolite Ltd, Université de Montpellier, TFP Hydrogen Products Ltd, Hydrogenics Europe NV, IRD Fuel Cells A/S, Uniresearch BV, Centre national de la recherche scientifique

https://anione.eu/

PROJECT AND OBJECTIVES

ANIONE aims to develop a high-performance, cost-effective and durable anion-exchange membrane (AEM) water electrolysis technology. The approach taken involves using an AEM and ionomer dispersion in the catalytic layers for hydroxide ion conduction. The project aims to validate a 2 kW AEM electrolyser with a hydrogen production rate of about 0.4 Nm^3/h (technology readiness level (TRL) 4). Advanced AEMs have been developed in conjunction with non-critical raw material non-CRM high-surface-area electrocatalysts and membrane electrode assemblies. These advanced AEMs have shown promising performance and stability.

NON-QUANTITATIVE OBJECTIVES

- **Enhanced oxygen evolution catalyst.** ANIONE aims to develop an advanced non-CRM Ni- and Fe-based catalyst for the oxygen evolution reaction, providing reduced overpotential and enhanced stability.
- **Enhanced hydrogen evolution catalyst.** ANIONE aims to develop an advanced non-CRM Ni-based catalyst for the hydrogen evolution reaction, providing reduced overpotential and enhanced stability.
- **Advanced cost-effective membrane.** ANIONE aims to develop cost-effective advanced AEMs with proper hydroxide ion conductivity and stability.
- **Process implementation.** ANIONE aims to develop an AEM electrolysis operating mode providing enhanced stability.
- **AEM electrolysis hardware components.** ANIONE aims to implement advanced AEM electrolysis components in terms of diffusion layers and current collectors.

PROGRESS AND MAIN ACHIEVEMENTS

- A highly conductive and chemically stable hydrocarbon ionomer/membrane for AEM water electrolysis.
- ANIONE has produced reinforced and composite AEM hydrocarbon membranes for water electrolysis showing the capability to operate at higher temperatures.
- It has also produced a high-performing and electrochemically stable NiFe oxide, oxygen evolution, anode electrocatalyst for AEM water electrolysis.
- Enhanced catalyst-coated electrode-based membrane electrode assemblies for AEM water electrolysis.
- It has also produced large-area membrane–electrode assemblies based on non-CRMs performing similarly to small-area membrane electrode assemblies.

FUTURE STEPS AND PLANS

- Large area stack assembling and testing will be carried out.
- There will be full validation of functional materials at the stack level.

QUANTITATIVE TARGETS AND STATUS

Target source	Parameter	Unit	Target	Achieved to date by the project	Target achieved?	SoA result achieved to date (by others)	Year of SoA target
Project's own objectives and AWP 2019	Cell voltage at 1 A/cm^2 (cell performance at 45 °C)	V	2	1.75	⚙	1.67	2020
	Degradation rate: voltage increase at 1 A/cm^2	mV/h	< 0.005	< 0.005	✓	2	
	Membrane conductivity	mS/cm	50	105	✓	80	2022
	Maximum operating temperature	°C	90	90	✓	60	
	Series resistance	$ohm.cm^2$	< 0.07	0.06	✓	0.1	

Clean Hydrogen Partnership

Co-funded by the European Union

CHANNEL

DEVELOPMENT OF THE MOST COST-EFFICIENT HYDROGEN PRODUCTION UNIT BASED ON ANION EXCHANGE MEMBRANE ELECTROLYSIS

Project ID:	875088
PRD 2023:	Panel 1 – H2 production
Call topic:	FCH-02-4-2019: New anion exchange membrane electrolysers
Project total costs:	EUR 1 999 906.25
Clean H_2 JU max. contribution:	EUR 1 999 906.25
Project period:	1.1.2020–30.6.2023
Coordinator:	SINTEF AS, Norway
Beneficiaries:	Enapter SRL, Evonik Creavis GmbH, Shell Global Solutions International BV, Evonik Operations GmbH, Norwegian University of Science and Technology

https://www.sintef.no/projectweb/channel-fch/

PROJECT AND OBJECTIVES

CHANNEL aims to build a cost-efficient 2 kW anion-exchange membrane (AEM) water electrolyser able to operate at differential pressure and under dynamic operation, optimal for producing high-quality, low-cost green hydrogen from renewable energy sources. CHANNEL will conduct a techno-economic analysis and determine detailed future size and cost targets for AEM electrolysers. It will identify markets and their requirements, establishing the production quantities essential to meet market needs, accounting for the expected cost decrease.

NON-QUANTITATIVE OBJECTIVES

- The project aims to contribute to science and technology through the submission of journal articles for publication and through conference contributions.
- The CHANNEL promotional video was released in early 2021.
- Two students from the University of St Andrews were trained and have been working on the project.
- CHANNEL aims to contribute to the AEM test protocol harmonisation workshop alongside NEWELY and ANIONE.
- The transient AEM model code is to be released on a public platform (GitHub).
- Education: two PhD students (Forschungszentrum Jülich) and one postdoctoral researcher (Norwegian University of Science and Technology) were hired as part of the project.

PROGRESS AND MAIN ACHIEVEMENTS

- Highly active and durable hydrogen and oxygen evolution reaction electrocatalysts were developed and production was scaled up.
- The single-cell electrolyser performance target of 1.85 V at 1 A/cm^2 using a non-PGM electrocatalyst was achieved.
- High-performance AEMs were developed.
- Stack design has been finalised and the deliverable was due to be submitted by the end of March 2023.

FUTURE STEPS AND PLANS

- A journal article based on the modelling of the transient pseudo-two-dimensional (P2D) AEM model and simulation of electrode catalyst loading and composition as a function of KOH concentration, temperature and cell current density is in the process of being published, offering additional insight into the drivers of AEM cell performance and assisting optimisation activities.
- The model will be shared through an open-source modelling system to allow others in the research community to utilise it to make informed decisions on how best to optimise AEM electrolyser technologies.
- A demonstration of the preliminary AEM stack prototype will take place, as will the assembly of the preliminary stack and validation. This is in addition to finalising the stack design.

QUANTITATIVE TARGETS AND STATUS

Target source	Parameter	Unit	Target	Achieved to date by the project	Target achieved?	SoA result achieved to date (by others)	Year of reported SoA result
Project's own objectives	OER catalyst performance	mV	< 300 (at 10 mA/cm^2 1 M KOH)	237 (1 M KOH) 270 (0.1 M KOH)	✓	250 at 10 mA/cm^2 (Ir-based catalyst)	2023
	HER catalyst performance	mV	< 150 (at – 0.2 V versus RHE)	60 in 1 M KOH 120 in 0.1 M KOH	✓	30 at – 10 mA/cm^2 (Pt-based catalyst) in 1 M KOH	2023
	OER catalyst stability	mV	< 25 degradation over 1 000 hours in RDE	33	⚙	N/A	N/A
	HER catalyst stability	mV	< 25 degradation over 1 000 hours in RDE	26	⚙		
	Single-cell performance (at 1 A/cm^2)	V	1.85	1.85	✓	1.85	2023
AWP 2019	Membrane OH^- conductivity (T = RT)	mS/cm	50	< 50	⚙	Approximately 120 (50-micron membrane from Sustainion) 40–45 FAA-3 (Fumatech)	2023
	Ionomer OH conductivity (60 °C)	mS/cm	Not specified	> 60	✓	N/A	N/A

Demo4Grid

DEMONSTRATION OF 4 MW PRESSURIZED ALKALINE ELECTROLYSER FOR GRID BALANCING SERVICES

Project ID:	736351
PRD 2023:	Panel 1 – H2 production
Call topic:	FCH-02-7-2016: Demonstration of large-scale rapid response electrolysis to provide grid balancing services and to supply hydrogen markets
Project total costs:	EUR 7 736 682.5
Clean H_2 JU max. contribution:	EUR 2 932 554.38
Project period:	1.3.2017–31.8.2023
Coordinator:	Diadikasia Business Consulting Symvouloi Epicheiriseon AE, Greece
Beneficiaries:	FEN Sustain Systems GmbH, MPREIS Warenvertriebs GmbH, Instrumentación y Componentes SA, Fundación para el Desarrollo de las Nuevas Tecnologías del Hidrógeno en Aragón, IHT Industrie Haute Technologie SA

http://www.demo4grid.eu/

PROJECT AND OBJECTIVES

The main aim of this project is the commercial set-up and demonstration of a technical solution utilising above-state-of-the-art pressurised alkaline electrolyser technology to provide grid-balancing services in real operational and market conditions. The ultimate goal is to provide grid-balancing services to the transmission system operator (primary and secondary balancing services). The electrolysis plant will be installed in Völs near Innsbruck.

PROGRESS AND MAIN ACHIEVEMENTS

The pressurised alkaline electrolyser has been installed. It has been producing hydrogen since 22 March 2022.

QUANTITATIVE TARGETS AND STATUS

Target source	Parameter	Unit	Target	Achieved to date by the project	Target achieved?	SoA result achieved to date (by others)	Year of SoA target
Project's own objectives	H_2 production electrolysis, hot start from min. to max. power	seconds	2		⚙	60	2015
	Start-up time KPIs from cold to minimum part-load for alkaline electrolysers	minutes	20	4–6 hours depending on thermal conditions		30	
	Minimum part-load operation targets for alkaline electrolysers	% (full load)	20			30	
	Ramp up	% (full load)/s	7	3		7	N/A
	Ramp down	% (full load)/s	10	2		10	

Djewels

DELFZIJL JOINT DEVELOPMENT OF GREEN WATER ELECTROLYSIS AT LARGE SCALE

Project ID:	826089
PRD 2023:	Panel 1 – H2 production
Call topic:	FCH-02-1-2018: Demonstration of a large-scale (min. 20 MW) electrolyser for converting renewable energy to hydrogen
Project total costs:	EUR 41 967 250
Clean H_2 JU max. contribution:	EUR 10 999 999
Project period:	1.1.2020–31.12.2025
Coordinator:	Nobian Industrial Chemicals BV, Netherlands
Beneficiaries:	McPhy Energy Italia SRL, BioMethanol Chemie Nederland BV, McPhy Energy Deutschland GmbH, Industrie De Nora SpA-IDN, Hinicio SA, McPhy Energy, NV Nederlandse Gasunie

https://djewels.eu

PROJECT AND OBJECTIVES

Djewels demonstrates the operational readiness of the 20 MW electrolyser for the production of green fuels (green methanol) in real-life industrial and commercial conditions. It will bring the technology from technology readiness level 7 to 8 and lay the foundation for the next scale-up step: a 100 MW electrolyser at 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 for the mass production of the stack and scale-up of the balance-of-plant components.

NON-QUANTITATIVE OBJECTIVES

Safety performance. The design has been finalised and the hazard and operability analysis has been completed.

PROGRESS AND MAIN ACHIEVEMENTS

- The Djewels 1 design was finalised.
- An irrevocable permit was issued.
- Testing of the 1 MW stack has started.

FUTURE STEPS AND PLANS

- Stack testing and optimisation will be completed.
- The investment decision is expected to be made in Q2 2023.
- Ground breaking is expected to take place in Q3 2023.
- Construction is expected to be completed in 2025.

QUANTITATIVE TARGETS AND STATUS

Target source	Parameter	Unit	Target	Target achieved?
Project's own objectives	System nominal capacity	MW	25	
MAWP addendum (2018–2020)	Energy consumption	kWh/kg	< 52.8	
	Degradation	%/year	0.72	
	Flexibility with degradation below 2 %/year	% of nominal power	3–110	

Clean Hydrogen Partnership

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GAMER

GAME CHANGER IN HIGH TEMPERATURE STEAM ELECTROLYSERS WITH NOVEL TUBULAR CELLS AND STACKS GEOMETRY FOR PRESSURIZED HYDROGEN PRODUCTION

Project ID:	779486
PRD 2023:	Panel 1 – H2 production
Call topic:	FCH-02-2-2017: Game changer high temperature steam electrolysers
Project total costs:	EUR 2 998 951.25
Clean H_2 JU max. contribution:	EUR 2 998 951.25
Project period:	1.1.2018–30.9.2022
Coordinator:	SINTEF AS, Norway
Beneficiaries:	MC2 Ingenieria y Sistemas SL, CRI EHF, CoorsTek Membrane Sciences AS, Shell Global Solutions International BV, Universitetet i Oslo, Stiftelsen SINTEF, Agencia Estatal Consejo Superior de Investigaciones Cientificas

https://www.sintef.no/projectweb/gamer/

PROJECT AND OBJECTIVES

GAMER is developing a novel cost-effective tubular proton ceramic electrolyser (PCE). The project focuses on a novel 'tube-in-shell' single engineering unit (SEU) design in which each tubular cell is placed in a steel shell, which has all necessary gas inlet/outlet connections. The steel shell also acts as a pressure containment vessel. The SEU stack technology is operational at 600 °C in pressurised operation. The main objectives of the project are to:

- design an innovative electrolysis system integrated in a renewable methanol plant with efficient thermal coupling of heat source (waste heat or heat from a renewable geothermal source);
- develop a high-volume cost-effective tubular SEU technology;
- assemble the novel SEUs and necessary balance-of-plant (BoP) equipment in a 10 kW prototype for pressurised operation;
- carry out techno-economic evaluation and life cycle analysis (LCA) of the integrated technology.

NON-QUANTITATIVE OBJECTIVES

The project has developed a novel design for a PCE stack in the form of tube-in-shell SEU operational at 600 °C and operated at up to 10 bar total pressure for more than 1 000 hours. It has also designed a 10 kW system, including assemblies of SEUs integrated in racks in a hot box, with BoP and power electronics developed for pressurised operation, delivering hydrogen with an output pressure of at least 30 bar. The containerised plant has been built and commissioned by Agencia Estatal Consejo Superior de Investigaciones Científicas. It has also been used to test two racks (each containing 16 SEUs) at a pressure of up to 7 bar. Due to some technical limitations and the project coming to an end, no more testing could be carried out. The plant will be exploited after project completion as part of the follow-up PROTOSTACK project, a new Clean Hydrogen JU project. The targeted production volume of the SEUs by CTMS was successfully achieved in the project, with reproducible results achieved when comparing the performance of the individual functional layers on both short segments (4–5 cm^2) and upscaled tubular cells (60 cm^2). The project demonstrates that PCE performance is improved by increasing the operational pressure from ambient pressure to at least 10 bar (in terms of both increasing the faradaic efficiency and reducing the cells' area-specific resistance).

PROGRESS AND MAIN ACHIEVEMENTS

Sixteen SEUs were tested in pressurised operation up to 10 bar at 600 °C. Good reproducibility was achieved after optimisation of the manufacturing process and steam electrode architectures. The stability of an SEU operating at 600 °C for more than 500 hours at 10 bar was successfully demonstrated in the project, while operated at a constant current density of 0.3 A/cm^2 (steam utilisation of 60 %).

The second rack of 16 SEUs was tested at atmospheric pressure at three different temperatures (600 °C, 575 °C, 550 °C). At 600 °C and atmospheric pressure, H_2 production of 0.47 Nl/min and a faradaic efficiency of 61 % were reached by applying a current of 100 A.

Techno-economic analysis and LCA have been conducted on this technology, integrated in various user cases (ammonia plant, refineries, geothermal plant). The results of this work show that a projected upscaled technology can reach a system cost below 8.8 M€/(t/d). Furthermore, a roadmap for further cost reduction below 2.7 M€/(t/d) post 2020, which relies on both the reduction of system cost and improved cell performance, has been set out.

FUTURE STEPS AND PLANS

- The finalisation of rack assembly and quality assurance is in progress.
- Integration of racks in the 10 kW testing unit and commissioning will take place. Testing will start with one rack, with the progressive integration of the other.
- The testing plant will be used in a new project named PROTOSTACK, funded by the Clean Hydrogen Joint Undertaking.

QUANTITATIVE TARGETS AND STATUS

Target source	Parameter	Unit	Target	Achieved to date by the project	Target achieved?	SoA result achieved to date (by others)	Year of SoA target
Project's own objectives	ASR of cell at 600 °C at 3 bar in electrolysis mode	ohm.cm^2	2	2.5	⚙	< 2	2022
	Faradaic efficiency of the SEU at 3 bar at 0.1 mA/cm^2 at 600 °C	%	> 85	95	✓	> 85	2020
	Degradation rate max. decrease of the voltage after 500 hours at 600 °C at 100 mA/cm^2	%/kh	1.2	< 5	⚙	N/A	2021
	System cost	M€	8.8	4.2–8.9	✓	N/A	N/A
	Hydrogen cost	€/kg	2.7	4.2–7.4	⚙	N/A	N/A

GrInHy2.0

GREEN INDUSTRIAL HYDROGEN VIA STEAM ELECTROLYSIS

Project ID:	826350
PRD 2023:	Panel 1 – H2 production
Call topic:	FCH-02-2-2018: Demonstration of large-scale steam electrolyser system in industrial market
Project total costs:	EUR 5 882 492.50
Clean H_2 JU max. contribution:	EUR 3 999 993.25
Project period:	1.1.2019–31.12.2022
Coordinator:	Salzgitter Mannesmann Forschung GmbH, Germany
Beneficiaries:	Paul Wurth SA, Sunfire GmbH, Salzgitter Flachstahl GmbH, Tenova SpA, Commissariat à l'énergie atomique et aux énergies alternatives

https://salcos.salzgitter-ag.com/de/grinhy-20.html

PROJECT AND OBJECTIVES

GrInHy2.0 is about implementing the world's biggest high-temperature electrolyser, with a capacity of 720 kW alternating current and electrical efficiency of 84 % lower heating value. During the assessment of the technology's carbon direct avoidance potential for the future European steel industry, the electrolyser will produce more than 100 t of green hydrogen based on steam from industrial waste heat produced over > 13 000 operational hours from steel production in Salzgitter.

PROGRESS AND MAIN ACHIEVEMENTS

- Electrolyser scale-up to 720 kWel and 200 Nm^3H_2/h was successful.
- The electrical efficiency target of 84 % lower heating value was reached.
- By the end of 2022, the system had been operating for more than 14 000 hours.
- Stack degradation at 15 mΩcm².kh-1 is below what was expected.
- Production of more than 100 t of climate-neutral hydrogen was achieved.
- Electrolyser investment costs were reduced to below 4 500 €/(kgH_2/d).

FUTURE STEPS AND PLANS

The project was successfully concluded, and no further steps are planned.

QUANTITATIVE TARGETS AND STATUS

Target source	Parameter	Unit	Target	Achieved to date by the project	Target achieved?	SoA result achieved to date (by others)	Year of SoA target
AWP 2018	Total production of green hydrogen	t	100	102	✓	N/A	2017
	Demonstration of hot start from min. to max. power	minutes	5	15	⚙	10	2018
	Hours of operation	hours	13 000	14 000	✓	10 000	2019
	Availability	%	95	85	⚙	66	
Project's own objectives	Hours of continuous stack testing	hours	20 000	10 000	⚙	8 700	2019

Haeolus

HYDROGEN-AEOLIC ENERGY WITH OPTIMISED ELECTROLYSERS UPSTREAM OF SUBSTATION

Project ID:	779469
PRD 2023:	Panel 1 – H2 production
Call topic:	FCH-02-4-2017: Highly flexible electrolysers balancing the energy output inside the fence of a wind park
Project total costs:	EUR 8 740 110.00
Clean H_2 JU max. contribution:	EUR 4 997 738.63
Project period:	1.1.2018–31.12.2023
Coordinator:	SINTEF AS, Norway
Beneficiaries:	Communauté d'universités et d'établissements université Bourgogne–Franche–Comté, École Nationale Superieure de Mécanique et des Microtechniques, Fundacion Tecnalia Research and Innovation, Hydrogenics Europe NV, Knowledge Environment Security SRL, Universita Degli Studi del Sannio, Université de Franche-Comté, Université de technologie de Belfort-Montbéliard, Varanger Kraft AS, Varanger KraftEnterprenor AS, Varanger KraftHydrogen AS, Varanger KraftMarked AS, Varanger KraftNett AS, Varanger KraftVind AS, Varanger KraftUtvikling AS

http://www.haeolus.eu/

PROJECT AND OBJECTIVES

The project has deployed a 1 t/day electrolyser, together with a storage tank and fuel cells for re-electrification, in connection with a wind farm in the remote village of Berlevåg in Norway. The objective is to test the operation of the electrolyser in different scenarios to demonstrate algorithms for energy storage, isolated grid operation and fuel production. After significant delays due to the COVID-19 pandemic, the project received a 2-year extension and is now following a new schedule.

NON-QUANTITATIVE OBJECTIVES

The objective is to promote the 'hydrogen valley' in Finnmark. Local authorities and business stakeholders are very interested in the project. Varanger Kraft has decided to proceed with building a distribution station, and local actors are involved in multiple multimillion-euro research and innovation proposals for further development.

PROGRESS AND MAIN ACHIEVEMENTS

- Varanger Kraft made its investment decision (EUR 4 million investment).
- Fuel cells were refurbished and redeployed.
- A cloud control system was deployed and open-sourced.
- Demonstration is ongoing.

FUTURE STEPS AND PLANS

Demonstration is to be completed and results are to be analysed.

QUANTITATIVE TARGETS AND STATUS

Target source	Parameter	Unit	Target	Achieved to date by the project	Target achieved?
Project's own objectives	CAPEX	M€/(t/d)	3	2.3	✓
MAWP addendum (2018–2020) and AWP 2017	Efficiency	kWh/kg	52	53.8	✓
	Degradation	%/year	1.5	2	⚙
	Cold start	minutes	0.5	20	⚙
	Hot start	seconds	2	30	⚙

HYDROSOL-beyond

THERMOCHEMICAL HYDROGEN PRODUCTION IN A SOLAR STRUCTURED REACTOR: FACING THE CHALLENGES AND BEYOND

Project ID:	826379
PRD 2023:	Panel 1 – H2 production
Call topic:	FCH-02-4-2018: Thermochemical hydrogen production from concentrated sunlight
Project total costs:	EUR 3 182 911.25
Clean H_2 JU max. contribution:	EUR 2 999 940.00
Project period:	1.1.2019–31.12.2023
Coordinator:	Ethniko Kentro Erevnas kai Technologikis Anaptyxis, Greece
Beneficiaries:	HyGear Operations BV, HyGear Hydrogen Plant BV, HyGear Technology and Services BV, EngiCer SA, Abengoa Innovacion Sociedad Anonima, HyGear Fuel Cell Systems BV, HyGear BV, Scuola universitaria professionale della Svizzera Italiana, Medioambientales y Tecnológicas (Ciemat) (Centro de Investigaciones Energéticas), Deutsches Zentrum für Luft- und Raumfahrt eV, Commissariat à l'énergie atomique et aux énergies alternatives

http://www.hydrosol-beyond.certh.gr/

PROJECT AND OBJECTIVES

HYDROSOL-beyond is a continuation of the Hydrosol-technology series of projects that focus on using concentrated solar power to produce hydrogen from the dissociation of water through redox-pair-based thermochemical cycles. The project is an ambitious scientific endeavour aiming to address the major challenges and bottlenecks identified during previous projects and to further boost the performance of solar hydrogen production technology through innovative solutions that will also increase the potential of the technology's future commercialisation.

NON-QUANTITATIVE OBJECTIVES

- Heat recovery.
- Minimisation of the parasitic losses mostly related to the high consumption of inert gas.
- Improvement of reactor design.

PROGRESS AND MAIN ACHIEVEMENTS

- Stable $NiFe_2O_4$ lattice structures have been produced.
- A small-scale hybrid ceramic/metallic heat exchanger has been constructed and tested. The results were taken into account in the development of the full-scale heat exchanger.
- The production of $NiFe_2O_4$ lattice structures for application on the tubular solar reactor at the solar platform has been scaled up.
- The scaled-up hybrid ceramic/metallic heat exchanger has been constructed and is ready for integration on the solar platform.

FUTURE STEPS AND PLANS

- The novel heat exchanger will be integrated in the existing solar platform. A small-scale apparatus has been manufactured and is being evaluated at the laboratory. The results will be taken into account in the development of the full-scale heat exchanger and its integration in the solar plant.
- The solar platform will be operated in H_2 production mode at the Plataforma Solar de Almería in Spain to run thermal tests on solar reactors.
- Operation of the solar reactor at the solar simulator facility at Forschungszentrum Jülich was achieved, with production of 8.8 gH_2/cycle. The desired temperatures for the operation were achieved using less power than expected (150 kW from solar simulator lamps).

QUANTITATIVE TARGETS AND STATUS

Target source	Parameter	Unit	Target	Achieved to date by the project	Target achieved?	SoA result achieved to date (by others)	Year of SoA target
AWP 2018	Demonstration of the process at realistic scale and in realistic working conditions, using an existing solar demonstration facility (> 200 kW range)	kW/reactor	250	150		250	2018
	Durability	cycles	1 000	150		602	
	Heat recovery rates of high-temperature heat in excess of 60 %	%	60	46		N/A	

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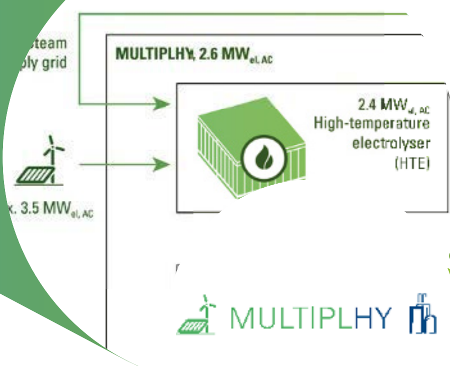
MultiPLHY

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



Project ID:	875123
PRD 2023:	Panel 1 – H2 production
Call topic:	FCH-02-2-2019: Multi megawatt high-temperature electrolyser for valorisation as energy vector in energy intensive industry
Project total costs:	EUR 10 907 722.50
Clean H_2 JU max. contribution:	EUR 6 993 725.39
Project period:	1.1.2020–31.12.2024
Coordinator:	Commissariat à l'énergie atomique et aux énergies alternatives, France
Beneficiaries:	Engie, Engie Energie Services, Neste Engineering Solutions BV, Neste Engineering Solutions Oy, Neste Netherlands BV, Neste Oyj, Paul Wurth SA, Sunfire GmbH

https://multiplhy-project.eu

PROJECT AND OBJECTIVES

MultiPLHY aims to install and integrate the world's first high-temperature electrolyser (HTE) system on a multi-MW scale at a biorefinery located in Rotterdam, the Netherlands, demonstrating both technological and industrial leadership of the EU in the application of solid oxide electrolyser cell (SOEC) technology. The central element of the project is the manufacture and demonstration of a multi-MW high-temperature electrolyser and its operation in a biorefinery. As a result, MultiPLHY promotes the SOEC-based HTE from technology readiness level 7 to 8.

PROGRESS AND MAIN ACHIEVEMENTS

- The project demonstrated stack durability for more than 7 000 hours without H_2 production loss.
- A new-generation HTE module was developed to decrease capital expenditure.
- FAT of all 12 modules has been completed, and the installation in Rotterdam is in progress.

FUTURE STEPS AND PLANS

Project tasks will be executed in accordance with a revised plan owing to a delay in completing some tasks. Tasks are continuously monitored regarding achievements and the timeline.

QUANTITATIVE TARGETS AND STATUS

Target source	Parameter	Unit	Target	Target achieved?	SoA result achieved to date (by others)	Year of SoA target
AWP 2019	Electrical consumption	kWh/kg	85	✓	39.7	2017
	H_2 production loss	%/1 000 h	< 1.2		1.9	
	Downtime	%	5		N/A	N/A

Clean Hydrogen Partnership

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NEPTUNE

NEXT GENERATION PEM ELECTROLYSER UNDER NEW EXTREMES

Project ID:	779540
PRD 2023:	Panel 1 – H2 production
Call topic:	FCH-02-1-2017: Game changer water electrolysers
Project total costs:	EUR 1 927 335.43
Clean H_2 JU max. contribution:	EUR 1 926 221.25
Project period:	2.1.2018–30.4.2022
Coordinator:	ITM Power (Trading) Limited, United Kingdom
Beneficiaries:	Consiglio Nazionale delle Ricerche, Engie, IRD Fuel Cells A/S, Pretexo, Solvay Specialty Polymers Italy SpA

https://cordis.europa.eu/project/id/779540

PROJECT AND OBJECTIVES

NEPTUNE addresses challenges associated with reducing capital costs and increasing production rates and output pressures of water electrolysis, which will be required to achieve large-scale application of polymer electrolyte membrane electrolysers. The project is developing a set of breakthrough solutions at the material, stack and system levels to increase hydrogen pressure to 100 bar and current density to 4 A/cm^2 for the base load, while keeping nominal energy consumption at < 50 kWh/kg of H_2. The novel solutions will be validated by demonstrating a robust and rapid-response electrolyser.

NON-QUANTITATIVE OBJECTIVES

The objective was to extend the protocols for testing electrolysis systems under the new operating conditions (high temperature and pressure).

PROGRESS AND MAIN ACHIEVEMENTS

- Under the project, a new simplified balance of plant for polymer electrolyte membrane electrolysis was designed and built to extend operating conditions.
- The membrane electrode assembly degradation rate achieved at 80 °C was 4.4 μV/h/cell at 4 A/cm^2 in a test lasting more than 2 000 hours (single-cell level).
- At 90 °C, cell voltages of 1.74 V at 4 A/cm^2 and 1.98 V at 8 A/cm^2 were achieved, with noble metal loading of 0.34 mg/cm^2 (anode) and 0.1 mg/cm^2 (cathode).

FUTURE STEPS AND PLANS

The project has been completed.

QUANTITATIVE TARGETS AND STATUS

Target source	Parameter	Unit	Target	Achieved to date by the project	Target achieved?	SoA result achieved to date (by others)	Year of SoA target
Project's own objectives	Anode catalyst loading per W	mg/W	0.05	0.0459	✓	0.23	2018
	Cathode catalyst loading per W	mg/W	0.0071	0.0135	⚙	0.035	
	Efficiency degradation per 1 000 hours for LT electrolyser	%/1 000 h	0.29	0.23	✓	0.2	

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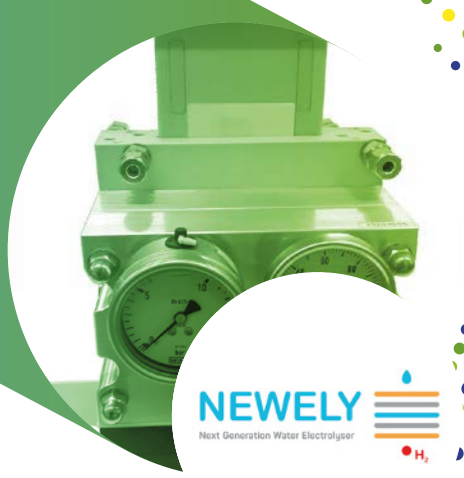
NEWELY

NEXT GENERATION ALKALINE MEMBRANE WATER ELECTROLYSERS WITH IMPROVED COMPONENTS AND MATERIALS



Project ID:	875118
PRD 2023:	Panel 1 – H2 production
Call topic:	FCH-02-4-2019: New anion exchange membrane electrolysers
Project total costs:	EUR 2 892 889.25
Clean H_2 JU max. contribution:	EUR 2 204 846.25
Project period:	1.1.2020–31.12.2022
Coordinator:	Deutsches Zentrum für Luft- und Raumfahrt eV, Germany
Beneficiaries:	Air Liquide Forschung und Entwicklung GmbH, Commissariat á l'énergie atomique et aux énergies alternatives, Cutting-Edge Nanomaterials (CENmat) UG Haftungsbeschrankt, DLR-Institut Für Vernetzte Energiesysteme EV, Fondazione Bruno Kessler, Korea Institute of Science and Technology, Air Liquide SA, Membrasenz SARL, Propuls GmbH, Ústav Makromolekulární chemie AV ČR v. v. i., Vysoká škola chemicko-technologická v Praze, Westfälische Hochschule Gelsenkirchen

https://newely.eu/

PROJECT AND OBJECTIVES

This project aims to redefine anion-exchange membrane water electrolysis (AEMWE), surpassing the current state of alkaline water electrolysis (WE) and bringing it one step closer to proton-exchange membrane WE in terms of efficiency, but at a lower cost. The three main challenges of AEMWE – membrane, catalyst and stack – are addressed by three small and medium-sized enterprises and a large hydrogen company supported by seven renowned research and development centres. With a prototypic five-cell stack at elevated pressure in a 2 000-hour endurance test, the performance of the state of the art (SoA) of AEMWE will be validated twice. This will have an impact on the cost of green hydrogen.

NON-QUANTITATIVE OBJECTIVES

The techno-economic assessment and life cycle assessment are expected to demonstrate a reduction of capital expenditure and operating expenses for AEMWE relative to proton-exchange membrane WE and alkaline WE. Data collection and evaluation are complete and under review.

PROGRESS AND MAIN ACHIEVEMENTS

- The membrane electrode assembly (MEA) with OXYGN-N anode, H2GEN-M cathode (both catalysts from project partner CENmat) and commercial anion-exchange membrane (AEM)/ionomer achieves 2 V at 2 A/cm^2 in 0.1 M KOH. No irreversible degradation was seen in a 400-hour test.
- AEM conductivity of 62 mS/cm and area-specific resistance of 0.065 ohm.cm^2 were achieved.
- The project created a new method for AEM membrane reinforcement with covalent bonds between the matrix and the ionomer, with conductivity of 62 mS/cm.

FUTURE STEPS AND PLANS

- MEAs for the stack will be prepared at 200 cm^2. Project materials will also be prepared, and targeted performance set. The long-term testing of the 25 cm^2 MEA is proceeding.
- Stack design will be finalised and constructed. The first draft has already been prepared and is awaiting finalisation of the configuration of components.
- The stack has not yet been put into operation at increased pressure.
- Long-term testing of the stack will seek to demonstrate the required stability. To date, testing has been up to 25 cm^2 (single cell). In-stack testing is still to be carried out.
- Data analysis for the life cycle assessment and cost analysis is at an advanced stage.

QUANTITATIVE TARGETS AND STATUS

Target source	Parameter	Unit	Target	Achieved to date by the project	Target achieved?	SoA result achieved to date (by others)	Year of SoA target
	Maximum AEMWE stack size realised in the project						
Project's own objectives and MAWP addendum (2018–2020)	Stack power	kW	2	0.075	⚙	2.4	2021
	Cell area	cm^2	200	25		N/A	
	Pressure	bar (relative)	≤ 40	0		≤ 35	
MAWP addendum (2018–2020)	Energy consumption @ power	kWh/kg @ W/cm^2	53.6 @ 2	53.6 @ 3.6		53.6 @ 2.4	
	Corresponding to cell voltage @ current	V @ A/cm^2	2 @ 1	2 @ 1.8		2 @ 1.2	
	Non-PGM catalysts						
Project's own objectives and MAWP addendum (2018–2020)	Added overpotentials (anode and cathode)	mV	415	232	✓	250	2020
	Current density	mA/cm^2	1	1		1	
MAWP addendum (2018–2020)	Stable operation for 2 000 hours, cell voltage gap after 2 000 hours of operation	mV	50	No 2 000-hour test yet	⚙	< 2	2021
	Extrapolation to efficiency degradation at rated power and assuming 8 000 hours of operation per year	Extrapolated to %/year	Extrapolated to 7.2	No test yet		< 0.3	
	Chemically, thermally and mechanically stable AEM ionomer and membrane with conductivity	mS/cm	≥ 50	62	✓	80	
	Area-specific resistance	ohm.cm^2	≤ 0.07	0.065		0.045	

Clean Hydrogen Partnership

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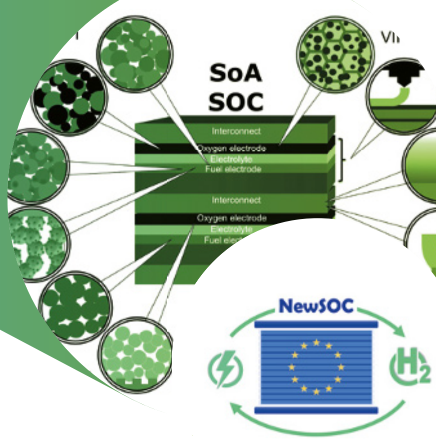
NewSOC

NEXT GENERATION SOLID OXIDE FUEL CELL AND ELECTROLYSIS TECHNOLOGY



Project ID:	874577
PRD 2023:	Panel 1 – H2 production
Call topic:	FCH-02-6-2019: New materials, architectures and manufacturing processes for solid oxide cells
Project total costs:	EUR 4 999 726.25
Clean H_2 JU max. contribution:	EUR 4 999 726.25
Project period:	1.1.2020–30.6.2023
Coordinator:	Danmarks Tekniske Universitet, Denmark
Beneficiaries:	Aktsiaselts Elcogen, Ceres Power Limited, Commissariat a l'énergie atomique et aux énergies alternatives, École polytechnique fédérale de Lausanne, Ethniko Kentro Erevnas Kai Technologikis Anaptyxis, Fundacio Institut de Recerca de L'energia de Catalunya, Hexis AG, Idryma Technologias Kai Erevnas, Instytut Energetyki, Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek TNO, Politecnico di Torino, SolydEra SpA, Sunfire GmbH, Teknologian tutkimuskeskus VTT Oy, Università degli Studi di Salerno

http://www.newsoc.eu/

PROJECT AND OBJECTIVES

NewSOC aims to significantly improve the performance, durability and cost competitiveness of solid oxide cells and stacks compared with the state of the art, focusing on (i) structural optimisation and innovative architectures, (ii) alternative materials and (iii) innovative manufacturing. The project succeeded in improving the cells, yielding a 25 % increase in applicable current density and a 25 % lower area-specific resistance (ASR), which marked the first milestone. Progress was achieved for all proposed concepts, and specific plans were agreed with the industry partners for integration into their commercial platforms.

NON-QUANTITATIVE OBJECTIVES

- Achieve redox stability in the cells.
- Produce a cell/stack with improved cycling stability.
- Reduce toxic organics/materials during manufacture.

PROGRESS AND MAIN ACHIEVEMENTS

- The integration of NewSOC development concepts into industrial platforms (cells and stacks) was achieved and tests were carried out.
- Quantities of toxic organics/materials were reduced through the development of a Co-free oxygen electrode. Cobalt was reduced in the protective coating for interconnects, and toxic solvents were removed for the deposition of sealants.
- A redox-stable cell with doped lanthanum chromite fuel electrodes was developed.

FUTURE STEPS AND PLANS

- The development of NewSOC concepts will be completed.
- Validation tests integrating the NewSOC developments into industrial cells and stacks will be completed.
- The 5 000-hour test is to be completed.

QUANTITATIVE TARGETS AND STATUS

Target source	Parameter	Unit	Target	Achieved to date by the project	Target achieved?
Project's own objectives	ASR (80 × 120 mm² solid power anode electrolyte half-cell)	ohm.cm² at 650 °C	0.4	0.5	⚙
	ASR (Co-free cell, LSF oxygen electrode with improved microstructure)	ohm.cm² at 650 °C	0.4	0.4	✓
	Electrolysis current for operation with a degradation rate below 1 %/1 000 h	A/cm²	0.75–1	0.5 ... 0 %/1 000 h	
	Electrolysis current for operation with a degradation rate below 1 %/1 000 h	A/cm²	0.75–1	0.3 ... 0.5 %/1 000 h	
	Operating temperature	°C	650	650–700	

OYSTER

OFFSHORE HYDROGEN FROM SHORESIDE WIND TURBINE INTEGRATED ELECTROLYSER

Project ID:	101007168
PRD 2023:	Panel 1 – H2 production
Call topic:	FCH-02-6-2020: Electrolyser module for offshore production of renewable hydrogen
Project total costs:	EUR 5 025 093.51
Clean H_2 JU max. contribution:	EUR 4 999 843.00
Project period:	1.1.2021–31.12.2024
Coordinator:	ERM, France
Beneficiaries:	Element Energy, Orsted Wind Power A/S, ITM Power (Trading) Limited, Siemens Gamesa Renewable Energy AS, Element Energy Limited

https://oysterh2.eu/

PROJECT AND OBJECTIVES

The overall aim of OYSTER is to justify, develop and demonstrate an electrolyser suitable for deployment in offshore environments. The end goal is to produce a marinised electrolyser that is integrated with offshore wind turbines to produce 100 % renewable, low-cost bulk hydrogen, while facilitating increased roll-out of offshore wind.

NON-QUANTITATIVE OBJECTIVES

- The project aims to develop an electrolyser system capable of operating reliably in an offshore environment.
- It aims to deploy and test a new MW-scale electrolyser designed for marine environments for 18 months, covering all seasons.
- It aims to complete a design exercise for an integrated offshore wind turbine electrolysis module, drawing on the lessons learned from the pilot trial and insights from expert partners in the offshore oil and gas sector. These lessons and insights will contribute to the basis of a detailed design of a complete offshore hydrogen production system.
- The project plans to undertake a preliminary front-end engineering and design study for a specific offshore wind farm site, linked to an existing industrial hydrogen customer.
- It aims to formulate business cases for further deployment of large-scale electrolysis systems in offshore environments. A business case will be developed for the use of hydrogen across different applications, including hydrogen for industrial users, transport applications and heating, by exploiting the onshore gas networks for use in hydrogen distribution.

PROGRESS AND MAIN ACHIEVEMENTS

- Early versions of the water treatment system design and system modelling to be used for simulation of direct connected power electronics have been finalised. These will form the basis for the design used by Stiesdal.
- The location of the trial has been selected. Following investigation, a site in Zeeland, the Netherlands, was selected.

FUTURE STEPS AND PLANS

- Stiesdal will start design and marinisation work for the electrolyser, focusing on compartmentalisation and component specification for marinisation.
- A shoreside trial and data collection are expected to start in 2024.

QUANTITATIVE TARGETS AND STATUS

Target source	Parameter	Unit	Target	Target achieved?
Project's own objectives	Electrolyser footprint	m^2/MW	50	
	Maintenance cost	€/(kg/year)	20	
	Efficiency degradation at rated power	%/1 000 h	0.11	
	Electrolyser CAPEX (at rated power), including ancillary equipment and commissioning	€/(kg/day)	800	
	Time for hot start (min. to max. power)	seconds		
	Current density	A/cm^2	0.2–0.4	

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PROMETEO

HYDROGEN PRODUCTION BY MEANS OF SOLAR HEAT AND POWER IN HIGH TEMPERATURE SOLID OXIDE ELECTROLYSERS

Project ID:	101007194
PRD 2023:	Panel 1 – H2 production
Call topic:	FCH-02-2-2020: Highly efficient hydrogen production using solid oxide electrolysis integrated with renewable heat and power
Project total costs:	EUR 2 765 206.25
Clean H_2 JU max. contribution:	EUR 2 499 531.25
Project period:	1.1.2021–30.6.2021
Coordinator:	Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile, Italy
Beneficiaries:	Capital Energy Services SLU, École Polytechnique Fédérale de Lausanne, Fondazione Bruno Kessler, Fundación Imdea Energia, NextChem SpA, SNAM SpA, SolydEra SA, Stamicarbon BV

https://prometeo-project.eu

PROJECT AND 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 the relevant environment, combined with intermittent sources: non-programmable renewable electricity and high-temperature solar heat with thermal energy storage. Partial-load operation, transients and hot standby periods will be studied.

NON-QUANTITATIVE OBJECTIVES

Demonstrate the capability to transfer the technology from component developers to system integrators and end users.

PROGRESS AND MAIN ACHIEVEMENTS

- The project defined end users' cases.
- Preliminary process flow diagrams were created.
- A thermal energy storage system was identified and was experimentally validated in the laboratory.
- Process modelling tools were developed.

FUTURE STEPS AND PLANS

- Experimental determination of the performance map for the SOE stack and the balance of plant in the laboratory is in progress – it was expected to be complete by January 2023.
- Process flow diagrams for the 25 kWe pilot plant under different operation modes are being finalised. They were expected to be complete by March 2023.
- The integrated pilot plant (25 kWe) will be designed and built. The basic design is in progress. The pilot plant is expected to be shipped to the project site in the first half of 2024.
- Based on finalised process flow diagrams for the pilot plant (25 kWe), analysis of case studies at multi-MW scale will be performed. This was expected to start by April 2023.

QUANTITATIVE TARGETS AND STATUS

Target source	Parameter	Unit	Target	Target achieved?
Project's own objectives	Demonstrate ≥ 98 % availability of the electrolyser: hours in which the SOE has been kept at ≥ 650 °C (i.e. ready to start) v total hours	%	98	
	Demonstrate the production of hydrogen by operation of > 1 000 hours: hours of experimental validation runs of the prototype	hours	1 000	
	Demonstrate, using SOE with renewable heat integration, electrical efficiency of ≥ 85 % based on lower heating value (LHV) and specific energy consumption of < 39 kWh/kg H_2 in a relevant market-representative environment: power-to-hydrogen energy conversion efficiency of the heat-integrated SOE system (LHV basis)	%	85	
	Obtain solar-to-hydrogen energy conversion efficiency from global solar radiation to H_2 energy (LHV basis): ≥ 10 %	%	10	

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REACTT

RELIABLE ADVANCED DIAGNOSTICS AND CONTROL TOOLS FOR INCREASED LIFETIME OF SOLID OXIDE CELL TECHNOLOGY

Project ID:	101007175
PRD 2023:	Panel 1 – H2 production
Call topic:	FCH-02-3-2020: Diagnostics and control of SOE
Project total costs:	EUR 2 712 322.50
Clean H_2 JU max. contribution:	EUR 2 712 322.50
Project period:	1.1.2021–31.12.2023
Coordinator:	Jožef Stefan Institute, Slovenia
Beneficiaries:	Agenzia nazionale per le nuove tecnologie (l'energia e lo sviluppo economico sostenibile), AVL LIST GmbH, Bitron SpA, Commissariat à l'énergie atomique et aux énergies alternatives, École Polytechnique Fédérale de Lausanne, Haute Ecole Spécialisée de Suisse occidentale, SolydEra SA, Teknologian tutkimuskeskus VTT Oy, Università degli Studi di Salerno

https://www.reactt-project.eu/

PROJECT AND OBJECTIVES

REACTT aims to realise a monitoring, diagnostic, prognostic and control (MDPC) tool and reversible solid oxide cell 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. The development of the hardware platform and embedded diagnostics and prognostics algorithms is under way.

NON-QUANTITATIVE OBJECTIVES

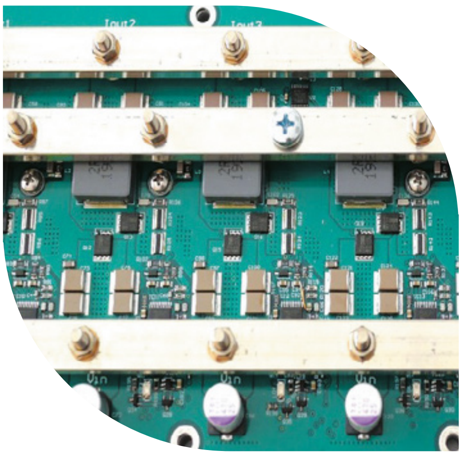
- **Education/training.** The possible inclusion of the topic of solid oxide cell technologies in MSc and PhD study programmes was to be considered.
- **Public awareness.** The project web page and dissemination material are the first step towards raising public awareness.
- **Safety.** Fault detection, isolation and mitigation in SOEC/SOFC preclude process disruption and potential hazards.
- **Regulations and standards.** The formulation of a new work item proposal set out in M12–M36 is to be submitted to Technical Committee 105 of the International Electrotechnical Commission.

PROGRESS AND MAIN ACHIEVEMENTS

The first prototype of the MDPC board was developed.

FUTURE STEPS AND PLANS

An application for a project extension has been made. Delays in stack delivery are likely to result in delayed data acquisition from the long-term experiments under various degradation modes. The data are an important prerequisite for the design and validation of the diagnostic and prognostic algorithms.



QUANTITATIVE TARGETS AND STATUS

Target source	Parameter	Unit	Target	Target achieved?	SoA result achieved to date (by others)
MAWP (2014–2020)	Availability	%	98		95
	Q & M cost	€/(kg/d)/year	120		N/A
	Electrical consumption at rated capacity	kWh/kg of H_2	39		40–45

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REFHYNE

CLEAN REFINERY HYDROGEN FOR EUROPE

Project ID:	779579
PRD 2023:	Panel 1 – H2 production
Call topic:	FCH-02-5-2017: Demonstration of large electrolysers for bulk renewable hydrogen production
Project total costs:	EUR 19 759 516.50
Clean H_2 JU max. contribution:	EUR 9 998 043.50
Project period:	1.1.2018–30.6.2024
Coordinator:	SINTEF AS, Norway
Beneficiaries:	Element Energy Limited, ITM Power (Trading) Limited, Shell Deutschland GmbH, Shell Energy Europe Limited, Sphera Solutions GmbH, SINTEF AS

https://refhyne.eu/

PROJECT AND OBJECTIVES

The overall objective of REFHYNE is to deploy and operate a 10 MW electrolyser in a power-to-refinery setting. REFHYNE will validate the business model for using large-scale electrolytic hydrogen as an input to refineries, show the revenues available from primary and secondary grid balancing in today's markets and create an evidence base for the policy/regulatory changes needed to underpin the required development of this market. The electrolysers have been installed, and the plant has been tested and is ready for commissioning.

NON-QUANTITATIVE OBJECTIVES

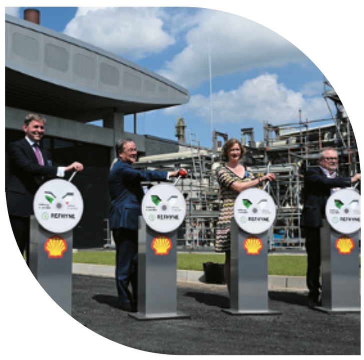
- The project aims to make recommendations for policymakers and regulators on measures required to stimulate the market for these systems. One of the key outputs of the project is a suite of reports providing the evidence base for changes to existing policies. This will include specific analysis aimed at policymakers, recommending changes to existing policies.
- It aims to assess the legislative implications of these systems and their implications for regulations, codes and standards. REFHYNE will produce a detailed assessment of the consenting process for the system and any safety or codes and standards issues encountered.

PROGRESS AND MAIN ACHIEVEMENTS

The electrolyser has been tested and operated at different modes of operation, up to 10 MW (not analysed or uploaded). Lessons learned from the design, construction and initial operation have been summarised and published (not yet analysed or uploaded).

FUTURE STEPS AND PLANS

- The full operation of the electrolyser, including dynamic response testing in grid connection mode, will begin. The system is ready for full operation. The main issue to be resolved is that of timing in relation to other site activities.
- REFHYNE will undertake economic and technical analysis of electrolyser performance. Data gathering, storage and transfer to relevant partners is not fully ready. However, data will be stored and made available for later analysis.
- The project will perform an environmental analysis of the electrolyser system and concept. The framework and models are in place, and analysis will begin once system data are available.

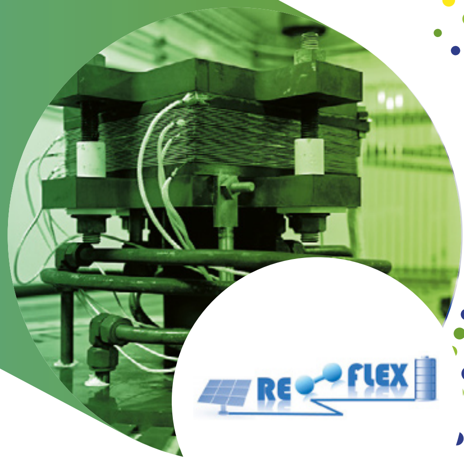


QUANTITATIVE TARGETS AND STATUS

Target source	Parameter	Unit	Target	Target achieved?	SoA result achieved to date (by others)	Year of SoA target
Project's own objectives and MAWP addendum (2018–2020)	Electricity consumption at nominal capacity	kWh/kg	52		55	2020
	Capital cost	€/(kg/day)	2 000		2 100	2020
	Degradation rate	%/1 000 h	0.15		0.19	2020
	Hot idle ramp time for H_2 production	seconds	1		2	2020

REFLEX

REVERSIBLE SOLID OXIDE ELECTROLYZER AND FUEL CELL FOR OPTIMIZED LOCAL ENERGY MIX



Project ID:	779577
PRD 2023:	Panel 1 – H2 production
Call topic:	FCH-02-3-2017: Reversible solid oxide electrolyser (rSOC) for resilient energy systems
Project total costs:	EUR 3 033 654.71
Clean H_2 JU max. contribution:	EUR 2 999 575.25
Project period:	1.1.2018–30.6.2023
Coordinator:	Commissariat à l'énergie atomique et aux énergies alternatives, France
Beneficiaries:	Aktsiaselts Elcogen, Danmarks Tekniske Universitet, Engie, Engie Servizi SpA, Green Power Technologies SL, Parco Scientifico Tecnologico per l'Ambiente SpA, Sylfen, Teknologian tutkimuskeskus VTT Oy, Universidad de Sevilla

http://www.reflex-energy.eu/

PROJECT AND OBJECTIVES

REFLEX aims to develop an innovative renewable energy storage solution, based on reversible solid oxide cell (rSOC) technology, that can operate in either electrolysis mode, to store excess electricity to produce H_2, or fuel cell mode, when energy needs exceed local production levels, to produce electricity and heat from H_2 or any other fuel that is locally available. It has developed improved rSOC components (cells, stacks, power electronics, heat exchangers) and has defined the system, its set points and advanced operation strategies. An in-field demonstration will be performed in 2023.

NON-QUANTITATIVE OBJECTIVES

- The project aims to complete a techno-economic assessment.
- It also aims to create an inventory of regulations, codes and standards applicable to rSOC systems in France and Italy.

PROGRESS AND MAIN ACHIEVEMENTS

- Enlarged cells were produced.
- The project has improved the stack for rSOC operation.
- The rSOC module design was completed.
- The rSOC module assembly has started.
- The site integration is almost complete.

FUTURE STEPS AND PLANS

- The modules and system assembly are being finalised.
- The installation of the system for an in-field test was planned for 2023.

QUANTITATIVE TARGETS AND STATUS

Target source	Parameter	Unit	Target	Achieved to date by the project	Target achieved?	SoA result achieved to date (by others)	Year of SoA target
Project's own objectives	Current density in SOEC mode	A/cm²	1.2	N/A	⚙	– 1.15 at 750 °C, – 1 at 800 °C	2015–2016
	Durability in SOEC step during rSOC operation at 0.58 A/cm² and SC = 68 %	%/1 000 h	2	1.2	⚙	2.3 for current densities of 0.6–0.7 A/cm² and SC = 50 %	2015
	Cell active area	cm²	200	200	✓	128	2021
	Power electronic efficiency	%	95	96	✓	88	2019
	Power modulation SC = 80 %	%	50–100 (SOFC), 70–100 (SOEC)	58–100 in SOEC, 13–100 in natural-gas SOFC and 23–100 in H_2 SOFC	⚙	57–100 in SOEC	2019

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SWITCH

SMART WAYS FOR IN-SITU TOTALLY INTEGRATED AND CONTINUOUS MULTISOURCE GENERATION OF HYDROGEN

Project ID:	875148
PRD 2023:	Panel 1 – H2 production
Call topic:	FCH-02-3-2019: Continuous supply of green or low carbon H2 and CHP via solid oxide cell based polygeneration
Project total costs:	EUR 3 746 753.75
Clean H_2 JU max. contribution:	EUR 2 992 521.00
Project period:	1.1.2020–31.3.2024
Coordinator:	Fondazione Bruno Kessler, Italy
Beneficiaries:	Deutsches Zentrum für Luft- und Raumfahrt EV, École Polytechnique Fédérale de Lausanne (EPFL), HyGear BV, Shell Global Solutions International BV, SolydEra SA, Sweco Polska sp. z.o.o.

https://switch-fch.eu/

PROJECT AND OBJECTIVES

SWITCH aims to design, build and test a 25 kW (solid oxide fuel cell) / 75 kW (solid oxide electrolyser cell) system prototype for hydrogen production, operating in an industrial environment for 5 000 hours. The SWITCH system will be a stationary, modular and continuous multisource H_2-production technology designed for H_2 refuelling stations. The core of the system will be a reversible solid oxide cell operating in electrolysis mode (SOE) and fuel cell mode (SOFC).

NON-QUANTITATIVE OBJECTIVES

- SWITCH aims to ensure the reliability and stability of power and hydrogen supply. A system with co-generation potential with substantial dynamic behaviour can deliver reliable and stable production of hydrogen and power to match demand-side management, securing the form of energy needed and connecting the generation profile to the end user.
- The project aims to ensure modularity through the development and validation of a 50 kg of H_2/day technology, realised by integrating modules composed of high-reliability stack modules provided by SOLIDpower.
- SWITCH aims to ensure that the hydrogen purity level complies with ISO standard 14687. Hydrogen will be purified to within the range of 99.7–99.99 % and will have a water content of less than 5 parts per million.
- In-field testing in a relevant environment will be assured, with the final SWITCH system prototype being installed in a bench infrastructure and in a real operational environment. The system operation time will be 5 000 hours in the relevant environment.
- Life cycle analysis and life cycle cost analysis will help to evaluate the benefits of the SWITCH technology in comparison with state-of-the-art (SoA) steam methane reforming and other H_2-production technologies (e.g. electrolysis).

PROGRESS AND MAIN ACHIEVEMENTS

- EPFL conducted the analysis on the SWITCH SOEC mode three damage impacts in OPENLCA and carried out a comparison of H_2-production technologies including SOE, AEL, CH2P OM3 and steam methane reforming (SMR).
- HyGEAR and SolydEra performed a hazard and operability analysis of the latest piping and instrumentation diagram.
- The cold balance of plant (BoP) and purification section have been designed and constructed.
- The hot BoP gamma has been finalised and successfully tested, and integrated in the SOE operating mode.
- The control system has been developed, and power electronics have been selected and acquired.
- The analysis of the experiments with the 25 kW LSM was finalised in work package 5. This included steady-state performance in electrolysis, polygeneration and fuel cell mode, and the analysis of the transient behaviour while switching between the modes. In addition, a transient model was developed and validated.
- A 1 000-hour durability test with daily switches between SOFC and SOE mode was performed by EPFL in work programme 5.
- Four articles have been published, with input from partners. The results have been presented in several conferences and workshops.

FUTURE STEPS AND PLANS

- The assembly of the full SWITCH system is in progress. Arrangements are being made to accommodate the testing of the full system at HyGear's premises. Initial work on operating condition optimisation has been carried out during the qualification test of the hot BoP and the LSM at SolydEra facilities.
- An exploitation workshop will be organised to enable work to start on the business model and business plan. The project consortium will apply for module B of the Horizon Results Booster to continue the activity related to the future exploitation of the SWITCH prototype. The focus will be on the business model and potential go-to-market strategy.

QUANTITATIVE TARGETS AND STATUS

Target source	Parameter	Unit	Target	Achieved to date by the project	Target achieved?	SoA result achieved to date (by others)	Year of SoA target
Project's own objectives	Electrolyser conversion efficiency	%	85	80		80	2021
	Fuel cell conversion efficiency	%	75	N/A		80	
	Hydrogen cost	€/kg	5			11.2	
	Stack lifetime	hours	10 000			3 000	
	Low switching time	minutes	30	15	✓	N/A	N/A

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II. PILLAR 2 - HYDROGEN STORAGE AND DISTRIBUTION

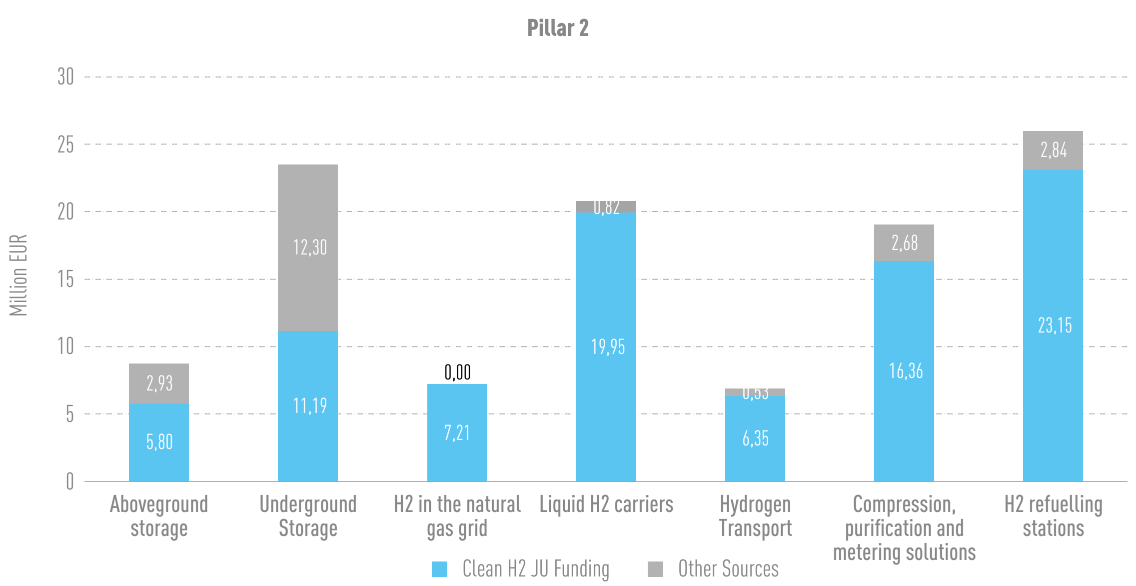
Objectives: Pillar 2 is subdivided into the following Research Areas:

- Aboveground storage
- Underground storage
- Hydrogen in the natural gas grid
- Liquid hydrogen carriers
- Compression, purification and metering solutions
- Hydrogen refuelling stations

The SRIA also has the Research Area "improving existing hydrogen transport means", which are pipelines, road transport and shipping. There is also a Research Area "hydrogen distribution (pipelines)". There are currently no projects under these topics.

Budget: For Pillar 2, around EUR 90 million have been made available so far. The Research Areas, underground storage and HRS, have received more than 50% of the total funding (see Figure 31). Half of the projects grouped in this Pillar are part of the 2022 Programme Technical Assessment, which demonstrates the increased importance of this topic in recent Calls.

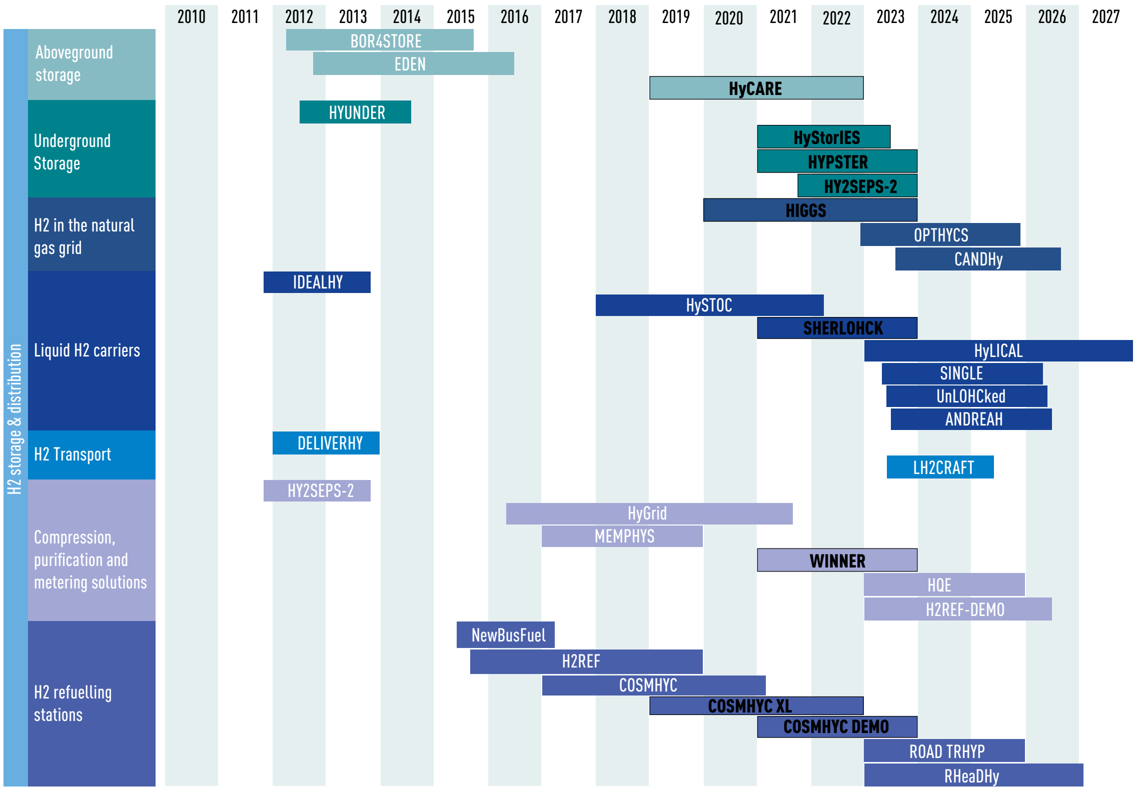
Figure 31: Funding for Pillar 2 projects (2008-2022)



Source: Clean Hydrogen JU

Projects: The timeline of Pillar 2 clearly shows the increased interest in these topics, as half of the 22 projects were selected in the Call in 2018 and are part of the Programme Review of 2022 (Figure 32). In particular, underground storage is receiving renewed attention after a long hiatus following the end of the HYUNDER project.

Figure 32: Project timelines of Pillar 2 – H2 storage and distribution



Source: Clean Hydrogen JU
NB. Projects highlighted in black were considered for the 2023 Programme Review.

Figure 33 reveals that a large number of research centres are involved in the 9 projects of Pillar 2[115]. Among the private companies, Shell, LBST, NEL Hydrogen and MAHYTEC, are the most prominent. This shows a good balance between large industry and SMEs. There seem to be strong links between participants, with the exception of the project HYPSTER, which has no connections to any other project. Among the member states, Germany and France are in the lead regarding participation for this Pillar.

115 The size of the node represents the number of projects a partner is involved in, whilst the thickness of the links represents the number of projects in common between the linked partners. The colour is based on the type of organisation as provided in CORDIS. The project not showing connection to others is HYPSTER.

Figure 33: TIM Plot showing the participants in the 11 projects reviewed

Top Participants

Participant	Number of Projects
Multiple participants (11)	2

Source: TIM (JRC)

ABOVE-GROUND STORAGE

Project **HyCARE** has started the 4 month testing period of a large-scale hydrogen storage system based on solid-state storage solutions and coupled with phase change materials. This final step will couple the storage system with an electrolyser and a fuel cell. It follows the optimisation and the production of the selected metal hydride material (a titanium-iron-manganese alloy) at scale, the finalisation of the full storage design and the completion of the qualification process. The storage system is formed by 12 tanks containing more than 6 000 pellets. The full storage rack, together with the PCM tanks, has a weight of about 14 tons and was placed and fixed in a 20ft container. It will be able to reversibly store around 44 kg of hydrogen (50 kg storage capacity was planned and can be reached compromising reversibility).

UNDERGROUND STORAGE

The project HYUNDER financed under the 7th Framework Programme and finished in 2014, already offered an analysis on 5 representative case studies with a focus on salt cavern storage. It provided a first techno-economic assessment for available technical solutions, defined possible business cases and offered a first inventory of geological formations suitable for bulk high pressure gas storage.

HYPSTER (2021-2023) wants to demonstrate viability for year-long cyclic hydrogen storage operations supporting local industrial clusters and other hydrogen consumers. The salt cavern used by the project is located in Etrez, in the Auvergne-Rhône Alpes region, in France. The project will operate a 1MW electrolyser coupled with renewable energy. The project is ongoing and has started the permitting procedure in order to finalise the construction. Modelling and necessary preparations for the underground storage installation have been completed and necessary aboveground installations such as the electrolysers and the compressor will be installed in 2023.

While storage of pure hydrogen in salt caverns has been practiced since the 70s, storage has not yet been carried out anywhere in porous rock formations such as depleted oil and gas fields or aquifers. Research activities have been performed by nationally funded projects. Both **HYSTORIES** (2021-2023) and **HYUSPRE** (2021-2023) have planned a full matrix of microbiological and mechanical tests able to identify the most suitable materials and conditions for storage of hydrogen in porous rock formations. Both projects are mapping out suitable geological formations present in the European territory, performing a legislative survey of relevant national legislation and pursuing a full techno-economic assessment to obtain clear feasibility options for hydrogen storage in

European porous formations from now until 2050. If successful, both projects should pave the way for future large demonstrations.

H_2 IN THE NATURAL GAS GRID

The **HIGGS** project aims to assess the hydrogen-readiness of gas transmission networks. As part of the experimental activities, materials and components will be tested in low (10 vol%), medium (10-30 vol%), and high hydrogen (up to 100 vol%) concentrations of up to 80 bar pressure. Other activities include the mapping of technical, legal, and regulatory barriers and enablers, techno-economic modelling of grid repurposing, and the preparation of guidelines towards enabling the injection of hydrogen in high pressure gas grids. The testing platform has been designed and tests are ongoing. Dynamic and static tests have been completed for blends of 20 vol% hydrogen in natural gas. The sensitivity to hydrogen and gas tightness of API 5L steels, valves, fittings and equipment present in NG European transmission grids, has been assessed. Most of the valves remain tight over 3 000 hours. No embrittlement or other kind of damage was found. Additional campaigns are planned with injections of 30 vol% hydrogen in natural gas and 100% hydrogen. A system has been created for separating low concentrations of hydrogen in natural gas, and promising results have been obtained from the experimental campaign. The first scenarios for the techno-economic assessment have been modelled but the results have not been published yet.

LIQUID H_2 CARRIERS

Lowering the energy demand of dehydrogenation is key to the **SHERLOHCK** project, that aims to develop highly active and selective catalyst material, with partial, or if possible, total substitution of PGM. There is also the target to reduce internal heat loss and increase (de)hydrogenation conversion rate. The catalyst material will be tested in a demonstration unit (>10 kW, >200 h). Benzyltoluene (BT) was chosen as the reference molecule and Pt-based catalysts were selected as the catalysts' benchmark. A catalyst design through Density Functional Theory (DFT) predictive analysis has led to reducing the use of PGM catalysts. The project has achieved the hydrogen productivity in dehydrogenation target (3 g H2/g catalyst/min), reaching a productivity of 5.3 g H2/g catalyst/min. The addition of 0.5 wt% Co over Pt-based catalyst with low metal content (0.5 wt% Pt) resulted in an increase in the dehydrogenation productivity. A cobalt content of 0.5 wt.% allowed to achieve almost the same dehydrogenation activity and selectivity as the catalysts with 1 wt.% Pt, but by cutting the amount of this noble metal in half. The project has also made progress against the targets of conversion degree (74% against a target of 90%) and catalyst selectivity (99.04% against a target of 99.8%). State of the art results have been obtained with catalysts with much higher Pt loading. The project also aims to assess the resistance of the catalysts to different poisons, and the effect of sulphur addition to the catalytic formulations for the dehydrogenation step has also been added to the activity plan. Finally, promising results were obtained for catalyst reactivation procedures by oxidative treatment in batch operation. The procedure will now be optimised and transferred to a larger scale, potentially leading to an efficient way of increasing the lifetime of the catalyst.

COMPRESSION, PURIFICATION AND METERING SOLUTIONS

More fundamental research will be carried out by the project **WINNER**, which started in January 2022. The project will develop PCC[116] for different applications; ammonia cracking to pressurised hydrogen, the dehydrogenation of ethane, and the reversible electrolysis at high pressure. The PCC electrolyser allows for an extraction, compression and purification of hydrogen from gas streams (ethane, ammonia, steam). The project reached its technical target of area specific resistance (ASR) <1 ohm/cm^2 at 650 °C in 2022 for the reversible electrolysis and the ammonia cracking process. So far, the project has achieved an 85% Faraday efficiency for the reverse electrolysis and ammonia cracking process, below the 95% target. The project plans to implement an interfacial layer (two candidate materials are considered: La2Ce2O7 (LCO) based oxide and CeO2 (CO) based oxide) to block the p-type conductivity and improve the electrochemical performance of the electrode architecture. However, the

116 Proton conducting ceramic electrochemical cells (PCC) are a promising option for the compression and purification of hydrogen. The aim is to demonstrate the flexibility of this technology.

project is facing challenges at materials level, in particular related to the preparation of thin interfacial layers. The project also aims at developing a multi-scale multi-physics modelling platform which will be used for the design of mechanically stable cells and modules. The project exhibits a good integration with other projects, mainly as a follow-up of the project **GAMER**[117].

H_2 REFUELLING STATIONS

The **COSMHYC XL** project has already achieved a high number of its objectives. Compression is a major challenge for the operation of HRS, both in terms of cost and reliability and availability of the station. A high flow rate of hydrogen is also needed. The project seeks to advance compression technology by combining mechanical with metal hydride compression, based on the outcomes of the COSMHYC project. At present, the mechanical compressor is operational; 120 kg/h in two-stage configuration and 240 kg H2/h in duplex configuration. The metal hydride compressor is assembled in a 20 foot container, including all subsystems (thermal integration, control and monitoring system). The production of the metal hydride material has been concluded, and the reactors will have to be integrated with the rest of the systems. The metal hydride does not contain rare earth elements. The pre-certification of the test site for the metal hydride compressor has been completed and all safety studies have been performed. The project is conducting the prototypes' long term tests, so no KPI values have been reported yet. The target for Energy Consumption (5 to 900 bar) is 6.18 kWh/kg H_2. The consortium is currently collecting and analysing all data generated during the tests.

COSMHYC DEMO is the continuation of COSMHYC XL. From 2023 onwards, the results of COSMHYC XL will continue to be disseminated through COSMHYC DEMO. The start-up company[118] responsible for the metal hydride compressor, which was created under COSMHYC XL, is already part of COSMHYC DEMO. The **COSMHYC DEMO** project includes design, construction and integration of the metal-hydride compressor demonstrator in a new public hydrogen refuelling station (HRS), with a capacity of 200 kg H_2/day on the test site in France, for a variety of mobility applications[119]. This project seeks to demonstrate the capability and flexibility of the innovative compression solution. The hybrid compressor will be used to supply hydrogen both at 350 and 700 bar. The HRS has been fully constructed throughout 2022. The site integration and filling center gas panel design has been completed, including safety studies. Some delays have been experienced due to supply chain and permitting issues and the project has not yet reached the demonstration phase. According to the project timeline, the installation of the HRS will be completed in summer 2023 and the integration of the metal hydride compressor[120] in early 2024. Following this, long-term tests of the demonstrator will be conducted with the on-site vehicle fleet.

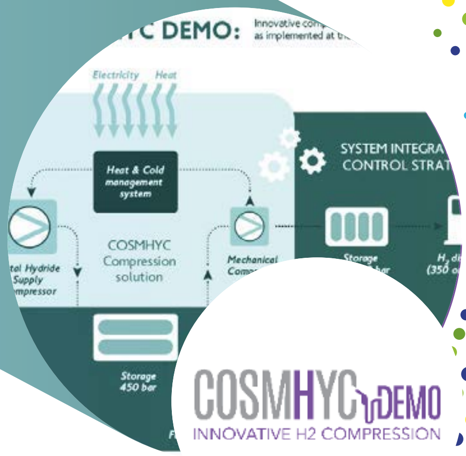
117 Synergies are established for the modelling activities, the development of materials and cells, and at the system integration level especially for ammonia cracking and the scaling up of demonstration system up to 5 kW.

118 https://eifhytec.com/products/

119 This HRS is a central part of HYSOPARC, a project implemented by CCTVI (a grouping of municipalities) near Tours, France, for driving regional development based on hydrogen technologies. The HRS will supply a fleet of 700 bar passenger vehicles, 350 bar utility vehicles and a 700-bar garbage truck.

120 The metal hydride compressor is to be standardised and achieve CE conformity. A large number of studies will be needed to get a CE certification, and the compression system has to be proven to comply with all relevant directives (such as ATEX, pressure equipment, and similar). These crucial steps are currently being undertaken.

COSMHYC DEMO



COMBINED SOLUTION OF METAL HYDRIDE AND MECHANICAL COMPRESSORS: DEMONSTRATION IN THE HYSOPARC GREEN H_2 MOBILITY PROJECT

Project ID:	101007173
PRD 2023:	Panel 2 – H2 storage and distribution
Call topic:	FCH-01-8-2020: Scale-up and demonstration of innovative hydrogen compressor technology for full-scale hydrogen refuelling station
Project total costs:	EUR 3 773 858.75
Clean H_2 JU max. contribution:	EUR 2 999 637.13
Project period:	1.1.2020–31.12.2024
Coordinator:	Europäisches Institut für Energieforschung EDF–KIT EWIV, Germany
Beneficiaries:	Communauté de Communes Touraine Vallée de l'Indre, Eifhytec, Mahytec SARL, Nel Hydrogen AS, Steinbeis Innovation gGmbH

https://cosmhyc.eu/cosmhyc-project

PROJECT AND OBJECTIVES

To meet the demands of a growing hydrogen economy, new technologies in the hydrogen refuelling infrastructure – including that of hydrogen compression – are necessary. In COSMHYC DEMO, the innovative COSMHYC compression solution, which combines a metal hydride compressor and a mechanical compressor, has been shown to be ready for commercial deployment. At the test site in France, a public hydrogen refuelling station (HRS) will be installed for a variety of vehicles (e.g. vehicle fleets and refuse trucks). The hybrid compressor will be used to supply hydrogen at both 350 bar and 700 bar.

NON-QUANTITATIVE OBJECTIVES

- The project aims to increase public acceptance of hydrogen mobility. Integrating the new compressor in a community in which there have been previous hydrogen mobility activities and demonstration projects is likely to increase overall acceptance.
- It also aims to include a smart gas hub for switching between storage, the HRS and the filling centre. A new gas panel has been designed and will allow for smart switching between the filling centre for trailers, on-site hydrogen supply storage and HRS.

PROGRESS AND MAIN ACHIEVEMENTS

- The HRS has been fully constructed and is ready to ship.
- The metal hydride composition has been decided upon for all compression stages.
- Site integration and filling centre gas panel design, including safety studies, have been completed.

FUTURE STEPS AND PLANS

- The HRS is due to be installed in summer 2023.
- The metal hydride compressor is due to be integrated in early 2024.
- Long-term tests of the demonstrator will be conducted with the on-site vehicle fleet.
- Final discussions regarding safety studies will take place, before authorisation is granted.
- An opening event for the launch of the HRS and compressor will be organised to bring together local stakeholders, the general public and EU officials at the demonstration site.

QUANTITATIVE TARGETS AND STATUS

Target source	Parameter	Unit	Target
Project's own objectives	Daily capacity	kg/day	200
	Storage capacity	kg	125
	Refuelling protocol	N/A	SAE J2601 (light-duty vehicles) / SAE J2601-2 (heavy-duty vehicles)
	Dispensing pressure	bar	350/700/200
	Nominal pressure of the on-site storage tank	bar	950

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COSMHYC XL

COMBINED HYBRID SOLUTION OF METAL HYDRIDE AND MECHANICAL COMPRESSORS FOR EXTRA LARGE SCALE HYDROGEN REFUELLING STATIONS

Project ID:	826182
PRD 2023:	Panel 2 – H2 storage and distribution
Call topic:	FCH-01-7-2018: Improvement of innovative compression concepts for large scale transport applications
Project total costs:	EUR 2 749 613.75
Clean H_2 JU max. contribution:	EUR 2 749 613.75
Project period:	1.1.2019–30.06.2023
Coordinator:	Europäisches Institut für Energieforschung EDF–KIT EWIV, Germany
Beneficiaries:	Ludwig-Bölkow-Systemtechnik GmbH, Mahytec SARL, Nel Hydrogen AS, Steinbeis 2i GmbH

https://cosmhyc.eu/cosmhyc-xl-project

PROJECT AND OBJECTIVES

Hydrogen mobility is one of the most promising solutions for a sustainable energy transition in large-scale transport modes, including trucks, buses, trains and professional vehicle fleets. For these applications, a well-functioning hydrogen refuelling infrastructure is necessary, including hydrogen compressors able to meet challenging constraints in terms of flow rate and availability. COSMHYC XL aims to develop an innovative compression solution for extra-large hydrogen refuelling stations, based on the combination of a metal hydride compressor and a mechanical compressor.

NON-QUANTITATIVE OBJECTIVES

- The project aims to create a hybrid system allowing for different configurations. Ludwig-Bölkow-Systemtechnik will show that only small adaptations for different refuelling applications and intermediate storage capacities are required to minimise total costs.
- The project aims to increase reliability. The results of COSMHYC and the preliminary results of COSMHYC XL show that reliability can be strongly improved compared with that of SoA mechanical compressors.
- The project aims to undertake a cost-of-ownership assessment. Activities dedicated to this are ongoing. The results of the previous COSMHYC project show that the target total cost of ownership can be achieved.

PROGRESS AND MAIN ACHIEVEMENTS

- A prototype of a dual-head mechanical compressor has been assembled and is operational; the compressor reaches 120 kg/h in two-stage configuration and 240 kg/h in duplex configuration (listed in the European Commission's Innovation Radar).
- Metal hydrides without rare-earth elements were produced for all three compression stages (listed in the Innovation Radar).
- The metal hydride compressor prototype is assembled in a 20-foot container, including all subsystems (e.g. thermal integration, control and monitoring system) (listed in the Innovation Radar).
- The test site has been in commission for the metal hydride compressor prototype. All risk assessments were successfully performed, and pre-certification is complete. The long-term test started in Q4 2022.

FUTURE STEPS AND PLANS

- The project is conducting long-term tests of the prototypes. The tests of the mechanical compressor are complete; the metal hydride compressor tests started in late 2022. The testing protocol validates the combination of the compression technologies.
- The consortium is collecting and analysing all data generated during the tests. Based on these data, a techno-economic analysis will be conducted and the project's final exploitation roadmap will be set.

QUANTITATIVE TARGETS AND STATUS

Target source	Parameter	Unit	Target	Target achieved?	SoA result achieved to date (by others)	Year of SoA target
Project's own objectives	Energy consumption	kWh/kg	6.18		8	2018
	Degradation	%/1 000 h	0.8		N/A	N/A
	Specific costs	k€/kg*day	1.47		3.7	2021
	Noise levels	dB	< 60		53.9	2021

HIGGS

HYDROGEN IN GAS GRIDS: A SYSTEMATIC VALIDATION APPROACH AT VARIOUS ADMIXTURE LEVELS INTO HIGH-PRESSURE GRIDS

Project ID:	875091
PRD 2023:	Panel 2 – H2 storage and distribution
Call topic:	FCH-02-5-2019: Systematic validation of the ability to inject hydrogen at various admixture level into high-pressure gas networks in operational conditions
Project total costs:	EUR 2 107 672.50
Clean H_2 JU max. contribution:	EUR 2 107 672.50
Project period:	1.1.2020–31.12.2023
Coordinator:	Fundación para el Desarrollo de las Nuevas Tecnologías del Hidrógeno en Aragón, Spain
Beneficiaries:	Deutscher Verein des Gas- und Wasserfaches – Technisch-Wissenschaftlicher Verein EV, European Research Institute for Gas and Energy Innovation, Fundacion Tecnalia Research & Innovation, OST – Ostschweizer Fachhochschule, Redexis SA

https://higgsproject.eu/

PROJECT AND OBJECTIVES

HIGGS aims to fill in the gaps in knowledge regarding the impact that high levels of H_2 could have on high-pressure natural gas infrastructure, its components and its management. To reach this goal, the project is mapping technical, legal and regulatory barriers and enablers; testing materials/components; completing techno-economic modelling; and preparing a set of conclusions as a pathway towards enabling the injection of hydrogen into high-pressure gas grids. The inventory of materials/equipment and the mapping of regulations, codes and standards (RCS) are mostly complete, tests are ongoing and the techno-economic model is under development.

NON-QUANTITATIVE OBJECTIVES

- The project aims to draw up recommendations on regulations, codes and standards. The first screening has been completed, and the work is ongoing.
- A pathway for stepwise integration of hydrogen into the EU gas network is being drafted.
- The project aims to develop a techno-economic model and study of the roles of technologies for integrating H_2/CH_4 and sector coupling at the EU level. This work has started with the Trans Europa Naturgas Pipeline and the Mittel-Europäische-Gasleitung.

PROGRESS AND MAIN ACHIEVEMENTS

- The testing platform has enabled dynamic and static tests to be carried out with blends of up to 20 % H_2.
- The project has adapted the techno-economic model, and initial scenarios have been modelled.
- A system has been created for hydrogen separation in natural gas blends with low concentrations of hydrogen. The gas separation prototype experimental campaign has been completed, with promising results.

FUTURE STEPS AND PLANS

- The project will complete all experimental campaigns in the testing platform and characterisation of materials before and after hydrogen exposure, using a 30 % H_2 blend and 100 % H_2, to evaluate the effect of the injection of hydrogen.
- Data from the RCS review at the European and national levels were collected, reviewed and compiled in a comprehensive report comprising diagrams and graphs that are to be presented on the project website and used for presentations and papers. The first review was shared publicly, and is due to be updated in 2023.
- The simulation of the initial scenarios on the Trans Europa Naturgas Pipeline and the Mittel-Europäische-Gasleitung and analysis of techno-economic aspects are ongoing and are due to be completed in late 2023. This work will finish with the publication of four publicly available reports.
- The main and final report will be the pathway description, due to be delivered by the end of 2023. The results are intended to be used beyond the project period.

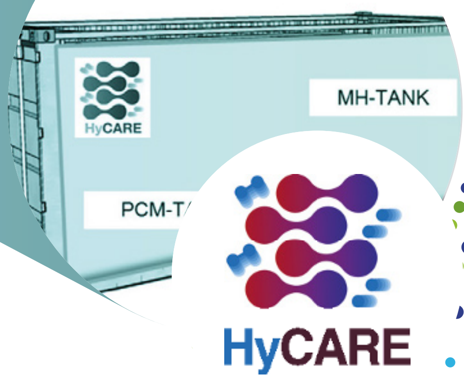
QUANTITATIVE TARGETS AND STATUS

Target source	Parameter	Target	Achieved to date by the project	Target achieved?
Project's own objectives	Blending percentage compatible with existing gas transmission networks	Technical compatibility of materials and equipment in transmission networks	Trials have been conducted with blends with 20 % hydrogen content, with and without trace impurities	⚙
	Readiness of gas transmission networks for H_2 distribution	Identify existing assets and their readiness for hydrogen transport	First inventory of the European grid	✓
	Techno-economic approach for grid repurposing	Start modelling	First scenarios modelled	⚙

HYCARE

AN INNOVATIVE APPROACH FOR RENEWABLE ENERGY STORAGE BY A COMBINATION OF HYDROGEN CARRIERS AND HEAT STORAGE

Demonstrator



Project ID:	826352
PRD 2023:	Panel 2 – H2 storage and distribution
Call topic:	FCH-02-5-2018: Hydrogen carriers for stationary storage of excess renewable energy
Project total costs:	EUR 2 039 230.00
Clean H_2 JU max. contribution:	EUR 1 999 230.00
Project period:	1.1.2019–31.7.2023
Coordinator:	Università degli Studi di Torino, Italy
Beneficiaries:	Stühff Maschinen- und Anlagenbau GmbH, Stühff GmbH, Tecnodelta SRL, GKN Sinter Metals Engineering GmbH, Parco Scientifico Tecnologico per l'Ambiente SpA, Institutt for Energiteknikk, Helmholtz-Zentrum Hereon GmbH, Fondazione Bruno Kessler, Engie, Centre national de la recherche scientifique

http://www.hycare-project.eu/

PROJECT AND OBJECTIVES

The main objective of HyCARE is the development of a prototype hydrogen storage tank using a solid-state hydrogen carrier on a large scale. The tank will be based on an innovative concept, joining hydrogen and heat storage, to improve the energy efficiency of the whole system. The tank will be joined to a proton-exchange membrane (PEM) electrolyser as the hydrogen provider and a PEM fuel cell as the hydrogen user at the Engie Crigen laboratory, located in Île-de-France. As of 2023, the system is undergoing testing.

NON-QUANTITATIVE OBJECTIVES

- **Safety.** The project aims to achieve low temperatures and pressures for storing hydrogen using carriers.
- **Energy efficiency.** The project aims to improve the energy efficiency of hydrogen storage through the use of heat storage using phase change materials.

PROGRESS AND MAIN ACHIEVEMENTS

- Finalisation of the tank's assembly – using metal hybrid and phase change material tanks and pumping system components – was achieved. Pre-commissioning tests (i.e. FAT tests) were concluded in November 2022, enabling the tank transfer.
- The tank was moved to the installation site at the beginning of December 2022.
- At the installation site, fuel cells genset were received in September 2022 and the final commissioning was performed (assembly with the tank and partial SAT) in mid December 2022.
- System integration procedures were concluded in terms of long-term shutdown and control logic. The activation procedure and testing are under way.
- Following the progress with the tank system, techno-economic analysis is under way. Dissemination and exploitation of the project results are also being conducted.

FUTURE STEPS AND PLANS

- Finalisation of system activation was planned for March 2023. Testing of the demonstrator will take at least 4 months.
- A final exploitation event was planned for 21 April 2023 to showcase the project's tank and results.
- Techno-economic analysis, life cycle analysis and a market deployment plan will be finalised at the end of the project, in July 2023. The project is receiving support from the Horizon Results Booster platform for business plan development.

QUANTITATIVE TARGETS AND STATUS

Target source	Parameter	Unit	Target	Achieved to date by the project	Target achieved?
Project's own objectives	Volumetric capacity of H_2 carrier	kg of H_2 per unit of volume of carrier	N/A	Reversible capacity at 55 °C at 1–25 bar of less than 70	⚙
	Gravimetric capacity of H_2 carrier	% of H_2 weight in the carrier		Reversible capacity at 55 °C at 2–20 bar is equal to 1.1	
	Hydrogen storage capacity	Maximum amount of H_2 in kg that can be stored in the system		Estimated reversible capacity of 44 at 55 °C, 1–25 bar	
	Max. tank pressure	Pressure rating of the H_2 carrier tank in bar	< 50	40	✓
	Cyclability	Number of full cycles until reaching a 2 % reduction in the gravimetric capacity of the H_2 carrier	250	250	

HYPSTER

HYDROGEN PILOT STORAGE FOR LARGE ECOSYSTEM REPLICATION

Project ID:	101006751
PRD 2023:	Panel 2 – H2 storage and distribution
Call topic:	FCH-02-7-2020: Cyclic testing of renewable hydrogen storage in a small salt cavern
Project total costs:	EUR 21 158 886.73
Clean H_2 JU max. contribution:	EUR 4 999 999.00
Project period:	1.1.2021–31.12.2023
Coordinator:	Storengy SAS, France
Beneficiaries:	Association pour la Recherche et le Développement des Méthodes et Processus Industriels, Axelera – Association Chimie-Environnement Lyon et Rhone-Alpes, Ecole Polytechnique, Element Energy Limited, Equinor Energy AS, ERM France, ESK GmbH, Inovyn ChlorVinyls Limited, Institut national de l'environnement industriel et des risques, Brouard Consulting SAS, Storengy SA

https://hypster-project.eu/

PROJECT AND OBJECTIVES

HyPSTER aims to demonstrate the industrial-scale operation of cyclic hydrogen storage in salt caverns to support the emergence of the hydrogen energy economy in Europe in line with Hydrogen Europe's overall roadmapping. The cavern is located in Étrez in Auvergne-Rhône-Alpes in France. For the production of green hydrogen, the Étrez 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 (the equivalent of the daily consumption of 16 hydrogen buses).

PROGRESS AND MAIN ACHIEVEMENTS

- The subsurface materials for hydrogen salt cavern storage were ordered and are now in place.
- The surface materials have been selected and ordered. The civil works necessary to install the facilities have been carried out.
- 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.

FUTURE STEPS AND PLANS

- The hydrogen production platform facilities (electrolyser, compressor, etc.) will be received in Q2 and Q3 2023.
- The workover of the EZ53 well is ongoing and was expected to finish in April 2023. The project will build surface facilities so that the cavern can be operational before the planned tightness tests, which will take place in Q3 2023.

QUANTITATIVE TARGETS AND STATUS

Target source	Parameter	Unit	Target	Target achieved?
MAWP addendum (2018–2020)	Power	MW	1	
	H_2 mass	kg	2 000	
	CAPEX	€/kg	450	
	OPEX	€/kg	1	

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HYSTORIES

HYDROGEN STORAGE IN EUROPEAN SUBSURFACE

Project ID:	101007176
PRD 2023:	Panel 2 – H2 storage and distribution
Call topic:	FCH-02-5-2020: Underground storage of renewable hydrogen in depleted gas fields and other geological stores
Project total costs:	EUR 3 024 631.68
Clean H_2 JU max. contribution:	EUR 2 499 911.75
Project period:	1.1.2021–30.6.2023
Coordinator:	Geostock SAS, France
Beneficiaries:	Agencia Estatal Consejo Superior de Investigaciones Científicas, Bureau de Recherches Géologiques et Minières, Česká Geologická Služba, CO2GeoNet – Reseau d'Excellence Européen sur le Stockage Geologique de CO2, Ethniko Kentro Erevnas Kai Technologikis Anaptyxis, Fundación para el Desarrollo de las Nuevas Tecnologías del Hidrógeno en Aragón, Geoinženiring Druzba Za Geoloski Inzeniring DOO, Geological Survey of Denmark and Greenland, Geologische Bundesanstalt, Główny Instytut Górnictwa, Helmholtz Zentrum Potsdam – Deutsches GeoForschungsZentrum, Institut royal des Sciences naturelles de Belgique, Institutul National de Cercetare-Dezvoltare Pentru Geologie si Geoecologie Marina – GeoEcoMar, Instytut Gospodarki Surowcami Mineralnymi i Energia PAN, Istituto Nazionale di Oceanografia e di Geofisica Sperimentale, Ludwig-Bölkow-Systemtechnik GmbH, MicroPro GmbH, Middle East Technical University, Montanuniversität Leoben, NORCE Norwegian Research Centre AS, Sveučilište u Zagrebu Rudarsko-geološko-naftni fakultet, Tallinna Tehnikaülikool, UK Research and Innovation, Universidade de Évora

https://hystories.eu

PROJECT AND OBJECTIVES

Although storing pure hydrogen in salt caverns has been practised in Europe since the 1970s, no pure hydrogen storage in depleted fields or aquifers has been undertaken. Hystories will deliver technical developments applicable to a vast range of future aquifer or depleted field sites, conduct techno-economic feasibility studies and provide insights into underground hydrogen storage for decision-makers in government and industry. The project started on 1 January 2021 and is now 60 % complete.

PROGRESS AND MAIN ACHIEVEMENTS

- The project has attained technological developments for pure hydrogen storage in depleted fields and aquifers.
- It has gained techno-economic insights into the development of underground storage of hydrogen.

FUTURE STEPS AND PLANS

- Hystories will proceed with the implementation of the work, which has been delayed; the focus is on completing this ambitious project on time.
- The main technical development analyses are complete: the key preliminary results have been obtained and the hydrogen storage needed by the European energy system has been identified. The remaining tasks related to the techno-economic assessments are ready to be carried out.
- The techno-economic analyses are complete; the focus is on elaboration of the final implementation plan.

QUANTITATIVE TARGETS AND STATUS

Target source	Parameter	Unit	Target	Achieved to date by the project	Target achieved?
MAWP addendum (2018–2020)	Large-scale H_2 storage capital cost	€/kg	0.6	0.017 (salt) 0.011 (porous)	✓
	Large-scale H_2 storage / release energy use	MWh/kg	9.3	1.7 (salt) 2.5 (porous)	
	Large-scale H_2 storage chain efficiency	%	72	95 (salt) 92.5 (porous)	

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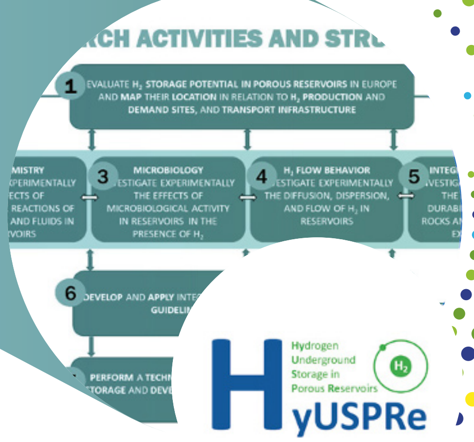
HYUSPRE

HYDROGEN UNDERGROUND STORAGE IN POROUS RESERVOIRS



Project ID:	101006632
PRD 2023:	Panel 2 – H2 storage and distribution
Call topic:	FCH-02-5-2020: Underground storage of renewable hydrogen in depleted gas fields and other geological stores
Project total costs:	EUR 3 714 850.00
Clean H_2 JU max. contribution:	EUR 2 499 850.00
Project period:	10.1.2021–31.12.2023
Coordinator:	Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek, Netherlands
Beneficiaries:	Centrica Storage Limited, Energie Beheer Nederland BV, Energieinstitut an der Johannes Kepler Universität Linz Verein, Equinor Energy AS, Fondazione Bruno Kessler, Forschungszentrum Jülich GmbH, Magyar Foldgaztarolo Zartkoruen Mukodo Reszvenytarsasag, Nafta AS, Neptune Energy Hydrogen BV, RAG Austria AG, Shell Global Solutions International BV, Snam SpA, Technische Universität Clausthal, University of Edinburgh, Uniper Energy Storage GmbH, Wageningen University

https://www.hyuspre.eu/

PROJECT AND OBJECTIVES

HyUSPRe studies the potential of large-scale hydrogen storage in porous reservoirs in Europe. This includes the identification of suitable geological storage reservoirs and a techno-economic feasibility assessment for hydrogen storage in these reservoirs. The project is addressing specific technical challenges regarding storage, and conducting an economic analysis to facilitate the decision-making process for the development of a portfolio of potential field pilots. The techno-economic assessment will allow for the development of a roadmap for widespread hydrogen storage towards 2050.

NON-QUANTITATIVE OBJECTIVES

- HyUSPRe aims to conduct a study assessing the potential matching of hydrogen supply and demand sites, including the necessity of hydrogen to buffer time-varying renewable energy demands.
- The project aims to conduct a study on the potential of European hydrogen underground storage to facilitate a zero-emission energy system by 2050.

PROGRESS AND MAIN ACHIEVEMENTS

HyUSPRe recently completed the first periodic reporting period, covering months 1–15; overall, the project is on track. Nearly all projected research activities were carried out, and related deliverables realised and published on the project website. Several activities and reports have been delayed – these are all related to the experimental work programme and show that laboratory experiments often do not proceed exactly as planned and need flexibility in execution. Part of the projected output and key exploitable results were able to be achieved by the end of the first reporting period.

FUTURE STEPS AND PLANS

It is expected that HyUSPRe will be executed in line with the project plan. The technical work is ongoing. For the laboratory experiments, agreements have been made with industrial partners, and rock and fluid samples and data have been collected from them. All but two deliverables planned in the first reporting period (months 1–15) were achieved. The consortium will continue to execute the research programme in the second period (months 16–27; ends in December 2023) and is optimistic that all activities, evaluations and reporting will be finalised within the originally agreed project timescales.

QUANTITATIVE TARGETS AND STATUS

Target source	Parameter	Target achieved?
Project's own objectives	GIS-based, visualise suitable H_2 underground stores and their H_2 storage potential	✓
	Establish geochemical, microbial, flow and transport, and geomechanical processes of H_2 in porous reservoirs	⚙
	Establish cost estimates and identify the business case for H_2 storage in porous reservoirs	⚙
	Map the proximity of hydrogen stores to large renewable energy infrastructure	✓
	Evaluate the amount of renewable energy that can be buffered in relation to time-varying demands	✓
	Develop future scenario roadmaps for EU-wide implementation	⚙

Clean Hydrogen Partnership

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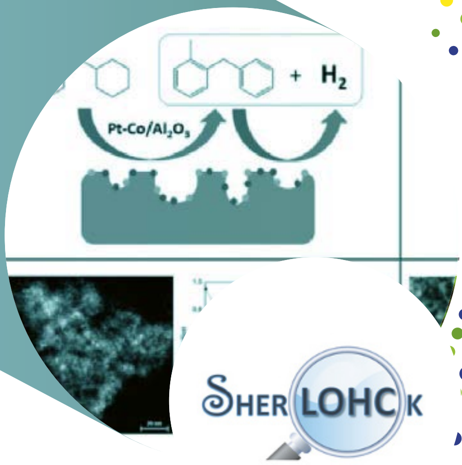

SHERLOHCK

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
PRD 2023:	Panel 2 – H2 storage and distribution
Call topic:	FCH-02-1-2020: Catalyst development for improved economic viability of LOHC technology
Project total costs:	EUR 2 563 322.50
Clean H_2 JU max. contribution:	EUR 2 563 322.50
Project period:	1.1.2021–31.12.2023
Coordinator:	Commissariat à l'énergie atomique et aux énergies alternatives, France
Beneficiaries:	Evonik Operations GmbH, Friedrich-Alexander-Universität Erlangen-Nürnberg, Hydrogenious LOHC Technologies GmbH, Kuwait Petroleum Research & Technology BV, Noordwes-Universiteit, Universidad del País Vasco / Euskal Herriko Unibertsitatea

https://sherlohck.eu/

PROJECT AND OBJECTIVES

Liquid organic hydrogen carriers (LOHCs) are attractive due to their ability to safely store large amounts of hydrogen (up to 7 wt% or 2 300 kWh/t) for a long time and to release pure hydrogen on demand. The project targets the development of (i) highly active and selective catalysts with partial/total substitution of platinum group metals (PGMs); (ii) a novel catalytic system architecture, including the catalyst and the heat exchanger, to minimise the internal heat loss and to increase the space–time yield; and (iii) novel catalyst testing, system validation and demonstration in the demonstration unit (> 10 kW, > 200 hours).

PROGRESS AND MAIN ACHIEVEMENTS

Requirements in line with the objectives of the project have been defined for the hydrogenation and dehydrogenation catalysts; liquid organic hydrogen carrier type and quality; hydrogen quality; testing routine; and energy consumption. This initial work has enabled the foundations to be laid for the whole project. Benzyltoluene was chosen as the reference molecule, and Pt-based catalysts from Clariant were selected as catalysts' benchmark.

The use of density functional theory predictive analysis in the catalyst design has led to a reduction in the use of PGM catalysts. Calculations were applied to the dehydrogenation of methylcyclohexane (to toluene) as a reference molecule, benzyltoluene being too complex for such calculation. The calculated overall dehydrogenation energies for the various considered alloys showed that alloys such as cobalt alloys (including Co_3Pt), SnPt, Sn_3Pt_2, Sn_2Pt and Sn_4Pt could be potential low-Pt-based catalytic materials. The catalyst materials have been synthesised and tested at laboratory scale. 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 the catalysts with 1 wt% Pt but using half the amount of this noble metal. PGM-free catalysts show very low activity. Furthermore, through experiments with model substances simulating by-product formation, it was also possible to gain better insights into the dehydrogenation reaction and catalyst deactivation. Further promising results were obtained for the first catalyst reactivation procedures by oxidative regeneration with synthetic air executed in batch operation.

In parallel, to explore the advantages of structured heat exchanger reactors combined with improved catalysts, models and simulations were used to support the choice of possible reactor geometries, in particular to define suitable heat-conductive reactor structures. The results indicate that, for both reactions, foam structure, catalyst activity, mass and operating conditions are first-order parameters. Initial three-dimensional monolith structures have been prepared to integrate catalyst materials.

A communication and dissemination plan was developed at the beginning of the project. The communication activities carried out involve:

- the project website;
- diffusion of activities on LinkedIn (https://www.linkedin.com/in/sherlohck/?originalSubdomain=es) and Twitter, now known as X (https://twitter.com/SherlohckProj);
- participation in promotional events (conferences, workshops);
- distribution of newsletters and press releases.

The project has standardised the test protocol.

FUTURE STEPS AND PLANS

- SherLOHCk will integrate the catalyst into the thermal conductive support. The design of the first conductive support is ongoing.
- Long-term testing in continuous operation (> 200 hours) has not started yet.
- Testing of the resistance of catalysts to different poisons has not started yet.
- The modelling of the reaction kinetics for the design of new reactors has started for the dehydrogenation reaction.

QUANTITATIVE TARGETS AND STATUS

Target source	Parameter	Unit	Target	Achieved to date by the project	Target achieved?	SoA result achieved to date (by others)	Year of SoA target
Project's own objectives	Catalyst productivity in dehydrogenation	g of H_2/g of catalyst/min	3	5.3	✓	0.85	2022
	Degree of conversion	%	90	74		~ 100	
	Catalyst selectivity	%	99.8	99.04		~ 100	

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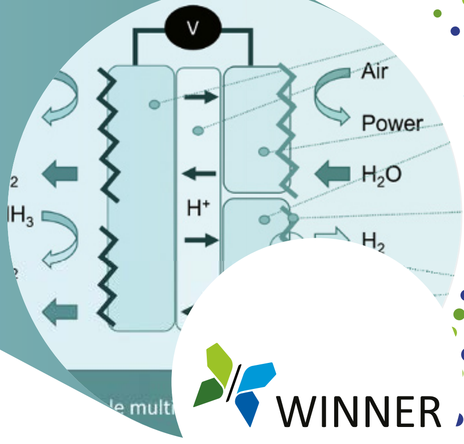
WINNER

WORLD-CLASS INNOVATIVE NOVEL NANOSCALE OPTIMISED ELECTRODES AND ELECTROLYTES FOR ELECTROCHEMICAL REACTION



Project ID:	101007165
PRD 2023:	Panel 2 – H2 storage and distribution
Call topic:	FCH-03-1-2020: HT proton conducting ceramic materials for highly efficient and flexible operation
Project total costs:	EUR 2 931 788.75
Clean H_2 JU max. contribution:	EUR 2 931 788.75
Project period:	1.1.2021–31.12.2023
Coordinator:	Sintef AS, Norway
Beneficiaries:	Agencia Estatal Consejo Superior de Investigaciones Cientificas, Alleima, CoorsTek Membrane Sciences AS, Danmarks Tekniske Universitet, Engie, Shell Global Solutions International BV, Universitetet i Oslo

https://www.sintef.no/projectweb/winner/

PROJECT AND OBJECTIVES

WINNER is contributing to the shift towards a more sustainable energy future by developing an efficient and durable technology platform based on electrochemical proton-conducting ceramic cells designed to unlock a path towards commercially viable production, extraction, purification and compression of hydrogen, at small or medium scale, using three process chains:

- cracking of ammonia to produce pressurised hydrogen or power, where proton-conducting ceramic reactors (PCCRs) 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 PCCRs open new sustainable pathways for electrically driven processes in the chemical industry;
- reversible steam electrolysis, where PCCRs allow for a shift from 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.

NON-QUANTITATIVE OBJECTIVES

WINNER is developing a multiscale multiphysics modelling platform integrating all disciplines (atomistic, electrochemical, mechanical, fluid flow, reactor engineering, electric, heat) with the goal of establishing rate-determining steps at meso scale in the electrochemical cell, and the most efficient dimensioning and arrangement of the cells in the multitube reactor design. The work is supported by relevant experimental data and enhanced experimentation methodologies applied in the project.

PROGRESS AND MAIN ACHIEVEMENTS

State-of-the-art (SoA) cell development. The project has developed novel tubular cells based on the production line established using the software CTMS. The half-tubular cells consist of a Ni-BZCY72 electrode with a BZCY81 dense electrolyte. Various electrode materials and architectures have been screened for the multiple applications of the project. The following performance criteria were successfully met for the reversible electrolysis cells and ammonia-to-hydrogen cells: cell area-specific resistance of below 1 Ωcm² at 650 °C, faradaic efficiency of 80–90 % and a degradation rate below 1.2 % per 1 000 hours under reversible operation. For the conversion of ammonia to hydrogen, the NH_3 conversion is above 99 % with H_2 extraction of > 98 %. Current work on dehydrogenation application is focusing on materials/electrode research. Results will be presented in the next period.

A tubular cell was successfully operating in reversible operation for more than 4 000 hours at 4 bar at 650 °C. The cell shows high faradaic efficiency at the end of the testing period (above 80 %). Post-characterisation analysis is currently being performed.

Engineering model. The results of these research and development activities are reported in several public deliverables (31–34). The partners initially worked on establishing a communication platform (i.e. defining common nomenclature, parameters and models) to put in place a link between the different models and competences developed from the atomistic scale to the process scale. An engineering model has been defined for each of the WINNER applications; these models are available in Excel format and in converted Aspen files. The models are built based on the definition of the process flowsheet with necessary balance of plant, operating conditions, electrochemistry, kinetic and heat balance, etc. The tool is now functioning with multiple integrated models (e.g. integrated atomistic + kinetics + electrochemistry models at the cell level; CFD + engineering tool + Aspen models at the cell, reactor and process levels; mechanical model to be integrated with CFD). The outputs of this tool include 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.).

Life cycle assessment. Life cycle assessment evaluation of the three applications is currently in progress, with user cases and benchmark cases defined for all applications.

FUTURE STEPS AND PLANS

WINNER is currently preparing for the multitube module demonstration, which will focus on reversible electrolysis operating at 600 °C with pressure ranging from 4 bar to 20 bar. Twelve cells will be tested in parallel. The production for this cell has started, as have all activities around the test unit (plant and analytic coupling, hazard and operability analysis, definition of operational protocols, commissioning).

QUANTITATIVE TARGETS AND STATUS

Target source	Parameter	Unit	Target	Achieved to date by the project	Target achieved?	SoA result achieved to date (by others)	Year of SoA target
Project's own objectives and MAWP addendum (2018–2020)	Levelised cost of the produced hydrogen	€/kg	5	N/A	⚙	> 6 based on GAMER technology with several scaling-up assumptions	2022
Project's own objectives	ASR of the cell	Ωcm² at 650 °C	< 1	< 1	✓	2.5	
	Round-trip efficiency of reversible steam electrolysis	% at 650 °C	> 75	N/A	⚙	N/A	2019
	Faradaic efficiency	%	> 95	> 90	⚙	> 90	2021
	Durability test	hours	3 000	> 4 000	✓	< 1 000	

Clean Hydrogen Partnership

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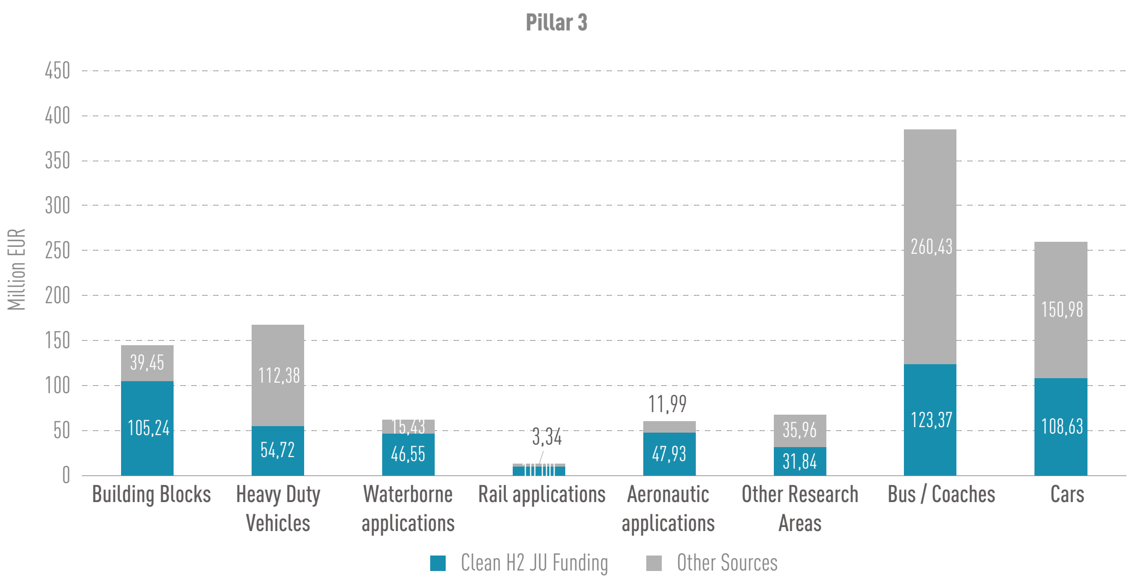
III. PILLAR 3 - H_2 END USES - TRANSPORT

Objectives: The Pillar 3 "Hydrogen End uses – Transport" of the Clean Hydrogen JU's SRIA aims to advance the adoption of hydrogen and fuel cell technologies in the transport sector. Pillar 3 encompasses both research projects and demonstration initiatives and is divided into 7 Research Areas: building blocks, aviation, heavy duty vehicles, waterborne applications, rail applications, buses and coaches, and cars.

Budget: Following the Calls between 2008 and 2022, the Clean Hydrogen JU supported 76 projects relevant for this Pillar with a total Clean Hydrogen JU contribution of EUR 528.3 million and a contribution from partners of EUR 630 million. The distribution of funding over the Research Areas considered in this panel is shown below in Figure 34.

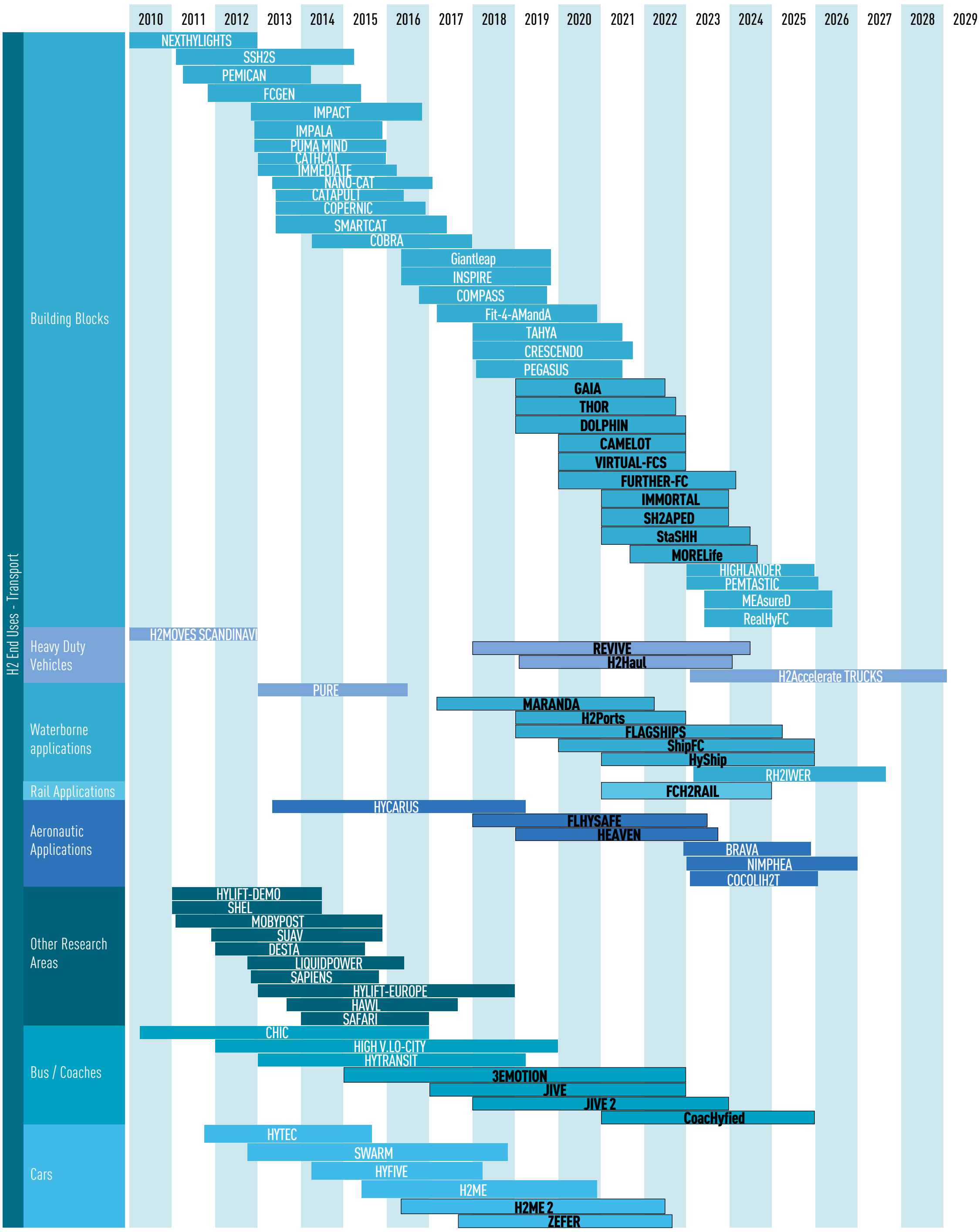
Figure 34: Funding for Pillar 3 projects (2008-2022)



Source: Clean Hydrogen JU

Projects: Figure 35 below, shows that 26 projects were ongoing and/or concluded in 2023 under Pillar 3, grouped by Research Area. Building blocks Research Area, with 13 projects since 2018, attracts a lot of attention to build capacity on the necessary components.

Figure 35: Project timelines of Pillar 3 – H2 end uses – Transport

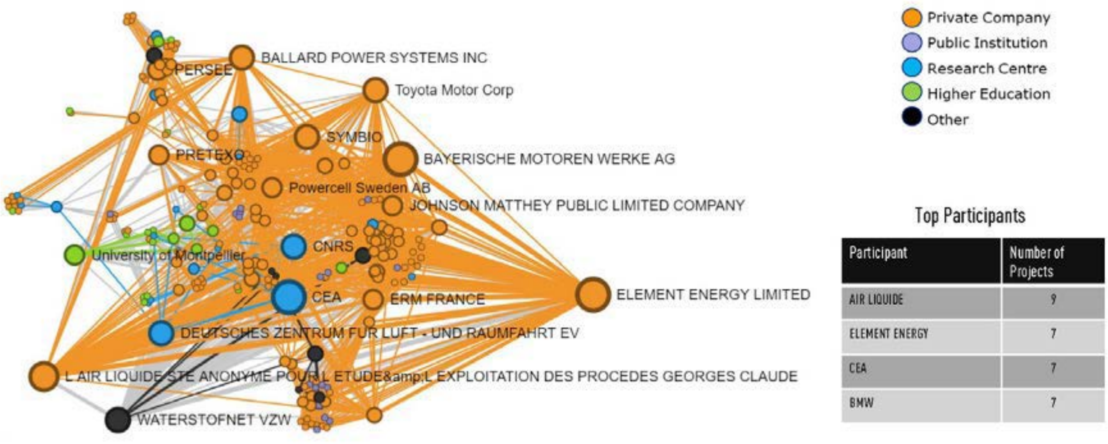


Source: Clean Hydrogen JU

NB. Projects highlighted in black were considered for the 2023 Programme Review.

[Figure 36](#) below is a plot produced using TIM (as described in Section 2.4) [121]. This plot shows the connections between partners present in the 26 projects reviewed within this year's Programme Review under Pillar 3[122]. The participants of the projects grouped under Pillar 3 often have strong links to each other. Research institutes (CEA, DLR and CNRS), along with the Air Liquide, Element Energy, and BMW, are the key participants in this Pillar (i.e. those present in the most projects).

Figure 36: TIM Plot showing the participants in the 26 projects reviewed



Top Participants

Participant	Number of Projects
AIR LIQUIDE	9
ELEMENT ENERGY	7
CEA	7
BMW	7

Source: TIM (JRC)

BUILDING BLOCKS

The Building Blocks Research Area includes projects on FC system technologies; FURTHER-FC, CAMELOT, GAIA, Virtual-FCS, IMMORTAL, DOLPHIN, MORELIFE and STASHH. Furthermore, 3 projects on on-board vehicle hydrogen storage are assessed within this Research Area, namely TAHYA, THOR and the recently started SHA2PED.

Projects on fuel cell system technologies

TRL for these projects are in the range of 2-3, except for DOLPHIN for which we assess targets are towards TRL 4 as it tackles a short stack of 5 kW and GAIA aiming to reach TRL 5 in MEA development. StasHH starts from TRL 5 targeting TRL 6-7 at the end of the project.

FURTHER-FC builds upon the PEMICAN[123] project. It aims to improve gas and proton transfer near catalytic structures, and to investigate and validate performance limitations owed to coupling between electrochemical and transport issues in the cathode catalyst layer. It uses structural 3D characterisations, local operando diagnostics coupled with advanced modelling, from sub-μm to full thickness addressing durability issues. Despite delays, it progressed with the characterisation of reference catalyst layers (with ultra-low loading), gas diffusion layer (with microporous layer) and first customised MEAs (common MEA with DOLPHIN project) by Atomic Force Microscopy, Raman and 3D imaging by FIB SEM, modelling based on these images and evaluation of transport and material properties (in-plane/through-plane conductivity, hydrophilicity and solvophilicity).

CAMELOT is focused on improving understanding of transport limitations in fuel cell electrodes. The project is using a combination of numerical modelling and advanced in-situ characterisation to build a scientific

121 The size of the node represents the number of projects a partner is involved in, whilst the thickness of the links represents the number of projects in common between the linked partners. The colour is based on the type of organisation as provided in CORDIS.

122 Note that only data aggregated for the 26 projects are reviewed under the Pillar 3. It has not been possible to make a distinction per SRIA research area.

123 https://cordis.europa.eu/project/id/256798/reporting

understanding of the limitations in state of the art MEA. The project suspended its activities between March 2021 and January 2022[124]. In 2022 the project prepared a new generation of ultra-thin catalyst coated membrane, CCM, with reduced Pt loadings produced using different techniques. These CCMs are not yet fully characterised nor optimised. The other main objective, the development of the model supposed to describe the innovative CCMs of the project, has started but the current developments (1D) could be difficult to extend to the real case (3D), also affecting the rest of the objectives.

GAIA, finished in June 2022, aimed to develop components (electro-catalysts, membranes, GDL[125] and MPL[126]) with improved interfaces to minimise polarisation resistance in next generation MEAs. It delivered a BoL[127] power density of 1.80 W/cm2 at 0.6 V (1.8 W/cm2 AWP 2019 target), validated performance of 10 cells short stack at anode and cathode stoichiometry ratios 1.5 and 2.0 respectively, RH 50% both sides. It is a major result, at least in terms of publicly known fuel cell performance. By reaching this high-power density without increasing platinum loading, the Pt-specific power density was reduced from 0.45 g Pt/kW (e.g. VOLUMETRIQ) to 0.25 g Pt/kW. A durability test of a full-size cell short stack for 600 hours has been performed not reaching the 1000 hours test duration target. The project is highly relevant in regards to the research and innovation for improving the MEA design and development catalysts, ionomers, membranes and gas diffusion layers for increasing power density, which will lower the overall stack cost. For its achievements, GAIA was given the best success story award during the Programme Review Days 2022.

VIRTUAL-FCS develops an open source (under MIT license) software-hardware toolkit for rapidly designing and optimising PEM fuel cells/battery hybrid powertrains and systems of rail, maritime, bus and truck[128]. Despite some COVID-19 related delays, the project defined a hybrid system design and parameters for initial platform and model development (i.e. battery/FC energy management, compressor, pressure regulation, air/H_2/cooling fluid subsystems, vehicle profiles – WLTC drive cycles, etc)[129], established a working model of a FC system and performed a critical review of existing BoP models. Project deadline is April 2023; remaining time shall be used for further validation and deployment with different end user types.

IMMORTAL develops new materials concepts for PEMFC components (electrocatalysts, membranes) by building mitigation strategies to fuel-cell-operation-induced degradation to ensure that both their activity and their stability are sustained. The potential of developed material components is utilised by introducing novel electrodes and MEA constructions to deliver step-change durability while exceeding 1.2 W/cm^2 at 0.675 V. Load profile tests for heavy-duty MEA performance and durability assessment will be developed, including input from real life usage profiles, from H2Haul project. The IMMORTAL project also aims on MEA performance and durability validation in full size cell short stacks using accelerated stress testing and develop a robust algorithm for lifetime prediction to 30,000 hours operation with less than 10% performance degradation. It has developed highly stable catalyst layers at the target platinum loading (0.3 mg/cm^2) that achieve a decay rate due to irreversible losses ≥50% lower than the reference CCM (from the INSPIRE project) and validated a highly durable reinforced membrane that has withstood >100 000 wet/dry cycles in an MEA held at open circuit voltage at 90 °C.

DOLPHIN, extended by one year, investigates an innovative route to produce lightweight and compact fuel cell and stack architecture featuring a Dual-Core Single Repeat Unit (DC-SRU) aiming to validate 100 kW lightweight and compact fuel cell stack designs, capable of reaching high power density and have improved durability compared to the present state of the art. Using mechanically strong and corrosion resistant structures redesigned for more coherent cell-internal interfaces to delay ageing and increasing system reliability compatible with automotive durability targets, projected Stack Production Costs will be less than 20 €/kW with target Power Density of 1.3 W/cm2 versus SoA of 1.13 W/cm2 while the 2024 target is 2.0 W/cm2 at 0.66 V under nominal condition. After some initial problems the achieved Power Density was lower than the AWP 2019 target (1.8W cm2). An increase of performance up to ~ 2W/cm² validated on 100 cm² single cell was obtained thanks to downsized rib/channel

124 Due to financial problems of project partner Fuel Cell Powertrain GmbH. The project consortium agreement was renegotiated hence two new entities are involved, namely Powercell Sweden and FAST Simulation UG.

125 Gas Diffusion Layers

126 Microporous Layer

127 Beginning of Life

128 www.sintef.no/projectweb/virtual-fcs/newsandevents/virtual-fcs-opensource_platform

129 available at https://github.com/Virtual-FCS/VirtualFCS

dimensions, new membrane, new catalyst layer materials and formulation, and alternative operating conditions (GAIA project).

Project **MORELife** matches highly innovative material developments with advanced operating condition optimisation strategies in a direct feedback-loop with test data from thorough small scale material evaluations, mechanistic modelling, and measurement data from relevant application environments. All activities are coupled with simulation and modelling to provide a deep theoretical understanding of the respective mechanisms, and allow for selective MEA and stack design improvements, provide model validation from test results at an early stage, and to establish a solid basis for predicting the extended lifetimes of 30000 h. MORELIFE developed AST and ADT protocols for SoA catalyst material, prepared 2 generations of novel catalyst material which is under investigation with promising first results in terms of performance, while catalyst leaching of copper is still an issue. Also, post-mortem analysis on aged SoA materials were performed to improve the mechanistic understanding of created models.

The **STASHH** project aims to facilitate designing and manufacturing of PEMFC systems for heavy-duty applications. STASHH's paramount objective is to create all the necessary conditions for fuel cells to become a competitive alternative to diesel and batteries. These conditions are affecting end users (lower TCO, reliable supply chain, fair competition), OEMs (market pooling, scalability, lower RDI) and FCM suppliers (automation). Subject to a revision once testing is completed at project end, the development of standardised heavy-duty fuel cell modules comprises 3 parts: definition of size, interfaces, and API. The modules have an immense potential for roll-out of fuel cell technologies in the heavy-duty sector as its competitiveness among the technology options available is expected to increase significantly due to demand pooling, scalability, automation, increased competition, supply chain reliability, tailored research, development and innovation and lower costs. StasHH designed 7 out of 8 FC modules with power rating between 30-125 kW (vs 30-100 kW SoA), prepared protocols for FAT, SAT and testing and VDI deployed a truck prototype. The project's interaction with Virtual-FCS resulted in the development of a new library for X-in-the-loop testing[130].

Projects on onboard vehicle hydrogen storage

Two projects form this Research Area onboard vehicle hydrogen storage in 2022; THOR and SHA2PED. TRL for these projects are in the range of 4-6. The onboard vehicle storage projects in this Research Area have high impact and are relevant for ongoing standardisation efforts at ISO/TC 197 WG18 on Gaseous hydrogen land vehicle fuel tanks and TPRDs and for future updates of the global technical regulation on hydrogen fuelled vehicles safety (GTR No.13).

THOR finished in September 2022. It aimed to develop a 700-bar nominal working pressure composite hydrogen tank based on thermoplastic resins and with embedded optical fibres for structural monitoring. 15 prototype tanks were produced and subjected to design qualification tests (burst pressure and hydraulic pressure cycling). A new design was prepared but the second prototype could not be manufactured within the project duration. Although the potential tank capability for resisting elevated temperatures during refuelling and leak-before-bursting during a fire has been demonstrated through numerical simulation and tests with samples it has not been possible to validate the thermoplastic tank design with embedded optical fibres, under hydrogen gas cycle and bonfire tests. THOR has also developed a process to recycle composite materials from end-of-life hydrogen tanks, preparing panels of recycled thermoplastic reinforced with carbon fibres that industry could further use.

SH2APED is developing a compressed hydrogen storage system of conformable size fitting the space of the battery onboard vehicles and significant progress has been made. The storage system is an assembly of 9 tubular vessels fitting into a design space of 1800x1300x140 mm. The storage system design is ready, and a patent is filed on the vessel end fitting. The vessel prototypes are undergoing design qualification testing. The results of the remaining qualification tests are expected in 2023. THOR built knowledge on the leak-before-burst is valuable for SH2APED project, which is also implementing this technology. The result of the bonfire test is important as it will confirm the safety improvement of the leak-before-burst technology. Reduction of tank manufacturing costs is expected thanks to the use of a blow moulding process for the tank liner Economic assessment for industrial

130 Where X stands for the abstraction level of the test object

mass manufacturing is in line with the expectations of the automotive industry; although a current challenge is the increasing cost for raw materials, namely the carbon fibres.

HEAVY DUTY VEHICLES

Two demonstration projects on heavy-duty trucks are assessed within this Research Area, namely REVIVE and H2HAUL. These 2 projects will deploy 29 fuel cell trucks and bin-lorries at 13 sites in 7 European countries, see Figure 30.

REVIVE will demonstrate 14 refuse trucks in 8 sites across Europe. Six trucks are already in operation: 2 in Belgium in Antwerp and 4 in the Netherlands in Breda, Arnhem and Son en Breugel. In 2022, those vehicles have driven almost 23 000 km and consumed 3.2 tons of hydrogen. REVIVE makes use of already existing infrastructure (for instance in Helmond, in Groningen area or in Bolzano) and of rented mobile refuelling stations. HRS permitting procedures are still burdensome and this is delaying the opening of the station in Amsterdam. The project managed to resolve the issue of dependency of a single fuel cell supply and REVIVE counts with several FC suppliers. In addition, REVIVE is working on improvements such as a new electro-motor that will increase the performance and quality of the FCET, which requires extensive testing before putting the truck in operation. Another challenge is the homologation and permitting of the refuse trucks as every unique truck configuration needs to go through the vehicle approval process which requires new testing. REVIVE is planning to carry out a life cycle environmental analysis, providing well-to wheel values specific for each demonstration site considering the respective supply chain. Additionally, REVIVE is developing a waste-to-wheel hydrogen business model tool.

REVIVE has synergies with other EU initiatives demonstrating fuel cell hydrogen garbage trucks such as the Interreg project HECTOR (deploying 7 FC trucks in 7 pilot sites in Northwest Europe) and the LIFE project LIFE N GRABHy (demonstrating garbage truck for a period of 2 to 3 weeks in 10 European cities)[131].

H2Haul aims at significantly increasing the technical maturity of the heavy-duty trucks, which are developed by 2 major European OEMs, IVECO FTP and VDL ETS, and will use fuel cells from 3 suppliers. The project will lead to the deployment of 16 trucks (including rigid and articulated vehicles up to 44 tonnes), which will be operated for at least 2 years in day-to-day service, in 4 European countries. The FCETs will be integrated into the fleets of supermarkets such as Carrefour in France, Colruyt in Belgium, a larger retailer in Switzerland, and used in logistics operations by DHL for BMW in Germany and by Air Liquide in France. Two existing HRSs will be upgraded and, additionally, 4 new HRSs for refuelling of trucks will be deployed. At present homologation is granted following an individual type-approval for each vehicle, with implies redundant tests to certify components and in some cases additional tests to meet regulations of each country. GTR No.13 Phase 2[132] has developed type-approval requirements for hydrogen fuelled vehicles, including FCETs; the participation of H2HAUL sharing technical knowledge and experiences at the next phase GTR No.13 is recommended. H2HAUL has synergies with Interreg funded project H2Share[133] . In addition, H2Haul receives funding from French ADEME for the hydrogen refuelling station in Fos-sur-Mer shared with the HyAMMED project. Also, H2Haul is collaborating with IMMORTAL, and both REVIVE and H2Haul provide input to STASHH, working towards standardisation of fuel cells for heavy duty vehicles and increased predicted lifetime.

REVIVE and H2HAUL experiences will serve to address other cross cutting issues such as vehicles and HRS safety, training of drivers and maintenance workers, risk assessments and customer acceptance. These 2 projects are setting the basis for the recently started flagship project H2Accelerate TRUCKS deploying 150 trucks, manufactured by Daimler, VOLVO and IVECO.

131 Both HECTOR and LIFE N GRABHy deploy the vehicles in locations where there are already HRSs. The three projects share lessons learned and dissemination activities as well as policy recommendations to foster the deployment of FCE trucks. A remarkable dissemination has been showing the REVIVE and HECTOR trucks in the Dutch television programme "Transportwereld".

132 GTR No.13 is the global technical regulation on hydrogen and fuel cell vehicles (https://unece.org/fileadmin/DAM/trans/main/wp29/wp29wgs/wp29gen/wp29registry/ECE-TRANS-180a13e.pdf); established in 2013. It is currently under revision (GTR N.13 Phase 2) to take into account scientific and technical progress since its creation, for instance including requirements for hydrogen trucks.

133 H2Share finished in 2022, but its truck is being refurbished, by common partner VDL, and will be further demonstrated within H2Haul.

WATERBORNE APPLICATIONS

Project **MARANDA** finished in 2022. It has developed a 165 kW (2 x 82.5 kW AC) PEMFC based hybrid powertrain system for marine applications, consisted of 2 containers, one with the compressed hydrogen storage and the other with the fuel cells assembly. The initial objective was to demonstrate the fuel cell performance on board the artic research vessel Aranda but the permit for installation was not granted. Hence MARANDA changed the scope and carried out the validation of the fuel cell system on-shore, simulating off-shore conditions in an industrial testing site. The performance and durability tests were completed in March 2022. It is also notable that some of the MARANDA hardware will be reused by the Horizon Europe project ESCALATE[134] and the Finnish project DECARBO[135].

ShipFC will develop a 2 MW ammonia solid oxide fuel cell (SOFC) and will operate a retrofitted containership for at least 3 000 hours per year. In 2022 the project has advanced the detailed designs of all the systems for their placement in the pilot vessel "Viking Energy". The design of the Viking Energy is being completed in a multiple iteration process including hazards identification (HAZID) analysis, together with DNV and the Norwegian Maritime Authority. The fuel cells are being scaled up and have undergone testing in laboratory. In these tests, the achieved power was 1.3 kW and the FC efficiency 60%. Before installation on-board Viking Energy, the complete 2-MW system will be tested, however that test campaign was delayed because of issues with the fuel cell stack's supply chain. In the meantime, SHIPFC has set up the infrastructure for the testing of SOFC systems in the megawatt scale at the Energy House in Norway. An achievement in this period is that the SOFC system design has been evaluated for compliance with DNV class rules and IMO guidelines for fuel cell installations and Approval in Principle has been granted for the containerised module that includes the fuel cell and the safety systems to handle ammonia as fuel[136]. SHIPFC's design will contribute to updating knowledge, as well as setting the state of the art, since the vessel will be the first one powered with ammonia and using SOFC in the range of MW.

FLAGSHIPS will demonstrate 2 hydrogen fuel cell vessels in commercial operation: one in France (Paris) and one in Netherlands (Rotterdam). The Paris demo is a self-propelled barge operating as a goods transport vessel in the city centre. The vessel for Paris, Zulu 06, is already built and is at the yard in Le Havre. There it is being equipped with two 200kW fuel cells and a 350 kg hydrogen storage unit containing compressed hydrogen at 300 bar and with all the necessary safety and operational systems[137]. The demo in Rotterdam is a container vessel transporting goods between Rotterdam and Duisburg. Design and retrofitting works of this vessel have started and are expected to be completed in the course of 2023. The process of gaining approval for the Zulu 06 vessel, involving Bureau Veritas and local authorities, is ongoing but is time consuming[138]. FLAGSHIPS has organised 3 Hazards Identification (HAZID) workshops with class societies. Its experiences regarding vessels approval will be essential for the new Clean Hydrogen JU project: "Renewable Hydrogen for Inland Waterway Emission Reduction - RH2IWER", demonstrating inland waterway vessels[139].

HyShip will demonstrate 1 vessel powered with 3 MW PEM fuel cell system using liquid hydrogen. The vessel will transport goods from port to port along the west coast of Norway. The preliminary designs of the vessel and hydrogen propulsion systems are completed. HYSHIP will benefit from the knowledge and experience of partners in common with HySeas III (Horizon 2020) deploying a passenger and car ferry in the Scottish Orkney Islands.

H2Ports' objective is to shine light on hydrogen as an alternative fuel in maritime ports. It will demonstrate and validate in the Port of Valencia, under real operation conditions, a hydrogen-powered reach stacker in a port container terminal, a fuel cell yard tractor for container transport and roll-on/roll-off ships loading/unloading operations, and a mobile hydrogen supply station. Both the reach stacker and the yard tractor will be the first

134 https://www.escalate-eu.com/

135 https://www.six.fi/post/new-mobile-machines-project-decarbo-decarbonization-of-mobile-machine-systems

136 https://shipfc.eu/almas-marine-fuel-cell-system-awarded-approval-in-principle-by-dnv/

137 https://flagships.eu/2022/02/10/zulu-06-en-route-pour-la-france/

138 This has caused the delay in starting the demonstrations in Paris. Nonetheless, the good news is that Bureau Veritas issued Design Review Attestation for the two fuel cell modules that will be installed on board the Zulu 06 vessel.

139 https://cris.vtt.fi/en/projects/renewable-hydrogen-for-inland-waterway-emission-reduction

of their kind using fuel cells to provide 90 kW and 70 kW power respectively. The reach stacker and the terminal tractor have completed the commissioning of the fuel cells, and the factory acceptance tests in 2022. In February 2023, an H2Ports delegation tested the operation of the hydrogen reach stacker in Germany. The terminal tractor has been delivered to the Port of Valencia in April 2023. The terminal tractor is completed, and its construction is ongoing. Finally, H2Ports has finalised the HRS construction phase and is currently undergoing the safety tests prior to the start of the operative period. The pilot demonstrations have started in the first half of 2023. At the end of the demonstration period, H2Ports will perform a LCA and an inventory of emissions reduction in ports.

The waterborne demo projects are integrated into national RD&D activities; FLAGSHIPS, SHIPFC and HYSHIP benefit from further funding from the Norwegian Research Council and ENOVA (SHIPFC and HYSHIP), and MARANDA received funding from Switzerland's State Secretariat for Education, Research, and Innovation (SERI). In addition, HYSHIP cooperates with the Norwegian HYDRA liquid hydrogen ferry project.

RAIL APPLICATIONS

FCH2Rail, that started in January 2021, is developing a hybrid, bi-modal drive system for trains powered by electrical supply from the overhead line with and by a hybrid pack consisting of fuel cells and batteries when no catenary line is available. In the course of 2022, the fuel cell hybrid power pack has been integrated in the demonstrator train (a refurbished electric commuter train)[140] and static tests have been successfully carried out. Dynamic tests of the demonstrator train on a closed rail track took place in 2022. FCH2RAIL is currently undergoing testing of the hydrogen train on public rail tracks[141]. The first test, in a demanding route of high gradients in the Pyrenees from the Zaragoza to Canfranc, was successfully accomplished[142]. In Spain and Portugal, permits for the train testing and homologation have been received and discussion with Germany is ongoing. FCH2Rail is participating to ongoing standardisation at IEC groups working on IEC63341 - Fuel cells in rail applications and it is recommended that that follows the developments of IEC TC 9 on PNW 9-2697 ED1: Railway applications – Rolling stock – Fuel cell systems for propulsion - Part 2: Hydrogen storage systems. Input from FCH2RAIL will also be valuable for the discussions at the ISO/TC 197 WG24 in charge of the standard ISO 19885-1 Gaseous hydrogen — Fuelling protocols for hydrogen fuelled vehicles Part 1 Design and development process for fuelling protocols. That standard will not only be applicable to road vehicles but also to rail, waterborne and aeronautic applications. FCH2RAIL analysis of gaps in regulation and standards for the introduction of FCE trains is compiled in the report "Gaps in regulatory framework prior to the demonstrator train test", which is publicly available in FCH2RAIL website[143].

AVIATION APPLICATIONS

This Research Area contains the projects FLHYSAFE and HEAVEN. FLHYSAFE will demonstrate a fuel cell serving as an emergency power unit in an airplane while in HEAVEN, the fuel cell will power a small aircraft.

FLHYSAFE draws on experience from HYCARUS to demonstrate a cost-efficient modular fuel cell system that can replace the most critical safety systems used as an emergency power unit (EPU) aboard a commercial airplane. The final technological demonstration aims at proving enhanced safety functionalities and the ability of integration into current aircraft designs respecting both installation volumes and maintenance constraints. The project completed the design for fuel cell integration into airborne applications, performing FC short stack testing (using oxygen instead of air) as well as start/stop cycle stack degradation analysis. The experiments show that 466 starts/stop cycles resulted in 0.05 W/cycle degradation rate. No premature degradation due to operating at O_2 instead of air is noticed. A virtual reality tool allowing design optimisation and maintenance instructions has also been developed. In the course of 2022, based on the initial results, the project went through a critical design review of the low-temperature module for the fuel cell system (theoretical A/C system specification done),

140 The transformation of the train can be seen at https://youtu.be/bFBR6nhyEVI

141 https://www.caf.net/en/sala-prensa/nota-prensa-detalle.php?e=423

142 https://verkehrsforschung.dlr.de/en/projects/fch2rail

143 https://verkehrsforschung.dlr.de/en/projects/fch2rail/project-results

demonstrator critical design review (for major subsystems). The first module test campaign was performed. The fuel cell stack was produced, and the converter integrated in the final demonstrator assembly.

HEAVEN project managed to equip an existing small 4-place aircraft with a FC based powertrain, hence increase of aeronautic FC-based powertrain TRL from 3 to 6. This requires further actions, namely an optimisation of balance-of-plant components using cryogenic hydrogen storage technology without employing a battery energy buffer, and implementation of BoP into FC based powertrain. Results are promising, showing a FC stack power mass density of 2.7 kW/kg meeting the target >2.0 kW/kg and a FC power volume density of 4.1 kW/litre also fulfilling the target of >3.5 kW/litre. The main challenges that HEAVEN is facing are first the definition of safety requirements to operate with liquid hydrogen and achieve proper venting conditions, and ultimately receiving the aircraft certification and the permit to fly.

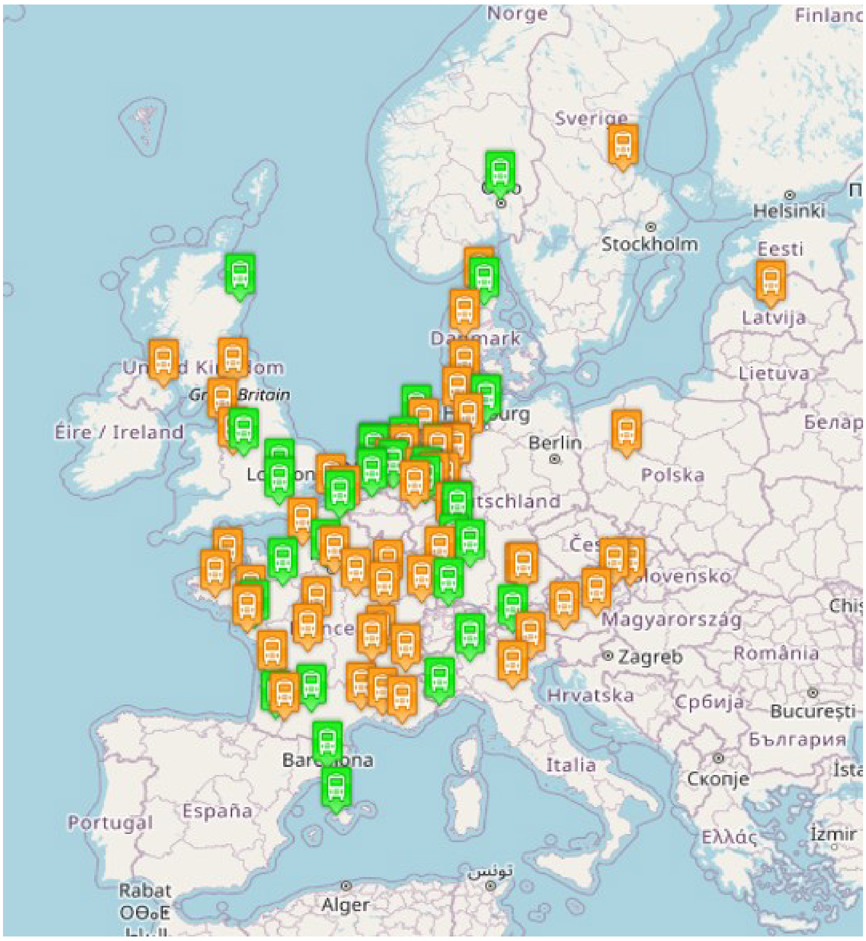
BUSES AND COACHES

3EMOTION, that was concluded at the end of 2022, deployed all the 29 buses it originally aimed to; 10 buses in London, 6 in Rotterdam and the South Holland province, 7 in Versailles, 3 in Pau and 3 in Aalborg. The project, which had been running for 8 years, has demonstrated the operability of buses from 4 different manufacturers with 2 different fuel cells systems. 3EMOTION has succeeded on gathering operational data throughout the project and on sharing operational experiences, attracting new cities, regions and operators into hydrogen buses. The project has also shown good synergies with other projects (JIVE initiatives), other funding calls such as H2 Bus Europe (CEF) and bus manufacturers (Van Hool, Toyota Motor Europe and Caetano Bus) by participating in meetings and sharing experiences and lessons learned. Additionally, 4 peer-reviewed scientific publications were developed under the project duration, mainly on hydrogen refuelling aspects related to buses. It is worth mentioning that the project also created spill-over effects and new activities not originally targeted. An example of this is that the bus concepts developed and tested in the project (range extender trailers) led to the development of the first VDL hydrogen truck, which used the same module on a fuel cell heavy duty truck. A more integrated system for trucks (H2Haul project) evolved from the initial concepts tested in **3EMOTION** with further development.

The buses in some sites of **3EMOTION** met the targets on Hydrogen Consumption (average of 8 kg H_2/100 km), Warranty Time (15 000 h) and Bus Cost (< 850 000 EUR) but fell behind slightly on Availability. The cumulative distance covered by the **3EMOTION** buses through the project duration was close to 3 980 000 km. Overall, the project met its targets in terms of deployment and KPIs.

Combined, **JIVE** and **JIVE 2** are deploying over 300 fuel cell buses in 16 cities across Europe, the largest deployment in Europe to date (Figure 37). The local fleets range from 5 to 50 FCBs, typically 10 to 20. As of 2022, JIVE has ordered all the 142 planned buses, and 132 are in operation, while JIVE 2 has ordered 122 buses out of the 156 planned, has 98 buses in operation and expects to have the committed fleet delivered by mid 2024.

Figure 37: Fuel cell bus demonstration sites in Europe



Source: https://www.fuelcellbuses.eu/

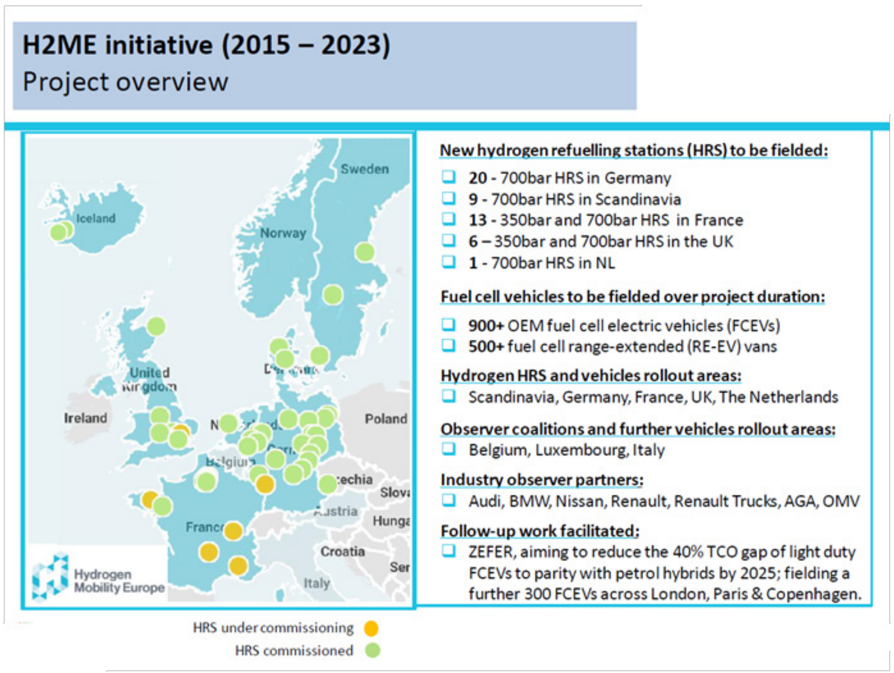
A major advantage for FCBs is the longer distance range they can achieve in comparison to battery electric buses; the new Clean Hydrogen JU project (2020 call). **CoachHyfied** project, which started in January 2021, is aiming to demonstrate coaches with fuel cell powertrains in regional and long-distance passenger transport, taking into account the special challenges for electrification of coaches regarding range, speed, comfort (air conditioning) and luggage space. The project is addressing 2 coach types, both for the medium range Regional Coaches (M3 class II) for regional or intercity transport, as well as the Long-Distance Coaches (M3 class III) for tourist transport. The demonstration comprises 6 coaches from 2 European coach manufacturers, with FC technology from 2 leading FC manufacturers and applies 2 standard compressed hydrogen tank solutions. The vehicles are to be demonstrated in 2 different European regions representing a bandwidth of different geography, climate and operational profiles. The demonstrations aim to cover the full value chain of coach design: power system development, vehicle integration, testing, commissioning, fuelling, operation, service and maintenance.

CARS

The **H2ME** initiative (**H2ME** and **H2ME2** projects) is the largest European deployment to date for hydrogen mobility, planning to deploy more than 1100 vehicles in 10 countries and 50 HRS from 10 suppliers in 6 countries (see Figure 38).

H2ME2 has deployed 759 from the over a thousand vehicles planned and put in operation 15 hydrogen refuelling stations (out of 20). The commissioning of new HRS has been impacted by the COVID-19 pandemic in 2020-2021 and by the lack of experience at local level for reviewing and approving permits authorisation. Consequently, the project has been extended until mid-2023. All 20 HRS should be commissioned and in operation by the end of the project. The H2ME initiative is also producing an ever-growing dataset and its analysis is progressing accordingly. The technical data accumulated will be the basis for further analysis on market and customer readiness. Additionally, H2ME2 has a work-package to assessing the way in which on-site HRS electrolytic hydrogen production can contribute to on-grid balancing of the energy system.

Figure 38: Overview of the H2ME initiative



Source: H2ME[144]

Project **ZEFER** started in 2017, aiming to demonstrating viable business cases for captive fleets of FCEVs (taxi, private hire and police services) and has been extended until August 2023. The fleet vehicles are subjected to high mileages and typically refuel at a centralised fuelling station at the depot, creating a favourable business case for a HRS. The 180 FCEVs planned have been already deployed and in operation (60 in Paris, 60 in London and 60 in Copenhagen). The cars in Paris have been added to the already existing 74 FCEVs HYPE taxi fleet[145], while in London 50 are private hire vehicles by Green Tomato and 10 are police operation vehicles. However, there is only now 10 in operation, the other 50 have been returned due to the lease end. **ZEFER** is upgrading 3 HRS (Zaventem, Paris and London) and at the same time it makes use of **H2ME** stations for refuelling operations. Upgrades are almost completed, leading to improvements in the technical performance and customer experience of HRS.

144 https://h2me.eu/wp-content/uploads/2023/01/H2ME2-D7.19-Public-FV-Emerging-conclusions-document-%E2%80%A6.pdf, December 2022)

145 https://hype.taxi/en/accueil-en/

3EMOTION

ENVIRONMENTALLY FRIENDLY, EFFICIENT ELECTRIC MOTION

Project ID:	633174
PRD 2023:	Panel 3 – H2 end uses – transport
Call topic:	SP1-JTI-FCH.2013.1.1: Large-scale demonstration of road vehicles and refuelling infrastructure VI
Project total costs:	EUR 38 181 930.72
Clean H_2 JU max. contribution:	EUR 14 999 983.00
Project period:	1.1.2015–31.12.2022
Coordinator:	Van Hool NV, Belgium
Beneficiaries:	Aalborg Kommune, Acetilene & Gastecnici Di Bagnoli Maria & C. SAS, Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile, Air Liquide Advanced Business, Air Liquide Advanced Technologies SA, Autocars Dominique, Azienda per la mobilità del Comune di Roma SpA, B.E. Green, Centro Interuniversitario di Ricerca Per lo Sviluppo sostenibile, Commissariat à l'énergie atomique et aux énergies alternatives, Communauté urbaine de Cherbourg, Commune de Cherbourg-en-Cotentin, Compagnia Trasporti Laziali, Connexxion Openbaar Vervoer NV, Connexxion Vloot BV, Dantherm Power AS, Fit Consulting SRL, London Bus Services Limited, Provincie Zuid-Holland, Regione Lazio, Region Nordjylland, Rotterdamse Elektrische Tram NV, Services Automobile de la Vallée de Chevreuse SAS, Syndicat mixte des transports urbains de Pau-Porte des Pyrénées, Università degli Studi di Roma 'La Sapienza', Vlaamse Vervoersmaatschappij De Lijn, WaterstofNet VZW

http://www.3emotion.eu/

PROJECT AND OBJECTIVES

3Emotion aims to operate 29 fuel cell buses (FCBs) in five leading European cities – Aalborg, London, Pau, Rotterdam (with intercity links throughout the province of South Holland) and Versailles – and develop three new hydrogen refuelling stations (HRSs).

Objectives:

- lower H_2 consumption to < 9 kg/100 km;
- integrate the latest drivetrain, fuel cell and battery technologies to lower the total cost of ownership and increase FCBs' lifetimes;
- ensure FCB availability of > 90 %;
- increase warranties (> 15 000 hours) and improve the delivery times of the key components;
- reduce bus investment costs to < EUR 850 000 for a 13 m bus.

PROGRESS AND MAIN ACHIEVEMENTS

- All 29 FCBs and all three HRSs are in operation.
- The project has engaged three manufacturers of original bus equipment to make two different fuel cells at the price per bus set in the initial call, operating at various EU sites.
- The buses are largely meeting their targets on H_2 consumption, average consumption and availability.

FUTURE STEPS AND PLANS

- The project was finalised on 31 December 2022.
- 3Emotion will meet the expectation of having higher capacities at the HRSs. In the final year of the project, as restrictions related to the COVID-19 pandemic have been lifted, the operation of the buses will be resumed, and full operation of HRSs can be achieved.
- The project will perform the data monitoring and gathering of operational and performance indicators for the FCBs and the HRSs.

QUANTITATIVE TARGETS AND STATUS

Target source	Parameter	Unit	Target	Achieved to date by the project	Target achieved?
Project's own objectives	Lower H_2 consumption for FCBs to < 9 kg/100 km	kg/100 km	9	Average: 8	✓
	Ensure availability of > 90 %	%	90	Average: ≤ 80	⚙
	Increased warranties (> 15 000 hours)	hours	15 000	15 000	✓
	Investment cost of EUR < 850 000 for a 13 m bus	€	850 000	850 000	✓

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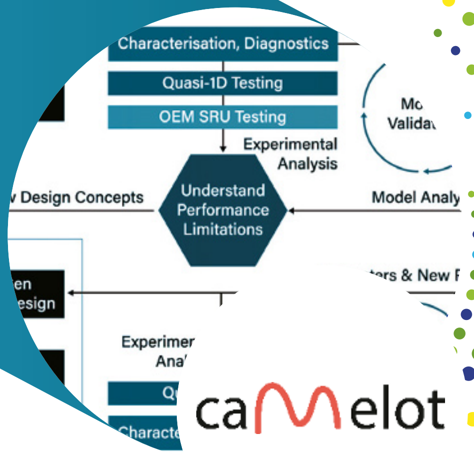


CAMELOT

UNDERSTANDING CHARGE, MASS AND HEAT TRANSFER IN FUEL CELLS FOR TRANSPORT APPLICATIONS

Project ID:	875155
PRD 2023:	Panel 3 – H2 end uses – transport
Call topic:	FCH-01-4-2019: Towards a better understanding of charge, mass and heat transports in new generation PEMFC MEA for automotive applications
Project total costs:	EUR 2 589 273.50
Clean H_2 JU max. contribution:	EUR 2 295 783.50
Project period:	1.1.2020–31.12.2023
Coordinator:	Sintef AS, Norway
Beneficiaries:	Albert-Ludwigs-Universitaet Freiburg, Bayerische Motoren Werke AG, Fast Simulations UG, FCP Fuel Cell Powertrain GmbH, Johnson Matthey Hydrogen Technologies Limited, Johnson Matthey plc, PowerCell Sweden AB, Pretexo, Technische Universität Chemnitz

http://camelot-fuelcell.eu

PROJECT AND OBJECTIVES

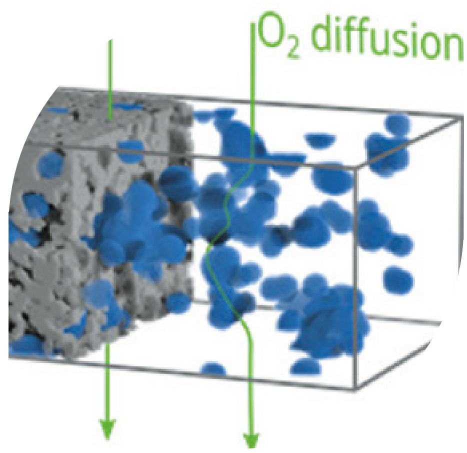
Camelot brings together highly experienced research institutes, universities, fuel cell membrane electrode assembly suppliers and transport original equipment manufacturers to improve understanding of the limitations of fuel cell electrodes. The purpose of this is to provide guidance on the next generation of membrane electrode assemblies required to achieve the 2024 performance targets.

PROGRESS AND MAIN ACHIEVEMENTS

- Ultra-thin membrane electrode assembly construction: the target is < 10 µm; it is currently stable down to 8 µm, with ongoing testing down to 6 µm.
- X-Y-Z graded catalyst-coated membrane layer construction: the initial catalyst-coated membranes have been made with graded catalyst content and graded ionomer content.
- The membrane permeability test set-up has been established.
- X-ray fluorescence and high-resolution scanning electron microscope characterisation of graded catalyst layers have been carried out.

FUTURE STEPS AND PLANS

- The project was on hold for 10 months in 2021 and restarted on 1 January 2022.
- The project timeline was extended by 12 months.

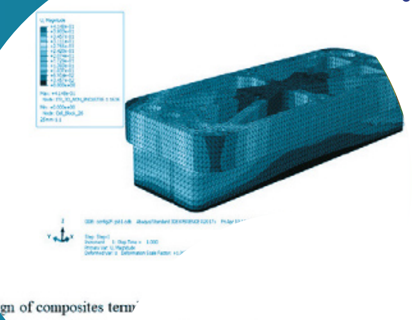


QUANTITATIVE TARGETS AND STATUS

Target source	Parameter	Unit	Target	Achieved to date by the project	Target achieved?
Project's own objectives	Membrane thickness	µm	< 10	6	✓
AWP 2019	Total MEA Pt loading	mgPt/cm²	< 0.08	0.18	⚙
	Power density	W/cm²	> 1.8	0.75	⚙

DOLPHIN

DISRUPTIVE PEMFC STACK WITH NOVEL MATERIALS, PROCESSES, ARCHITECTURE AND OPTIMIZED INTERFACES



DOLPHIN
Disruptive pemfc stack with nOvel materiaLs, Processes, arcHitecture and optimized INterfaces

Project ID:	826204
PRD 2023:	Panel 3 – H2 end uses – transport
Call topic:	FCH-01-6-2018: Game changer fuel cell stack for automotive applications
Project total costs:	EUR 3 244 066.25
Clean H_2 JU max. contribution:	EUR 2 962 681.25
Project period:	1.1.2019–31.12.2022
Coordinator:	Commissariat à l'énergie atomique et aux énergies alternatives, France
Beneficiaries:	Chemours Belgium, Chemours France SAS, Chemours International Operations SARL, DMG MORI Additive GmbH, Faurecia Systemes d'Echappement SAS, Hexcel Composites GmbH & Co KG, Hexcel Composites Ltd, Hexcel Reinforcements SAS, Symbio, Symbio France, University of Manchester, Zentrum für Sonnenenergie- und Wasserstoff-Forschung Baden-Württemberg

http://www.dolphin-fc.eu/

PROJECT AND OBJECTIVES

The overall aim of the project is to validate disruptive technologies for 100 kW lightweight and compact fuel cell stack designs, reaching outstanding (specific and volumic) power density while simultaneously featuring enhanced durability (under automotive application conditions) compared with state-of-the-art (SoA) stacks and being compatible with large-scale/mass production of full-power stacks. Validation of the DOLPHIN technologies will be supported by the design and fabrication of an automotive stack of 5 kW, representative of 100 kW power stacks.

NON-QUANTITATIVE OBJECTIVES

Evaluate interest in and limitations of different material and manufacturing technologies for PEMFC stacks.

PROGRESS AND MAIN ACHIEVEMENTS

- Performance has been increased to ~ 2 W/cm^2 validated on a 100 cm^2 single cell thanks to downsized rib/channel dimensions, a new membrane, new catalyst layer materials and formulation, and alternative operating conditions (Next generation automotive membrane electrode assemblies (GAIA) project).
- Interest in and limitations of different components and manufacturing processes for PEMFC stacks have been identified.
- Potentially even more efficient flow fields and catalyst layer manufacturing processes have been designed.
- The two best solutions have been defined for the manufacture of two stacks (5 kW).

FUTURE STEPS AND PLANS

- Manufacturing, assembly and testing of the 5 kW stacks based on the two technologies selected, for evaluation of the key performance indicators (kW/l, kW/kg, W/cm^2, €/kW, μV/h), are still to be carried out.
- In parallel, an assessment will be conducted to gauge interest in graphene coating of the membrane.
- Define and test an additional set of operating conditions as a trade-off between high stack efficiency (high Sto and RH, as for GAIA) and high system efficiency (as used in Dolphin).

QUANTITATIVE TARGETS AND STATUS

Target source	Parameter	Unit	Target	Target achieved?	SoA result achieved to date (by others)	Year of SoA target
AWP 2018	Weight-specific power density	kW/kg	4		3.4	2017 (by Auto-Stack CORE)
	Volume-specific power density	kW/l	5		4.1	
	Surface power density	W/cm^2	2		1.13	
	Durability	hours	6 000		3 500	
	Stack cost	€/kW	20		36.8	

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FCH$_2$RAIL

FUEL CELL HYBRID POWERPACK FOR RAIL APPLICATIONS

Project ID:	101006633
PRD 2023:	Panel 3 – H2 end uses – transport
Call topic:	FCH-01-7-2020: Extending the use cases for FC trains through innovative designs and streamlined administrative framework
Project total costs:	EUR 18 137 313.98
Clean H_2 JU max. contribution:	EUR 9 999 999.12
Project period:	1.1.2021–31.12.2024
Coordinator:	Deutsches Zentrum für Luft- und Raumfahrt EV, Germany
Beneficiaries:	Administrador de Infraestructuras Ferroviarias, CAF Digital & Design Solutions SA, CAF Power & Automation SL, CAF Turnkey & Engineering SL, Centro de Ensayos y Analisis Cetest SL, Centro Nacional de Experimentación de Tecnologías de Hidrógeno y Pilas de Combustible Consorcio, Construcciones y Auxiliar de Ferrocarriles Investigacion y Desarrollo SL, Construcciones y Auxiliar de Ferrocarriles, SA, Faiveley Transport Leipzig GmbH & Co. KG, Infraestruturas de Portugal SA, Renfe Operadora, Renfe Viajeros SA, Stemmann-Technik GmbH, Toyota Motor Europe NV

www.fch2rail.eu

PROJECT AND OBJECTIVES

The project consortium is developing and testing a new train prototype. At the heart of the project is a hybrid, bimodal drive system that combines the advantages of an electrical power supply from the overhead line with a hybrid power pack consisting of fuel cells and batteries. This system allows for 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 was held in 2022 to support the analysis of gaps in the normative framework.

PROGRESS AND MAIN ACHIEVEMENTS

- Fuel cell hybrid powerpack (FCHPP) development and tests on the CNH$_2$ test bench were successfully completed.
- Physical integration of two FCHPPs into the demonstrator train was successfully completed.
- The first static test of FCHPP in the demonstrator train has been conducted.

FUTURE STEPS AND PLANS

- Dynamic testing of the demonstrator train on closed tracks will be carried out.
- The implementation of the hydrogen refuelling station will be completed.
- The first test runs of the demonstrator train on open tracks will take place.

QUANTITATIVE TARGETS AND STATUS

Target source	Parameter	Achieved to date by the project
Project's own objectives	System lifetime/durability	
	Hydrogen and electricity consumption	

FLAGSHIPS

CLEAN WATERBORNE TRANSPORT IN EUROPE

Project ID:	826215
PRD 2023:	Panel 3 – H2 end uses – transport
Call topic:	FCH-01-2-2018: Demonstration of fuel cell applications for midsize passenger ships or inland freight
Project total costs:	EUR 6 766 811.83
Clean H_2 JU max. contribution:	EUR 4 999 978.75
Project period:	1.1.2019–31.3.2025
Coordinator:	Teknologian tutkimuskeskus VTT Oy, Finland
Beneficiaries:	VTT, ABB Oy, Ballard Power Systems Europe AS, Compagnie Fluviale de Transport, Future Proof Shipping BV, LMG Marin AS, LMG Marin France, Maritime CleanTech, Norled AS, Persee, Seam AS Sogestion, Sogestran

https://flagships.eu/

PROJECT AND OBJECTIVES

Two commercially operated hydrogen fluvial fuel cell vessels will be demonstrated, one in France (Paris) and one in the Netherlands (Rotterdam). The Paris demonstrator (*Zulu*) is a self-propelled barge operating as a goods transport vessel in the city centre; the Rotterdam demonstrator (*FPS WAAL*) is a container vessel transporting goods between Rotterdam and Duisburg. The Paris demonstrator vessel has been built, and H_2 fuel cell systems and storage will be installed. The Rotterdam demonstrator entered the project at the end of 2021, and the design work for that vessel has begun.

PROGRESS AND MAIN ACHIEVEMENTS

- The FCwave fuel cell module has gained the necessary approval from DNV.
- The *Zulu* vessel design was completed, and the vessel has been built. It is at the yard in Le Havre. ABB and Ballard Power Systems Europe systems are in place and installation work has started.

FUTURE STEPS AND PLANS

- The process of gaining approval for the *Zulu* vessel is ongoing, involving Bureau Veritas, CCNR and local authorities.
- The project will demonstrate the *Zulu* vessel in commercial operation. Operations were expected to begin in Autumn 2023.
- The project will finalise the design and retrofitting of the *FPS WAAL* vessel. Work started at the beginning of 2022 after an amendment was accepted. It is expected to be finalised in 2023–2024.

QUANTITATIVE TARGETS AND STATUS

Target source	Parameter	Unit	Target	Target achieved?
MAWP (2014–2020)	PEMFC system lifetime	hours	25 000	
Project's own objectives	Fuel cell systems demonstrated in on-board vessel in commercial operation	months	2 × 18	
	Develop necessary safety measures of H_2 and FC vessels to enable their class approval	–	Class approval gained	
	PEMFC system availability	%	95	
	Cost of a complete FC and H_2 system	€/kW	4 000	

Clean Hydrogen Partnership

Co-funded by the European Union

FLHYSAFE

FUEL CELL HYDROGEN SYSTEM FOR AIRCRAFT EMERGENCY OPERATION

Project ID:	779576
PRD 2023:	Panel 3 – H2 end uses – transport
Call topic:	FCH-01-1-2017: Development of fuel cell system technologies for achieving competitive solutions for aeronautical applications
Project total costs:	EUR 7 296 552.51
Clean H_2 JU max. contribution:	EUR 5 063 023.00
Project period:	1.1.2018–30.6.2023
Coordinator:	Safran Power Units, France
Beneficiaries:	ARTTIC, Commissariat à l'énergie atomique et aux énergies alternatives, Deutsches Zentrum für Luft- und Raumfahrt EV, Instituto Nacional de Técnica Aeroespacial Esteban Terradas, Safran Aerotechnics, Universität Ulm

https://www.flhysafe.eu/

PROJECT AND OBJECTIVES

In the shift towards 'more electric aircraft', fuel cell systems are considered one of the best options for efficient power generation. The main objective of FLHYSAFE is to demonstrate that a cost-efficient modular fuel cell system can replace the most critical safety systems and be used as an emergency power unit aboard a commercial aeroplane, providing enhanced safety functionalities. In addition, the project has the ambition of virtually demonstrating that the system can be integrated, respecting both installation volumes and maintenance constraints, using current aircraft designs.

NON-QUANTITATIVE OBJECTIVES

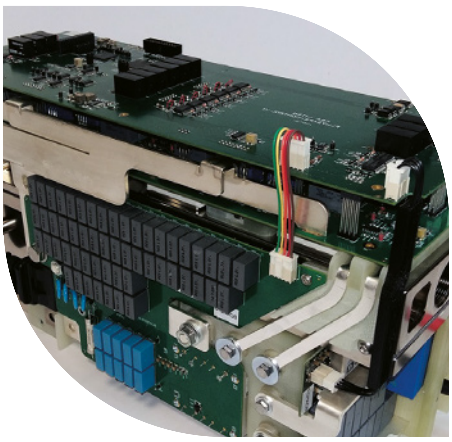
The project aims to demonstrate the capability of a fuel cell system to hold a profile load of a RAT in a demonstrator. Operational tests are ongoing, and a partial environmental test plan is in progress.

PROGRESS AND MAIN ACHIEVEMENTS

- The short stack was validated by H_2/O_2 tests.
- A critical design review of the low-temperature module for the fuel cell system was performed (theoretical A/C system specification has been completed).
- A demonstrator critical design review (for major subsystems) was performed.
- The first module campaign test was performed.
- The fuel cell stack was produced, and the converter integrated.
- The final demonstrator was assembled.

FUTURE STEPS AND PLANS

Operational and environmental tests of the FLHYSAFE demonstrator are ongoing.



QUANTITATIVE TARGETS AND STATUS

Target source	Parameter	Unit	Target	Achieved to date by the project	Target achieved?
Project's own objectives	EPU weight	kg	150	220	⚙
	System power density	W/kg	≤ 100	78	⚙
	Nominal continuous electrical power	kW	18.1	18.1	✓

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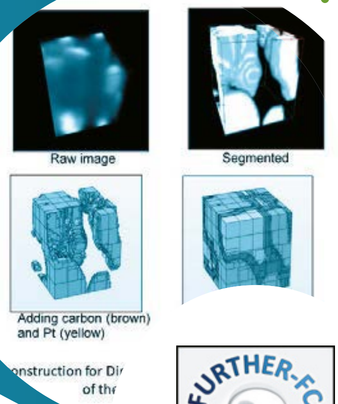
FURTHER-FC

FURTHER UNDERSTANDING RELATED TO TRANSPORT LIMITATIONS AT HIGH CURRENT DENSITY TOWARDS FUTURE ELECTRODES FOR FUEL CELLS



Project ID:	875025
PRD 2023:	Panel 3 – H2 end uses – transport
Call topic:	FCH-01-4-2019: Towards a better understanding of charge, mass and heat transports in new generation PEMFC MEA for automotive applications
Project total costs:	EUR 3 122 598.75
Clean H_2 JU max. contribution:	EUR 2 199 567.35
Project period:	1.1.2020–29.2.2024
Coordinator:	Commissariat à l'énergie atomique et aux énergies alternatives, France
Beneficiaries:	Centre national de la recherche scientifique, Chemours France SAS, Deutsches Zentrum für Luft- und Raumfahrt EV, École Nationale Supérieure de Chimie de Montpellier, Hochschule Esslingen, Imperial College of Science Technology and Medicine, Institut National Polytechnique de Toulouse, Paul Scherrer Institut, Chemours Company FC LLC, Toyota Motor Europe NV, Université de Montpellier, University of Calgary

https://further-fc.eu/

PROJECT AND OBJECTIVES

FURTHER-FC proposes complete experimental and modelling coupled platforms to better understand the performance limitations of the cathode catalyst layers (CCLs) of low-Pt-loaded proton-exchange membrane fuel cells. Based on this, CCL improvements will be discussed and tested. Up-to-date references and some customised membrane electrode assemblies (different ionomer-to-carbon ratio, thickness, etc.) have been produced, models of the CCLs are progressing based on their structural characterisation, and the first effective properties have been derived.

PROGRESS AND MAIN ACHIEVEMENTS

- Progress has been made on the characterisation of the CCLs (atomic force microscopy, Raman thermography, three-dimensional focused ion beam scanning electron microscopy, limiting current, etc.), including reference and first customised MEAs.
- Three-dimensional (3D) images of the GDL (with MPL) have been produced, and 3D images of CCLs are in progress.
- Modelling has been done on GDL, based on 3D images of fibrous substrate (X-ray) and of MPL (FIB-SEM), as has the evaluation of transport properties.
- Modelling of CCLs is ongoing (LBM, DNS). This is also based on 3D images.
- The definition and validation of test protocols allows for reliable comparison between the partners.
- Limiting-current analysis is ongoing (differential cells) to better understand the main contributors to the performance limitations.
- Progress has been made on the ultra-low loading catalyst layers, enabling a better understanding of the ORR kinetics.
- Bulk in-plane and through-plane electronic conductivities as a function of relative humidity and compression have been determined, as have through-plane proton conductivities as a function of relative humidity.
- The hydrophilicity and solvophilicity of the catalyst and catalyst layers have provided insights into the water sorption of these powders and layers during ink formulation and testing.
- The calibration of Raman thermography on the membrane has been achieved.

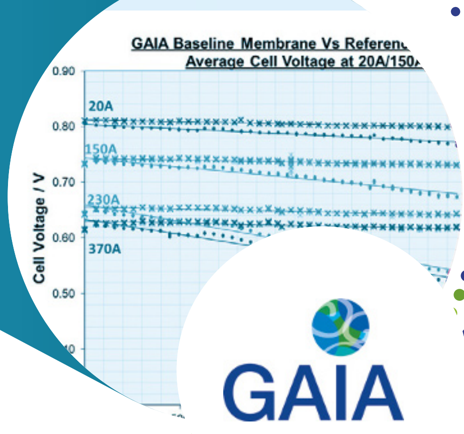
FUTURE STEPS AND PLANS

- The finalisation of the characterisations of customised membrane electrode assemblies is ongoing.
- The finalisation of the modelling of the CCLs at different scales is ongoing.
- The definition of the most performance-limiting mechanisms is ongoing.
- The upscaling of the models has started and will continue.
- Reproducibility of the fuel cell thermal behaviour is being checked.

QUANTITATIVE TARGETS AND STATUS

Target source	Parameter	Unit	Target	Target achieved?	SoA result achieved to date (by others)	Year for reported SoA result
MAWP (2014–2020)	Volumetric power density	kW/l	9.3		4.1	2017 (by Auto-Stack Core)
	Weight power density	kW/kg	4		3.4	
	Surface power density	W/cm²	1.8		1.13	
	Cost	€/kW	20		36.8	
	Durability	hours	6 000		3 500	
	Total Pt loading	mg/cm²	0.144		0.4	
	Total Pt loading	g/kW	0.08		0.35	
	Pt efficiency	A/mg	15		4.5	

GAIA



NEXT GENERATION AUTOMOTIVE MEMBRANE ELECTRODE ASSEMBLIES

Project ID:	826097
PRD 2023:	Panel 3 – H2 end uses – transport
Call topic:	FCH-01-5-2018: Next generation automotive MEA development
Project total costs:	EUR 5 065 614.39
Clean H_2 JU max. contribution:	EUR 4 493 025.00
Project period:	1.1.2019–30.6.2022
Coordinator:	Centre national de la recherche scientifique, France
Beneficiaries:	3M Deutschland GmbH, Bayerische Motoren Werke AG, Dyneon GmbH, Elmarco SRO, Freudenberg Performance Materials SE & Co. KG, Johnson Matthey Hydrogen Technologies Limited, Johnson Matthey plc, Pretexo, Technische Universität München, Technische Universität Berlin, Université de Montpellier, Zentrum für Sonnenenergie- und Wasserstoff-Forschung Baden-Württemberg

https://www.gaia-fuelcell.eu/

PROJECT AND OBJECTIVES

GAIA aims to develop high-performance automotive membrane electrode assemblies (MEAs) capable of achieving a 6 000-hour lifetime. By month 42, GAIA had developed new carbon support, catalyst, ionomer, membrane, reinforcement, gas diffusion and microporous layer components that were incorporated in MEAs and tested using optimised automotive drive cycle protocols in full automotive-sized 4-cell stacks and 10-cell short stacks. This testing demonstrated that the GAIA MEAs achieved a world-leading power density of 1.8 W/cm^2 at 0.6 V. By reaching this high power density without increasing platinum loading, the Pt-specific power density was reduced from 0.45 g Pt/kW to 0.25 g Pt/kW. Taking catalyst and ionomer recycling into consideration, the cost per kW of the final GAIA MEA approaches the €6/kW target of the 2019 Fuel Cells and Hydrogen 2 Joint Undertaking annual work plan. Furthermore, the voltage loss rate of a short stack with the GAIA MEAs was within the target range over the first 600 hours of operation of an automotive drive cycle, including at 105 °C, to achieve a predicted 6 000 hours of operation.

NON-QUANTITATIVE OBJECTIVES

- The project aimed to perform outreach through two videos. The first was on catalyst preparation and characterisation by rotating disc electrode and catalyst integration into MEAs and testing/diagnostics. It was prepared by Technische Universität Berlin and Technische Universität München. The second was on electrospun nanofibre reinforcement development and fabrication of reinforced membranes at scale. It was prepared by Centre national de la recherche scientifique, Elmarco, Dyneon and Johnson Matthey plc.
- The project aimed to disseminate the results through articles in international journals; eight articles have been published to date, and others will follow.
- It also aimed to communicate results through the publication of newsletters on its website; three newsletters are available for download.

PROGRESS AND MAIN ACHIEVEMENTS

- GAIA developed MEAs that provide 1.8 W/cm^2 at 0.6 V, corresponding to a Pt-specific power density of 0.25 g Pt/kW.
- The GAIA MEA cost approaches the €6/kW target, based on the assumptions of a high-volume production of 1 million m^2 MEA per year and the potential for platinum group metal and ionomer recycling.
- The stack voltage decay rate with GAIA MEAs was within the target range over the first 600 hours of automotive drive cycle testing, including at 105 °C, which represents a step change for the industry, especially for incursions at higher temperatures.

FUTURE STEPS AND PLANS

GAIA ended on 30 June 2022. However, the advances in materials, components and MEAs are being transferred to the heavy-duty transport projects IMMORTAL and HIGHLANDER.

QUANTITATIVE TARGETS AND STATUS

Target source	Parameter	Unit	Target	Achieved to date by the project	Target achieved?
AWP 2019	Power density at 0.6 V	W/cm^2	1.8	1.8	✓
	Stack durability (voltage decay rate)	%	< 10 after 6 000 hours of operation, as extrapolated from 1 000 hours of actual testing	Voltage decay rate within target to achieve a predicted 6 000 hours of operation over the first 600 hours of automotive drive cycle	⚙
	MEA cost	€/kW	6	9	✓

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H2HAUL

HYDROGEN FUEL CELL TRUCKS FOR HEAVY-DUTY, ZERO EMISSION LOGISTICS

Project ID:	826236
PRD 2023:	Panel 3 – H2 end uses – transport
Call topic:	FCH-01-1-2018: Large scale demonstration of H2 fueled HD trucks with high capacity hydrogen refueling stations (HRS)
Project total costs:	EUR 33 274 858.50
Clean H_2 JU max. contribution:	EUR 12 000 000.00
Project period:	2.1.2019–31.12.2025
Coordinator:	Element Energy Limited, United Kingdom
Beneficiaries:	ERM France, Dats 24, Plastic Omnium New Energies Wels GmbH, H2 Energy AG, Air Liquide France Industrie, VDL Enabling Transport Solutions BV, VDL Special Vehicles 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, Union Internationale des Transports Routiers (IRU), Bayerische Motoren Werke AG, Robert Bosch GmbH, Hydrogen Europe

https://www.h2haul.eu/

PROJECT AND 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 at 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 hydrogen refuelling stations (HRSs) funded in the project are expected to be deployed in the next 12 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 truck designs 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 Europe's roads. 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.
- It 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 commercialisation of this sector. The business case is to 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 costs involved in the technology. Analysis will be carried out to highlight the economics of more ambitious deployments of many 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. Communication activities in the first and second years of the project have stimulated significant interest from relevant audiences.

PROGRESS AND MAIN ACHIEVEMENTS

- The fuel cell truck technical specifications were finalised. Data were gathered on the technical specifications of the fuel cell trucks and HRSs.
- The first project HRS was deployed.
- The second observer group meeting took place.

FUTURE STEPS AND PLANS

- H2Haul will deploy the VDL and IVECO trucks. The VDL trucks were due to be delivered to Colruyt between March and June 2023, to start commercial operation. The IVECO beta trucks are currently being assembled with fuel cells from Bosch and will serve as prototypes for the 12 gamma trucks that will be delivered to end users in France, Germany and Switzerland between November 2023 and March 2024.
- The project will commission and start the operation of all remaining project HRSs. Currently, one HRS is in operation in Switzerland; the Belgian and French HRSs are planned to be commissioned by the beginning of summer 2023. The HRSs in Germany are currently being planned, and supplier selection is ongoing. Deployment is expected to take place at the end of 2023 or beginning of 2024.
- H2Haul will continue high-profile dissemination and lobbying work through attending and delivering presentations at key conferences and events. The next observer group meeting was due to be held in April 2023, and other stakeholder engagement activities will continue. The results will be disseminated extensively.

QUANTITATIVE TARGETS AND STATUS

Target source	Parameter	Unit	Target	Target achieved?
Project's own objectives and MAWP addendum (2018–2020)	Truck operational period	months	Start of operation including ramp-up phase: minimum of 24	
	Truck distance travelled	km	Minimum of 30 000 per truck and year, on average per site	
	Truck availability	%	> 90 on a fleet basis after an initial ramp-up phase of a maximum of 6 months	
	Truck-specific fuel consumption	kg/100 km	< 7.5 (rigid, @ 30–50 % load, inner-city delivery (< 25 km/h on average)) < 8.5 (tractor with semi-trailer @ 30–50 % load, long-haul delivery (> 65 km/h on average))	
	Availability of HRSs (by end of project)	%	99	
	MDBF	km	> 2 500	
	Well-to-wheel CO_2 emissions of < 50 % of those of diesel trucks	kg CO_2/km	kg CO_2/vehicle-km (per vehicle type, average across fleet) < 50 % compared with a diesel truck	
	Speed of hydrogen dispensing	kg/min	> 2.5 kg/min	
	Cost of hydrogen dispensed to HRS	€/kg	≤ €7.50/kg dispensed (excl. taxes) at end of project – in practice, lower values are expected	
	Amount of hydrogen dispensed to project trucks	kg/year	> 2 500 kg per truck per year	

H2ME 2

HYDROGEN MOBILITY EUROPE 2

Project ID:	700350
PRD 2023:	Panel 3 – H2 end uses – transport
Call topic:	FCH-03.1-2015: Large scale demonstration of hydrogen refuelling stations and FCEV road vehicles – including buses and on site electrolysis
Project total costs:	EUR 100 015 655.40
Clean H_2 JU max. contribution:	EUR 34 999 548.50
Project period:	1.5.2016–31.12.2023
Coordinator:	Element Energy Limited, United Kingdom
Beneficiaries:	ERM France, HYGO – Hydrogene Grand Ouest, R-Hynoca, Hysetco, Reseau GDS, Toyota Norge AS, Toyota Danmark AS, Mercedes-Benz AG, McPhy Energy Italia Società a Responsabilità Limitata, Element Energy, Stichting Cenex Nederland, B. Kerkhof & ZN BV, Tech Transports Compagnie, Air Liquide France Industrie, Alphabet Fuhrparkmanagement GmbH, Linde Gas GmbH, Islenska Vetnisfelagid EHF, Communauté Urbaine du Grand Nancy, Stedin Diensten BV, HYPE, H2 Mobility Deutschland GmbH & Co. KG, HYOP AS, Brintbranchen, New Nel Hydrogen AS, Compagnie Nationale du Rhone SA, Hydrogene De France, Honda R&D Europe (Deutschland) GmbH, Gnvert SAS, AGA AB, Symbio, Air Liquide Advanced Technologies SA, Elogen, Société d'économie mixte des transports en commun de l'agglomération nantaise (Semitan), Ministerie van Infrastructuur en Waterstaat, Intelligent Energy Limited, Manufacture Francaise des Pneumatiques Michelin, ITM Power (Trading) Limited, CENEX – Centre of Excellence for Low Carbon and Fuel Cell Technologies, Københavns Kommune, hySOLUTIONS GmbH, McPhy Energy, Mercedes-Benz Fuel Cell GmbH, WaterstofNet VZW, Nissan Motor Manufacturing (UK) Limited, Air Liquide Advanced Business, Renault Trucks SAS, NEL Hydrogen AS, Icelandic New Energy Ltd, Eifer Europäisches Institut für Energieforschung EDF KIT EWIV, Stedin Netbeheer BV, Renault SAS, Bayerische Motoren Werke AG, Audi AG, Open Energi Limited, Daimler AG, The University of Manchester

https://h2me.eu/

PROJECT AND OBJECTIVES

H2ME 2 brings together actions in 10 countries in a 7-year collaboration to deploy 20 hydrogen refuelling stations (HRSs) and around 1 000 vehicles. The project has performed a large-scale market test of a large fleet of fuel cell electric vehicles operated in real-world customer applications across multiple European regions. In parallel, it has demonstrated that the hydrogen mobility sector can support the wider European energy system via electrolytic hydrogen production.

NON-QUANTITATIVE OBJECTIVES

- A minimum of 1 000 fuel cell vehicles and 20 HRSs are to be deployed by the end of the project.
- The project aimed to demonstrate the electrolyser-integrated HRS operating in grid balancing. H2ME 2 included a dedicated work package to assess how electrolytic hydrogen production in the mobility sector can link to the wider energy system.
- Multiple original equipment manufacturers (OEMs) supplied vehicles, including cars and utility vehicles. H2ME 2 aimed to deploy cars and light-duty vans from OEMs including Mercedes, Honda, Symbio (Renault and Stellantis), Hyundai and Toyota.
- H2ME 2 aimed to ensure the cross-fertilisation of knowledge acquired in the project. A dedicated work plan and a dissemination and exploitation plan were developed to achieve this. Three observer countries are included in the coalition.

PROGRESS AND MAIN ACHIEVEMENTS

- There were c. 800 vehicles and 15 HRSs in operation as of Q1 2023 (in the H2ME 2 project alone).
- Demonstration in real-world operation has been under way since 2015 – jointly with H2ME – for over 1 100 vehicles from five OEMs (Mercedes, Honda, Hyundai, Symbio and Toyota) across 10 countries and c. 50 HRSs from 10 suppliers across six countries (Denmark, France, Iceland, the Netherlands, Sweden and the United Kingdom).
- The demonstration of positive business cases under H2ME 2 has led to further commitments from partners to expand fleets in Denmark, Germany and France.
- The project is building a rich dataset for Europe, jointly with H2ME. Since 2015, 25 million km have been driven and 377 t of H_2 distributed in 148 600 events (figures from November 2022).

FUTURE STEPS AND PLANS

- All 20 planned HRSs are expected to have been commissioned and be in operation by the end of the project. The commissioning of new HRSs has been affected by the COVID-19 pandemic and by the lack of experience at the local level for reviewing and approving permits.
- Over 1 100 vehicles are planned for deployment in H2ME 2 by the end of the project. The deployment of vehicles has been affected by the COVID-19 pandemic and its restrictions (lockdowns, curfews), which have delayed delivery and affected demand.
- The project has built a solid and growing base of operational data from vehicles and HRSs, and undertaken further fact-based analysis of vehicles' and HRSs' performances.
- Prior to H2ME, there were few large deployments of fuel cell hydrogen vehicles in Europe. The H2ME projects have contributed to the deployment of one third of fuel cell hydrogen vehicles on the road and 20 % of operational HRSs in Europe. In addition, H2ME has encouraged further activity in other vehicle segments (including buses and trucks) by supporting the deployment of HRSs.
- Across H2ME and H2ME 2, c. 100 reports have been prepared, with the majority publicly available on the project's website.

QUANTITATIVE TARGETS AND STATUS

Target source	Parameter	Unit	Target	Achieved to date by the project	Target achieved?	SoA result achieved to date (by others)	Year of SoA target
	HRSs						
Project's own objectives, MAWP addendum (2018–2020) and AWP 2015	HRS availability	%	98	96	⚙	98	2017
	Min. HRS operation	months	36	58	✓	32	
	Hydrogen purity	%	99.99	99.99	✓	99.99	
	Fuel cell vehicles						
	Min. vehicle operation during the project	months	36	60	✓	12	2017
	Vehicle availability	%	98	≈ 100	✓	98	

H2PORTS

IMPLEMENTING FUEL CELLS AND HYDROGEN TECHNOLOGIES IN PORTS

Project ID:	826339
PRD 2023:	Panel 3 – H2 end uses – transport
Call topic:	FCH-03-1-2018: Developing fuel cell applications for port/harbor ecosystems
Project total costs:	EUR 4 265 947.50
Clean H_2 JU max. contribution:	EUR 3 999 947.50
Project period:	1.1.2019–31.12.2024
Coordinator:	Fundación de la Comunidad Valenciana para la Investigación, Promoción y Estudios Comerciales de Valenciaport, Spain
Beneficiaries:	Agenzia Nazionale per le Nuove Tecnologie, l'Energia e lo Sviluppo Economico Sostenibile, Atena Scarl – Distretto Alta Tecnologia Energia Ambiente, Autoridad Portuaria de Valencia, Ballard Power Systems Europe AS, Cantieri del Mediterraneo SpA, Centro Nacional de Experimentación de Tecnologías de Hidrógeno y Pilas de Combustible Consorcio, Enagás SA, Grimaldi Euromed SpA, Hyster-Yale Nederland BV, Mediterranean Shipping Company Terminal Valencias SA, Sociedad Española de Carburos Metálicos SA, Università degli Studi di Napoli Parthenope, Università degli Studi di Salerno, Valencia Terminal Europa SA

https://h2ports.eu/

PROJECT AND OBJECTIVES

H2Ports 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 2 years of real operational activities at the Port of Valencia, and a mobile hydrogen refuelling station (HRS) designed and built during the project will provide the required hydrogen. All three elements are currently in advanced stages of building, and the piloting period is planned to start in summer 2023.

NON-QUANTITATIVE OBJECTIVES

- The project aims to disseminate H_2 technologies to the ports 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.
- It will gather information on the use of H_2 as fuel for vessels.

PROGRESS AND MAIN ACHIEVEMENTS

H2Ports has completed the HRS construction phase and is currently undertaking safety testing prior to the start of the operative period.

The fuel cell Reach Stacker is at a very advanced construction stage. The fuel cell's commissioning process has started, and the testing phase has been scheduled, prior to the delivery of the machine to the Port of Valencia.

The design and component selection of the terminal tractor has been completed; it is entering the final stage of the construction process, and the commissioning of the machine, the safety tests and CE certification will take place before its delivery to the Port of Valencia.

FUTURE STEPS AND PLANS

The pilot period was expected to start in August 2023.

QUANTITATIVE TARGETS AND STATUS

Target source	Parameter	Unit	Target	Target achieved?
	HRS daily capacity	kg/day	60	
Project's own objectives	Reach stacker vehicle power	kW	90	⚙
	Vehicle power	kW	70	

Clean Hydrogen Partnership

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HEAVEN

HIGH POWER DENSITY FC SYSTEM FOR AERIAL PASSENGER VEHICLE FUELED BY LIQUID HYDROGEN

Project ID:	826247
PRD 2023:	Panel 3 – H2 end uses – transport
Call topic:	FCH-01-4-2018: Fuel cell systems for the propulsion of aerial passenger vehicle
Project total costs:	EUR 6 953 835.06
Clean H_2 JU max. contribution:	EUR 3 995 305.00
Project period:	1.1.2019–30.9.2023
Coordinator:	H2FLY, Germany
Beneficiaries:	Air Liquide Advanced Technologies SA, Deutsches Zentrum für Luft- und Raumfahrt EV, Ekpo Fuel Cell Technologies GmbH, Fundación Ayesa, Air Liquide SA, Pipistrel Vertical Solutions Doo Podjetje Za Napredne Letalske Resitve

https://heaven-fch-project.eu/

PROJECT AND OBJECTIVES

The overall objective of this project is to address the gap between the research and product stages of a zero-emission fuel-cell-based propulsion technology to achieve emission- and noise-reduction scenarios, and meet the 2050 environmental goals for aviation. To that end, a high-efficiency, high-power-density, fuel-cell-based serial hybrid-electric propulsion architecture will be combined with the high energy density of cryogenic hydrogen storage. It will be advanced up to TRL6.

NON-QUANTITATIVE OBJECTIVES

- HEAVEN aims to increase the credibility of the solution for the propulsion of passenger aircraft and UAVs.
- The project aims to advance towards zero-emission hydrogen-powered regional commuter airliners.

PROGRESS AND MAIN ACHIEVEMENTS

- The cryogenic systems have been manufactured and the GSE has been developed.
- The cryogenic system was tested and verified.
- The powertrain was integrated into the aircraft.

FUTURE STEPS AND PLANS

- Fuel cell and hydrogen fuel system coupling and testing with liquid hydrogen (March 2023).
- Ground tests (June 2023).
- Flight test (September 2023).

QUANTITATIVE TARGETS AND STATUS

Target source	Parameter	Unit	Target	Achieved to date by the project	Target achieved?
Project's own objectives and AWP 2018	FC stack power density in weight	kW/kg	2	2.7 (stack including end plates)	✓
	FC power density in volume	kW/l	3.5	4.1 (stack including end plates)	
	Air subsystem	%	> 50	Preliminary results are in compliance with this value but have not been achieved yet	⚙
	Power converter	kW/kg	8	Preliminary results are in compliance with this value but have not been achieved yet	
	System lifetime	hours	500 (stack)	N/A	
	Hydrogen system	wt%	> 5.5	11.50	✓

HYSHIP

DEMONSTRATING LIQUID HYDROGEN FOR THE MARITIME SECTOR

Project ID:	101007205
PRD 2023:	Panel 3 – H2 end uses – transport
Call topic:	FCH-01-6-2020: Demonstration of liquid hydrogen as a fuel for segments of the waterborne sector
Project total costs:	EUR 13 409 121.25
Clean H_2 JU max. contribution:	EUR 7 993 942.00
Project period:	1.1.2021–31.12.2025
Coordinator:	Wilh. Wilhelmsen Holding ASA, Norway
Beneficiaries:	Air Liquide Norway AS, Diana Shipping Services SA, DNV AS, DNV GL SE, Eidgenössische Technische Hochschule Zürich, Equinor Energy AS, Kongsberg Maritime AS, LMG Marin AS, LMG Marin France, Maritime Cleantech, Massterly AS, National Center For Scientific Research 'Demokritos', Norled AS, Norsea Group AS, Persee, Stolt Tankers B.V., University of Strathclyde, Wilhelmsen Ship Management Norway AS

https://hyship.eu/

PROJECT AND OBJECTIVES

HyShip is building a vessel that will run on liquid hydrogen (LH_2). The vessel 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 main key performance indicator of the project is the demonstration of 3 000 hours of operation of 3 MW fuel cells. The design of the vessel is ongoing, and the vessel has not been ordered yet.

NON-QUANTITATIVE OBJECTIVES

- HyShip aims to conceptually design a full range of vessel and hydrogen systems.
- It aims to develop and describe a business ecosystem with a timeline for cost-efficient operation.
- It also aims to integrate the demonstrator into a larger sociotechnical system – with business models, policy models and LH_2 supply – that will help move towards use of LH_2.
- The project aims to use further robust holistic design approach (RHODA) ship design methods, lowering the cost of estimating complex projects with novel fuel and infrastructure, and allowing real-time data collection on the effects of the use of novel fuels (no real-time data provided yet).
- It aims to develop input to the International Maritime Organization, which will help the systems transition to its rules instead of following the alternative design approach.

PROGRESS AND MAIN ACHIEVEMENTS

The preliminary design of vessel and LH_2 propulsion systems is complete.

FUTURE STEPS AND PLANS

- The ship-building contract will be signed.
- The vessel will be delivered.
- Vessel operation will begin.

QUANTITATIVE TARGETS AND STATUS

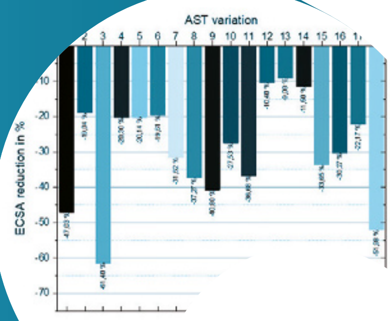
Target source	Parameter	Unit	Target	Target achieved?
Project's own objectives	Fuel cell power output	MW	3.0	
	Hours of operation of LH_2-powered propulsion	hours	3 000	
	Development of an intelligent energy management system that reduces the CAPEX of the energy system by > 5 %	%	5	
	Reduction of > 40 % of cost of design and ship integration cost related to the hydrogen/fuel cell systems themselves	%	40	

Clean Hydrogen Partnership

Co-funded by the European Union

IMMORTAL

IMPROVED LIFETIME STACKS FOR HEAVY DUTY TRUCKS THROUGH ULTRA-DURABLE COMPONENTS



Project ID:	101006641
PRD 2023:	Panel 3 – H2 end uses – transport
Call topic:	FCH-01-2-2020: Durability-lifetime of stacks for heavy duty trucks
Project total costs:	EUR 4 461 953.75
Clean H_2 JU max. contribution:	EUR 3 825 927.50
Project period:	1.1.2021–31.12.2023
Coordinator:	Centre national de la recherche scientifique, France
Beneficiaries:	Albert-Ludwigs-Universität Freiburg, AVL List GmbH, FPT Industrial SpA, FPT Motorenforschung AG, Johnson Matthey Hydrogen Technologies Limited, Johnson Matthey plc, Pretexo, Robert Bosch GmbH, Université de Montpellier

https://immortal-fuelcell.eu

PROJECT AND OBJECTIVES

IMMORTAL aims to develop high-performance and high-durability membrane electrode assemblies (MEAs), and their components, specifically designed for heavy-duty truck application. By month 14, an initial set of accelerated and load profile cell and stack tests had been developed and applied to baseline MEAs. Selected actual truck missions were simulated to produce load profiles that will be used to produce updated load profile testing procedures. By month 18, new materials (support, catalyst, membrane), which were integrated into an initial heavy-duty MEA, had been developed. The performance of these MEAs comes within 93 % of the final power density target of 0.675 V in short-stack testing.

NON-QUANTITATIVE OBJECTIVES

IMMORTAL aims to contribute to activities on Mission Innovation's hydrogen innovation challenge through cooperation with the US Department of Energy's Million Mile Fuel Cell Truck Consortium. Several workshops have been held with the consortium, and with Japan's fuel cell platform, which included discussions on, inter alia, heavy-duty stressors, the second-generation Toyota Mirai and advanced characterisation techniques.

PROGRESS AND MAIN ACHIEVEMENTS

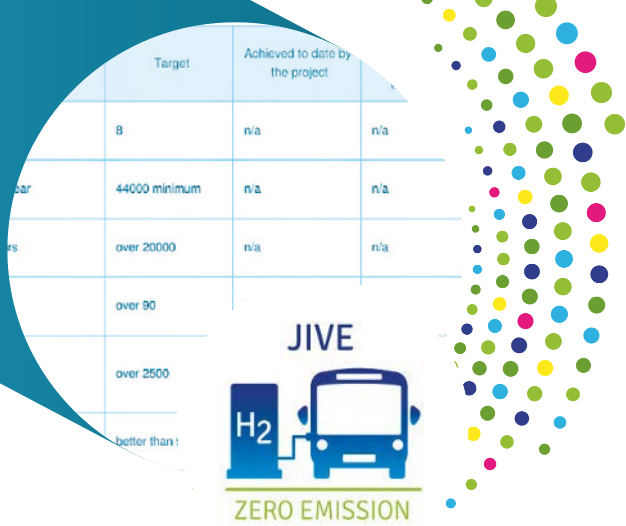
- IMMORTAL has developed highly stable catalyst layers at the target platinum loading (0.3 mg/cm²) that achieve a decay rate due to irreversible losses ≥ 50 % lower than the reference catalyst-coated membrane (from the INSPIRE project) using a project accelerated stress test protocol (Milestone 5).
- IMMORTAL has developed and validated a highly durable reinforced membrane that has withstood > 100 000 wet/dry cycles in an MEA held at open circuit voltage at 90 °C.
- IMMORTAL has developed MEAs integrating these novel components that achieve 93 % of the final target power density in short-stack testing (target: 0.675 V).

FUTURE STEPS AND PLANS

- IMMORTAL will deliver further optimised materials for a second generation of heavy-duty-specific MEAs (expected spring 2023).
- It will deliver this second generation of heavy-duty-specific MEAs for single-cell and short-stack accelerated stress testing and load-profile testing as part of work package 2 (expected from June 2023).

QUANTITATIVE TARGETS AND STATUS

Target source	Parameter	Unit	Target	Achieved to date by the project	Target achieved?	SoA result achieved to date (by others)	Year of SoA target
AWP 2020	Cell voltage at 1.77 A/cm²	V	0.675	0.661	⚙	0.675	2021
AWP 2020	Durability	hours	30 000 with < 10 % degradation	Durability testing is planned in RP2; MEAs have been developed for heavy-duty trucks	⚙	8 500 with < 10 % degradation	2020
Project's own objectives	Catalyst surface area and mass activity	cm²/g of Pt and A/mg of Pt	Exceeding values of reference Pt and better retention after accelerated degradation cycles than reference Pt/C	Two catalyst designs achieve this objective	✓	N/A	N/A
Project's own objectives	Membrane durability in MEA AST cycles	cycles	50 000	110 000	✓	No public result comes close to this number of cycles	N/A



JIVE

JOINT INITIATIVE FOR HYDROGEN VEHICLES ACROSS EUROPE

Project ID:	735582
PRD 2023:	Panel 3 – H2 end uses – transport
Call topic:	FCH-01-9-2016: Large scale validation of fuel cell bus fleets
Project total costs:	EUR 88 770 205.25
Clean H_2 JU max. contribution:	EUR 32 000 000.00
Project period:	1.1.2017–30.6.2024
Coordinator:	Element Energy Limited, United Kingdom
Beneficiaries:	Aberdeen City Council, Birmingham City Council, EE Energy Engineers GmbH, ESWE Verkehrsgesellschaft mbH, Fondazione Bruno Kessler, Gelderland, HyCologne – Wasserstoff Region Rheinland e.V., Hydrogen Europe, London Bus Services Limited, Planungsgruppe Energie und Technik GbR, Rebelgroup Advisory BV, Regionalverkehr Köln GmbH, Sphera Solutions GmbH, SASA SpA AG, Union Internationale des Transports Publics, WSW mobil GmbH

https://www.fuelcellbuses.eu/projects/jive

PROJECT AND 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 142 FCBs in eight locations. This will more than double the number of FCBs currently operating in Europe.

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.
- The project 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. This group monitors discussions and best practices emerging from the project. This will ensure that the momentum for FCB uptake in Europe continues beyond the project.
- JIVE aims to deliver positive environmental impacts by operating FCBs for extended periods. As per the project objectives, 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 AND MAIN ACHIEVEMENTS

- All 142 buses have been ordered, from four bus manufacturers.
- In total, 132 buses have started operating, representing 93 % of all the buses.

FUTURE STEPS AND PLANS

- By the end of the first half of 2023, all buses are expected to be operational.
- To date, only one city does not yet have operational buses.
- Uncertainties around ongoing issues related to hydrogen supply (undelivered hydrogen, hydrogen prices, etc.) are expected to be clarified in the upcoming period to ensure that all buses are fully operational.

QUANTITATIVE TARGETS AND STATUS

Target source	Parameter	Unit	Target	Target achieved?
	Vehicle operational lifetime	years	8	
	Distance travelled	km/year	≥ 44 000	
	Operating hours per fuel cell system	hours	> 20 000	
	Availability	%	> 90	
Project's own objectives and AWP 2016	MDBF	km	> 2 500	⚙
	Specific fuel consumption	kg/100 km	> 9	
	Efficiency	%	> 42	
	Vehicle OPEX	€	Max. 100 % more than diesel bus OPEX	
	Vehicle CAPEX	€	< 650 000	✓

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JIVE 2

JOINT INITIATIVE FOR HYDROGEN VEHICLES ACROSS EUROPE 2

Project ID:	779563
PRD 2023:	Panel 3 – H2 end uses – transport
Call topic:	FCH-01-5-2017: Large scale demonstration in preparation for a wider roll-out of fuel cell bus fleets (FCB) including new cities – phase two
Project total costs:	EUR 89 972 571.27
Clean H_2 JU max. contribution:	EUR 25 000 000.00
Project period:	1.1.2018–30.6.2025
Coordinator:	Element Energy Limited, United Kingdom
Beneficiaries:	ERM France, Transdev Occitanie Ouest, Hyport, Engie Energie Services, CA de l'Auxerrois, Connexxion Vloot BV, Société publique locale d'exploitation des transports publics et des services à la mobilité de l'agglomération paloise, TwynstraGudde Mobiliteit & Infrastructuur BV, Openbaar Lichaam OV-bureau Groningen en Drenthe, Pau Béarn Pyrénées Mobilités, Rebelgroup Advisory BV, Regionalverkehr Köln GmbH, Connexxion Openbaar Vervoer NV, Messer SE & Co. KGaA, WSW Mobil GmbH, Rīgas Pašvaldības Sabiedrība ar Ierobežotu Atbildību Rīgas Satiksme, Transports de Barcelona SA, EE Energy Engineers GmbH, Sphera Solutions GmbH, Brighton & Hove Bus and Coach Company Limited, Provincie Zuid-Holland, Vätgas Sverige Ideell Förening, Union Internationale des Transports Publics, Hydrogen Europe

https://www.fuelcellbuses.eu/projects/jive-2

PROJECT AND OBJECTIVES

JIVE 2 aims to deploy 156 fuel cell buses (FCBs). Combined, the JIVE projects will deploy nearly 300 FCBs in 16 cities across Europe by the end of the early 2020s – 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.
- The project 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. This group monitors discussions and best practices emerging from the project. This will ensure that the momentum for the 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 objectives, 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 AND MAIN ACHIEVEMENTS

- To date, 122 buses have been ordered.
- To date, 98 buses have become operational, representing 63 % of all the buses.
- To date, one site has been operating its fuel cell electric buses for more than 3 years.

FUTURE STEPS AND PLANS

- By Q2 2023, all buses will have been ordered.
- By Q3 2024, all buses will have been delivered and put into operation. At present, only one site does not yet have its buses in operation.

QUANTITATIVE TARGETS AND STATUS

Target source	Parameter	Unit	Target	Achieved to date by the project	Target achieved?
Project's own objectives and AWP 2017	Vehicle operational lifetime	years	8	N/A	
	Distance travelled	km/bus	> 50 000 minimum	27 627	
	Operating hours per fuel cell system	hours	> 20 000	2 015	
	Availability	%	> 90	86.10	
	MDBF	km	< 3 500	10 242	
	Specific fuel consumption	kg/100 km	> 9.0	7.21	
	Efficiency	%	> 42		
	Vehicle OPEX	€	Max. 100 % more than diesel bus OPEX	N/A	
	Vehicle CAPEX	€	< 650 000		✓

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MARANDA

MARINE APPLICATION OF A NEW FUEL CELL POWERTRAIN VALIDATED IN DEMANDING ARCTIC CONDITIONS

Project ID:	735717
PRD 2023:	Panel 3 – H2 end uses – transport
Call topic:	FCH-01-5-2016: Develop new complementary technologies for achieving competitive solutions for marine applications at an economic scale of implementation
Project total costs:	EUR 3 704 757.50
Clean H_2 JU max. contribution:	EUR 2 939 457.50
Project period:	3.1.2017–31.3.2022
Coordinator:	Teknologian tutkimuskeskus VTT Oy, Finland
Beneficiaries:	ABB OY, OMB Saleri SpA, Persee, PowerCell Sweden AB, Suomen ympäristökeskus, Swiss Hydrogen SA

https://projectsites.vtt.fi/sites/maranda/

PROJECT AND OBJECTIVES

In MARANDA, an emission-free hydrogen-fuelled proton-exchange-membrane-fuel-cell-based hybrid powertrain system (3 × 82.5 kW alternating current) was developed for marine applications. It was validated onshore, simulating offshore operation, and at a durability test site, as approval for testing the systems in the *Aranda* vessel was not granted. The project increased the market potential of hydrogen fuel cells in the marine sector. General business cases for different marine and harbour actors or fuel cell business actors were created.

NON-QUANTITATIVE OBJECTIVES

- The MARANDA project has already had a significant impact on the development of regulations, codes and standards.
- The fuel cell systems should be able to withstand the shocks, vibrations, saline environment and ship motions commonly encountered on the water, and other marine-application-relevant requirements.
- MARANDA aimed to evaluate the economic and environmental impacts for a prospective customer. A report on the business analysis of hydrogen fuel cells for marine applications has been prepared.
- The project aimed to formulate an initial go-to-market strategy. The report on the business analysis includes this strategy.
- MARANDA aimed to map opportunities for future demonstration actions. This mapping is included in the report on the business analysis.

PROGRESS AND MAIN ACHIEVEMENTS

- Three fuel cell systems from Swiss Hydrogen were assembled, delivered to Teknologian tutkimuskeskus VTT, integrated in containers and tested at the durability test site.
- A significant improvement in stack durability has been shown by PowerCell Sweden.
- Containers and equipment for the integration of fuel cell systems and hydrogen storage, including all safety systems, were designed, manufactured and tested.

FUTURE STEPS AND PLANS

All test runs were completed by the end of May 2022.

QUANTITATIVE TARGETS AND STATUS

Target source	Parameter	Unit	Target	Achieved to date by the project	Target achieved?
AWP 2016	Fuel cell system power	kW	75	75	✓
	Stack durability	mV/1 000 h	4.6	1.7	
	Fuel-to-electricity efficiency (alternating current)	%	48	42	

MORELIFE

MATERIAL, OPERATING STRATEGY AND RELIABILITY OPTIMISATION FOR LIFETIME IMPROVEMENTS IN HEAVY DUTY TRUCKS

Project ID:	101007170
PRD 2023:	Panel 3 – H2 end uses – transport
Call topic:	FCH-01-2-2020: Durability-lifetime of stacks for heavy duty trucks
Project total costs:	EUR 3 499 913.75
Clean H_2 JU max. contribution:	EUR 3 499 913.75
Project period:	9.1.2021–31.8.2024
Coordinator:	AVL List GmbH, Austria
Beneficiaries:	EKPO Fuel Cell Technologies GmbH, Mebius, Raziskovalno Razvojna Dejavnost, Zastopanje in Trgovina DOO, Nedstack Fuel Cell Technology BV, Technische Universität München, Technische Universiteit Eindhoven, Univerza v Ljubljani

https://morelife-info.eu/

PROJECT AND OBJECTIVES

MORELife is addressing the need for highly efficient material utilisation, maximised durability and optimised matching of the 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 the material and operation strategy levels;
- create advanced degradation models;
- find the optimised and validated operating conditions based on the improved materials;
- achieve a fuel cell predicted lifetime of 30 000 hours.

PROGRESS AND MAIN ACHIEVEMENTS

- Accelerated stress testing and accelerated durability testing protocols and accelerated stress tests for state-of-the-art (SoA) catalyst material have been created.
- Two generations of novel catalyst material have been created and are under investigation, with promising initial results in terms of performance. However, the catalyst is dealing with leaching of copper.
- Post-mortem analysis on aged SoA material has been performed in order to improve mechanistic degradation models created in this project.

FUTURE STEPS AND PLANS

- Accelerated stress testing protocols and accelerated stress tests for novel catalyst material will be created.
- A second generation of promising novel catalysts will be investigated. If performance is sufficient, a third generation will be created, with improvements based on the previous generations.
- If proven sufficient, the third generation of catalysts will be integrated in a 5- to 10-cell short stack for testing and validation, while a reference stack with SoA material will be built in order to compare durability and performance.

QUANTITATIVE TARGETS AND STATUS

Target source	Parameter	Unit	Target	Target achieved?
Project's own objectives	Power density cell	W/cm^2	1.2 @ 0.675 V/cell	
	PGM loading	g/kW	< 0.3 Pt loadings of corresponding 0.36 $mgPt/cm^2$ MEA	

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REVIVE

REFUSE VEHICLE INNOVATION AND VALIDATION IN EUROPE

Project ID:	779589
PRD 2023:	Panel 3 – H2 end uses – transport
Call topic:	FCH-01-7-2017: Validation of fuel cell trucks for the collect of urban wastes
Project total costs:	EUR 10 566 750.68
Clean H_2 JU max. contribution:	EUR 4 993 851.00
Project period:	1.1.2018–30.6.2024
Coordinator:	Tractebel Engineering, Belgium
Beneficiaries:	Azienda Servizi Municipalizzati di Merano SpA, Commissariat à l'énergie atomique et aux énergies alternatives, Element Energy Limited, Engie Impact Belgium, E-Trucks Europe, Gemeente Amsterdam, Gemeente Breda, Gemeente Groningen, Gemeente Noordenveld, PowerCell Sweden AB, Prezero Nederland Holding BV, Proton Motor Fuel Cell GmbH, Renova AB, Saver NV, Servizi Energia Ambiente Bolzano SpA, Stad Antwerpen, WaterstofNet VZW

https://h2revive.eu/

PROJECT AND OBJECTIVES

REVIVE will significantly advance the state of development of fuel cell bin lorries by integrating fuel cell powertrains into 14 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. Today, three trucks are in operation, and the remaining ones will be deployed in the coming months.

NON-QUANTITATIVE OBJECTIVES

- The project aims to involve EU fuel cell suppliers. Currently, two such suppliers are involved in the project: Proton Motor and PowerCell Sweden. In addition, two trucks are equipped with Hydrogenics FC systems.
- The project aims to demonstrate a route to high utilisation of hydrogen refuelling stations to support the roll-out of H_2 mobility for light vehicles. Even with limited running hours, the three trucks deployed in the project have already consumed 1 t of H_2 during the project.

PROGRESS AND MAIN ACHIEVEMENTS

- Trucks are in the building phase.
- The first Proton Motor fuel cell system has been delivered and successfully integrated.
- The first REVIVE truck has been deployed.

FUTURE STEPS AND PLANS

- **Deployment preparation.** At the project consortium level, experience and relevant documentation are being shared to fully prepare for truck deployment.
- **Increased dissemination activities.** To catch up following the delays experienced in 2020, a plan for dissemination will be developed.
- **Decrease in teething issues.** The trucks are being tested thoroughly before delivery.

QUANTITATIVE TARGETS AND STATUS

Target source	Parameter	Unit	Target	Achieved to date by the project	Target achieved?	SoA result achieved to date (by others)
AWP 2017	Number of FCs deployed in the project	–	15	6	⚙	6
	FC power	kW	> 40	45	✓	90
	Lifetime	hours	25 000	N/A	⚙	> 25 000
	Tank-to-wheel efficiency	%	50	45	⚙	N/A
	Availability	%	90	81.5	⚙	
	Driving distance between failures	km	3 500	785	⚙	

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SH$_2$APED

STORAGE OF HYDROGEN: ALTERNATIVE PRESSURE ENCLOSURE DEVELOPMENT

Project ID:	101007182
PRD 2023:	Panel 3 – H2 end uses – transport
Call topic:	FCH-01-1-2020: Development of hydrogen tanks for electric vehicle architectures
Project total costs:	EUR 2 146 925.00
Clean H$_2$ JU max. contribution:	EUR 1 993 550.00
Project period:	1.1.2021–31.12.2023
Coordinator:	Plastic Omnium Advanced Innovation and Research, Belgium
Beneficiaries:	Bundesanstalt für Materialforschung und -prüfung, Misal SRL, OMB Saleri SpA, Optimum CPV, University of Ulster

https://sh2aped.eu/

PROJECT AND OBJECTIVES

The goal of SH$_2$APED is to develop and test at technology readiness level 4 a conformable and cost-effective 70 MPa hydrogen storage system with increased efficiency and advanced safety performance.

NON-QUANTITATIVE OBJECTIVES

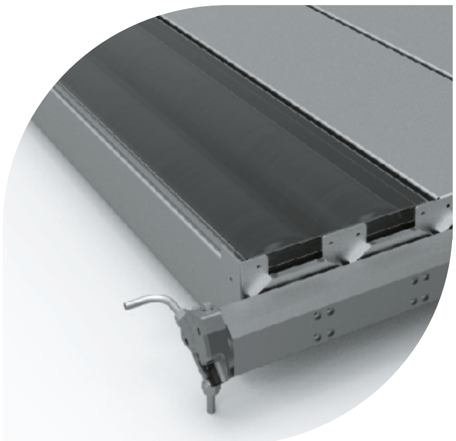
Regarding certification procedures, the project aims to contribute to the revision of regulations.

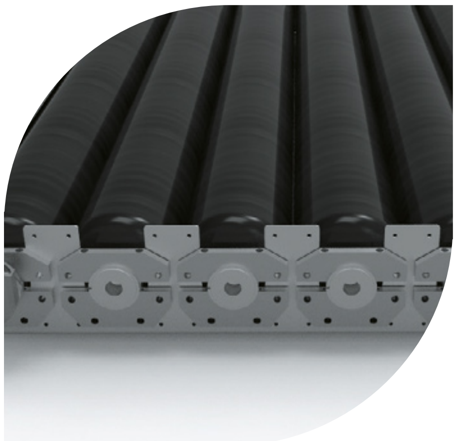
PROGRESS AND MAIN ACHIEVEMENTS

- The first assembly design – vessel design, and manifold and thermal pressure relief device design – has been finalised.
- Vessel prototypes are available.
- System testing of the model's reaction to fire is in progress.

FUTURE STEPS AND PLANS

Frame design is ongoing.





QUANTITATIVE TARGETS AND STATUS

Target source	Parameter	Unit	Target	Achieved to date by the project	Target achieved?	SoA result achieved to date (by others)	Year of SoA target
Project's own objectives	Cost of tank system	€/kg of H$_2$	< 400	> 580		< 500	2022
	Permeation	Ncm³/l/h @ 55 °C	< 46	Not yet available		N/A	N/A
	Hydraulic pressure cycle test at 87.5 MPa, 20 °C	–	22 000	> 22 000	✓	Not published	Not published

SHIPFC

PILOTING MULTI MW AMMONIA SHIP FUEL CELLS

Project ID:	875156
PRD 2023:	Panel 3 – H2 end uses – transport
Call topic:	FCH-01-2-2019: Scaling up and demonstration of a multi-MW fuel cell system for shipping
Project total costs:	EUR 3 179 056.25
Clean H_2 JU max. contribution:	EUR 9 975 477.50
Project period:	1.1.2020–31.12.2025
Coordinator:	Maritime Cleantech, Norway
Beneficiaries:	Eidesvik Shipping AS, Wärtsilä Gas Solutions Norway AS, Sustainable Energy AS, North Sea Shipping AS, Star Bulk Ship Management Co. (Cyprus) Ltd, Wärtsilä Norway AS, Capital-Executive Ship Management Corp., Maritime CleanTech, Persee, Prototech AS, Equinor Energy AS, Yara International ASA, University of Strathclyde, National Center for Scientific Research 'Demokritos', Fraunhofer-Gesellschaft zur Förderung der angewandten Forschung EV

https://shipfc.eu/

PROJECT AND OBJECTIVES

ShipFC's main mission is to prove and show 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. The onboard fuel system design is in progress, together with the integration design for the fuel cell power system. ShipFC is building the knowledge base for the development of a global green ammonia fuel infrastructure.

NON-QUANTITATIVE OBJECTIVES

- The fourth iteration of the design for the container ship is now complete.
- Concept evaluations of bulk carriers are ongoing.

PROGRESS AND MAIN ACHIEVEMENTS

- The detailed design of the fuel system is under development.
- The detailed vessel design is under development. This includes the hazard identification process with class and the Norwegian Maritime Authority.

FUTURE STEPS AND PLANS

A challenging supply chain situation for fuel cell stacks is causing delays for the project. Full-scale testing has been delayed.

QUANTITATIVE TARGETS AND STATUS

Target source	Parameter	Unit	Target	Achieved to date by the project	Target achieved?
Project's own objectives	Greenhouse gas reduction as a result of using ammonia fuel	%	70	–	
	Ammonia SOFC system power	MW	2	1.3 kW	⚙
	MW-scale SOFC operational experience	hours	3 000	–	
Project's milestone/ objective	FC system approval in principle (AiP)	–	–	1.1.2023	✓

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STASHH

STANDARD-SIZED HEAVY-DUTY HYDROGEN

Project ID:	101005934
PRD 2023:	Panel 3 – H2 end uses – transport
Call topic:	FCH-01-4-2020: Standard sized FC module for heavy duty applications
Project total costs:	EUR 14 315 057.05
Clean H_2 JU max. contribution:	EUR 7 500 000.00
Project period:	1.1.2021–30.6.2024
Coordinator:	Sintef AS, Norway
Beneficiaries:	Volvo Penta AB, Alstom Transport SA, AVL List GmbH, Ballard Power Systems Europe AS, CETENA SpA, Commissariat à l'énergie atomique et aux énergies alternatives, Damen Global Support BV, Damen Research Development & Innovation BV, FEV Europe GmbH, FEV Software and Testing Solutions GmbH, Freudenberg Fuel Cell e-Power Systems GmbH, Future Proof Shipping BV, Hyster-Yale Italia SpA, Hyundai Motor Europe Technical Center GmbH, Intelligent Energy Limited, Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek, Plastic Omnium New Energies Wels GmbH, Proton Motor Fuel Cell GmbH, Scheepswerf Damen Gorinchem BV, Solaris Bus & Coach sp. z o.o., Toyota Motor Europe NV, VDL Enabling Transport Solutions BV, VDL Energy Systems, VDL Special Vehicles BV, Volvo Construction Equipment AB, Volvo Technology AB, WaterstofNet VZW

https://stashh.eu/

PROJECT AND OBJECTIVES

StasHH's objectives are to agree 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 – and several partners are already developing prototypes.

NON-QUANTITATIVE OBJECTIVES

- The project aims to disseminate the standard. This dissemination only recently started, as the standard was only recently agreed upon.
- StasHH plans to update the standard based on experience in 2023.

PROGRESS AND MAIN ACHIEVEMENTS

- Seven out of eight fuel cell modules have been designed.
- Protocols for factory acceptance and site acceptance testing have been prepared.
- The truck prototype has been deployed at VDL.

FUTURE STEPS AND PLANS

- Fuel cell module testing in three campaigns: two in 2023 and one in early 2024.
- Field demonstration in a heavy-duty vehicle.
- Production of an OEM best practice manual.
- Use of X-in-loop software.
- Finalisation of standard and designs.

QUANTITATIVE TARGETS AND STATUS

Target source	Parameter	Unit	Target	Achieved to date by the project	Target achieved?
Project's own objectives	Number of sizes	–	≤ 3	3	✓
	Number of fuel cell module partners	–	7	7	
	Fuel cell module power rating	kW	30–100	30–125	

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THOR

THERMOPLASTIC HYDROGEN TANKS OPTIMISED AND RECYCLABLE

Project ID:	826262
PRD 2023:	Panel 3 – H2 end uses – transport
Call topic:	FCH-01-3-2018: Strengthening of the European supply chain for compressed storage systems for transport applications
Project total costs:	EUR 2 969 253.29
Clean H_2 JU max. contribution:	EUR 2 853 958.75
Project period:	1.1.2019–30.9.2022
Coordinator:	Faurecia Systemes d'Echappement SAS, France
Beneficiaries:	Centre national de la recherche scientifique, Centre technique des industries mécaniques, Cetim Grand Est, COVESS NV, École Nationale Supérieure de Mécanique et d'Aérotechnique, ETIM, Air Liquide SA, Norges teknisk-naturvitenskapelige universitet, Rina Consulting – Centro Sviluppo Materiali SpA, Sirris het collectief centrum van de technologische industrie, Université de Poitiers

https://thor-fch2.eu/

PROJECT AND OBJECTIVES

The project aims to validate hydrogen technology and its associated process regarding a recyclable thermoplastic composite tank for the storage of high-pressure gaseous hydrogen for mobility.

NON-QUANTITATIVE OBJECTIVES

- THOR will conduct health and safety monitoring using optical fibres, for temperature control and fire detection. Tests were scheduled to take place in July 2022.
- The project aims to create a recycled panel of thermoplastic reinforced with carbon fibres. Recycling activities are scheduled to take place at the end of the project. The performance of the panels will be tested to define their best use.
- The tanks are intended to be recyclable.
- The project is working on the reuse of the end-of-life tank with a recycling process for producing carbon-fibre composite sheets (the materials and the manufacturing process for the reused sheets are being prepared).

PROGRESS AND MAIN ACHIEVEMENTS

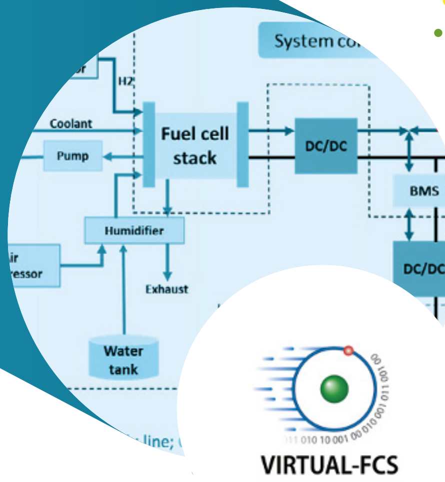
- Fifteen tanks have been prepared by CETIM.
- Burst results were below the qualification threshold (94 % of the burst pressure), meaning hydrogen could not be used for the final test.
- Recycling activities: recycled panels have been manufactured and prototypes' formed parts have been prepared successfully.

FUTURE STEPS AND PLANS

The project ended in September 2022.

QUANTITATIVE TARGETS AND STATUS

Target source	Parameter	Unit	Target	Achieved to date by the project	Target achieved?
MAWP (2014–2020)	Gravimetric efficiency	%	> 6 %	4.35	
	Cost of tanks	€/kg of H_2	400	760	
	AWP 2018	Burst pressure	bar	1 575	



VIRTUAL-FCS

VIRTUAL & PHYSICAL PLATFORM FOR FUEL CELL SYSTEM DEVELOPMENT

Project ID:	875087
PRD 2023:	Panel 3 – H2 end uses – transport
Call topic:	FCH-01-3-2019: Cyber-physical platform for hybrid fuel cell systems
Project total costs:	EUR 2 349 018.75
Clean H_2 JU max. contribution:	EUR 1 897 806.25
Project period:	1.1.2020–31.4.2023
Coordinator:	Sintef AS, Norway
Beneficiaries:	Ballard Power Systems Europe AS, Banke APS, Communauté d'universités et d'établissements université Bourgogne-Franche-Comté, École nationale supérieure de mécanique et des microtechniques, SEAM AS, Solaris Bus & Coach sp. z o.o., Université de Franche-Comté, Université de technologie de Belfort-Montbéliard, Vivarail Ltd

https://www.sintef.no/projectweb/virtual-fcs/

PROJECT AND OBJECTIVES

The overall objective of VIRTUAL-FCS is to make the design of hybrid fuel cell and battery systems easier, cheaper and quicker. VIRTUAL-FCS will produce a toolkit combining software and hardware parts for designing and optimising hybrid systems of proton-exchange membrane fuel cells and batteries. The platform will be entirely open source, allowing everyone in both industry and research to benefit from and contribute to the development of the framework. The software tools are being developed in close collaboration with end users and system integrators, securing widespread accessibility.

NON-QUANTITATIVE OBJECTIVES

- VIRTUAL-FCS aims for a significant reduction in development times for new fuel cell and battery hybrid systems. The advanced modelling, simulation and emulation tools developed in the project will enable end users with limited experience of fuel cell systems to design and implement new systems more quickly.
- The project aims to create a development platform for hybrid fuel cell systems with integration capabilities and corresponding simulation models. The real-time software platform combined with a full range of emulated components will enable end users to seamlessly integrate real, simulated and emulated components together in a mixed software–hardware system.
- It aims to create analytical tools and instrumentation to validate the different systems and energy management methodologies developed. VIRTUAL-FCS will validate different energy management systems on the mixed software–hardware system. The characterisation of the systems will be carried out using the standard techniques to validate system performance.
- VIRTUAL-FCS aims to create high-performance, real-time emulators of the dynamic behaviour of real components and subsystems. VIRTUAL-FCS will develop new and improved balance-of-plant and stack models capable of accurate real-time emulation of components' dynamic performance, along with their degradation.
- The project aims to enable the establishment of an EU-based supply industry for hybrid fuel cell system simulation and the experimental tool environment (X-in-the-loop platform) to boost the competitiveness of the EU fuel cell industry. The system simulation tools and methods for setting up and using the experimental platform will be available to the entire European industry free of charge to boost competitiveness.

PROGRESS AND MAIN ACHIEVEMENTS

- VIRTUAL-FCS has demonstrated cyber–physical hardware integration.
- The project has carried out fuel cell electric vehicle simulations.
- It has also carried out real-time system simulation.
- The project has carried out real-time system emulation. The project has demonstrated this capability by emulating a full-stack system with an energy management strategy that can take real-time input from a physical sensor, use this feedback for real-time control of a standard fuel cell stack test bench and simulate various load cycles on the physical stack.
- The project has integrated components from the physical hybrid system into the system simulated in the software tools and into those systems emulated on a controller.
- The project has arranged explanatory webinars and participated in conferences to demonstrate the feasibility of the VIRTUAL-FCS library.
- A simple-fuel cell stack degradation model has been developed.

FUTURE STEPS AND PLANS

- Full validation of the fuel cell stack, battery and balance-of-plant models will be carried out.
- An industrial workshop was arranged for 26 April 2023.

ZEFER

ZERO EMISSION FLEET VEHICLES FOR EUROPEAN ROLL-OUT

Project ID:	779538
PRD 2023:	Panel 3 – H2 end uses – transport
Call topic:	FCH-01-6-2017: Large scale demonstration of hydrogen refuelling stations and fuel cell electric vehicle (FCEV) road vehicles operated in fleet(s)
Project total costs:	EUR 13 676 254.48
Clean H_2 JU max. contribution:	EUR 4 998 843.00
Project period:	9.1.2017–31.8.2023
Coordinator:	Element Energy Limited, United Kingdom
Beneficiaries:	ERM France, Drivr Danmark A/S, Air Liquide Advanced Technologies GmbH, Linde GmbH, Toyota Danmark AS, Element Energy, Green Tomato Cars Limited, Breath, Air Liquide France Industrie, Air Liquide Belge, Hype, Air Liquide Advanced Technologies SA, ITM Power (Trading) Limited, CENEX – Centre of Excellence for Low Carbon and Fuel Cell Technologies, Air Liquide Advanced Business, Ville de Paris, Linde AG, Bayerische Motoren Werke AG, Mayor's Office for Policing and Crime (London)

https://zefer.eu/

PROJECT AND OBJECTIVES

ZEFER aims to demonstrate viable business cases for fuel cell electric vehicles (FCEVs) in high-mileage fleet applications. The project aims to deploy 180 FCEVs into taxi, private-hire and emergency-service operations in three major European cities in which the operational benefits and zero-emission credentials of FCEVs can be monetised. The vehicles have used existing hydrogen refuelling station (HRS) networks to increase local utilisation levels and improve the business case for HRS operators. As of December 2022, the 180 vehicles had amassed 11.3 million km, and the prediction for the end of the project, in August 2023, is 13.9 million km.

NON-QUANTITATIVE OBJECTIVES

- ZEFER aims to develop comprehensive lessons from the deployment project. Public deliverables have been produced, covering topics such as customer acceptance, the business case for FCEVs and the technical performance of HRSs and FCEVs under high utilisation.
- The project aims to increase investor and policymaker confidence in FCEV and HRS roll-out. Analysis in ZEFER has proven that FCEVs and HRSs can meet the demands of high-mileage fleet operations. This has led to fleet operators increasing the number of FCEVs in their fleets. It has also attracted investors.
- Of the 15 ZEFER partners, 6 are small and medium-sized enterprises (SMEs). In particular, the three largest fleet operators are SMEs, and therefore a large proportion of the ZEFER funding (84 %) is allocated to SMEs.
- ZEFER aims to reduce the production cost of fuel cell systems to be used in transport applications, while increasing their lifetimes, to compete with conventional technologies. The project aims to demonstrate, at utilisation levels, a significantly longer lifetime of fuel cells in FCEVs than that of those currently deployed. The bulk procurement of FCEVs is expected to reduce their costs to their lowest level to date.
- The project aims to increase the energy efficiency of hydrogen production while reducing operating and capital costs so that the combined system can compete with alternatives on the market. ZEFER aims to reduce the hydrogen cost at the pump. This can be achieved by providing a stable demand for hydrogen at an HRS. The project also aims to trigger further cost reductions by creating a climate of investment in the low-cost green production systems required to drive down the overall cost.

PROGRESS AND MAIN ACHIEVEMENTS

- Nearly all 180 FCEVs have been deployed into everyday operation in Paris (60), London (10 in operation, 50 returned at lease end) and Copenhagen (32 in operation, 28 delivered).
- Most of the HRS upgrades have been completed, leading to improvements in the technical performance and customer experience of HRSs.
- Most deployment partners in the project have plans to scale up their FCEV fleets as a result of the ZEFER project.

FUTURE STEPS AND PLANS

- ZEFER will complete all activities in Q2 2023.
- The project is due to be successfully completed with an immense dataset collected for the FCEVs and HRSs in operation. Public findings from the project related to better understanding how performance is affected by long-term high utilisation. Reports analysing the business case for FCEVs in high-mileage applications, and customer value propositions can be found on the project website (https://zefer.eu/reports/).
- ZEFER contributed to increasing awareness of the business case for FCEVs in fleet applications. There are now many FCEV taxi projects in Europe.

QUANTITATIVE TARGETS AND STATUS

Target source	Parameter	Unit	Target	Achieved to date by the project	Target achieved?	SoA result achieved to date (by others)	Year of SoA target
	FCEVs						
Project's own objectives	Min. distance for vehicles	km/vehicle	90 000 (60 000 for Copenhagen deployment)	62 900	⚙	FCEVs operated as taxis in H2ME drive an average of ~ 45 000 km per year	2020
	Vehicle availability	%	> 98	> 99	✓	> 99	2021
	Range	km	500	470 in Mirai gen 1 and 530 in Mirai gen 2	✓	756	2020
	HRSs						
	HRS availability	%	> 98	94.3	⚙	98	2016
	Hydrogen purity	%	99.99	99.99	✓	99.99	
	Level of back-to-back vehicle refuelling	refuelling events/hour	6	6	✓	6	2020
	Cost of hydrogen	€/kg	≤ 10	10	✓	10	

Clean Hydrogen Partnership

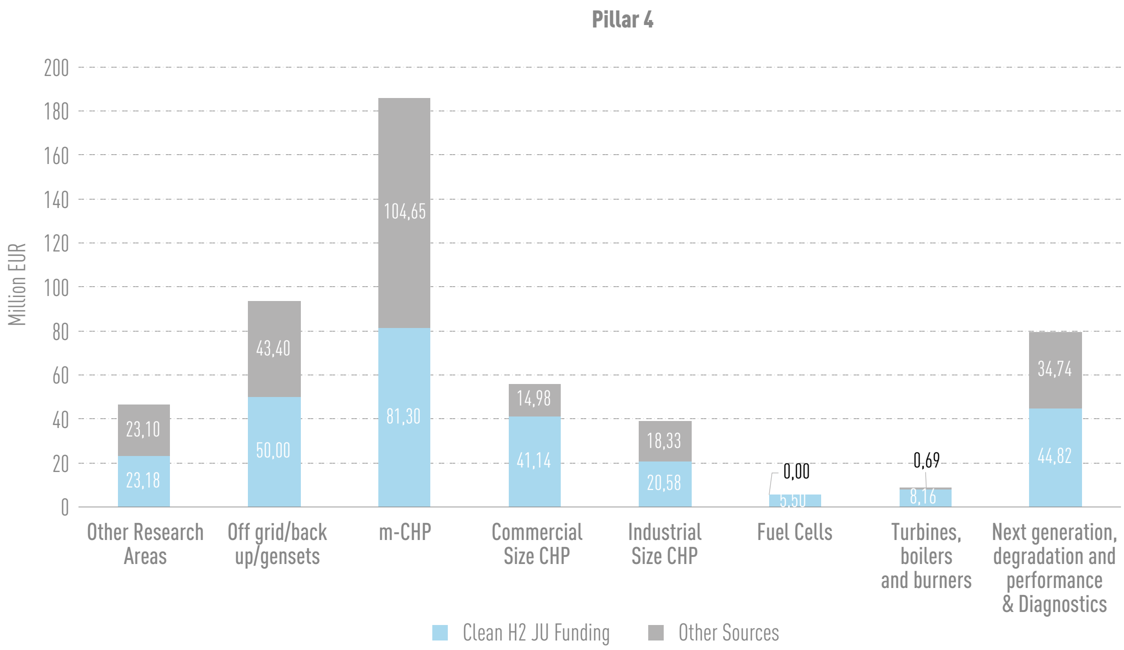
Co-funded by the European Union

IV. PILLAR 4 - H_2 END USES – CLEAN HEAT AND POWER

Objectives: Stationary fuel cell systems for power and combined heat and power generation, as well as for provision of back-up power still need additional development and larger production volumes to allow competition with well-established traditional ones, aiming to reduce investment and operational costs whilst improving system durability. Half of the projects (6 out of 12) are focused on the use of SOFC technology, 3 projects are addressing PEMFC technology, from which 1 is dedicated to high temperature PEM technology, 1 is looking into both Alkaline and PEMFC and 2 projects are related to both SOFC and PEMFC.

Budget: Between 2010 and 2020, 81 projects have been supported with a total JU contribution of EUR 275 million and a contribution from partners of EUR 241 million. A detailed split per Research Area is presented in Figure 39.

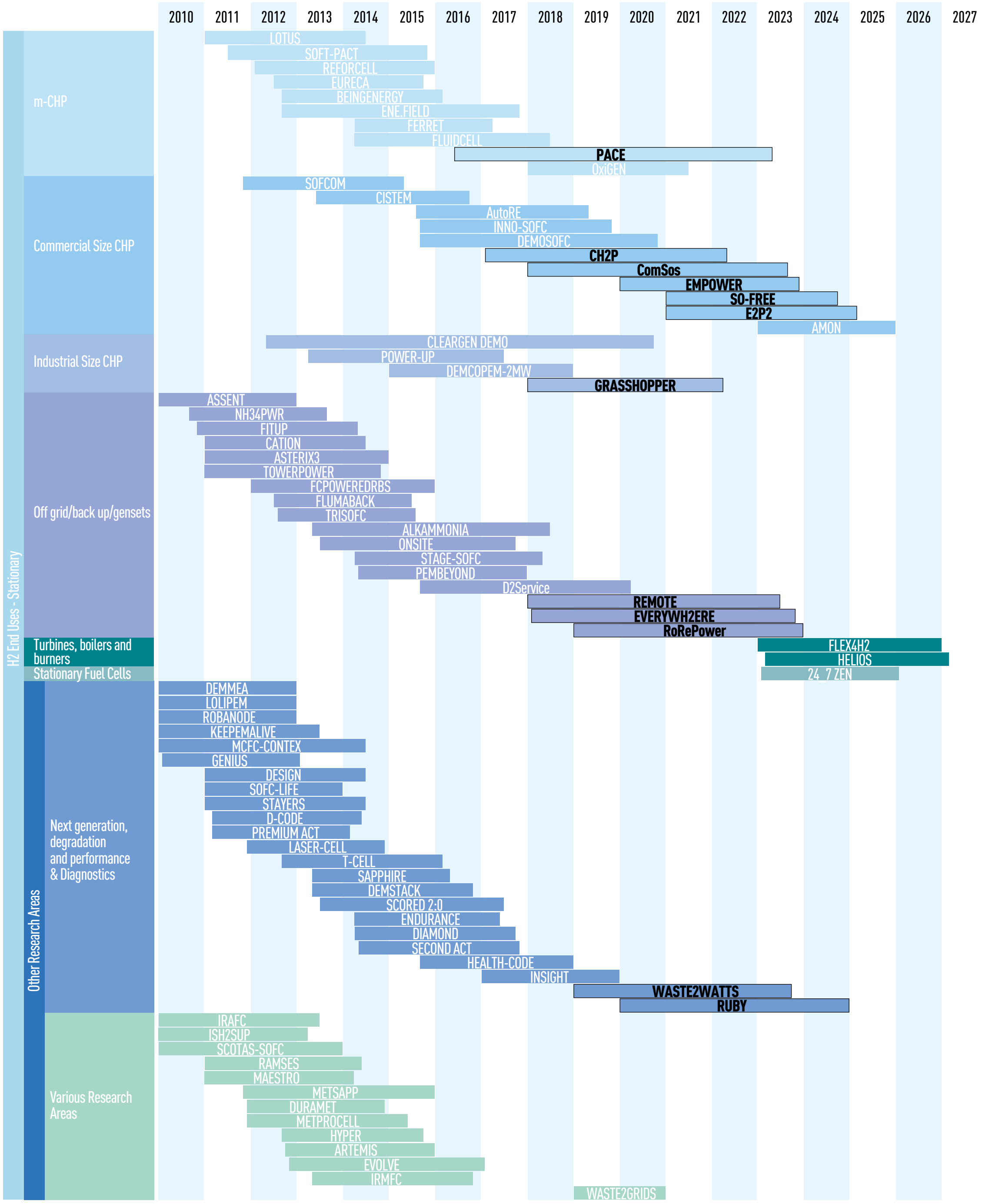
Figure 39: Funding for Pillar 4 projects (2008-2022)



Source: Clean Hydrogen JU

Projects: The Clean Hydrogen JU programme portfolio of stationary fuel cell applications projects as of 2010 is shown in Figure 40. The present review covers the 12 projects emphasised in bold that are still under execution or will be completed in 2023. These projects are funded under calls from 2015 until 2020.

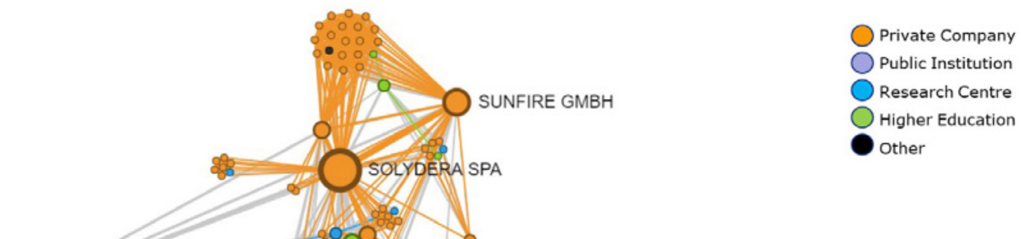
Figure 40: Project timelines of Pillar 4 – H2 End Uses – Clean Heat and Power



Source: Clean Hydrogen JU
NB. Projects highlighted in black were considered for the 2023 Programme Review.

Figure 41 shows the connections between partners present in the 12 projects in Pillar 4[146]. Private companies dominate the participants. The key partners present in multiple projects in Pillar 4 are the FC stacks/system providers (Solydera, previously called SolidPower and Sunfire) and the research institute VTT[147].

Figure 41: TIM plot showing the participants in the 12 projects reviewed



Top Participants

Participant	Number of Projects
SOLYDERA	11
SUNFIRE	8
VTT	5
Multiple participants	3

Source: TIM (JRC)

MICRO CHP

PACE is a big deployment initiative engaging 5[148] leading European fuel cell manufacturers: Bosch, Solydera (previously called SOLIDpower), Viessmann, BDR Thermea Group and Sunfire. PACE is a natural continuation of the ENEFIELD project, during which more than 1 000 residential fuel cell Combined Heat and Power micro-CHP (FC-µCHP) installations were deployed across 10 key European countries. The project ended in April 2023, having sold 3 091 units, out of which 2 502 units are commissioned. The project demonstrated that fuel cells can operate seamlessly for a long period of time: 5 years operational time was already demonstrated while - 15 years projected system lifetime should be expected (5 years more than the initially planned 10 years). More than 50% reduction in stack replacement or no stack replacement during a 10 year service plan and high units' availability between 96% and 99% can be achieved. In addition, the manufacturing capacity has reached 2 300 systems/year per OEM, while the target was set at 1 000. The number of trained installers has increased as well. These results are excellent in comparison to SoA considering the limited number of global fuel cell stack suppliers and the associated supply chain challenges.

In terms of standardisation, the existing standards are developed for other technologies and thus do not reflect the specificity of the FC-µCHP technology. The regulation used for labelling of FC-µCHP units fails to recognise their 90% energy efficiency due to their ability to output both useful electric and heat and, hence, their decarbonisation potential, having in mind that they can be powered also by hydrogen and LPG. Despite the difficulties, the project enabled manufacturers to move towards product industrialisation and fostered market development at national level by working together with building professionals and the wider energy community. Most of the installations occurred in Germany and Belgium, followed by Italy and France. Overall, the PACE project was the largest market

146 The size of the node represents the number of projects that has at least one participating organisation from that country. The thickness of the links between the nodes is proportional to the number of projects those countries have in common. The table insert shows the top 5 countries.

147 Technical Research Centre of Finland

148 Hexis was the 6th manufacturer in the beginning of the project. Although some Hexis units have been installed, the company has recently entered in bankruptcy and will not continue with their SOFC.

introduction trial of µCHP fuel cells technology and a strong basis for the success of the Clean Hydrogen JU programme. The project is a success story and one of the JU's flagship projects.

COMMERCIAL SIZE CHP

The key objective of the **ComSos** project is to validate and demonstrate fuel cell based combined heat and power solutions in the mid-sized power ranges of 10-12 kW, 20-25 kW, and 50-60 kW (referred to as Mini FC-CHP). The core of the consortium consists of 3 SOFC system manufacturers aligned with individual strategies along the value chain: Solydera, Sunfire and Convion. In total 23 Units were intended to be installed during the project, namely: 15 units of 12 kWe each (total 180 kWe) by Solydera, 2 units of 60 kWe each (total 120 kWe) by Convion, and 6 units of 25 kWe each (total 150 kWe) by Sunfire. The 3 different OEM's products are targeting different markets and geographical areas, exploring the potential in Europe and Asia. Sunfire and Convion units are generating thousands of hours of demonstration data. Still 9000 hours demonstration time for all units will not be achieved during the project duration. COMSOS has achieved 2 MAWP targets, namely Electrical Efficiency of more than 50 % and NOx emission of less than 40 mg/kWh. CAPEX target can be achieved only through the automated mass production (more than 100 units a year per manufacturer). The project is important for the EU to create a new market for SOFC units. In general, the activity developed during the project has increased the OEM manufacturing capability, in some cases bringing innovation to the technology (e.g. reducing the number of components and reducing costs).

Project **E2P2** is focused on providing a proof of concept for fuel cells to be deployed as economic, energy efficient, quiet, environmentally friendly and resilient prime power sources for data centres in populated areas, providing thus negligible demand on the electrical grid. The project will contribute to fuel cells market enlargement, anticipating opportunities for the European fuel cell suppliers, including social, environmental and commercial impact for the European market. The project will develop 2 FCs of 45 kW Solydera BG60 fuel cell CHP System with total power of 90 kW for residential and commercial applications in Europe. The E2P2 has synergies with WEDISTRICT project. Both projects are investigating fuel cell powered data centres. The RISE Research Institute and Solydera group have learnt from the WEDISTRICT on the implementation of the fuel cells. There is a new player in the project as a third party in-kind contributor – Deerns company, specialised in design and optimisation of installations for high performance buildings.

SO-FREE aims at the development and demonstration of a fully future-ready solid oxide fuel cell (SOFC)-based system for combined heat and power (CHP) generation allowing an operation window from 0 to 100% H_2 in natural gas and 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-CHP system. The 2 short stack designs, coming from Elcogen and Fraunhofer IKTS, were validated and the preliminary performance maps, consisting in stationary load points under constant operation for >5/10 h of each short stack design are done as a benchmark for performance tests under real gas compositions. The final system design will be finalised in the first half of 2023. Stack production and delivery is expected to be done by the end 2023 and the system should be ready for demonstration in the beginning of 2024. SO-FREE project has realised 6 patent applications in 2022.

The **EMPOWER** project will develop, manufacture and validate a methanol fuelled 5 kWe CHP system based on HT PEMFC technology. The developed CHP unit will be capable of fast start-up and fast dynamic response to help the integration of intermittent power production from renewable energy sources. The system was initially planned to involve a methanol reforming stage comprising of an Aqueous Phase methanol Reformer (APR), and a downstream gas phase methanol reforming reactor followed by a HT PEMFC to be fed with reformate mixture by the two-stage methanol reforming, and to operate under pressurised conditions. Instead of a two-phase methanol reforming, an oversized gas phase reformer, to be integrated in the final pilot, has been designed, constructed, and validated by CATATOR. First tests have shown that the reformer is preforming well and is suitable for the pilot. A mobile workspace to host the integrated methanol HT-PEMFC micro-CHP system has been also designed and constructed. Automated quality control methods for stack components were developed. The project contributed to increased visibility and awareness of the potential of renewable methanol. Also, EMPOWER supported knowledge exchange and production ramp-up through stakeholder search, info and linkage. Another overarching achievement of the project is the production of affordable and secure electricity with low carbon footprint; the carbon footprint has been analysed in 2022. Scientific studies on APR catalysts were also finalised during 2022, resulting in a new scientific publication.

The **CH2P** project aims to develop a combined hydrogen and power production system, with low carbon footprint and a high overall efficiency, by using Solid Oxide Fuel Cell technology. The capability to modulate between power and hydrogen production, according to the demand, is a key factor of the CH2P system, therefore aimed to be used to cover the corresponding fluctuating demands in hydrogen refuelling stations (HRS) and other stationary applications. The system also co-generates heat using Solid Oxide Cell technology fuelled by carbon lean natural gas[149] (NG) or bio-methane. CH2P targets 6 use cases and has the ambition of producing hydrogen below 5 €/kg. Using the lessons learnt from the prototype system (20 kg/day H2), the design of an upscaled 400 kg/day system has also been developed, targeting 80% efficiency.

INDUSTRIAL SIZE CHP (BEYOND 100 KW)

The **GRASSHOPPER** project aimed to create a next generation MW-size Fuel Cell Power Plant (FCPP), which is more cost-effective and flexible in power output to match the grid necessities. The project ended in March 2022. The FCPP is demonstrated in the field as a 100 kW sub-module pilot plant, implementing newly developed BoP system components and stacks. The project managed to develop, build and test the next generation of PEMFC for industrial applications. Tests done to date have demonstrated automatic mode operation and power demand adaptation capabilities; 50% electrical efficiency, even at dynamic operation, has been achieved.

The advancements in the project at MEA, stack and BoP levels, led the CAPEX of a unitary 2 MW flexible and dynamic fuel cell power plant for grid balancing to be estimated at 1 500 EUR/kWe. The mass production of several of these plants at a production scale of 25 MW/year could reduce the total cost by 10-20%, reaching thus 1 200-1 360 EUR/kWe. The project has also achieved outstanding results at MEA and stack levels. MEA platinum content has been reduced by > 80%. A cell with an active area of 300 cm^2 designed for mass manufacturing was finalised and tested in a short stack showing a performance of 0.689 V at 1 A/cm^2, increasing the power density by 60% in relation to previous technology. This has allowed the design of single stacks of 27 KW nominal power that represents 4 times the power of the stacks used for the first generation of this type of plants (developed in the former Clean Hydrogen JU project DEMCOPEM 2MW). In addition, the project has developed business plans for different sectors and markets as well as early adopters for the technology.

OFF GRID / BACK UP / GENSETS

REMOTE project aims to demonstrate the technical and economic feasibility of 2 hydrogen FC-based energy storage solutions (integrated P2P, non-integrated P2G+G2P systems), originally deployed in 4 demos, based on renewable energy in isolated micro-grid or off-grid remote areas. Despite the hurdles that led to the change of the initial installation sites in Italy with a new site in Spain, the project managed to take mitigation measures and make the necessary changes to assure total power installation of 250 kW in the sum of the demos. The REMOTE project has synergies with other 7 ongoing and ended projects, as well as with the Clean Energy for EU Islands initiative and the GRID4EU Large-Scale Demonstration of Advanced Smart Grid Solutions project. The scientific impact of the project is also rather high; to date 10 scientific publications were published, 9 of which are peer-review articles.

The overall objective of the **RoRePower** project is to further develop and demonstrate SOFC systems for off-grid power generation in markets, such as the gas and oil infrastructure in remote regions with harsh climate conditions (from -40 to +50°C) and the power supply of telecommunication towers, especially in emerging countries. At the end of 2022 all customer sites have been identified and 41 units out of the 47 units in total have been installed. The remaining RoRePower units will be installed in 2023. The operation of Sunfire-Remote units in harsh climates as Alaska (-40 °C even with Propane) and Malaysia (hot tropical climate) could be demonstrated successfully. Thanks to the activity done within RoRePower, Solydera has decided to place on the

149 Lean gas contains an average of 10.3 kWh per m^3, while Rich gas contains an average of 11.4 kWh per m^3.

market containerised solution also, based on the same approach of BG-Remote, acquiring a new order for more than 109 kW power output's containers.

The **EVERYWH2ERE** project will integrate already demonstrated robust PEMFC stacks and low weight intrinsically safe pressurised hydrogen technologies into easy to install, easy to transport FC based transportable gensets. Validation and conformity assessment of the first 2 transportable gensets (1x25 kW and 1x100 kW) and of related hydrogen storage bundles has been completed. Demonstration of the 100 kW system took place at a construction site near San Sebastian in Spain. The 25 kW system was demonstrated in the HESE Bologna fair. The project will end in October 2023. Based on lessons learnt, the consortium has redesigned the internals of the genset containers, leading to an improved 'model 2' design of the pending 5 units.

OTHER RESEARCH AREAS

WASTE2WATTS is developing cleaning technologies for biogas to make it compatible with solid oxide fuel cells (SOFCs), aiming to reduce the costs for biogas pollutant removal processing and to achieve optimal thermal system integration. The project is designing an integrated SOFC CHP system fed with biogas using innovative purification solutions. Solutions for small-scale units (5-50 kWe) will be based on a solid sorbent matrix, while for medium-to-large scale units (≥ 500 kWe) a novel cooling approach to purification is pursued. A 1.5 kWe small-scale SOFC unit is manufactured by Solydera instead of the initially planned 6 kWe. It will run on an agro-biogas site in Switzerland, connected to a sorbent gas cleaning unit. The medium-to-large scale unit will be tested in Lithuania. A 100 m^3/hour sized gas cleaning system will be installed on a mixed biowaste digestion site in Vilnus to demonstrate the deep cooling approach. Currently 2 skids (the biogas treatment unit and the cold generation unit) have been mounted at Biokomp's facilities in Italy and are being tested. Mass manufacturing and cheaper biogas can help the SOFC to hit the mass market. Sunfire and Solydera did cost estimates for 25-50 MWe/year SOFC manufacturing, achieving stack cost of 1 000 €/kWe (Solydera) and 1 800 €/kWe (Sunfire) and system cost of 3 300 €/kWe (Solydera) and 4 000 €/kWe (Sunfire). Further cost calculations will follow from the two demo-installations in 2023.

The **RUBY** project developed a diagnostic/control tool based on the use of the Electrochemical Impedance Spectroscopy (EIS) technique and conventional signals (e.g. voltage, current, temperature, etc). It performs monitoring, diagnosis, prognosis control and mitigation for Stack and Balance of Plan (BoP) for PEMFC in backup applications and SOFC for micro-CHP applications. The tool monitors the State-of-Health of the stacks and the systems, detects faults at stack and BoP level, estimates stacks lifetime, applies advanced control actions and proposes mitigation strategies at system level. The pilot version of the monitoring, diagnostics and prognostics algorithms is developed and tested.

CH2P

COGENERATION OF HYDROGEN AND POWER USING SOLID OXIDE BASED SYSTEM FED BY METHANE RICH GAS

Project ID:	735692
PRD 2023:	Panel 4 – H2 end uses – stationary applications
Call topic:	FCH-02-4-2016: Co-generation of hydrogen and electricity with high-temperature fuel cells (> 50 kW)
Project total costs:	EUR 7 239 100.08
Clean H_2 JU max. contribution:	EUR 3 999 896.00
Project period:	1.2.2017–30.4.2022
Coordinator:	Fondazione Bruno Kessler, Italy
Beneficiaries:	Deutsches Zentrum für Luft- und Raumfahrt EV, École Polytechnique Fédérale de Lausanne, HyGear BV, HyGear Fuel Cell Systems BV, HyGear Operations BV, HyGear Technology and Services BV, Shell Global Solutions International BV, SolydEra SA, SolydEra SpA, Vertech Group

https://ch2p.eu/

PROJECT AND OBJECTIVES

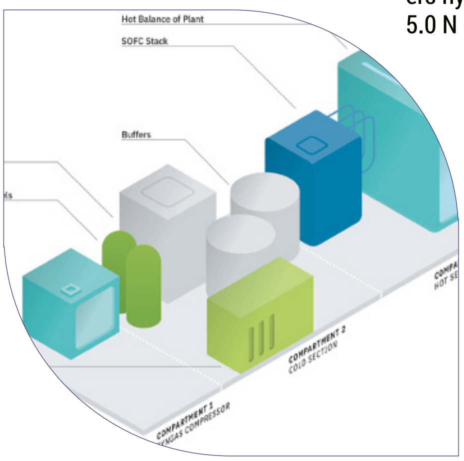
CH2P is designing, constructing and partially validating an innovative system prototype for hydrogen production. The system co-generates hydrogen, heat and electricity using solid oxide cell technology fuelled by carbon-lean natural gas or biomethane. The CH2P system operates in five modes, enabling flexibility in hydrogen and electricity supply. The prototype is placed in two 40-foot containers, and it is modular to support future upscaling. CH2P has been designed as a transition technology for application at hydrogen refuelling stations and has the ambition of producing hydrogen at < €4/kg.

NON-QUANTITATIVE OBJECTIVES

- CH2P targets six use cases.
- The project aims to co-generate hydrogen and electricity for hydrogen refuelling stations. With a single technology, CH2P will deliver natural gas, hydrogen and power – the fuels of the EU directive on alternative fuels infrastructure.

PROGRESS AND MAIN ACHIEVEMENTS

- The CH2P project designed, simulated, constructed and validated a novel system prototype for hydrogen production.
- The system produces 20 kg/day of hydrogen and 25 kW of electric power.
- The system operates in five modes and delivers hydrogen at 7 bar with a purity level of 5.0 N of hydrogen.



QUANTITATIVE TARGETS AND STATUS

Target source	Parameter	Unit	Target	Achieved to date by the project	Target achieved?
	System size	kgH_2/day	20	25	
	Flexible co-generation of H_2 and POWER	%	50 + 50	30 + 30	
	System efficiency	%	65	66	
AWP 2016	Fuel utilisation and steam conversion rate at large stack module level	%	> 80 %	90	✓
	Stack voltage deviation	%		< 1 %	
	Gas purification unit producing 5 N of hydrogen	–	5N Purity CO < 200 ppb	5N Purity CO < 200 ppb	
	1 000 hours of testing in a real environment	hours	1 000	1 000	

COMSOS

COMMERCIAL-SCALE SOFC SYSTEMS

Project ID:	779481
PRD 2023:	Panel 4 – H2 end uses – stationary applications
Call topic:	FCH-02-11-2017: Validation and demonstration of commercial-scale fuel cell core systems within a power range of 10–100 kW for selected markets/applications
Project total costs:	EUR 10 277 897.50
Clean H_2 JU max. contribution:	EUR 7 486 954.75
Project period:	1.1.2018–31.8.2023
Coordinator:	Teknologian tutkimuskeskus VTT Oy, Finland
Beneficiaries:	Convion Oy, Energy Matters BV, Politecnico di Torino, SolydEra SA, SolydEra SpA, Sunfire GmbH

https://www.comsos.eu/

PROJECT AND OBJECTIVES

The key objective of ComSos is to validate and demonstrate fuel-cell-based combined heat and power solutions (FC-CHP) in the mid-sized power ranges of 10–12 kW, 20–25 kW and 50–60 kW (referred to as mini FC-CHP). The core of the project consortium consists of three solid oxide fuel cell (SOFC) system manufacturers aligned with individual strategies along the value chain: SolydEra, Sunfire and Convion.

PROGRESS AND MAIN ACHIEVEMENTS

- All five Sunfire systems have been installed at the customer sites.
- Both Convion units have been installed at the customer sites.
- The first SOLIDpower (SolydEra) unit has been installed at the customer site.

FUTURE STEPS AND PLANS

- The Sunfire and Convion units are generating thousands of hours of demonstration data for project purposes.
- The rest of the SOLIDpower (SolydEra) units were expected to be installed during spring 2023.

QUANTITATIVE TARGETS AND STATUS

Target source	Parameter	Unit	Target	Achieved to date by the project	Target achieved?
MAWP addendum (2018–2020)	Electrical efficiency	%	> 50	> 50	✓
	NOx emission	mg/kWh	< 40	< 40	✓
	Durability	years	10	2	
Project's own objectives	SME participation	%	25	50	✓

E2P2

ECO EDGE PRIME POWER

Project ID:	101007219
PRD 2023:	Panel 4 – H2 end uses – stationary applications
Call topic:	FCH-02-9-2020: Fuel cell for prime power in data-centres
Project total costs:	EUR 4 053 460.38
Clean H_2 JU max. contribution:	EUR 2 499 715.50
Project period:	1.1.2021–28.2.2025
Coordinator:	Research Institutes of Sweden AB, Sweden
Beneficiaries:	Vertiv Croatia DOO za trgovinu i usluge, Vertiv, InfraPrime GmbH, Equinix Netherlands BV, Snam SpA, TEC4FUELS, SolydEra SpA

https://www.e2p2.eu/

PROJECT AND OBJECTIVES

The main objectives of E2P2 are to define the fuel cell prime power concept for data centres and to create an authoritative open standard for fuel cell adaptation 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 their uptake across multiple markets, with improved energy efficiency and cost-effectiveness.

FUTURE STEPS AND PLANS

The main target is to get the demonstrator up and running.

QUANTITATIVE TARGETS AND STATUS

Target source	Parameter	Unit	Target	Target achieved?
MAWP addendum (2018–2020)	Availability (% of plant available power)	%	97	
	Electrical efficiency	% LHV	42–62	
	CAPEX	€/kW	3 500–6 500	

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EMPOWER

EUROPEAN METHANOL POWERED FUEL CELL CHP

Project ID:	875081
PRD 2023:	Panel 4 – H2 end uses – stationary applications
Call topic:	FCH-02-7-2019: Development of highly efficient and flexible mini CHP fuel cell system based on HTPEMFCs
Project total costs:	EUR 1 499 876.25
Clean H_2 JU max. contribution:	EUR 1 499 876.25
Project period:	1.1.2020–30.11.2023
Coordinator:	Teknologian tutkimuskeskus VTT Oy, Finland
Beneficiaries:	Blue World Technologies APS, Catator AB, THT Control Oy, Universidade do Porto

https://www.empower-euproject.eu/

PROJECT AND OBJECTIVES

The project will develop, manufacture and validate a methanol-fuelled 5 kWe combined heat and power (CHP) system based on high-temperature proton-exchange membrane fuel cell (HT-PEMFC) technology. The project will enhance the system's efficiency to target the mini-CHP market and provide a cost-competitive and low-carbon option. The developed CHP unit will be capable of fast start-up and fast dynamic response to help the integration of intermittent power production from renewable energy sources. Currently, the subsystems of the CHP system are being finalised by project partners. The integration of the final CHP system has started.

NON-QUANTITATIVE OBJECTIVES

- EMPOWER aims to increase the visibility and awareness of the potential of renewable methanol. The project results are being openly communicated and disseminated, for example through public deliverables and scientific publications. The project has also arranged an international summer school on hydrogen technologies.
- The project aims to conduct business analysis for the use of renewable methanol in CHP systems and other applications. Preliminary market analysis was performed in 2021, and this will be updated at the end of the project.
- EMPOWER aims to support knowledge exchange and production ramp-up through stakeholder identification, information sharing and linkages. An industry webinar was arranged for January 2021, a workshop was arranged to take place in Denmark in May 2022 and another is planned to take place in Finland in November 2023.
- The main goal of the project is to produce affordable and secure electricity with a low carbon footprint. The carbon footprint was analysed in December 2022.

PROGRESS AND MAIN ACHIEVEMENTS

- The HT-PEMFC stack has been designed for pressurised operation.
- The CHP system enclosure and system balance-of-plant components have been finalised.
- The automated quality control methods for stack components have been developed.
- The carbon footprint of the 5 kW HT-PEMFC CHP system has been analysed.
- Scientific studies on aqueous-phase-reforming catalysts have been finished and reported on.

FUTURE STEPS AND PLANS

- EMPOWER will demonstrate the project's 5 kW HT-PEMFC CHP system in the relevant end-user environment. The designed system will be demonstrated in summer/autumn 2023 in Finland to evaluate its performance and the project's key performance indicators.
- The HT-PEMFC subsystem will be integrated into the CHP system (planned for summer 2023).
- The system scale-up study (50–100 kW) and business analysis were expected to be performed in spring 2023.

QUANTITATIVE TARGETS AND STATUS

Target source	Parameter	Unit	Target	Achieved to date by the project	Target achieved?
Project's own objectives	Stack electrical efficiency (LHV reformate gas)	%	55	N/A	⚙
	Fuel-processing efficiency	%	85	> 85	✓
MAWP addendum (2018–2020)	CHP electrical efficiency (LHV methanol)	%	37–67	N/A	⚙
	CAPEX	€/kWh	5 500	2 600	✓

EVERYWH$_2$ERE

MAKING HYDROGEN AFFORDABLE TO SUSTAINABLY OPERATE EVERYWHERE IN EUROPEAN CITIES

Project ID:	779606
PRD 2023:	Panel 4 – H2 end uses – stationary applications
Call topic:	FCH-02-10-2017: Transportable FC gensets for temporary power supply in urban applications
Project total costs:	EUR 6 827 124.45
Clean H$_2$ JU max. contribution:	EUR 4 999 945.76
Project period:	2.1.2018–31.10.2023
Coordinator:	RINA Consulting SpA, Italy
Beneficiaries:	Acciona Construcción SA, Delta1 gUG (Haftungsbeschränkt), FRIEM SpA, Fundación para el Desarrollo de las Nuevas Tecnologías del Hidrógeno en Aragón, Genport SRL – Spin Off del Politecnico di Milano, ICLEI European Secretariat GmbH (ICLEI Europasekretariat GmbH), Iren Energia SpA, Iren Smart Solutions SpA, Iren SpA, Linde Gas Italia SRL, Mahytec SARL, Parco Scientifico Tecnologico per l'Ambiente SpA, PowerCell Sweden AB, Swiss Hydrogen SA, Teknologian tutkimuskeskus VTT Oy, THT Control Oy

http://www.everywh2ere.eu/

PROJECT AND OBJECTIVES

EVERYWH$_2$ERE will integrate the previously demonstrated robust proton-exchange membrane fuel cell stacks and the low-weight, intrinsically safe pressurised-hydrogen technologies into easy-to-install, easy-to-transport, fuel-cell-based transportable gensets. Eight fuel cell 'plug and play' gensets fitted in containers will be produced and tested through a pan-European demonstration campaign in a demonstration-to-market approach. The prototypes will be tested at construction sites, music festivals and urban public events across Europe, demonstrating their flexibility and increased lifetimes.

NON-QUANTITATIVE OBJECTIVES

EVERYWH$_2$ERE aims to support the development of a regulatory framework for transportable hydrogen-fuelled systems.

PROGRESS AND MAIN ACHIEVEMENTS

- The first two fuel-cell-based transportable gensets (1 × 25 kW and 1 × 100 kW) and related hydrogen storage bundles have been validated.
- The assessments of conformity for the 110 kW and 25 kW gensets have been completed (declaration of conformity).
- The 100-01 genset has been demonstrated at the Acciona construction site (San Sebastian, Spain) and at Aragón MotorLand. Preliminary activities for the cold-ironing demonstration in the Port of Tenerife are being carried out.
- The 025-01 genset was demonstrated at the 2023 Hydrogen Energy Summit & Expo, in Bologna. Further demonstrations are being designed for use in Rome (lighting of a historical monument during a public event) and Genoa (electricity supply during a public event associated with The Ocean Race grand finale).
- Commissioning of the 100-02, 025-02, 100-03 and 025-03 gensets is ongoing, with their release expected at the start of spring 2023 for the second batch and the end of spring 2023 for the third batch, ready for the summer demonstration campaign.
- The second stakeholder workshop was planned for 23 March 2023.

FUTURE STEPS AND PLANS

- The definition of the final exploitation plan is ongoing. This includes the assignment of the gensets to technical partners after the end of the project, the identification of responsibilities for maintenance and support during operation, and potential involvement in follow-up funded projects.
- The summer demonstration campaign will be clusterised in order to reduce transportation and its related costs, not least because of the energy crisis.

QUANTITATIVE TARGETS AND STATUS

Target source	Parameter	Unit	Target	Achieved to date by the project	Target achieved?
Project's own objectives	Levelised cost of energy of the genset (identification of replication market with contractual costs ± 10 % of those of current power supply solutions)	€/kWh	1.1	N/A	⚙
	Noise emission of the full genset (not only the FC SuSy)	dB	< 65	60	✓
	Future manufacturing CAPEX (of the system)	€/kW	5 500	6 850	⚙

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GRASSHOPPER

GRID ASSISTING MODULAR HYDROGEN PEM POWER PLANT

Project ID:	779430
PRD 2023:	Panel 4 – H2 end uses – stationary applications
Call topic:	FCH-02-7-2017: Development of flexible large fuel cell power plants for grid support
Project total costs:	EUR 4 387 063.75
Clean H_2 JU max. contribution:	EUR 4 387 063.75
Project period:	2.1.2018–31.3.2022
Coordinator:	Informatizacija Energetika Avtomatizacija DOO, Slovenia
Beneficiaries:	Abengoa Innovación Sociedad Anónima, Johnson Matthey Hydrogen Technologies Limited, Nedstack Fuel Cell Technology BV, Politecnico di Milano, Zentrum für BrennstoffzellenTechnik GmbH

http://www.grasshopperproject.eu/

PROJECT AND OBJECTIVES

The GRASSHOPPER project aims to create a next-generation MW-sized fuel cell power plant (FCPP) that is more cost-effective and flexible in power output than current FCPPs. The FCPP will be demonstrated in the field as a 100 kW submodule pilot plant, implementing newly developed balance-of-plant system components and stacks. A new stack design has been developed with increased power density, and short-stack testing has been concluded. The pilot plant is undergoing factory acceptance testing on hydrogen. A dynamic simulation model of the pilot plant has been developed to support optimisation in the field and the scaling up of the design.

NON-QUANTITATIVE OBJECTIVES

The project aims to ensure operation flexibility and grid stabilisation capability through fast responses. The operation strategy was defined considering the requirements in terms of response time for grid stabilisation.

PROGRESS AND MAIN ACHIEVEMENTS

- The project has developed, built and tested the next generation of proton-exchange membrane (PEM) fuel cells for industrial applications. The tests carried out to date have demonstrated automatic mode operation and power demand adaptation capabilities. 50 % electrical efficiency, even in dynamic operation, has been achieved. The pilot plant can achieve full power (100 kWe gross power, 80 kWe net power) over time and modulate from 50 % to 100 % in less than 20 seconds and from zero to full load in less than 60 seconds from a warm standby mode.
- Building on the experiences of the pilot plant, the GRASSHOPPER team designed a modular 2 MW-scale low-cost FCPP with grid-supporting capability. The CAPEX of a unitary 2 MW flexible and dynamic FCPP for grid balancing has been estimated to be €1 500/kW (assuming stack costs of < €450/kW). The mass production of several of these plants at a production scale of 25 MW/year could reduce the total costs further.
- The project has also achieved outstanding results at the membrane electrode assembly (MEA) and stack levels. MEA platinum content has been reduced by > 80 %. A cell with an active area of 300 cm^2 designed for mass manufacturing was finalised and tested in a short stack, showing a performance of 0.689 V at 1 A/cm^2, increasing the power density by 60 % relative to previous technology. This has allowed the design of single stacks of 27 kW nominal power, representing four times the power of the stacks used for the first generation of this type of power plant (developed and demonstrated in the Clean Hydrogen Joint Undertaking project DEMCOPEM-2MW).
- The pilot plant has been successfully transported and commissioned in Arnhem, the Netherlands, where testing will continue until the final site preparations are completed. The tests have already contributed significantly to the continuation of the development of stack and operation modes.

FUTURE STEPS AND PLANS

- The project activities will continue in the years to come. In the very short term, tests of the GRASSHOPPER fuel cell system prototype will continue in an operational environment. This should allow the GRASSHOPPER solution to reach TRL 7. Although the project has ended, the consortium has committed to report operational data to the Clean Hydrogen Joint Undertaking through the Technology Reporting Using Structured Templates (TRUST) platform.
- In parallel, and with the support of Dutch funding, it is expected that the GRASSHOPPER technology will be developed with a view to reaching TRL 8–9 by the end of 2025.
- In addition, support has been awarded (under the umbrella of the IPCEI Hy2Tech) to build a GW-scale factory, which should allow, among other activities, the mass manufacturing of the GRASSHOPPER solution.

QUANTITATIVE TARGETS AND STATUS

Target source	Parameter	Unit	Target	Achieved to date by the project	Target achieved?
Project's own objectives	MEA cost reduction	%	65	65	✓
	Stack efficiency	%	55	55	
	Stack CAPEX	€/kWe	450	450	
	Operation flexibility	–	Load following capacity over a 20–100 % power range	Load following capacity of 20–100 % for stack and 0–100 % for FCPP	
			50 % power in < 20 seconds	50 % power in < 20 seconds	
			100 % power in < 60 seconds	100 % power in < 60 seconds	
	Availability	%	95	N/A	⚙
	System electrical efficiency	%	50	43	⚙
MAWP addendum (2018–2020)	System CAPEX	€/kWe	1 500	1 500	✓
AWP 2017	Stack lifetime	hours	20 000	N/A	⚙

PACE

PATHWAY TO A COMPETITIVE EUROPEAN FC MCHP MARKET

Project ID:	700339
PRD 2023:	Panel 4 – H2 end uses – stationary applications
Call topic:	FCH-02.9-2015: Large scale demonstration µCHP fuel cells
Project total costs:	EUR 91 681 943.33
Clean H_2 JU max. contribution:	EUR 33 932 752.75
Project period:	6.1.2016–30.4.2023
Coordinator:	European Association for the Promotion of Cogeneration VZW, Belgium
Beneficiaries:	Baxi Innotech GmbH, BDR Thermea Group BV, Bosch Thermotechnik GmbH, Danmarks Tekniske Universitet, Element Energy, Element Energy Limited, ERM France, EWE AG, Fachhochschule Zentralschweiz – Hochschule Luzern, Hexis AG, Hexis GmbH, Remeha BV, Remeha GmbH, Remeha NV, Senertec Kraft-Wärme-Energiesysteme GmbH, SOLIDpower GmbH, SolydEra SpA, Sunfire Fuel Cells GmbH, Sunfire GmbH, Vaillant GmbH, Viessmann Climate Solutions SE, Viessmann Elektronik GmbH, Viessmann Werke Allendorf GmbH, Viessmann Werke GmbH & Co. KG

http://www.pace-energy.eu

PROJECT AND OBJECTIVES

PACE is unlocking the large-scale European deployment of the state-of-the-art smart energy solution for private homes: fuel cell micro-co-generation. PACE will see up to 2 800 households across Europe reaping the benefits of this home energy system. The project enables manufacturers to move towards product industrialisation and fosters market development at the national level by working with building professionals and the wider energy community. The project uses modern fuel cell technology to produce efficient heat and electricity in homes, empowering consumers in their energy choices.

NON-QUANTITATIVE OBJECTIVES

- Deploy new manufacturing processes for increased capacity.
- Develop efficient routes to market: innovation in sales, marketing and the consumer offer.
- Provide efficient field support.
- Identify potential revenue streams from participation in the power markets and the economic added value from the avoidance of grid expansions.
- Develop a platform approach to component standardisation for fuel cell micro combined heat and power (mCHP) units across the EU supply chain.
- Create the conditions for expansion of the market for fuel cell mCHP units across Europe.
- Increase awareness of fuel cell mCHP systems in European markets.

PROGRESS AND MAIN ACHIEVEMENTS

- The installation of units will continue until the end of the project.
- The project has increased the system lifetime to more than 15 years and improved the maintenance interval using new/improved components. The system (excluding stack) lifetime was 10 years at the start of project; this increased to a minimum of 15 years by the end of the project.
- By the end of the project, all partners will eliminate the need for stack replacement during a customer's 10-year service plan (the worst case is 7 years, as reported at the project's start).

FUTURE STEPS AND PLANS

- All of the 2 800 units to be deployed in the project will be installed.
- PACE will continue data collection and analysis to provide a fact-based understanding of the performance and benefits of the technology.
- The project will identify ongoing regulatory barriers to the deployment of mCHP units across Europe, and collaborate with industry and policymakers to remove such barriers.
- The project will develop use cases for fuel cell mCHP units relevant beyond the project finish point, including an assessment of the economic potential of fuel cell mCHP units.

QUANTITATIVE TARGETS AND STATUS

Target source	Parameter	Unit	Target	Achieved to date by the project	Target achieved?
Project's own objectives	No of units sold	units	2 800	3 091	✓
	Time before stack replacement	years	10-year system lifetime with > 50 % reduction in stack replacement or no stack replacement during a 10-year service plan	15-year system lifetime with > 50 % reduction in stack replacement or no stack replacement during a 10-year service plan	✓
	Manufacturing capacity (average company level)	units per year per OEM	1 000	2 300	✓
	Availability	%	99	96.2–99	(for some units)

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REMOTE

REMOTE AREA ENERGY SUPPLY WITH MULTIPLE OPTIONS FOR INTEGRATED HYDROGEN-BASED TECHNOLOGIES

Project ID:	779541
PRD 2023:	Panel 4 – H2 end uses – stationary applications
Call topic:	FCH-02-12-2017: Demonstration of fuel cell-based energy storage solutions for isolated micro-grid or off-grid remote areas
Project total costs:	EUR 6 740 031.40
Clean H_2 JU max. contribution:	EUR 4 995 950.25
Project period:	1.1.2018–30.6.2023
Coordinator:	Politecnico di Torino, Italy
Beneficiaries:	Ballard Power Systems Europe AS, Enel Green Power SpA, Engie EPS Italia SRL, Ethniko Kentro Erevnas Kai Technologikis Anaptyxis, Grupo Capisa Gestión y Servicios Sociedad Limitada, Hydrogenics Europe NV, Instituto Tecnológico de Canarias SA, Instrumentación y Componentes SA, Iris SRL, Orizwn Anonymh Techniki Etaireia, Powidian, Sintef AS, Stiftelsen Sintef, TrønderEnergi AS

https://www.remote-euproject.eu/

PROJECT AND OBJECTIVES

REMOTE is demonstrating the technical and economic feasibility of H_2-based energy storage solutions (integrated power-to-power (P2P) systems, non-integrated power-to-gas and gas-to-power systems (P2G + G2P), customised P2P systems) deployed in three demonstrations, based on renewable energy source (RES) inputs (solar, wind, hydro) in isolated microgrid or off-grid remote areas. In the 5 years of the project (up to December 2022), the design, procurement, installation, operation and analysis of two demonstrations (in Greece and Norway) have been assessed; the third demonstration (in Spain) is in the commissioning phase. The demonstration analysis and the exploitation plans are being finalised.

NON-QUANTITATIVE OBJECTIVES

- REMOTE aims to complete the demonstrations' design, installation and operation. REMOTE has created fundamental know-how for the next generation of P2Ps based on fuel cells and H_2 technologies adapted to the market and society's needs, making use of scientific advances in the management of off-grid areas and isolated microgrids.
- The project aimed to build experience throughout the value chain of P2P systems and validate real demonstration units in representative applications of isolated microgrid or off-grid areas. This enables suppliers, end users and general stakeholders to gain experience for the future deployment of these energy solutions.
- REMOTE aimed to gather technical data on the operation of H_2-based devices (PEMFC, electrolysers) in long-term real operation in P2P applications. The operation of the P2P systems (lasting more than a year) has generated learning experiences regarding the behaviour of technologies such as fuel cells and electrolysers in P2P applications. Companies now know what to improve.
- The project aimed to complete detailed life cycle analysis of RES-fed, H_2-based P2P systems in remote locations. The project allows for a detailed understanding of the complete life cycle analysis achieved by the RES-based P2P systems in remote areas, in terms of metrics such as global greenhouse gas reduction thanks to the adoption of H_2 in a local RES-storage system at seasonal range.

PROGRESS AND MAIN ACHIEVEMENTS

- REMOTE has achieved 1 year of experience of operation of the demonstration in Norway.
- It has achieved 2.5 years of experience of operation of the demonstration in Greece.
- The project has significant experience of the design, commissioning and operation of three H_2-based P2P plants.

FUTURE STEPS AND PLANS

- The running and full analysis of the demonstration in Norway have been completed. Technical analysis of the demonstration experience in terms of performance and lessons learned is being finalised.
- The running and full analysis of the demonstration in Greece have been completed. The technical analysis of the collected data is being finalised.
- REMOTE has finalised the installation of the new demonstration in Spain. The demonstrator has been commissioned and is operational.
- Complete techno-economic analysis of the demonstration experience has been performed with real data, to develop an understanding of how to optimise P2P plants in the future, with improved efficiency and reduced costs.
- A business analysis of the H_2-based P2P plants for remote locations is being developed and will be presented to the market stakeholders.

QUANTITATIVE TARGETS AND STATUS

Target source	Parameter	Unit	Target	Achieved to date by the project	Target achieved?	SoA result achieved to date (by others)	Year of SoA target
MAWP addendum (2018–2020)	Rated efficiency of the electrolyser (PEM)	kWh/kg	55 (2020) 52 (2024)	50	✓	50	2020
	Electrolyser footprint (PEM)	m^2/MW	100 (2020) 80 (2024)	273	⚙	10	2018–2020
	Rated efficiency of the fuel cell (PEM)	% LHV	42–62 (2024)	45–55	✓	51	2018
	Rated efficiency of the electrolyser (Alkaline)	kWh/kg	50 (2020) 49 (2024)	55–60	⚙	55–60	2020

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ROREPOWER

ROBUST AND REMOTE POWER SUPPLY

Project ID:	824953
PRD 2023:	Panel 4 – H2 end uses – stationary applications
Call topic:	FCH-02-3-2018: Robust, efficient long term remote power supply
Project total costs:	EUR 4 220 093.75
Clean H_2 JU max. contribution:	EUR 2 999 190.26
Project period:	1.1.2019–31.12.2023
Coordinator:	Teknologian tutkimuskeskus VTT Oy, Finland
Beneficiaries:	3E Energy Oy, European Fuel Cell Forum AG, SolydEra SpA, Sunfire Fuel Cells GmbH, Sunfire GmbH

https://rorepower.com/

PROJECT AND OBJECTIVES

The overall objective of this project is to further develop and demonstrate solid oxide fuel cell (SOFC) systems for off-grid power generation in markets – such as oil and gas infrastructure in remote regions – with harsh climate conditions (from – 40 °C to 50 °C), and the power supply of telecommunication towers, especially in emerging countries (e.g. telecommunication base stations or microwave transceivers). A total of 36 units had been installed at the customer sites by the end of 2022. RoRePower is further strengthening and building the European value chain for fuel cell technologies.

PROGRESS AND MAIN ACHIEVEMENTS

- A total of 36 units had been installed at the customer sites by the end of 2022.
- All customer sites have been identified.

FUTURE STEPS AND PLANS

The remaining RoRePower units will be installed before summer 2023.

QUANTITATIVE TARGETS AND STATUS

Target source	Parameter	Unit	Target	Achieved to date by the project	Target achieved?
	Electrical efficiency	%	> 35	> 35	✓
	Operation in harsh conditions	°C	– 40	– 40 can be achieved with the project solutions	✓
AWP 2019	Maintenance frequency	months	15	13.7	⚙
	Long-term desulphurisation	months	15	15	✓
	System start-up in harsh conditions	°C	– 40	– 40 can be achieved with the project solutions	✓

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RUBY

ROBUST AND RELIABLE GENERAL MANAGEMENT TOOL FOR PERFORMANCE AND DURABILITY IMPROVEMENT OF FUEL CELL STATIONARY UNITS

Project ID:	875047
PRD 2023:	Panel 4 – H2 end uses – stationary applications
Call topic:	FCH-02-8-2019: Enhancement of durability and reliability of stationary PEM and SOFC systems by implementation and integration of advanced diagnostic and control tools
Project total costs:	EUR 3 037 430.00
Clean H_2 JU max. contribution:	EUR 2 999 715.00
Project period:	1.1.2020–31.12.2024
Coordinator:	Università degli Studi di Salerno, Italy
Beneficiaries:	Ballard Power Systems Europe AS, Bitron SpA, Commissariat à l'énergie atomique et aux énergies alternatives, Communauté d'universites et d'établissements université Bourgogne-Franche-Comté, École Polytechnique Fédérale de Lausanne, Europäisches Institut für Energieforschung EDF Kit EWIV, Fondazione Bruno Kessler, Institut Jožef Stefan, SOLIDpower SpA, Sunfire Fuel Cells GmbH, Teknologian tutkimuskeskus VTT Oy, Université de Franche-Comté

https://www.rubyproject.eu/

PROJECT AND 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 the features of EIS, RUBY will improve the efficiency, reliability and durability of solid oxide fuel cell (SOFC) and proton-exchange membrane 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 environment.

NON-QUANTITATIVE OBJECTIVES

The MDPC tool performs monitoring, diagnosis, prognosis and control and mitigation of the stack and balance of plant (BoP) for PEMFC in back-up applications and for SOFC for micro combined heat and power (micro-CHP) applications.

PROGRESS AND MAIN ACHIEVEMENTS

- Tests on the proton-exchange membrane (PEM) stack and system have been performed in nominal conditions.
- Tests on the SOFC stack have been commissioned.
- Preliminary tests on the SOFC system have been performed in nominal conditions.
- Preliminary versions of monitoring, diagnostics and prognostics algorithms have been developed and tested.
- The MDPC tool's hardware has been designed, manufactured and tested.
- The concept and preliminary design of the hardware for EIS perturbation stimuli have been produced.

FUTURE STEPS AND PLANS

- Tests on PEM stack and system in faulty conditions.
- Tests on the SOFC stack in nominal and faulty conditions.
- Tests on the SOFC system in faulty conditions.
- Integration of the MDPC tool algorithms into the hardware.
- Commissioning of hardware for EIS perturbation stimuli.
- Implementation and testing of the MDPC tool.

QUANTITATIVE TARGETS AND STATUS

Target source	Parameter	Unit	Target	Achieved to date by the project	Target achieved?	SoA result achieved to date (by others)	Year of SoA target
Project's own objectives	Lifetime of micro-CHP applications (SOFC)	years	15	10	⚙	10	2020
		% of the appliance	98.5	97.5	⚙	97.5	
	Lifetime of backup applications (PEMFC)	years	15	12	⚙	12	
		% of the appliance	99.99	99.99	✓	99.99	

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SO-FREE

SOLID OXIDE FUEL CELL COMBINED HEAT AND POWER: FUTURE-READY ENERGY

Project ID:	101006667
PRD 2023:	Panel 4 – H2 end uses – stationary applications
Call topic:	FCH-02-4-2020: Flexi-fuel stationary SOFC
Project total costs:	EUR 3 100 605.00
Clean H_2 JU max. contribution:	EUR 2 739 094.00
Project period:	1.1.2021–31.8.2024
Coordinator:	Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile, Italy
Beneficiaries:	AVL List GmbH, Elcogen Oy, Fraunhofer-Gesellschaft zur Förderung der angewandten Forschung EV, ICI Caldaie SpA, Instytut Energetyki, Kiwa Limited, Kiwa Nederland BV, PGE Polska Grupa Energetyczna SA, Università degli Studi Guglielmo Marconi – Telematica

www.so-free.eu

PROJECT AND OBJECTIVES

The project's development and demonstration of a fully future-ready solid oxide fuel cell (SOFC)-based system for combined heat and power (CHP) 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 CHP system.

NON-QUANTITATIVE OBJECTIVES

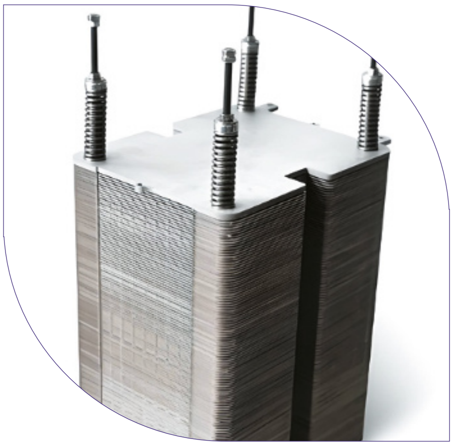
SO-FREE aims to realise a unique, standardised stack module–system interface for flexible system integration. The first alignment of two stack modules with a single interface has been proposed.

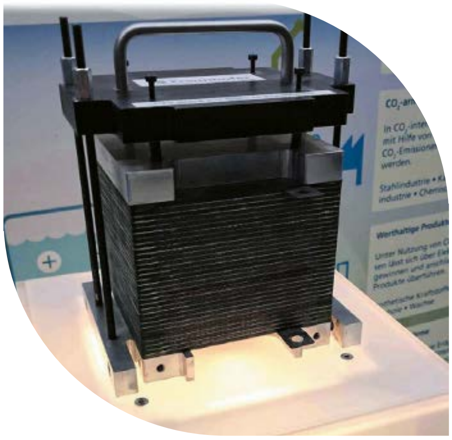
PROGRESS AND MAIN ACHIEVEMENTS

- The project has made two identical test stations for independent stack validation.
- SO-FREE has designed a unique stack module–system interface for flexible system integration.

FUTURE STEPS AND PLANS

- Stack validation and mapping were expected to be completed by February 2023.
- The final design of the system was due to be finalised in April 2023.
- Stack production and delivery are due to be completed in October 2023.
- The systems are expected to be ready for demonstration in December 2023.

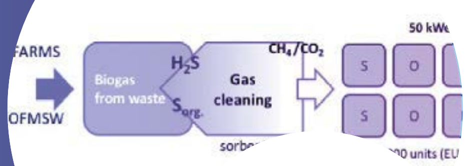




QUANTITATIVE TARGETS AND STATUS

Target source	Parameter	Unit	Target	Achieved to date by the project	Target achieved?
AWP 2020	Degradation	%	< 1	N/A	⚙
	Efficiency in H_2 consumption	%	48	53	✓
	CAPEX	€/kW	8 000	N/A	⚙

WASTE2WATTS



UNLOCKING UNUSED BIO-WASTE RESOURCES WITH LOW COST CLEANING AND THERMAL INTEGRATION WITH SOLID OXIDE FUEL CELLS

Project ID:	826234
PRD 2023:	Panel 4 – H2 end uses – stationary applications
Call topic:	FCH-02-7-2018: Efficient and cost-optimised biogas-based cogeneration by high temperature fuel cells
Project total costs:	EUR 1 681 602.50
Clean H_2 JU max. contribution:	EUR 1 681 602.50
Project period:	1.1.2019–30.9.2023
Coordinator:	École Polytechnique Fédérale de Lausanne, Switzerland
Beneficiaries:	Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile, Arol Energy, Biokomp SRL, Commissariat à l'énergie atomique et aux énergies alternatives, EREP SA, Etudes et Applications d'Energies Renouvelables et d'Epuration, Paul Scherrer Institut, Politecnico di Torino, SolydEra SA, SolydEra SpA, Sunfire GmbH

https://waste2watts-project.net/

PROJECT AND OBJECTIVES

Waste2Watts is developing cleaning technologies for biogas to make the gas compatible with solid oxide fuel cells (SOFCs). It determines what needs to be cleaned from the gas and to what purity level to clean the gas. It also defines the appropriate scale for the best application of SOFCs with biogas, and the bioresources available at that scale. It assesses reformer catalysts and cells/stacks with biogas impurities and representative gas mixtures. A system layout proposes operating strategies without external water addition. A 6 kWe SOFC on agro-biogas has been prepared, and novel cryogenic cleaning of biogas at a scale of 100 m^3/h has been carried out.

NON-QUANTITATIVE OBJECTIVES

- Test runs with six or seven sorbents each at three different laboratories were conducted, under dry and wet conditions, with different contaminants. The best sorbent (among those tested) was tested in humid conditions with a multi-contaminant gas matrix. Retention capacity was 0.16 g COS, 3 g DMS, 19 g CH_4S and 223 g H_2S per kg of sorbent, which allows the sorbent volume to be calculated for a given biogas flow and contaminant content. However, it was also established that sorption capacity for non-H_2S compounds is much improved for dry biogas. For example, sorption of COS, the most critical compound in terms of removal difficulty, increased fivefold (to 0.8 g/kg sorbent). This guided the design of the reforming in two steps: wet for H_2S, dry for the other contaminants, with a chiller in between.
- New reforming catalysts were fully tested with dry and mixed reformed biogas and H_2S and DMS contaminants.
- Cells tested with COS (1, 2, 5 ppm) show a 1–2 % performance drop. COS blocks the water–gas shift reaction. It reacts with steam to H_2S and with electrochemical oxygen to SO_2. Performance is partially recovered within 100 hours. It is likely to recover entirely over a longer period. It is clear that mixed reformed biogas behaves better than dry reformed biogas (i.e. steam must be added for reforming).

PROGRESS AND MAIN ACHIEVEMENTS

- Sorbents have been characterised specifically for biogas cleaning, allowing for the choice of an adapted cleaning solution. This point has been analysed by the Innovation Radar as an innovative solution.
- Reformer catalysts, cells and stacks characterised with specific sulphur compounds show resilience of up to 5 ppm of trace content.
- System cost analysis shows that biogas SOFC can achieve a levelised cost of electricity of < 0.15 ct€/kWhe, even at 20 kWe, for a 4-year stack life (stack cost €1 000/kWe).

FUTURE STEPS AND PLANS

- A cryogenic cleaning chain for biogas flow of 100 m^3/g has been mounted at Biokomp premises and has been prepared for shipping to the biogas site in Vilnius.
- The project is testing the 1.5 kWe SOFC at the agro-biogas site, with adapted biogas cleaning based on project sorbent results. This will involve looking for co-financing, preparing analysis of the biogas site and setting up a site visit to establish project connections.
- Long-term testing of cells and stacks will be performed with 3–5 ppm of sulphur. All set-ups, gas analytics and detailed electrochemical characterisation methods have been established. Stacks and cells are being tested for longer durations than they were previously (> 1 000 hours).
- The final cleaning cost will be updated from Biokomp and Arol after delivery and installation, for integration into the established system model.

QUANTITATIVE TARGETS AND STATUS

Target source	Parameter	Unit	Target	Achieved to date by the project	Target achieved?
MAWP addendum (2018–2020)	SOFC CAPEX	€/kWe	3 500–6 500 (2024)	2 000–4 000	✓
Project's own objectives	Pollutant tolerance	ppm	5	3	
	Pollutant nature and mix	Sulphur compounds	Identification	Critical compounds identified	✓
	Biogas cleaning	€/kWe	< 1 000	< 1 000	
	Levelised cost of energy	€/kWhe	< 15	0.09	
	Voltage loss under constant current (SOFC degradation on biogas reformate)	%/kh	0.4	0.7	

Clean Hydrogen Partnership
Co-funded by the European Union

V. PILLAR 5 – CROSS – CUTTING TOPICS

Objectives: The cross-cutting activity area is structured around 3 Research Areas with the following overarching objectives:

Sustainability, LCSA, recycling and eco-design objectives:

- Develop life cycle thinking tools addressing the 3 dimensions of sustainable development: economic, social, and environmental;
- Develop eco-design guidelines and eco-efficient processes; and
- Develop enhanced recovery processes (recycling) particularly for materials belonging to the platinum group, other critical raw materials and per- and polyfluoroalkyl substances.

Education and public awareness objectives:

- Develop educational and training material and build training programmes for professionals and students on hydrogen and fuel cells; and
- Raise public awareness and trust towards hydrogen technologies and their system benefits.

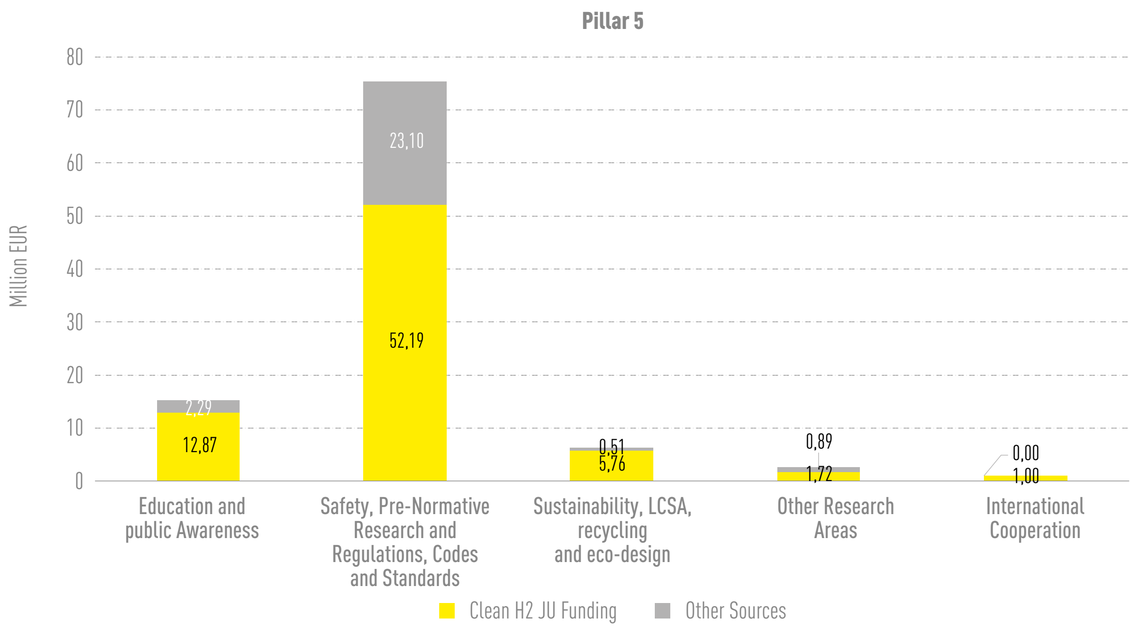
Safety, PNR and RCS objectives:

- Increase the level of safety of hydrogen technologies and applications; and
- Support the development of RCS for hydrogen technologies and applications, with the focus being on standards.

The first Research Area ensures that the technology solutions developed are aligned to the overall principles and goals of the European energy transition towards a sustainable and decarbonised energy system. For example, the development of robust and hydrogen-specific LCA methodology will allow to rank the sustainability of existing and future technology solutions in terms of their contributions to GHG emission avoidance and more generally of their impact to the environment. The other 2 fields are enablers for the market penetration of hydrogen technologies and systems. The development of know-how and skills must provide the availability of personnel able to design, install and operate hydrogen systems and face the enormous increase in demand expected in the short term. Similarly, a fit-for-purpose RCS framework will facilitate deployment. It is an enabler for innovation and safety, specifically public safety, which has to be guaranteed along the whole supply chain.

Budget: To date (Project Calls from 2008 until 2022), the JU supported 51 projects relevant to this Pillar with a total contribution of EUR 73.5 million complemented by EUR 27 million of other contributions. The distribution of total historical budgets over the 3 main Research Areas is shown in Figure 42 and indicates that approximately 75% of funding for Pillar 5 went to support safety, PNR and RCS development. Education and training activities received around 15%. The sustainability dimension shows the lowest value, 6% due to its relative novelty, but is expected to grow considerably in the next years. Moreover, the sustainability dimension will play a more relevant role in the majority of the Clean Hydrogen JU's projects.

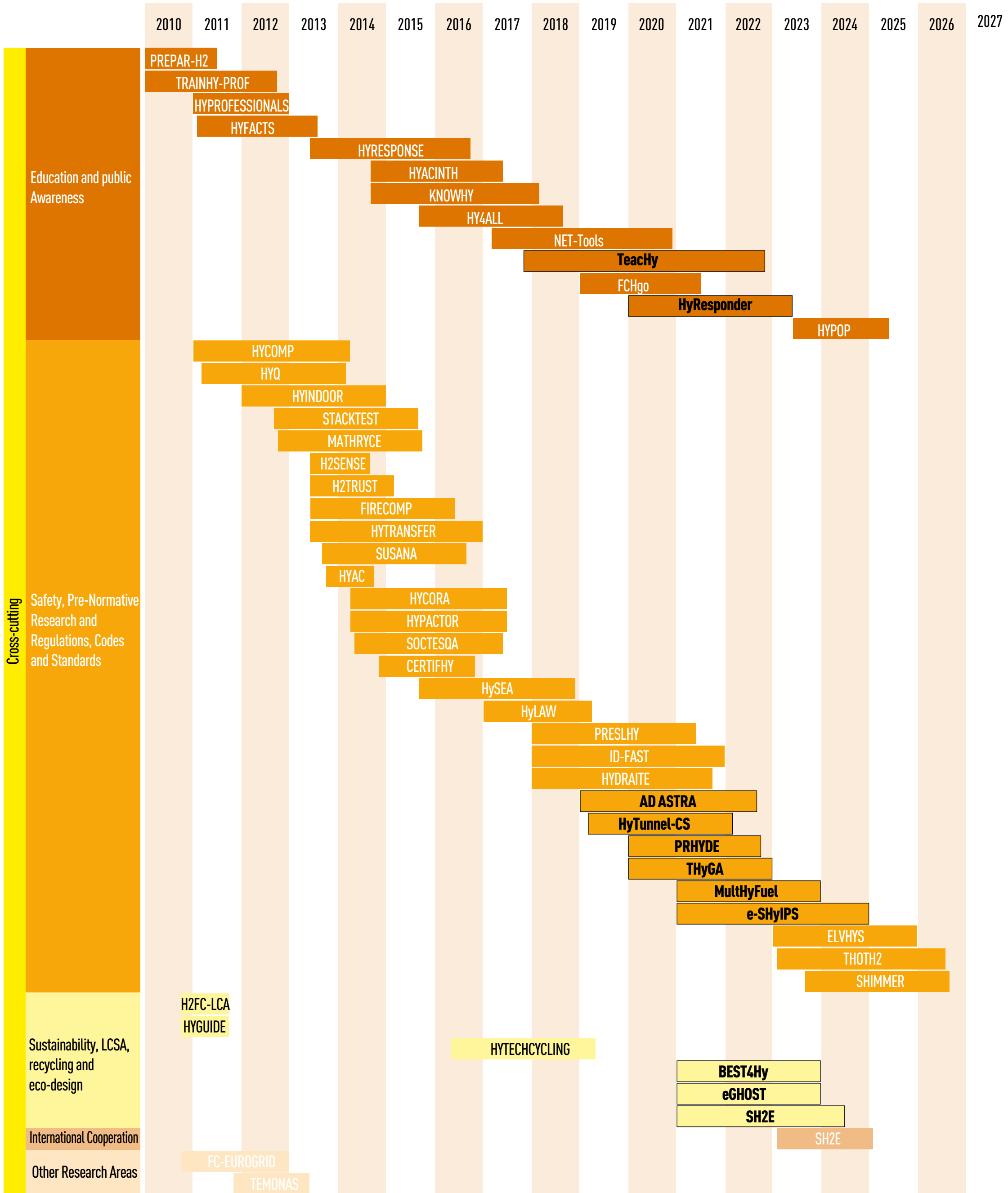
Figure 42: Funding for Pillar 5 projects (2008-2022)



Source: Clean Hydrogen JU

Projects: The 2023 Programme Review covers the 11 projects under Pillar 5, the ones highlighted in black in Figure 43. Since 2010, most projects remain with the Safety, PNR and RCS area, with 10 projects reviewed out of 16 in total, although most of them are expected to be concluded by the end of 2023.

Figure 43: Project timelines of Pillar 5 – Cross - cutting topics



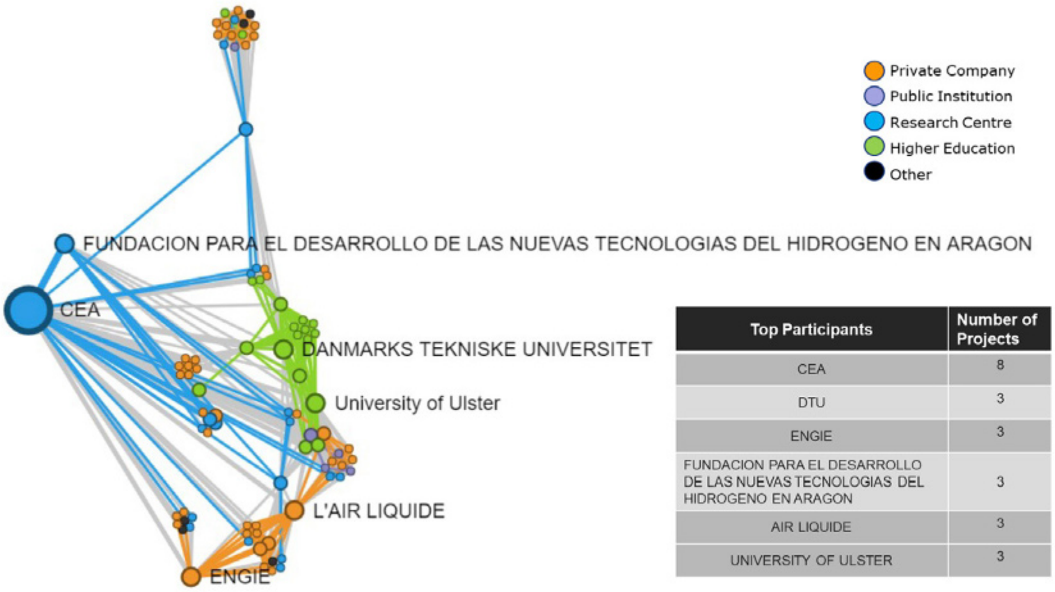
Source: Clean Hydrogen JU
NB. Projects highlighted in black were considered for the 2023 Programme Review.

Figure 44 is a plot produced using TIM[150]. This plot shows the connections between partners present in the Cross-Cutting Pillar projects. In general, it can be noticed that the public research and academic centres represent the majority of the cross-cutting activities. This is a specific characteristic of this Pillar, due in particular to the education and sustainability dimensions, but also to some projects dedicated to public safety, focusing on

150 The size of the node represents the number of projects a partner is involved in, whilst the thickness of the links represents the number of projects in common between the linked partners. For clarity, only the partners involved in the largest numbers of projects are named.

fundamental hydrogen behaviour knowledge. Nevertheless, in the specific set of this year, 2 private companies play a key role as well.

Figure 44: TIM Plot showing the participants in the 15 projects reviewed



Top Participants	Number of Projects
CEA	8
DTU	3
ENGIE	3
FUNDACION PARA EL DESARROLLO DE LAS NUEVAS TECNOLOGIAS DEL HIDROGENO EN ARAGON	3
AIR LIQUIDE	3
UNIVERSITY OF ULSTER	3

Source: TIM (JRC)

SUSTAINABILITY, LCSA, ECO-DESIGN AND RECYCLING

The project **SH2E** is working on Guidelines for Life Cycle Sustainability Assessment and Prospective Benchmarking. The environmental LCA guidelines build on the FC-HyGUIDE by updating the methodology, filling gaps (e.g. the influence of time and product development in the results), and expanding its applicability (i.e. the intent is to have a methodology that can be applied not only in Europe, but worldwide). In addition, guidelines for life cycle costing (LCC) and social LCAs (S-LCA) will be produced. The final step of the project is the development of a software tool to perform life cycle studies for hydrogen technologies. The project has already performed a review of the existing guidelines for LCA of FCH systems, the environmental LCA as well as the life cycle cost assessment guidelines have already been issued, while the life cycle sustainability assessment guidelines will be issued at the end of 2023.

The project **BEST4HY** continues the activities of project HYTECHCYCLING and is developing recycling technologies for material recovery from two FCH products: PEMFC and SOFC. The recycling processes will be brought to TRL 5, and the recycled materials will be validated in terms of quality and performance when re-used in new components and new stacks. The project already achieved most of its targets, with a Pt recovery of more than 90%, an anode recovery for SOFC of more than 80%, and a La and Co recovery of more than 80%. The target for the recycling of the membrane is yet to be achieved, together with the overarching 20% GHG emission reduction (LCA coming in early 2023).

The project **EGHOST** will deliver eco-design guidelines for PEMFC and SOEC, and a white book for the eco-design of any FCH product. The goal is to facilitate future standardisation as well as the categorisation of FCH products as eco-efficient and sustainable solutions. So far, the project performed a preliminary sustainability assessment of the 2 systems under study and applied the methodology for eco-design of Energy-related Products to the PEMFC case. Moreover, product concepts to improve the life-cycle profile of PEMFC and SOEC have been completed. The concepts will then be assessed and prioritised as a function of the impact reduction goals. In addition to environmental issues, criticality and social aspects are taken into account.

EDUCATION AND PUBLIC AWARENESS

The project **TEACHY**, that ended in October 2022, managed to establish a European MSc course dedicated to fuel cells and hydrogen technologies. Only 1 University out of the 12 involved in the project, however, has been testing the MSc course in the academic year 2021-22 and only one additional has formally implemented a MSc course in its learning system. For all the others, accreditation has been hindered by differences in national laws. Nevertheless, the MSc course modules have been used for Continuous Professional Development (CPD) courses with the participation of engineers and teachers (200 participants).

Project **HYRESPONDER** targets a specific group of professionals to develop a Train-the-Trainer programme in hydrogen safety throughout Europe. HYREPSPONDER completes the already available set of tools of project HYRESPONSE (2013-2016). Trainers from across Europe have undertaken online and operational trainings. The trainers will then use this training to deliver training in their regions and to ensure that a plan is in place beyond the project. The HYRESPONDER has also developed an e-platform consisting of educational, operative and virtual reality training for trainers of responders. The e-platform provides an e-laboratory as well which allows the assessment of hydrogen releases and flames parameters under various initial and boundary conditions. Finally, the project has also revised The European Emergency Response Guide developed by project HYRESPONSE. An important aspect of the project was its pan-European dimension.

SAFETY, PNR AND RCS

Project **AD ASTRA** has developed AST protocols for solid oxide cell stacks, operating in both fuel cell and electrolysis modes for stationary applications. To understand the nature of degradation, the project harvested results from previous JU projects that operated in the field and tested systems that have already operated for thousands of hours, characterising also microstructural evolutions. The project is concluded and has produced a set of validated models able to predict the degradation of SOC and the Remaining Useful Life of the cell, correlating the accelerated tests to the real-life operation conditions. These tests will allow to assess durability in a time which is only 10% of the total lifetime of the cells. This project has already achieved a publication record of almost 20 peer-reviewed articles, provided a technical report to the IEC/TC 105 and formed an Ad Hoc Group (AHG11) to assess the feasibility of an international standard for AST protocols.

The project **THYGA** that ended in March 2023, has tested how domestic and commercial gas appliances (boilers, burners and cookers) perform in the presence of hydrogen up to 30% in volume with natural gas. The project has completed an experimental campaign on approximately 100 appliances, to identify the concentration limit below which hydrogen can be added to natural gas without changing existing certification of the appliances. This project has a considerable impact on the RCS framework and the European technical legislation covering the natural gas value chain. THYGA has provided guidelines for assessment of gas appliance standards for H2NG, and experts have to revise the existing standards and/or draft new standards based on PNR results. The project presents excellent relevance of objectives vs the international State of the Art and current activities in standardisation world.

The project **PRHYDE** developed refuelling approaches for heavy-duty vehicles, such as trucks and buses, aiming at minimising filling time and maximising travel autonomy, while simultaneously guaranteeing safety. The project's scope covered protocols for onboard storage systems with multiple tanks, with 35, 50, and 70 MPa nominal working pressures. The project's outcome is required for the deployment of an interoperable infrastructure for heavy goods transports in Europe and represents a first step towards solutions addressing the needs of the rail and water sectors. The non-proprietary filling protocol designed by PRHYDE is now being integrated in the standard ISO 19885-3[151] under preparation by the ISO/TC 197 WG24 and has been shared with two more standardisation bodies, SAE[152] and the European CEN[153].

151 ISO/AWI 19885, Part 3 - Gaseous hydrogen — Fuelling protocols for hydrogen-fuelled vehicles — Part 3: High flow hydrogen fuelling protocols for heavy duty road vehicles.

152 SAE FCEV Interface Task Force (ITF)

153 CEN/TC 268 Cryogenic vessels, Working Group WG5 - Specific hydrogen technologies applications

The project **MultHyFuel** will deliver guidelines for the design, construction, and operation of refuelling stations able to deliver several fuels at the same location, including hydrogen. The project has already performed an analysis of the legal framework regarding permitting requirements throughout Europe. Critical accidental scenarios, specific for a multi-fuel refuelling station, have been identified as well. Experimental assessment of hydrogen leakage behaviour and consequences is ongoing. MultHyFuel's starting point was the project HyLaw, which has mapped EU and Member States legislation on HRS permitting processes and will contribute to update HyLaw database. MultHyFuel is contributing to the HyLaw project's existing database in the field of current legislation on permitting processes across the EU for the deployment of HRS.

The project **HYTUNNEL-CS** which ended in 2022, has studied the conditions under which public infrastructure can be safely used by hydrogen vehicles. This is an aspect which has not been considered relevant so far, due to the low numbers of hydrogen vehicles and consequently the negligible probability of a hydrogen releases in a tunnel or a public garage. An increase of hydrogen systems and hydrogen quantities on the road and in public spaces is expected, enabled by the objectives of the European hydrogen strategy and the proposed Regulation on the deployment of alternative fuels infrastructure aiming to replace the similar Directive 2014/94/EU. It is important to deliver the data and the methodology required by local and national authorities to grant permission to use tunnels and underground garages, and to inform all stakeholders of the rules governing safety of the new nobility technology. The project is building on projects HYNDOOR (2012-2015) and HYSEA (2015-2018) which have provided data on hydrogen behaviour in semi-confined spaces.

E-SHYIP deals with risk and safety assessment methodologies applied to hydrogen-based-fuels passenger ships. It will produce a roadmap to boost the hydrogen maritime economy and develop a pre-standardisation plan to support ongoing work at the International Maritime Organisation (IMO). The IMO is working to extend the scope of its IGF Code,[154] to hydrogen as a fuel. The project approach is technology-independent, considering different vessels sizes, different fuel cell types and both liquid and compressed gas storages, covering also vessels bunkering. It also has a sustainability dimension, with a link with project e-GHOST in relation with eco-design of fuel cells. The project has already performed experimental and modelling activities, studying the general arrangement on board, the safe installation of the systems and the effect of marine environment and operation on fuel cells degradation (e.g. salty air, inclined operation).

154 **IMO IGF** (2017): International Code of Safety for Ship Using Gases or Other Low-flashpoint Fuels. It is mainly written for natural gas.

AD ASTRA

HARNESSING DEGRADATION MECHANISMS TO PRESCRIBE ACCELERATED STRESS TESTS FOR THE REALIZATION OF SOC LIFETIME PREDICTION ALGORITHMS

Project ID:	825027
PRD 2023:	Panel 5 – cross-cutting
Call topic:	FCH-04-3-2018: Accelerated stress testing (AST) protocols for solid oxide fuel cells (SOFC)
Project total costs:	EUR 3 008 426
Clean H_2 JU max. contribution:	EUR 3 008 426
Project period:	1.1.2019–31.8.2022
Coordinator:	Agenzia Nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile, Italy
Beneficiaries:	Commissariat à l'énergie atomique et aux énergies alternatives, Danmarks Tekniske Universitet, École Polytechnique Fédérale de Lausanne, Europäisches Institut für Energieforschung EDF KIT EWIV, Institute of Electrochemistry and Energy Systems, SolydEra SpA, Sunfire GmbH, Università degli Studi di Genova, Università degli Studi di Salerno

https://www.ad-astra.eu/

PROJECT AND OBJECTIVES

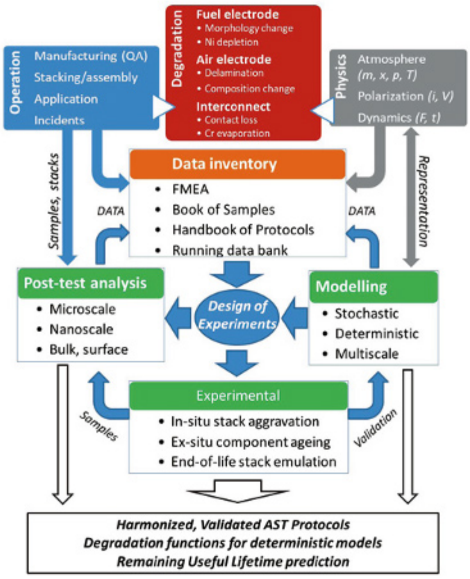
Accelerated stress tests deliberately stress a test material, component or product for a short period to assess the stability of new materials without having to use them in an operational system over a long period. The EU-funded AD ASTRA project aims to define accelerated stress testing protocols deduced from a systematic understanding of degradation mechanisms in aged components of solid oxide cell stacks operating in both fuel cell and electrolysis modes. Benchmarking has been completed, as have the first two campaigns of possible accelerated tests. Validation of the test protocols is the next step.

PROGRESS AND MAIN ACHIEVEMENTS

- Twelve accelerated stress testing (AST) protocols have been developed through three cycles of testing campaign.
- AST protocols have been verified qualitatively, by comparison with analyses of field-tested samples, and quantitatively, using dedicated experiments to estimate degradation rates and accelerating factors.
- AD ASTRA completed the model for transfer functions developed from accelerated stress testing for real-life operation.
- It designed a multiple-model prognosis algorithm for estimating remaining useful life.

FUTURE STEPS AND PLANS

- AD ASTRA will support the development of an international standard for AST protocols and its implementation at the industry level.
- Accelerated stress testing protocols will be validated on solid oxide cell stacks.



QUANTITATIVE TARGETS AND STATUS

Target source	Parameter	Target	Achieved to date by the project	Target achieved?
Project's own objectives	Degradation acceleration	10 ×	More than 10 ×	✓
	Published articles	2 for each of work packages (WPs) 3, 4 and 5	8 for WP3, 4 for WP4, 7 for WP5	✓

BEST4Hy

SUSTAINABLE SOLUTIONS FOR RECYCLING OF END OF LIFE HYDROGEN TECHNOLOGIES

Project ID:	101007216
PRD 2023:	Panel 5 – cross-cutting
Call topic:	FCH-04-4-2020: Development and validation of existing and novel recycling technologies for key FCH products
Project total costs:	EUR 1 586 015
Clean H_2 JU max. contribution:	EUR 1 586 015
Project period:	1.1.2021–31.12.2023
Coordinator:	Parco Scientifico Tecnologico per l'Ambiente SpA, Italy
Beneficiaries:	Aktsiaselts Elcogen, Commissariat à l'énergie atomique et aux énergies alternatives, EKPO Fuel Cell Technologies GmbH, ElringKlinger AG, Hensel Recycling GmbH, IDO-Lab GmbH, Politecnico di Torino, RINA Consulting SpA, Univerza v Ljubljani

https://best4hy-project.eu/

PROJECT AND OBJECTIVES

The overall objective of BEST4Hy is to identify and develop viable recycling strategies, supported by innovative technologies, that will provide the best solution for material recovery from fuel cell and hydrogen products (i.e. proton-exchange membrane fuel cells (PEMFCs) and solid oxide fuel cells (SOFCs)), and to establish proof of concept for the recovery of iridium and palladium from proton-exchange membrane water electrolysis with novel technologies. Currently, the project is validating four recovery processes at laboratory scale (technology readiness level (TRL) 3) on materials of different ages (PEMFCs and SOFCs). BEST4Hy is performing life cycle analysis / life cycle cost analysis on fuel cell and hydrogen products and end-of-life processes. The regulatory aspects study / policymakers' involvement and the standardisation aspects started in December 2021.

PROGRESS AND MAIN ACHIEVEMENTS

- BEST4Hy achieved Pt recovery via the hydrometallurgical process (listed in the Innovation Radar).
- The project created a novel membrane electrode assembly gaseous-phase dismantling process (listed in the Innovation Radar).
- It achieved Ni-YSZ anode component recovery by HTH and HTM (listed in the Innovation Radar).
- It developed a novel electroleaching and electrolisciviation process for PEMFCs (listed in the Innovation Radar).

FUTURE STEPS AND PLANS

- Scaling up from TRL 3 to TRL 5 will be finalised in 2023.
- The initial results of the life cycle assessment / life cycle costing were expected in early 2023.
- The standardisation and regulations assessment will be performed, supporting the development of a final policy paper and a standardisation roadmap for end-of-life fuel cells.
- A dissemination and exploitation action plan will be created, involving several workshops and events to boost the project's impact and raise market awareness of the technologies.

QUANTITATIVE TARGETS AND STATUS

Target source	Parameter	Unit	Target	Achieved to date by the project	Target achieved?
Project's own objectives	Incoming Pt recovered	%	80	90	✓
	Incoming anode material recovered overall for SOFCs	%	80	> 80	✓
	Incoming Pt recovered	%	90	95	✓
	La and Co recovery	%	> 80	La > 78, Co > 87	✓
	Incoming membrane	%	100	N/A	⚙
	Greenhouse gas emissions in the overall production	%	– 20	N/A	⚙

eGHOST

ESTABLISHING ECO-DESIGN GUIDELINES FOR HYDROGEN SYSTEMS AND TECHNOLOGIES

Project ID:	101007166
PRD 2023:	Panel 5 – cross-cutting
Call topic:	FCH-04-3-2020: Development of eco-design guidelines for FCH products
Project total costs:	EUR 1 133 541.25
Clean H_2 JU max. contribution:	EUR 998 991.25
Project period:	1.1.2021–31.12.2023
Coordinator:	Fundación IMDEA Energía, Spain
Beneficiaries:	Commissariat à l'énergie atomique et aux énergies alternatives, Fundación para el Desarrollo de las Nuevas Tecnologías del Hidrógeno en Aragón, Symbio France, Institute of Applied Energy, Univerza v Ljubljani

https://eghost.eu/

PROJECT AND OBJECTIVES

eGhost will reach the first milestone in the development of ecodesign criteria in the European hydrogen sector. Two guidelines for specific fuel cell and hydrogen (FCH) products are being prepared, and the lessons learned will be integrated into the eGHOST white book: a reference guidance book for any future ecodesign project on FCH systems. The project addresses the eco(re)design of mature products (proton-exchange membrane fuel cell (PEMFC) stacks) and those emerging with low technology readiness level (TRL) (solid oxide electrolysers) in such a way that sustainable design criteria can be incorporated from the earliest stages of product development.

NON-QUANTITATIVE OBJECTIVES

- eGHOST aims to contribute to FCH systems' sustainability. Ecodesigning products will improve their sustainability performance.
- The project aims to contribute to social acceptance. Sustainable products are better accepted by end users and stakeholders, including civil society.

PROGRESS AND MAIN ACHIEVEMENTS

- The preliminary life cycle sustainability assessment of the PEMFC stack is complete.
- The preliminary life cycle sustainability assessment of the solid oxide electrolysis cell stack is complete.
- The PEMFC stack has been evaluated in accordance with the EU ecodesign directive.
- Product concepts have been designed.

FUTURE STEPS AND PLANS

- Product concepts will be assessed and prioritised as a function of the reduction goals (month 30).
- Methodological and technical ecodesign guidelines for the PEMFC stack will be issued (month 33).
- Methodological and technical ecodesign guidelines for the solid oxide electrolysis cells will be issued (month 33).
- The eGHOST white book will contain the main recommendations for FCH products' eco(re)designing, drawing on the lessons learned (month 36).

QUANTITATIVE TARGETS AND STATUS

Target source	Parameter	Unit	Achieved to date by the project	Target achieved?
AWP 2020	Cumulative cost reduction	%	3	
	Cumulative environmental reduction	%	10	
	Ecoefficiency improvement	%	10	

E-SHyIPS

ECOSYSTEMIC KNOWLEDGE IN STANDARDS FOR HYDROGEN IMPLEMENTATION ON PASSENGER SHIPS

Project ID:	101007226
PRD 2023:	Panel 5 – cross-cutting
Call topic:	FCH-04-2-2020: PNR on hydrogen-based fuels solutions for passenger ships
Project total costs:	EUR 2 560 000
Clean H_2 JU max. contribution:	EUR 2 500 000
Project period:	1.1.2021–31.12.2024
Coordinator:	Politecnico di Milano, Italy
Beneficiaries:	Agenzia Nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile, Atena Scarl – Distretto Alta Tecnologia Energia Ambiente, Cineca Consorzio Interuniversitario, Danaos Shipping Company Limited, Dimos Andravidas-Kyllinis, DNV Hellas Single Member SA, Ghenova Ingeniería SL, Ingegneria del Fuoco SRL, Levante Ferries Naftiki Etaireia, Oy Woikoski AB, Proton Motor Fuel Cell GmbH, Scheepswerf Damen Gorinchem BV, Teknologian tutkimuskeskus VTT Oy, UNI – Ente Italiano di Normazione, Università degli Studi di Napoli Parthenope

https://e-shyips.com/

PROJECT AND OBJECTIVES

Hydrogen is considered an option for reaching emission reduction targets; however, there is currently no regulatory framework applicable to hydrogen-fuelled ships. e-SHyIPS brings together hydrogen and maritime stakeholders to gather new knowledge based on regulatory framework review and experimental data. The project's 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 – regarding passenger ships using hydrogen-based fuels – to the International Code of Safety for Ships using Gases or other Low-flashpoint Fuels, and a roadmap to boost the hydrogen maritime economy.

NON-QUANTITATIVE OBJECTIVES

- e-SHyIPS aims to define functional scenarios relating to the project concept. In close cooperation with the project's 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.
- The project aims to determine vessel scenario and bunkering functional and technical requirements for the purpose of producing a scenario report. The technical features of hydrogen-based-fuels passenger ships will be described for the associated subsystem (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.
- The results of the analysis of emergency hydrogen discharge or major leaks from the vessel were expected at the end of 2022. The test is focused 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 vessel and of hydrogen storage were expected to be finalised at the end of 2022.
- The project aims to determine best risk and safety practices for the maritime sector. It 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 AND MAIN ACHIEVEMENTS

- The project has developed ecosystemic knowledge of standards for hydrogen implementation for passenger ships.
- Fuel cell stack inclination testing has been completed (listed in the Innovation Radar).
- Fuel cell salt spray testing has been carried out.
- Hazard identification analysis for gas-compressed hydrogen has been undertaken.
- The safety system has been reviewed.
- Hazard identification analysis for liquid hydrogen has been undertaken.
- Explosion risk has been assessed.
- New forcing/damping methods have been tested in OpenFOAM.
- Mesh has been optimised, with a focus on seakeeping.
- The zero hull velocity wave–hull interaction simulation (in LincoSim) has been validated.
- The new LincoSim production web application for external expert users has been tested.

FUTURE STEPS AND PLANS

- e-SHyIPS will continue to develop the hydrodynamic analysis. The LincoSim platform using the updated mesh and wave–hull interaction simulation will be rolled out (expected to be completed in 2023).
- The safety assessment of each vessel design for each scenario is expected to be completed at the end of 2023.
- The technical report on the H_2-based fuel bunkering system's basic design is expected to be completed by the end of 2023.
- The onboard H_2 dispersion and explosion model test will be carried out, with enhanced results expected by the end of 2023.
- Results from the material and component testing and post-mortem analysis are expected at the end of 2023.
- Initial results for the fuel delivery and bunkering solutions for ships were expected at the end of 2022.
- NMA and ISO dissemination of gaps and research considerations is expected to take place at the end of 2023.

QUANTITATIVE TARGETS AND STATUS

Target source	Parameter	Unit	Target	Achieved to date by the project	Target achieved?
Project's own objectives	Performance degradation (potential loss at constant current)	mV		– 10 mV to – 20 mV during U–I curve – 13 mV during continuous operation	
	Constant operation of stack possible	–	Yes	Yes	✓
	To find materials that do not induce additional degradation of the fuel cell compared with baseline	Comparison with reference samples	No additional degradation	Certain ethylene propylene diene monomer materials that may be suitable for the cathode sides have been identified	✓

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HyResponder

EUROPEAN HYDROGEN TRAIN THE TRAINER PROGRAMME FOR RESPONDERS

Project ID:	875089
PRD 2023:	Panel 5 – cross-cutting
Call topic:	FCH-04-1-2019: Training of responders
Project total costs:	EUR 1 000 000
Clean H_2 JU max. contribution:	EUR 1 000 000
Project period:	1.1.2020–31.5.2023
Coordinator:	University of Ulster, United Kingdom
Beneficiaries:	Association Comité National Français du Comité Technique International de prévention et d'extinction de Feu, Ayuntamiento de Zaragoza, Commissariat à l'énergie atomique et aux énergies alternatives, Crisis Simulation Engineering SARL, Deutsches Zentrum für Luft- und Raumfahrt EV, DLR Institut für Vernetzte Energiesysteme EV, Ecole nationale supérieure des officiers de sapeurs-pompiers, Fire Service College Limited, International Fire Academy, Air Liquide SA, Landes-Feuerwehrverband Tirol, Ministry of the Interior of the Czech Republic, Persee, Service Public Fédéral Intérieur, Università degli Studi di Roma la Sapienza, Universitetet i Sørøst-Norge

https://hyresponder.eu/

PROJECT AND OBJECTIVES

The aim of HyResponder is to develop and implement a sustainable trainers' programme on hydrogen safety for responders throughout Europe. The updated operational, virtual reality and educational training reflects state-of-the-art hydrogen safety. The *European Emergency Response Guide* has been revised. Translated materials for responders will be available in eight languages via a purpose-built e-platform. The translated materials will be utilised by trainers to deliver workshops and impact training nationally in 10 European countries, enhancing the reach of the programme.

NON-QUANTITATIVE OBJECTIVES

- HyResponder aimed to embed elements of the training at national level. Each country has a short- to medium-term plan to maximise impact during and beyond HyResponder.
- The project aimed to develop a formal module/certificate. A draft document has been prepared with the key learning outcomes, content, etc., which will be trialled by some partners during national training.
- It aimed to develop training packages at different levels. Stratified educational materials are now available.

PROGRESS AND MAIN ACHIEVEMENTS

Three activities have been evaluated by the Innovation Radar. The translated material is now available:

- e-platform to support training of responders in hydrogen safety (https://innovation-radar.ec.europa.eu/innovation/44458);
- stratified training materials for responders spanning four learning levels (https://innovation-radar.ec.europa.eu/innovation/44457);
- novel training sequences to support online training of responders (https://innovation-radar.ec.europa.eu/innovation/44454).

FUTURE STEPS AND PLANS

- Within HyResponder, trainers from across Europe have undertaken online (June 2021) and operational (June 2022) training.
- The trainers used this training to deliver training in their regions, as part of HyResponder, but also to ensure that a plan is in place beyond the project.
- The consortium is documenting this through a deliverable and through a paper submitted to the *International Journal of Hydrogen Energy*.

QUANTITATIVE TARGETS AND STATUS

Target source	Parameter	Target	Achieved to date by the project	Target achieved?
Project's own objectives	Training events (1 train-the-trainer event, 10 national events)	12	5	⚙
	Threefold training materials (lectures, operational training, virtual reality training)	3	3	✓
	Revised *European Emergency Response Guide*	1	1	✓
	Materials translated into eight languages	8	8 but not all elements	⚙

HyTunnel-CS

PNR FOR SAFETY OF HYDROGEN DRIVEN VEHICLES AND TRANSPORT THROUGH TUNNELS AND SIMILAR CONFINED SPACES

Project ID:	826193
PRD 2023:	Panel 5 – cross-cutting
Call topic:	FCH-04-1-2018: PNR for safety of hydrogen driven vehicles and transport through tunnels and similar confined spaces
Project total costs:	EUR 2 500 000
Clean H_2 JU max. contribution:	EUR 2 500 000
Project period:	1.3.2019–31.7.2022
Coordinator:	University of Ulster, United Kingdom
Beneficiaries:	Commissariat à l'énergie atomique et aux énergies alternatives, Danmarks Tekniske Universitet, Fundación para el Desarrollo de las Nuevas Tecnologías del Hidrógeno en Aragón, Health and Safety Executive, International Fire Academy, Karlsruher Institut für Technologie, National Center for Scientific Research 'Demokritos', Pro-Science – Gesellschaft für Wissenschaftliche und Technische Dienstleistungen mbH, Service Public Fédéral Intérieur, Stichting Koninklijk Nederlands Normalisatie Instituut, Università degli Studi di Roma la Sapienza, Universitetet i Sørøst-Norge

https://hytunnel.net

PROJECT AND OBJECTIVES

This pre-normative research project aimed to improve the safety of hydrogen-driven vehicles in underground infrastructure. HyTunnel-CS aimed to synthesise analytical, numerical and experimental research to produce recommendations for intervention strategies and tactics for first responders, recommendations for the safer use of hydrogen vehicles in underground transportation systems and recommendations for regulations, codes and standards (RCS). The project also aimed to reduce overconservatism in infrastructure safety design for hydrogen accidents and to reduce the costs of underground systems. The outcomes can be directly implemented in relevant RCS.

NON-QUANTITATIVE OBJECTIVES

The project aimed to ensure that fuel cell electric vehicles entering tunnels are at a level of risk equal to / below that of fossil fuel vehicles. This was addressed by considering tunnel vehicles as a system through experimental, theoretical and numerical studies.

PROGRESS AND MAIN ACHIEVEMENTS

The project achieved all objectives and milestones.

- Work on the state of the art in safety provisions for underground transportation systems and in prioritising accident scenarios was completed in the first reporting period, with all public deliverables being achieved. This work formulated problems and prepared the field for pre-normative research in work package (WP) 2–WP5 (all publicly available on the project website).
- Analytical, numerical and experimental pre-normative research in WP2–WP4 started with the development of detailed research plans, reported in deliverables 2.1, 3.1 and 4.1. The work performed in WP2–WP4 from the beginning of the project to its end was reported in deliverables 2.3, 3.3 and 4.3 (final report on analytical, numerical and experimental studies for each work package). Most analytical and numerical research plans have been completed in a timely manner, sometimes ahead of the schedule (e.g. engineering tools in deliverable 4.2). The experimental studies were affected by the COVID-19 pandemic but mostly recovered during the 5-month extension period. Experimental work at the Health and Safety Executive suffered from off-design test conditions at a large-scale tunnel facility, but was completed in December 2022 (final reports on deliverables 2.3, 3.3 and 4.3 are available on the project website) (relevant Innovation Radar entry: https://www.innoradar.eu/innovation/40447).
- All deliverables in WP5 (first responders' intervention strategies and tactics for hydrogen accidents in underground transportation systems and risk assessment) – deliverables 5.1, 5.2, 5.3 and 5.4 – have been achieved on time and are publicly available on the project website. The stakeholder workshop (milestone 6.2) and the international workshop of emergency services (milestone 5.2 and deliverable 5.2) were changed from face-to-face to online events due to the COVID-19 pandemic (reports on deliverables 5.3 and 5.4 are available on the project website) (relevant Innovation Radar entry: https://www.innoradar.eu/innovation/40450).
- WP6 (synthesis, outreach and dissemination) was responsible for the two principal project outcomes – deliverables 6.9 (recommendations for inherently safer use of hydrogen vehicles in underground traffic systems) and 6.10 (recommendations for RCS). National networks and a stakeholder advisory board were formed and operated within WP6. The board meeting minutes are reported in deliverables 6.2, 6.4, 6.6, 6.7, 6.8 and 6.13. The list of publications was compiled and maintained as part of milestone 6.5 (report 6.9, deliverable 6.10 and the publication list are available on the project website).
- The safety strategies developed in the project, the closed knowledge gaps and the main public outcomes (deliverables 5.4, 6.10 and 10) were presented at the dissemination conference (deliverable 6.12), which was organised as a face-to-face event on 14–15 July 2022 in Brussels (all conference presentations are available on the project website).

FUTURE STEPS AND PLANS

- The project completed its work.
- Final periodic and financial reports were submitted.
- Partners continue to communicate the project results through scientific publications and at the meetings of standardisation organisations.

QUANTITATIVE TARGETS AND STATUS

Target source	Parameter	Target	Achieved to date by the project	Target achieved?
Project's own objectives	D5.4 Harmonised recommendations on response to hydrogen accidents	1	1	✓
	D6.10 Recommendations for RCS	1	1	
	D6.9 Recommendations for inherently safer use of hydrogen vehicles in underground traffic systems	1	1	
	Engineering models and simulations	34	34	
	Two seminars (M6, M30), two workshops (both M15), dissemination conference (M36).	5	5	
AWP 2018	Unique experimental data / experimental data to support development of physical models, simulations and engineering tools	20	20	

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MultHyFuel

MULTI-FUEL HYDROGEN REFUELING STATIONS (HRS): A CO-CREATION STUDY AND EXPERIMENTATION TO OVERCOME TECHNICAL AND ADMINISTRATIVE BARRIERS

Project ID:	101006794
PRD 2023:	Panel 5 – cross-cutting
Call topic:	FCH-04-1-2020: Overcoming technical and administrative barriers to deployment of multi-fuel hydrogen refuelling stations (HRS)
Project total costs:	EUR 2 121 906.25
Clean H_2 JU max. contribution:	EUR 1 997 406.25
Project period:	1.1.2021–31.12.2023
Coordinator:	Hydrogen Europe, Belgium
Beneficiaries:	Engie, Health and Safety Executive, Institut national de l'environnement industriel et des risques, ITM Power (Trading) Limited, Kiwa Nederland BV, Air Liquide SA, Shell Nederland Verkoopmaatschappij BV, Snam SpA, Zentrum für Sonnenenergie- und Wasserstoff-Forschung Baden-Württemberg

https://multhyfuel.eu/

PROJECT AND OBJECTIVES

MultHyFuel's ultimate goal is the amendment of best practice guidelines for the design, construction and development of multifuel refuelling stations. An analysis of the current legal framework regarding permitting requirements throughout Europe has been carried out. A risk assessment analysis and experimental data acquisition on the leakage characteristics and consequences in the station's forecourt will take place shortly.

NON-QUANTITATIVE OBJECTIVES

The project aims to contribute to safety improvement by selecting the critical scenarios identified in a multifuel refuelling station and proceeding to experimental testing of hydrogen leakage and its consequences.

PROGRESS AND MAIN ACHIEVEMENTS

- *Permitting requirements and risk assessment methodologies for HRS in the EU* (first edition) was submitted and presented to the stakeholders, with a summary of the main commonalities and differences found in permitting requirements from 14 European countries.
- Feedback from public authorities was received, as was feedback from experts during the interim review meeting.
- In work package (WP) 3, three case-study models with different configurations were identified and designed, and a preliminary risk assessment was performed on them to identify the most critical scenarios to study in WP2.
- In WP2, *Assessment of dispersion for high pressure H_2* was submitted, with results from computational fluid dynamics modelling simulations performed to evaluate the size of clouds expected considering different scenarios of leakage in H_2 dispensers.

FUTURE STEPS AND PLANS

- MultHyFuel will complete testing on the leakage characteristics of the dispenser. The project was waiting for equipment to be delivered and to acquire the data needed for the correct design of the system – testing was expected to start in January 2023.
- The project will complete testing of leakage consequences (fire and explosion) in the forecourt. Testing was expected to start in January 2023.
- MultHyFuel will organise a workshop with hydrogen refuelling station operators and public authorities. This is to take place once results from the experimental WP 2 are ready, so that they can be presented to the key stakeholders and so that feedback can be acquired.
- The project will perform a risk assessment and amend the best practice guidelines. This will take place once the experimental results have been released.

QUANTITATIVE TARGETS AND STATUS

Target source	Parameter	Unit	Achieved to date by the project	SoA result achieved to date (by others)	Year of SoA target
Project's own objectives	Safety refuelling distance	m	N/A	5–35, depending on the country	2021
	Guidelines for safety barriers	–	N/A	Dependent on the country	N/A
	Number of stakeholders endorsing project's results	number	17	N/A	N/A

PRHYDE

PROTOCOL FOR HEAVY DUTY HYDROGEN REFUELLING

Project ID:	874997
PRD 2023:	Panel 5 – cross-cutting
Call topic:	FCH-04-2-2019: Refuelling protocols for medium and heavy-duty vehicles
Project total costs:	EUR 3 167 078.16
Clean H_2 JU max. contribution:	EUR 1 494 417.00
Project period:	1.1.2020–30.9.2022
Coordinator:	Ludwig-Bölkow-Systemtechnik GmbH, Germany
Beneficiaries:	Commissariat à l'énergie atomique et aux énergies alternatives, Engie, ITM Power plc, Air Liquide SA, NEL Hydrogen A/S, Nikola Corporation, Shell Deutschland GmbH, Toyota Motor Europe SA, Toyota Motor North America, Zentrum für Brennstoffzellen-Technik GmbH

https://prhyde.eu/

PROJECT AND OBJECTIVES

PRHYDE, running between January 2020 and September 2022, had the aim of developing recommendations for non-proprietary heavy-duty refuelling protocols used for future standardisation activities for trucks and other heavy-duty transport systems applying hydrogen technologies. Based on existing fuelling protocols and the current state of the art for compressed gaseous hydrogen fuelling, different hydrogen fuelling protocol concepts were developed for large tank systems with 35 MPa, 50 MPa and 70 MPa nominal working pressures using simulations, and experimental verification was carried out. A broad industry perspective was captured as a result of a comprehensive stakeholder participation process, with several workshops held throughout the project.

PROGRESS AND MAIN ACHIEVEMENTS

- PRHYDE has formulated four new fuelling protocol concepts for the heavy-duty segment.
- Complementary to the four PRHYDE fuelling concepts, a protocol feature that can apply to all concepts was also developed. This feature, called the SOC taper, can adjust the fuelling speed when the station encounters non-ideal situations such as low storage capacity or high-flow restrictions.
- Numerical approaches (thermodynamic and computational fluid dynamics modelling) and an experimental test campaign at different test sites were conducted to validate the modelling efforts and provide proof of concept that the protocol concepts work as intended.

FUTURE STEPS AND PLANS

The project has been completed.

QUANTITATIVE TARGETS AND STATUS

Target source	Parameter	Target	Achieved to date by the project	Target achieved?
Project's own objectives	Meetings with standards organisation groupings	4	4	✓
	Reports sent to standard-developing organisations	18	21	
	Publicly accessible workshops/webinars	6	6	

SH2E

SUSTAINABILITY ASSESSMENT OF HARMONISED HYDROGEN ENERGY SYSTEMS: GUIDELINES FOR LIFE CYCLE SUSTAINABILITY ASSESSMENT AND PROSPECTIVE BENCHMARKING

Project ID:	101007163
PRD 2023:	Panel 5 – cross-cutting
Call topic:	FCH-04-5-2020: Guidelines for life cycle sustainability assessment (LCSA) of fuel cell and hydrogen systems
Project total costs:	EUR 2 142 778.75
Clean H_2 JU max. contribution:	EUR 1 997 616.25
Project period:	1.1.2021–30.6.2024
Coordinator:	Fundación IMDEA Energía, Spain
Beneficiaries:	Commissariat à l'énergie atomique et aux énergies alternatives, Forschungszentrum Jülich GmbH, Fundación para el Desarrollo de las Nuevas Tecnologías del Hidrógeno en Aragón, Greendelta GmbH, Symbio, Institute of Applied Energy

https://sh2e.eu/

PROJECT AND OBJECTIVES

The goal of SH2E is to provide a harmonised (i.e. methodologically consistent) multidimensional framework for the life cycle sustainability assessment (LCSA) of fuel cell and hydrogen (FCH) systems. To that end, SH2E will develop and demonstrate specific guidelines for the environmental, economic and social life cycle assessment and benchmarking of FCH systems, while addressing their consistent integration into robust FCH LCSA guidelines. The aim is for these guidelines to be globally accepted as the reference document for LCSA of FCH systems and to set the basis for future standardisation.

NON-QUANTITATIVE OBJECTIVES

- SH2E aims to contribute to FCH systems' sustainability. The development of harmonised guidelines will contribute to assessing the sustainability of FCH systems.
- The project aims to contribute to social acceptance. Better knowledge of FCH systems' social and environmental impacts will contribute to their acceptance.
- It aims to contribute to standardisation. Harmonised guidelines will pave the way for a standard.

PROGRESS AND MAIN ACHIEVEMENTS

- SH2E reviewed the existing guidelines.
- It reviewed case studies and projects.
- Environmental life cycle assessment guidelines were issued.
- Life cycle cost assessment guidelines were issued.

FUTURE STEPS AND PLANS

- Social life cycle assessment guidelines will be issued in mid 2023.
- LCSA guidelines will be issued at the end of 2023.
- The software tool for performing FCH life cycle studies will be issued in month 36.

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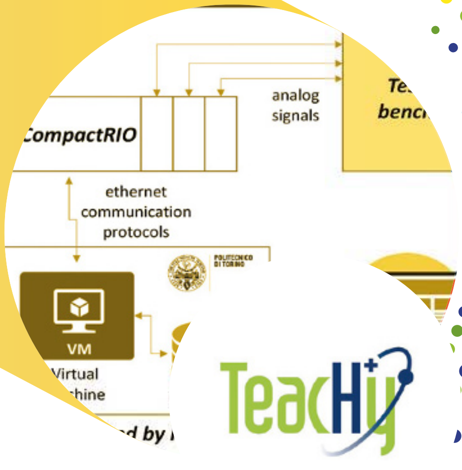
TeacHy

TEACHING FUEL CELL AND HYDROGEN SCIENCE AND ENGINEERING ACROSS EUROPE WITHIN HORIZON 2020



Project ID:	779730
PRD 2023:	Panel 5 – cross-cutting
Call topic:	FCH-04-3-2017: European higher training network in fuel cells and hydrogen
Project total costs:	EUR 1 248 528.75
Clean H_2 JU max. contribution:	EUR 1 248 528.75
Project period:	1.11.2017–31.10.2022
Coordinator:	University of Birmingham, United Kingdom
Beneficiaries:	Danmarks Tekniske Universitet, École Polytechnique Fédérale de Lausanne, Institut polytechnique de Grenoble, Karlsruher Institut für Technologie, National Technical University of Ukraine 'Igor Sikorsky Kyiv Polytechnic Institute', Politecnico di Torino, Technische Universiteit Delft, Universitatea Politehnica din București, Université libre de Bruxelles, University of Ulster, Vysoká škola chemicko-technologická v Praze

http://www.teachy.eu/

PROJECT AND OBJECTIVES

The project has developed an MSc programme on fuel cells and hydrogen. The MSc modules are also being offered as part of continuous professional development (CPD). The first run of the MSc programme is coming to a close, with the first student cohort starting their final research projects. Approximately 150 engineers and college teachers have been trained using the CPD modules, with 50 more to be added by the end of the project. The programme is being transferred from the University of Birmingham to Vysoká škola chemicko-technologická v Praze, and the programme started in September 2022.

NON-QUANTITATIVE OBJECTIVES

TeacHy aims to develop an accreditation system for CPD modules, despite the substantial challenges in achieving this.

PROGRESS AND MAIN ACHIEVEMENTS

- The MSc programme was created.
- The CPD modules were created.
- The project ensured the transferability of the learning management system (LMS) content.

FUTURE STEPS AND PLANS

- The project aims to transfer the programme to more universities; it is waiting for the results of the transfer to Vysoká škola chemicko-technologická v Praze.
- TeacHy will develop tools for transfer between different LMSs.
- The project will develop concise CPD programmes.
- It will establish a business entity for post-project activities.

QUANTITATIVE TARGETS AND STATUS

Target source	Parameter	Unit	Target	Achieved by the project	Target achieved?
Project's own objectives	Start of the MSc course	Date	October 2019	October 2021	✓
	Modules established on the LMS	Number of modules	12	15	
	MSc modules used for CPD delivery	Number of modules run	N/A	8	⚙
	Modules translated into various languages	Number of modules	12	6 (partly)	⚙

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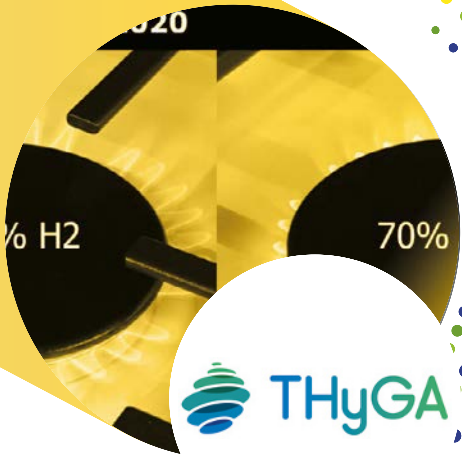

THyGA

TESTING HYDROGEN ADMIXTURE FOR GAS APPLICATIONS

Project ID:	874983
PRD 2023:	Panel 5 – cross-cutting
Call topic:	FCH-04-3-2019: Hydrogen admixtures in natural gas domestic and commercial end uses
Project total costs:	EUR 2 468 826.25
Clean H_2 JU max. contribution:	EUR 2 468 826.25
Project period:	1.1.2020–31.3.2023
Coordinator:	Engie, France
Beneficiaries:	BDR Thermea Group BV, Commissariat à l'énergie atomique et aux énergies alternatives, Dansk Gasteknisk Center AS, DVGW Deutscher Verein des Gas- und Wasserfaches – Technisch-Wissenschaftlicher Verein EV, Electrolux Italia SpA, gas.be, Gaswärme-Institut Essen EV, Gerg – le Groupe Européen de Recherches Gazières

https://thyga-project.eu/

PROJECT AND OBJECTIVES

The THyGA project is investigating the amount of hydrogen that can be injected without compromising the safety, emissions and efficiency of existing and new applications. It focuses on the end-user perspective, specifically domestic and commercial gas appliances (space heating, hot water, cooking and catering), which account for > 40 % of the EU's gas consumption. The objectives are to close knowledge gaps on the impact of H_2NG blends, support standardisation activities and identify potential mitigation opportunities.

NON-QUANTITATIVE OBJECTIVES

- THyGA aims to involve external partners in the project. Some laboratories and manufacturers expressed their wish to use the THyGA protocol to create their own tests and contribute to the analysis.
- The project aims to have an international reach. THyGA's test protocol has been requested for use as a test reference by international partners (in Canada, Chile and the United States).

PROGRESS AND MAIN ACHIEVEMENTS

- THyGA tested around 100 appliances, including as part of the preparation of reports for work packages 4 (standardisation) and 5 (mitigation).
- Thirteen public deliverables/newsletters were created and distributed, and five public workshops were organised.

FUTURE STEPS AND PLANS

Results were expected to be disclosed during the final workshop on 24 March 2023. All results will be published on the THyGA website. In addition, the results will be disseminated to the European Committee for Standardization technical committees, with the opportunity for experts to request dedicated meetings and discussions.

QUANTITATIVE TARGETS AND STATUS

Target source	Target	Achieved to date by the project	Target achieved?
Project's own objectives	Understanding the actual theoretical and experimental information on the impact of H_2NG blends on combustion	12 public deliverables and 7 additional deliverables to be published by April 2023	⚙
	Understanding the actual theoretical and experimental information on the impact of H_2NG blends on materials	Theoretical and practical reviews released	✓
	Segmentation of the types of appliances	Segmentation validated with stakeholders (advisory panel group)	✓
	Tests of up to 100 appliances	95 % of tests done	⚙
	Establishing how the existing certification can be modified to allow higher concentrations, including the related additional costs and the required changes to common gas burners	State-of-the-art reports	⚙
	Recommendations for revision of EN for ISO standards, or drafting of new standards based on PNR results and a review of the existing testing methods	Ongoing	⚙

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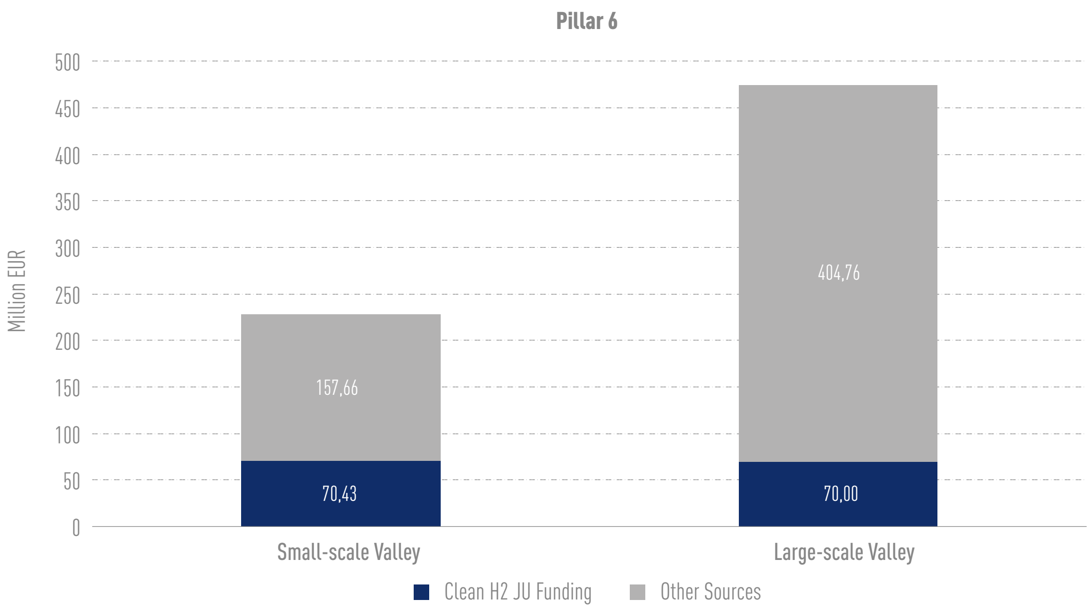
VI. PILLAR 6 – HYDROGEN VALLEYS

Objectives: Three Hydrogen Valleys, benefited so far by the Clean Hydrogen JU, are part of the Programme Review; on the Orkney Islands (BIG HIT - ended in 2022), in the Netherlands (HEAVENN) and on Majorca (GREEN HYSLAND). All 3 projects are centred around the production of hydrogen from renewable sources.

Budget: As can be observed from Figure 45, the funding percentage for Hydrogen Valley projects is low, almost 25% on average. This means that these projects rely on external sources of funding and/or financing (beyond the funding provided by the Clean Hydrogen JU).

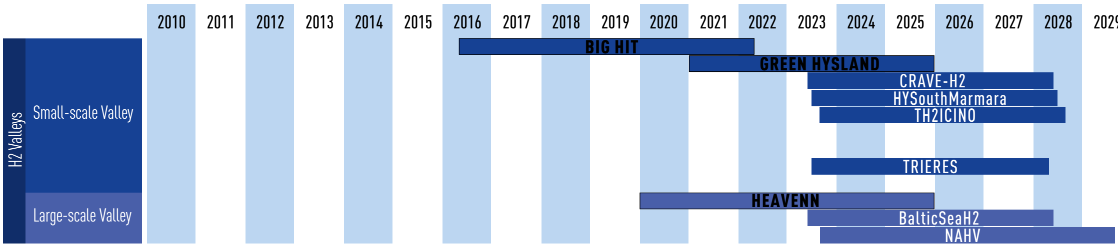
Figure 45: Funding for Pillar 6 projects (2008-2022)



Source: Clean Hydrogen JU

Projects: 3 projects are contributing to this Research Area, namely BIG HIT, HEAVENN and GREEN HYSLAND, covering the period between 2016 and 2022 (Figure 46). The description of the projects can be found in Section 5.6.

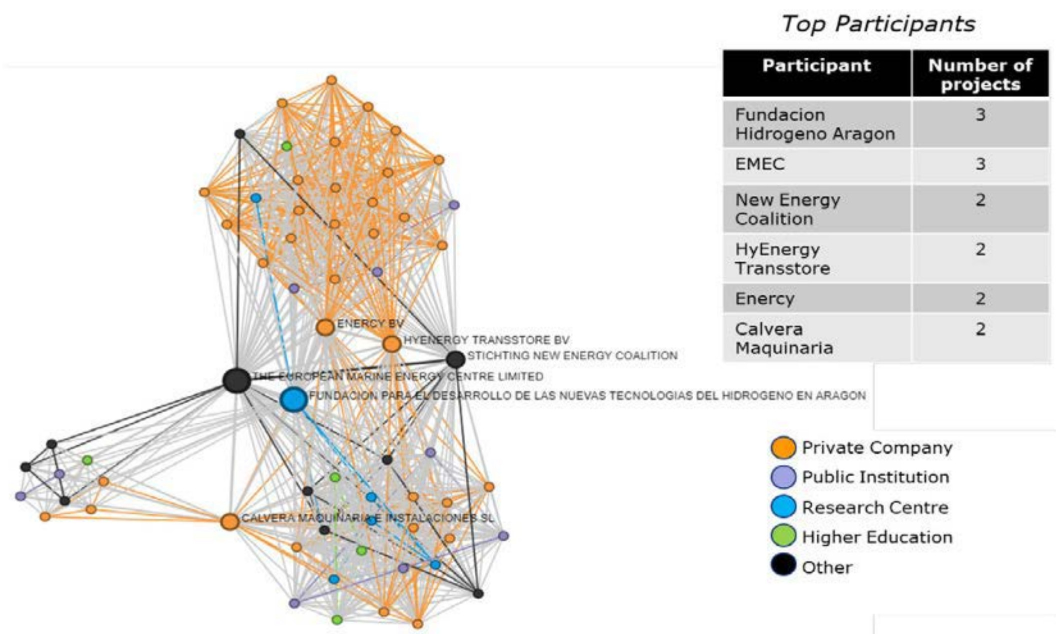
Figure 46: Project timelines of Pillar 6 – Hydrogen valleys



Source: Clean Hydrogen JU
NB. Projects highlighted in black were considered for the 2023 Programme Review.

The projects are well connected to each other, as can be seen from Figure 47. The HEAVENN project has a high share of private companies (top cluster).

Figure 47: TIM Plot showing the participants in the 3 projects reviewed



Participant	Number of projects
Fundacion Hidrogeno Aragon	3
EMEC	3
New Energy Coalition	2
HyEnergy Transstore	2
Enercy	2
Calvera Maquinaria	2

Source: TIM (JRC)

BIG HIT project, finished in 2022, planned to use hydrogen from curtailed wind power for transport, heating and power applications, and 5 hydrogen trailers (250 kg hydrogen storage), a hydrogen catalytic boiler (30 kW), 1 MW electrolyser (ITM Power), 5 hydrogen FC vans and a 75 kW fuel cell system for co-generation have been deployed. Unfortunately, there was much less curtailed wind power than expected, and subsequently no locally produced hydrogen. Nevertheless, BIG HIT has been successful in raising interest from other regions, stakeholders and the general public of these communities and has acted as a precursor of the Hydrogen Valley concept taken-up by others. Most dissemination activities moved on-line, which enabled the project to reach out to a much larger and geographically distributed audience than was previously possible. The project has created the Hydrogen Territories Platform (HTP)[155] which offers useful tools, such as the replicability tool. The HTP has now been taken over by the HEAVENN and GREEN HYSLAND projects. BIG HIT has been very active in maintaining links to

155 https://h2territory.eu/about-the-htp/

other JU projects, like HEAVENN, GREEN HYSLAND and OYSTER. It is also connected to SURF & TURF, HYDIME, PITCHES and HyFLYER. The project has been instrumental in facilitating other hydrogen projects in the area. A potential large-scale project on the island of Flotta would create a green hydrogen hub powered by offshore wind around Orkney.

HEAVENN, located in the northern Groningen and Drenthe area, is deploying hydrogen related infrastructure across 4 clusters. In the Chemical Park Delfzijl (Cluster I), the supply of green hydrogen for the production of green methanol and the production of green kerosene at SkyNRG is facilitated. A hydrogen hub will be built to store and distribute hydrogen, having received additional funding[156] of 1.9 M EUR from the Nationaal Programma Groningen and Waddenfonds. A 135m hydrogen-powered inland waterway vessel, the MS Antonie, has been delivered to the Netherlands. The salt barge hull will be operational around June 2023. In Emmen region (cluster III), a 4-MW electrolyser is planned, which will supply an industrial park with green hydrogen through a newly constructed pipeline. The pipeline will be part of the future Hydrogen Backbone (gas network) planned in the Netherlands. An HRS has been built and is operational. It is used by several companies to refuel at 350 bars. Hydrogen fuelled vehicles have been ordered or purchased and will be delivered in 2023. There is also cluster IV around green mobility applications where the procurement of refuse trucks and other utility vehicles has been completed. The creation of a hydrogen district in Hoogeween (cluster II) is underway. The zoning plan for houses has been approved; these will be fitted with a hydrogen boiler. In total, more than 500 houses are planned to be constructed, thus creating a market for hydrogen boilers. The construction of a hydrogen pipeline network has commenced (May 2023). In addition, HEAVENN is also investigating the use of a salt cavern for hydrogen storage (Cluster II) the testing is ongoing and, so far, successful. Economic data and plans to be sustainable after funding ends will be generated.

The project is facing lack of co-funding, therefore there are uncertainties about the financial situation. In addition, cost of labour and equipment has increased making some business cases untenable, according to the project.

GREENHYSLAND will create a 'green hydrogen ecosystem' on Mallorca, in the Balearic Islands. The project will deploy 3 main infrastructures: a green H2 production plant in Lloseta, an HRS and tube trailers. The tenders for purchasing the fuel cells are expected to be launched in 2023. Green hydrogen will be used to supply fuel cell buses (to be purchased through additional regional funding) and fuel cell light duty vehicles. In 2023 the Municipal Transport Company of Palma received the five 12-metre Solaris hydrogen buses. A grant of 1.123.360€ from a national funding programme for H2 buses was awarded. The recently installed Hydrogenics/Cummins 2.5 MW PEM electrolyser (delivered in December 2021) will receive electricity from a newly built PV plant (also through additional national funding). The connection to the PV panels is in place. The hydrogen production facility is almost fully built and is expected to be operational in 2023. The project has been declared to be of Strategic Interest at regional level, which apparently helped to reduce time given to public consultations. This accelerated the process of licensing and permitting, reducing the needed time by more than half [157].

A network has been established between BIG HIT, HEAVENN and GREEN HYSLAND to exchange lessons learnt for joint events and collaboration between the projects. This project is trying for the replicability (building on the HTP concept developed in BIG HIT) of its concept in other isolated territories[158]. GREEN HYSLAND aims to establish an EU Coalition for hydrogen deployment on islands; the Hysland Hub. This strategic partnership aims to raise awareness of the potential of hydrogen technologies for the decarbonisation of EU islands.

156 https://heavenn.org/news/waddenfonds-and-province-of-groningen-invest-over-e1-9-million-in-hydrogen-hub-delfzijl/

157 H2 Valleys Workshop Outcomes.pdf (europa.eu)

158 There is the plan that the follower territories, Madeira, Tenerife, Aran, Greek Islands, Ameland, Chiloé and Morocco, can reproduce aspects of the GREEN HYSLAND project model in their territories. GREEN HYSLAND has also developed a methodology for designing tailored solutions that integrate hydrogen production, storage, and multiple end-use.

BIG HIT

BUILDING INNOVATIVE GREEN HYDROGEN SYSTEMS IN AN ISOLATED TERRITORY: A PILOT FOR EUROPE

Project ID:	700092
PRD 2023:	Panel 6 – H2 valleys
Call topic:	FCH-03.2-2015: Hydrogen territories
Project total costs:	EUR 7 748 848.00
Clean H_2 JU max. contribution:	EUR 5 000 000.00
Project period:	1.5.2016–30.4.2022
Coordinator:	Fundación para el Desarrollo de las Nuevas Tecnologías del Hidrógeno en Aragón, Spain
Beneficiaries:	Calvera Maquinaria e Instalaciones SL, Community Energy Scotland Limited, Danmarks Tekniske Universitet, Giacomini SpA, ITM Power (Trading) Limited, Ministry for Transport, Infrastructure and Capital Projects (Malta), Orkney Islands Council, Shapinsay Development Trust, Symbio, European Marine Energy Centre Limited, Scottish Hydrogen and Fuel Cell Association Ltd

https://www.bighit.eu/

PROJECT AND OBJECTIVES

The BIG HIT project is a major first step towards creating a genuine hydrogen territory in the Orkney Islands. Orkney has over 50 MW of installed wind, wave and tidal capacity, generating over 46 GWh of renewable power per year, and it has been a net exporter of electricity since 2013. Hydrogen is proposed as a solution to minimise the curtailment problems in Orkney caused by the weak connection with the UK mainland. The hydrogen produced is used in thermal, power (co-generation) and transport applications locally.

NON-QUANTITATIVE OBJECTIVES

- BIG HIT aimed to perform a life cycle assessment study; this is now complete. The first report was submitted during the second year of the project, and the final report, including operational data, was submitted at the end of the project.
- The project aimed to perform a business model study for integrated energy systems based on hydrogen technologies across the islands. The first report was submitted during the second year of the project, and the final report, including operational data, was submitted at the end of the project.
- It aimed to perform a social life cycle assessment. The first report was submitted during the second year of the project, and the final report, including operational data, was submitted at the end of the project.
- The project aimed to set up the Hydrogen Territories Platform; this platform was launched. Four webinars have been conducted to date. The platform will be used in the Hydrogen energy applications for valley environments in northern Netherlands (HEAVENN) and Deployment of a H_2 ecosystem on the island of Mallorca (Green Hysland) projects as well, with a continuation of its activities and goals.
- BIG HIT aimed to perform a first analysis of lessons learned from the project about the connection of electrolysers in power grids with high penetration of renewable energy sources (optimal model), marinisation of electrolysers, etc. The outputs were included in the final report and in the deliverables related to project operation and maintenance.

PROGRESS AND MAIN ACHIEVEMENTS

- The main project equipment has been built: five H_2 trailers (250 kg of H_2 storage), a H_2 catalytic boiler (30 kW), a 1 MW electrolyser, five H_2 fuel cell vans and a 75 kW fuel cell (co-generation).
- The project developed the logistics of moving hydrogen through an archipelago (a multielement gas container moving H_2 between the islands by ferry, and logistics optimisation).
- BIG HIT developed the Hydrogen Territories Platform.

FUTURE STEPS AND PLANS

- The project finished in 2022. Some of the equipment and facilities remain operational in Orkney.
- BIG HIT performed an impact analysis. Final reports on the environmental and social impact and the business model analysis were published and made available to the public.
- The main project results, conclusions and lessons learned have been presented at the Hydrogen Territories Platform webinars.

QUANTITATIVE TARGETS AND STATUS

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	Hydrogen catalytic boiler power	kW	40	30	⚙	30 kW commissioned; 10 kW FAT completed	N/A
	Availability of fuel cell light-duty vehicles (including cars)	%	98	98	✓	98	2017
	HRS durability	years	10	5	⚙	Other projects / HRSs have been running for longer periods	5 years SoA in 2020 according to the FCH 2 JU MAWP

GREEN HYSLAND

DEPLOYMENT OF A H_2 ECOSYSTEM ON THE ISLAND OF MALLORCA

Project ID:	101007201
PRD 2023:	Panel 6 – H2 valleys
Call topic:	FCH-03-2-2020: Decarbonising islands using renewable energies and hydrogen – H2 islands
Project total costs:	EUR 23 717 171.22
Clean H_2 JU max. contribution:	EUR 9 999 999.50
Project period:	1.1.2021–31.12.2025
Coordinator:	Enagás SA, Spain
Beneficiaries:	Enagás Renovable, Acciona Generación Renovable SA, Agência Regional da Energia e Ambiente da Região Autónoma da Madeira, Ajuntament de Lloseta, Asociación Chilena de Hidrogeno, Asociación Española del Hidrógeno, Association marocaine pour l'Hydrogène et le Développement Durable, Autoridad Portuaria de Baleares, Baleària Eurolíneas Marítimas SA, Calvera Maquinaria e Instalaciones SL, Centro Nacional De Experimentación de Tecnologías de Hidrógeno y Pilas de Combustible Consorcio, Commissariat à l'énergie atomique et aux énergies alternatives, Consultoria Tecnica Naval Valenciana SL, Diktyo Aeiforikon Nison Toy Aigaiouae, Empresa Municipal de Transports Urbans de Palma de Mallorca SA, Energy BV, Energy Co-operatives Ireland Limited, Fédération européenne des agences et des régions pour l'énergie et l'environnement, Fundación para el Desarrollo de las Nuevas Tecnologías del Hidrógeno en Aragón, Gasnam – Asociación Ibérica de Gas Natural y Renovable para la Movilidad, Gemeente Ameland, HyCologne GmbH, HyEnergy Consultancy Limited, HyEnergy Trans-Store BV, Instituto Balear de la Energía, University of Galway, Redexis Gas Servicios Sl, Redexis Infraestructuras Sl, Redexis SA, Stichting New Energy Coalition, the European Marine Energy Centre Limited, Universidad de La Laguna, Universitat de les Illes Balears, Power to Green Hydrogen Mallorca, Enagás

https://greenhysland.eu/

PROJECT AND OBJECTIVES

Green Hysland is developing all the infrastructure the island of Mallorca (Spain) needs to produce and consume at least 330 t of green hydrogen from newly built photovoltaic plants per year. Green hydrogen will have multiple applications on the island: a fuel supply for a fleet of fuel cell buses and other vehicles, generation of heat and power for commercial and public buildings, a new hydrogen refuelling station and injection into the island's gas pipeline network. The project includes the development of a roadmap to 2050 in Mallorca and activities to replicate the experiments on seven other islands.

NON-QUANTITATIVE OBJECTIVES

- Green Hysland aims to develop public awareness and create a basis for skills development. The project has been presented at almost 120 events.
- Thirteen workshops have been conducted and 15 activities have been organised jointly with other EU projects.

PROGRESS AND MAIN ACHIEVEMENTS

- Green Hysland has delivered and installed a 2.5 MW electrolyser.
- The project has awarded the tender for the Empresa Municipal de Transports (EMT) in Palma H_2 buses.
- It has completed the conceptual design of the six project sites.

FUTURE STEPS AND PLANS

- The H_2 plant will go into operation. The electrolyser was delivered in December 2021 and the plant was expected to be operational in March 2023.
- The tender for H_2 buses was launched in December 2021 and was awarded in March 2022. They were expected to be delivered in the first quarter of 2023 (first bus available and in operation in March).
- During 2023, tenders are expected to be launched for the purchase of the fuel cells for the Puerto Deportivo Naviera Balear, Lloseta and hotel sites in Palma, and for a fleet of 10 vehicles (rental cars and vans). The project is working on defining the technical and administrative specifications of the tender documents.
- The sites are expected to receive the equipment at the end of 2023. Around 2 years of operation of the complete ecosystem is expected within the project period.

QUANTITATIVE TARGETS AND STATUS

Target source	Parameter	Unit	Target	Achieved to date by the project
MAWP addendum (2018–2020)	Commitment of public authorities	M€	–	6.25
Project's own objective	Electrolyser	MW	7.5	2.5

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HEAVENN

HEAVENN

HYDROGEN ENERGY APPLICATIONS FOR VALLEY ENVIRONMENTS IN NORTHERN NETHERLANDS

Project ID:	875090
PRD 2023:	Panel 6 – H2 valleys
Call topic:	FCH-03-1-2019: H2 valley
Project total costs:	EUR 96 191 883.00
Clean H_2 JU max. contribution:	EUR 20 000 000.00
Project period:	1.1.2020–31.12.2025
Coordinator:	Stichting New Energy Coalition, Netherlands
Beneficiaries:	Shell Nederland Verkoopmaatschappij BV, TotalEnergies Marketing Nederland NV, TotalEnergies Gas Mobility BV, Gemeente Hoogeveen, Hydrogen Ireland Natural Resources Association Company LBG, Nederlandse Particuliere Rijnvaart-Centrale Cooperatie UA, U.V.O. Vervoer BV, Lenten Scheepvaart BV, Bytesnet Groningen BV, EWE Gasspeicher GmbH, Enercy BV, Green Planet Real Estate BV, Emmtec Services BV, Gemeente Emmen, HyEnergy TransStore BV, H2Tec BV, Gemeente Groningen, Groningen Seaports NV, ENGIE Energie Nederland NV, EBN – Energie Beheer Nederland BV, HyEnergy Consultancy Limited, European Research Institute for Gas and Energy Innovation, PitPoint. Crew BV, PitPoint.Pro BV, Qbuzz BV, Nederlandse Aardolie Maatschappij BV, PitPoint.CNG BV, Cemtec Fonden, Gemeenschappelijke Regeling Samenwerkingsverband Noord-Nederland, Logan Energy Limited, Hinicio, Nobian Industrial Chemicals BV, Fundación para el Desarrollo de las Nuevas Tecnologías del Hidrógeno en Aragón, NV Nederlandse Gasunie, the European Marine Energy Centre Limited, Rijksuniversiteit Groningen

https://heavenn.org/

PROJECT AND OBJECTIVES

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. The main goal is to make use of green H_2 across the entire value chain, while developing replicable business models for wide-scale commercial deployment of H_2 across the entire regional energy system.

NON-QUANTITATIVE OBJECTIVES

- HEAVENN aims to achieve certification of regulations, codes and standards. All relevant green H_2 value chains will be tested against the CertifHy protocol.
- Safety issues will be covered by permitting procedures.

PROGRESS AND MAIN ACHIEVEMENTS

- The salt barge hull has been delivered to the Netherlands and will be operational around June 2023. Salt cavern testing is ongoing and has been successful so far.
- Emmen hydrogen refuelling station was delivered in June 2022 and has been successfully used by Qbuzz and other companies to refuel at 350 bar. A large proportion of the mobility applications (i.e. vehicles) have been ordered or purchased and will be delivered this year.
- Work package 4 is currently on hold. Work packages 5, 6 and 7 are operating mostly on schedule.

FUTURE STEPS AND PLANS

Securing co-funding is a prerequisite for the project to succeed. Talks with governments about State aid will continue, aiming to speed up the process and secure all co-funding.

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VII. PILLAR 7 – SUPPLY CHAIN

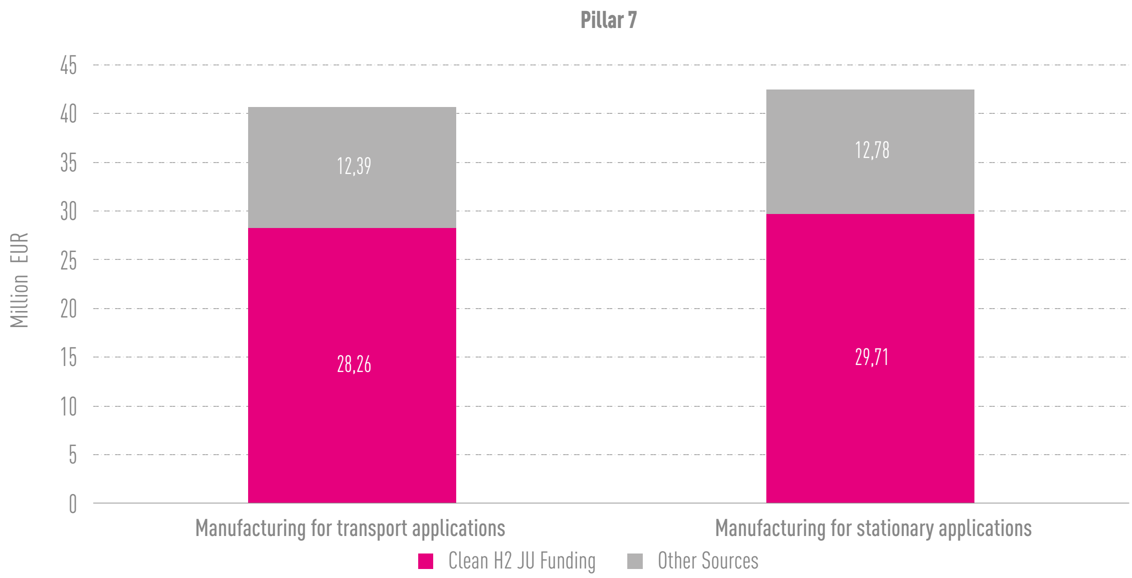
Objectives: The main objectives of this Pillar, according to the SRIA, can be summarised as below.

- Identification of potential vulnerabilities in the EUs hydrogen supply chain;
- Development of new and improved manufacturing technologies and production processes that facilitate the safe and sustainable use of non-critical (raw) materials as well as facilitate the adoption of the circular economy principles; and
- Reducing the use of critical (raw) materials with sustainability or environmental concerns, such as for instance those deriving from poly/perfluoroalkyls.

Pillar 7 contributes towards achieving the above objectives through the following areas of research and development: manufacturing for stationary applications, manufacturing for transport applications and Critical Raw Materials (CRM). Currently there are no projects addressing priorities within the 3rd Research Area of CRM use.

Budget: Between 2010 and 2020, the JU supported 18 projects relevant to this pillar with a total contribution of EUR 83 million and a contribution from partners of EUR 25 million. The historic distribution of total budgets over the 2 Research Areas, shown in Figure 48, indicates that 49% of JU funding went to support 7 projects on manufacturing for transport applications and 51% was dedicated to 11 projects on manufacturing for stationary applications. The JU's funding contribution amounts to about 70% of the total funding for the portfolio of projects considered in this Pillar.

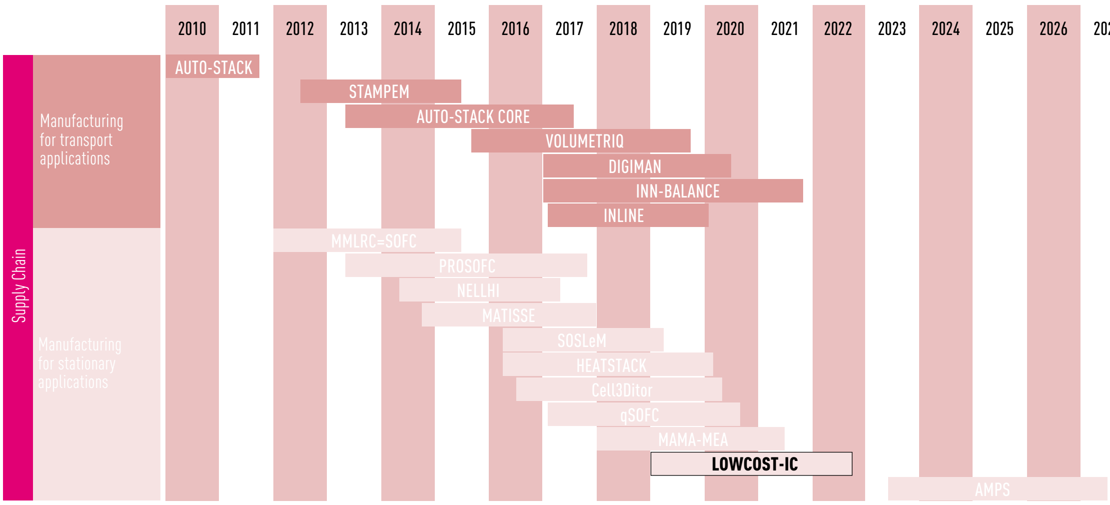
Figure 48: Funding for Pillar 7 projects (2008-2022)



Source: Clean Hydrogen JU

Projects: The Clean Hydrogen JU programme portfolio of Pillar 7 related projects is shown in Figure 49.

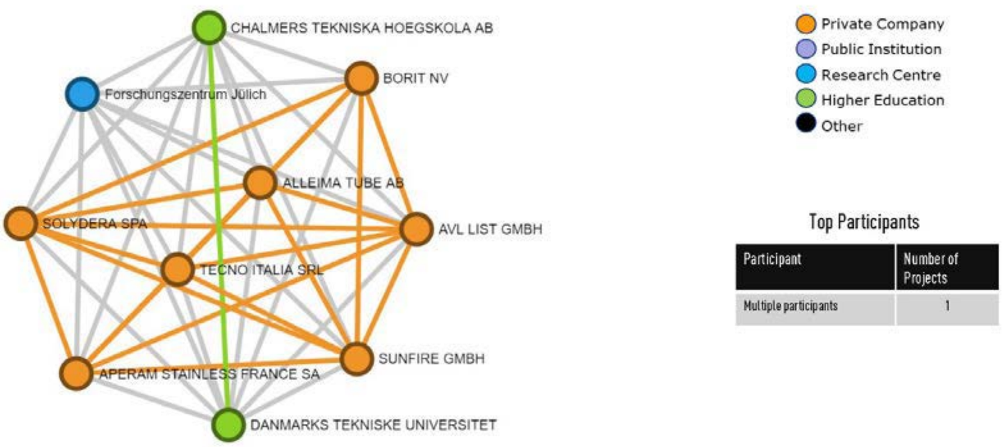
Figure 49: Project timelines of Pillar 7 – Supply chain



Source: Clean Hydrogen JU
NB. Projects highlighted in black were considered for the 2023 Programme Review.

The TIM plot presents the main organisations and EU Member State contributing to Pillar 7, shown in Figure 50[159].

Figure 50: TIM plot showing the participants in the project reviewed



Source: TIM (JRC)

MANUFACTURING FOR STATIONARY APPLICATIONS

In the 2023 Annual Programme Review, Pillar 7 will address one project, LOWCOST-IC, within the first Research Area.

Project **LOWCOST-IC** addresses the degradation phenomenon related to the steel interconnect (IC) material and insufficient robustness of the contact between the IC and the SOFC, known to be one of the main challenges in this respect. Thus, the aim of the project is to implement new interconnect steels, coatings and contact layers

159 The size of the node represents the number of projects a partner is involved in, whilst the thickness of the links represents the number of projects in common between the linked partners. The colour is based on the type of organisation as provided in CORDIS.

in SOC stacks of 2 commercial manufacturers (Solydera and Sunfire), which should undergo extensive testing in an industrially relevant environment. Finally, the cost-effectiveness of the proposed production route should be assessed and compared with existing production routes to facilitate the project innovations' fast market entry. Large-scale mass manufacturing methods was demonstrated for application of the coating by physical vapour deposition (PVD), for subsequent shaping of the ICs by hydroforming and finally for fast printing of contact layers by a drop-on-demand (DoD) process. Reduction of the fabrication costs to < 5 € per unit of interconnect, including coatings and contact materials for processing at 50 MW/year capacity has been reached by the project.

Sandvik's PVD-coated interconnect plates were hydroformed for Sunfire stacks, and the corrosion resistance was shown to be retained after hydroforming. DoD printing on interconnect tops have also been demonstrated. Novel robust contact layers based on Mn-Co and Mn-Cu spinels have been developed. The project is progressing well towards the achievement of its target of reducing the Ohmic resistance across the interconnect to < 15mΩcm2 at 750°C and < 20 mΩcm2 at 850°C (evaluated after 3,000 h). Demonstration of stable operation for > 3000 hours and 50 cycles with the new contact layers and coated interconnects in multiple 1 kW stacks were done. Stack tests have been run for 3000 hours, including thermal cycling of stacks with new contact layers. Finally, demonstration of a flexible and cost-effective interconnect development route has been completed. Cheap hydroforming of commercial interconnects is demonstrated. The project published 10 scientific articles in total, 4 of them in the last reporting period. Moreover, despite the project end, the beneficiaries are preparing more articles to be published.

LOWCOST-IC

LOW COST INTERCONNECTS WITH HIGHLY IMPROVED CONTACT STRENGTH FOR SOC APPLICATIONS

Project ID:	826323
PRD 2023:	Panel 7 – supply chain
Call topic:	FCH-02-6-2018: Cost-effective novel architectures of interconnects
Project total costs:	EUR 2 335 997.50
Clean H_2 JU max. contribution:	EUR 2 335 997.50
Project period:	1.1.2019–30.9.2022
Coordinator:	Danmarks Tekniske Universitet (DTU), Denmark
Beneficiaries:	Sandvik Materials Technology AB, Aperam Stainless France SA, AVL List GmbH, Borit NV, Chalmers Tekniska Högskola AB, Forschungszentrum Jülich GmbH, SolydEra SpA, Sunfire GmbH, Tecno Italia SRL

http://www.lowcost-ic.eu/

PROJECT AND OBJECTIVES

The overall objective of LOWCOST-IC is to contribute to the successful upscaling of the widespread commercialisation of solid oxide cell (SOC) technologies by:

- increasing the robustness of the lifetime of SOC stacks by developing novel highly robust air electrode contact layers and testing new interconnect coatings in SOC stacks;
- minimising the interconnect development and production cost by introducing cheaper high-volume steel, applying state-of-the-art (SoA) large-scale roll-to-roll manufacturing methods for SOC manufacturing and developing a novel interconnect shape design process.

PROGRESS AND MAIN ACHIEVEMENTS

- Work package (WP) 2 aimed to reduce interconnect costs without affecting performance by exploring steel grades, coatings and manufacturing processes. The highlights are as follows:
- roll-to-roll manufacturing – feasibility demonstrated, including shaping with hydroforming;
- chromium evaporation – reduced by 30 times;
- low-cost steels – comparable performance to specialised steel in terms of corrosion rate, chromium evaporation and area-specific resistance (ASR);
- ASR of < 20 mΩcm^2 at 850 °C after 3 000 hours of operation achieved.
- In WP3, a new interconnect design with optimised flow distribution was developed, based on an efficient three-dimensional multiphysics model considering flow, heat transfer, mechanical stresses and electrochemical reactions.
- In WP4, novel contact layers were developed by DTU, based on *in situ* reactive bonding, using metallic powders as precursors to form strong bonds through oxidation and reaction.
- In WP5, four stack designs were produced using different materials to demonstrate developed materials. A stack with Sanergy 441 HT interconnect steel-coating solution was tested for 3 500 hours at 800–850 °C. Sanergy HT 441 with CeCo coating showed more ASR degradation than Crofer 22 APU with MCF coating but performed better at lower temperature. A stack with the new contact layers performed similarly to standard solutions without optimisation.
- In WP6, the technical improvements converted into monetary values showing that the mass manufacturing routes would be commercially competitive compared with in-house production because of the scalable processes of roll-to-roll and high-speed printing.
- In WP7, the work was disseminated through 12 published papers, with 4 more in preparation; 11 conference presentations; and 2 workshops, each with 32 participants comprising academics and most of the SOC stack manufacturers in Europe.

FUTURE STEPS AND PLANS

- Stack modelling will continue in national and EU projects, e.g. the AMON project.
- The material development for contact layers will be paused due to lack of funding.
- A recommendation will be made to Hydrogen Europe to put more effort back into material research.

QUANTITATIVE TARGETS AND STATUS

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	Fracture energy of contact layer	J/m^2	5.1	19.6	✓	1.7	2013
	ASR of contact layer at 750 °C	mΩcm^2	15	18	✓	15	2019
	ASR of contact layer at 850 °C	mΩcm^2	25	15		N/A	N/A

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