Strategic Research and Innovation Agenda

Final Draft

July 2020

Contents

Acronyms, abbreviations & definitions

Acronyms & abbreviations

A	Ampere
AC	Alternative Current
AI	Artificial Intelligence
AEL	Alkaline Electrolyser
AEMEL	Anionic Exchange Membrane Electrolyser
AFC	Alkaline Fuel Cell
API	Application Programming Interface
APU	Auxillary Power Unit
ATEX	ATmosphere EXplosible
ATM	Air Traffic Management
ATR	Autothermal Reforming
AWP	Annual Work Plan
BAU	Business As Usual
BEV	Battery Electric Vehicle
BoL	Beginning of Life
BoP	Balance of Plant
CA	Clean Aviation
CAPEX	Capital Expenditure
CCGT	Combined Cycle Gas Turbine
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilisation
CEF	Connecting Europe Facility
CH_4	Methane
CHE	Clean Hydrogen for Europe
CHP	Combined Heat and Power
µCHP	micro Combined Heat and Power
cm^2	square centimeter
CO_2	Carbon Dioxide
COP21	Conference of Parties 21
COPV	Composite overwrap pressure vessel
CSA	Coordination and Support Action
CSR	Corporate Social Responsibility
DC	Direct Current
DLE	Dry Low Emissions
DOE	Department of Energy
DSO	Distribution System Operator
EC	European Commission
EIB	European Investment Bank
EIC	European Innovation Council
EoL	End of Life
ERDF	European Regional Development Fund
ESIF	European Structural and Investment Fund
ETS IF	European Trading Scheme Innovation Fund
EU	European Union
FC	Fuel Cell
FCEV	Fuel Cell Electric Vehicle
FCH	Fuel Cell and Hydrogen
FCH2-JU	Fuel Cell and Hydrogen Joint Undertaking
FEED	Front-End Engineering Design
FRP	Fiber Reinforced Polymer
G&A	General and Administrative
GFCS	Generic Fuel Cell System
GHG	Green House Gas
GT	Gas Turbine
GW	Giga Watt
H_2	Hydrogen
HD	Heavy-Duty
HDV	Heavy-Duty Vehicle
HELLEN	Hydrogen Event and Lessons LEarNed
HHV	Higher Heating Value
HIAD	Hydrogen Incident and Accident Database
hrs	Hours
HRS	Hydrogen Refueling Station
HTE	High Temperature Electrolysis
IEP	Institutionalised European Partnership
IA	Innovation Action
IEA	International Energy Agency
IEC	International Electrotechnical Commission
IMO	International Maritime Organisation
IPCEI	Important Projects of Common European Interest
IrOx	Iridium Oxide
ISO	International Standard Organisation

kg	kilo
KOH	Potassium hydroxide
Kw	Kilowatt
kWel	Kilowatt electrical
kWth	Kilowatt thermal
kWh	Kilowatt hour
KPI	Key Performance Indicator
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCSA	Life Cycle and Sustainability Assessment
LD	Light Duty
LDV	Light Duty Vehicle
LH_2	Liquid Hydrogen
LHV	Lower heating Value
LNG	Liquified Natural Gas
LOHC	Liquid Organic Hydrogen Carrier
LR	Long Range
m^2	square meter
m^3	cubic meter
MAWP	Multi Annual Work Plan
MCFC	Molten Carbonate Fuel Cell
MDV	Medium Duty Vehicle
MEA	Membrane Electrode Assembly
MEUR	Million Euro
mg	milligram
MOF	Metal–organic framework
MoU	Memorandum of Understanding
MRL	Manufacturing Readiness Level
Mt	Million ton
MW	Megawatt
MWe	Megawatt electrical
MWh	Megawatt hour
MTBF	Mean Time Between Failure
NG	Natural Gas
NGO	Non-Governmental Organisation
NH_3	Ammonia
NO_x	Nitrogen Oxides
O&M	Operation and Maintenance
OCGT	Open Cycle Gas Turbine
OEM	Original Equipment Manufacturer
OPEX	Operational Expenditure
P2G	Power to Gas
PCCEL	Proton Conducting Ceramic Electrolyser
PEFCR	Product Environment Footprint Category Rules
PEM	Proton Exchange Membrane
PEMEL	Proton Exchange Membrane Electrolyser
PGM	Platinum Group Metals
PNR	Pre-Normative Research
POC	Point of Connection
PPP	Public Private Partnership
ppmv	Part per Million by Volume
PSA	Pressure Swing Adsorption
PV	Photovoltaic
R&D	Research and Development
R&D&I	Research and Development and Innovation
R&I	Research and Innovation
RIA	Research Innovation Action
RCS	Regulations Codes and Standards
RES	Renewable Energy Source
RM	Roadmap
ROI	Return on Investment
ROPAX	roll on/roll off a passenger
RORO	roll on/roll off
rSOC	reversible Solid Oxide Cell
RuO_2	Ruthenium dioxide
Sec	second
SLCA	Social Life Cycle Assessment
SME	Small and Medium Entreprise
SMR	Steam Methane Reforming / Short Medium Range
SO	Strategic Objective / Solid Oxide
SoA	State of the Art
SDO	Standard Developing Organisation
SOC	Solid Oxide Cell
SOEL	Solid Oxide Electrolyser
SRIA	Strategic Research and Innovation Agenda
T&D	Transmission and Distribution

TC	Technical Committee
TCO	Total Cost of Ownership
TEA	Techno Economic Analysis
TRL	Technology Readiness Level
TSO	Transmission System Operator
TWh	Terawatt hour
UAV	Unmanned Aerial Vehicle
UK	United Kingdom
US	United States
W	Watt
WEO	World Energy Outlook
WLE	Wet Low Emissions
WtW	Well to Wheel
ZE	Zero Emission
ZEWT	Zero Emission Waterborne Transport

Definitions

- **Clean hydrogen**: an umbrella term to describe hydrogen with a GHG footprint of <36.4 g CO_2 eq/MJH_2, produced from renewable sources (green hydrogen) or non-renewable sources (low-carbon hydrogen) as defined by the CertifHy programme.
- **Green hydrogen**: hydrogen derived from biogenic and non-biogenic renewable resources with a GHG footprint of <36.4 g CO_2 eq/MJH_2. (Also referred to as renewable hydrogen).
- **Low-carbon hydrogen**: hydrogen of <36.4 g CO_2 eq/MJH_2 derived from non-renewable sources.
- **Net-Zero hydrogen**: hydrogen with a GHG footprint of zero.
- **Grey hydrogen**: hydrogen with a GHG footprint of >36.4 g CO_2 eq/MJH_2

The CO_2 threshold comes from the CertifHy project. If during the lifetime of CHE, EU regulations adopt new threshold they will be applied in the partnership.

1. INTRODUCTION

This document contains the Strategic Research and Innovation Agenda (SRIA) of the Clean Hydrogen for Europe institutionalized partnership (IEP) proposed by the private partner (Hydrogen Europe and Hydrogen Europe Research), at a time where a political process evaluating whether the partnership should be retained or not is still ongoing.

Hydrogen Europe and Hydrogen Europe Research prepared this document with vital input from the Fuel Cell and Hydrogen 2 Joint Undertaking (FCH2-JU), as part of the process of requesting an IEP devoted to developing hydrogen technologies in the EU.

The SRIA is an integral part of the IEP request. It has been prepared in a form of a series of interrelated technology development roadmaps.

These roadmaps are based on data and information from:

- Hydrogen Europe Industry and Research members
- Data from the following sources:
  - "Hydrogen Roadmap Europe, A Sustainable Pathway for The European Energy Transition", FCH2-JU, 2019
  - "Hydrogen: enabling a zero emission Europe" Hydrogen Europe's Strategic Plan 2020-2030, and underlying data
  - FCH2-JU Multi-Annual Work Plan, 2014-2020
  - The Hydrogen Council's 2017 report "Hydrogen Scaling up: A sustainable pathway for the global energy transition".
- "Hydrogen and fuel cells: opportunities for growth. A roadmap for the UK" E4Tech and Element Energy for Innovate UK, 2016"Study on hydrogen from renewable production resources in the EU" LBST and Hinicio for the FCH2-JU, 2015.

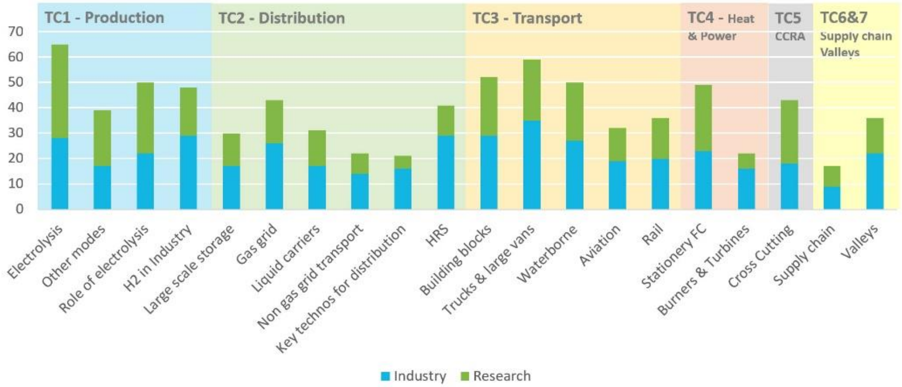
The document is the result of many iterations done throughout a continuous process started before 2019, as depicted in Figure 1.

Figure 1. Iterations of the SRIA

Source: Hydrogen Europe

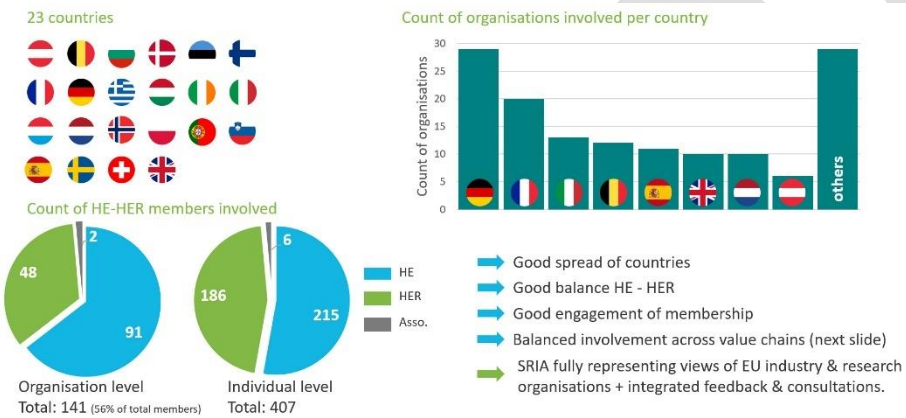
This current version integrates feedback received from the EC early 2020 as well as feedback received from the public consultation, which has been left open until May 2020. Synergies emanating from discussions held with others private partners are also reflected in this document (further details in section 2.5 and throughout roadmaps). Involvement and consultations of/with key players has also been conducted; it includes relevant European associations representing sectors where hydrogen could play a key role, without having a partnership (renewables, power generation, etc.). and Technology Platforms (ETIP SNET). Last but not least, we engaged from May 2020 in a bottom-up, inclusive and transparent approach with all members of Hydrogen Europe and Hydrogen Europe Research in a vast exercise to update the roadmaps, translating in some 100+ teleconferences organised over the past weeks. The repartition by roadmap of participation, totalling 407 individuals, is shown on Figure 2 and Figure 3.

Figure 2. Working Groups: participation of our members



Source: Hydrogen Europe

Figure 3. Statistics participation of HE-HER members



Source: Hydrogen Europe

We are confident that this work has led to a comprehensive, ambitious yet realistic SRIA that constitutes an excellent basis for progressing the discussion with the EC.

2. VISION, INSTRUMENTS & EXPECTED IMPACTS

2.1. The need for an EU Partnership on Hydrogen

Europe's transition to a decarbonized energy system is underway. All Member States of the EU have signed and ratified the Conference of the Parties (COP21) Paris agreement to keep global warming "well below 2 degrees Celsius above preindustrial levels, and to pursue efforts to limit the temperature increase even further to 1.5 degrees Celsius." This transition will radically transform how the EU generates, distributes, stores, and consumes energy. It will require virtually carbon-free power generation, increased energy efficiency, and the deep decarbonization of transport, buildings, and industry.

The pressure to deliver results in our common efforts to decarbonise our societies without causing disruptive economic damage has never been greater. This challenge is recognised at the highest political levels. A European "Green Deal" is necessary to show that Europe is committed to achieve ambitious climate and environmental goals without sacrificing prosperity.

President Ursula von der Leyen has expressed a wish for the European Commission to pursue CO_2 emission reduction ambitions which go beyond the current targets of 40% reduction by 2030. Furthermore, the political goals of the new Commission include the desire to help decarbonise energy-intensive industries[1]. Frans Timmermans, Executive Vice President of the European Commission, rightly pointed out in his nomination statement that *"Hydrogen could be a huge opportunity for our economy"*[2].

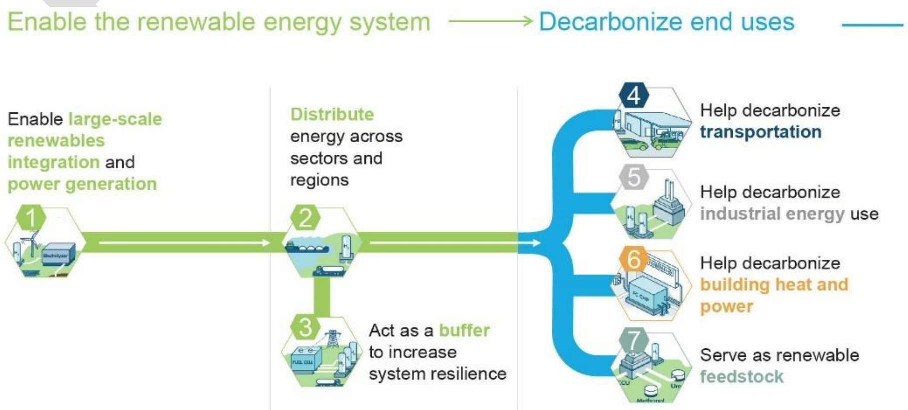
Europe is undergoing the early stages of an enormous energy transition in order to decarbonise all aspects of our daily lives in a short time. This shift is underpinned by three main elements: energy efficiency and sovereignty, increased use of renewable sources to provide a cleaner electricity grid, and a switch to other energy carriers. The overarching mission to enable this shift is clear: towards a zero-emission, carbon-neutral Europe.

"The energy transition in the EU will require hydrogen at large scale. Without it, the EU would miss its decarbonisation objective."

Alongside electricity, hydrogen will become the main energy vector that enables a zero-emission Europe. The overarching reason for this is straightforward: in an energy system dominated by the use of renewable power from wind and solar, using these green electrons to power whole sectors of the economy poses insurmountable challenges if not complemented by hydrogen. Hydrogen will play a necessary role in integrating large amounts of renewable power in the transport, industrial processes and heating and cooling sectors, which are today hard to decarbonise. As shown in the Figure 4, hydrogen can:

- serve as an ideal energy vector, linking renewable energy sources with several final uses
- have a net zero or low GHG footprint, when respectively produced from electrolysis or natural gas (CCS/CCU)
- be transported over long distances, allowing distribution of energy between countries
- store energy for long periods of time, serving as a needed system buffer and providing resilience, e.g. in underground storage
- decarbonize a wide range of final uses, providing clean power and/or heat to transport and stationary applications

Figure 4. The need for Hydrogen for deep decarbonization of Europe's economy



Source: Hydrogen scaling-up, Hydrogen Council, 2017

Hydrogen is not simply a potential contributor to solving the challenges posed by the energy transition, offering a future solution with several advantages, particularly when used in fuel cells.

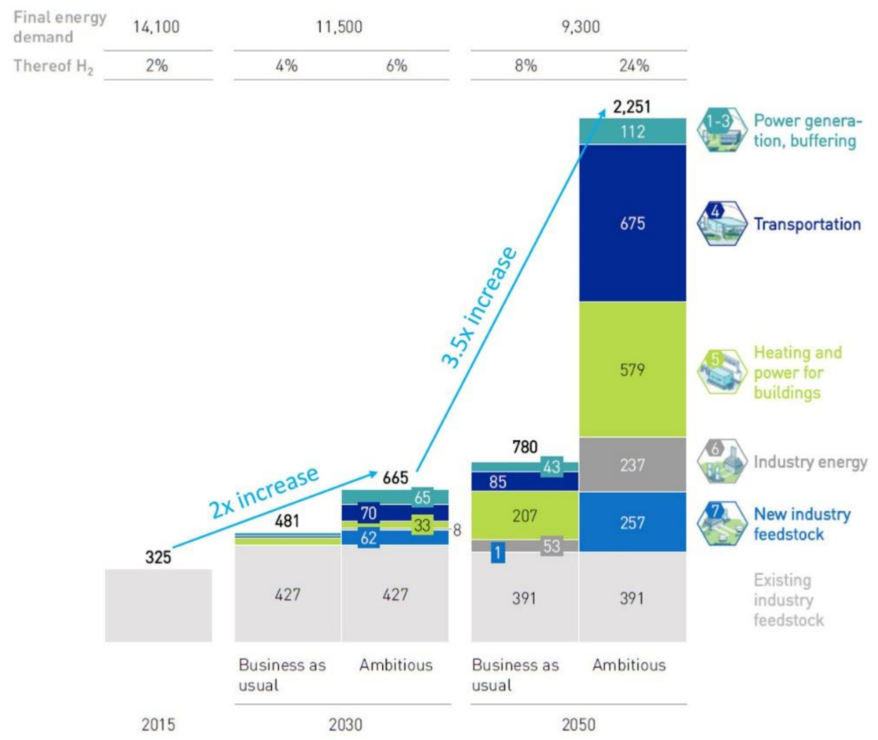
[1] Political Guidelines for The Next European Commission 2019-2024, https://ec.europa.eu/commission/sites/beta-political/files/political-guidelines-next-commission_en.pdf.

[2] Frans Timmermans, Executive Vice President of the European Commission, 8th October 2019, Brussels, https://www.europarl.europa.eu/resources/library/media/20191009RES63850/20191009RES63850.pdf.

Hydrogen is a solution without which Europe cannot achieve its 2050 goals on GHG emissions reduction[3].

However, despite significant progress achieved by research and industry with the support of the EU Commission, through the FCH JUs, work remains to be done before hydrogen can live up to the immense potential for revolutionising our fossil fuel-based economies. If the right measures are taken at EU, national and local level, hydrogen could provide up to 24% of the total energy demand, or up to ~2,250 TWh of energy in the EU by 2050. Realizing this ambition will require a significant step up of activities along the whole value chain. The ramp-up should start now as hydrogen and fuel cell technologies are technically ready for most segments and the **EU industry must scale up** to reduce costs and gain a leading position in the global energy transition economy. Towards 2030, research and deployment should focus on priority segments such as: large-scale clean hydrogen production, cost-efficient hydrogen storage and distribution, and key end-uses such as industrial use, heavy-duty transport (including shipping and aviation) and heat & power.

Figure 5. Hydrogen demand in 2050 in Europe, under various scenarios



Source: Hydrogen Roadmap Europe, FCH2-JU, 2019

Achievement of this positive vision of the future will require a coordinated approach by policymakers, industry, and investors. If this level of cooperation does not emerge and current policies remain in place, hydrogen will see much lower deployment levels and decarbonization targets will

[3] This does not mean that other technology solutions cannot/should not contribute to these decarbonisation goals. Rather, hydrogen can help solve inherent deficiencies that pose constraints to such solutions becoming enough on their own to achieve these objectives.

remain unmet. Figure 5 describes such a development, the business-as-usual (BAU) scenario. In this scenario, hydrogen demand would amount to only about 780 TWh in 2050 (compared with 2,250 TWh in the ambitious scenario). The use of hydrogen would abate about 100 Mt of CO_2 by 2050, leaving a gap of approximately 960 Mt to the 2-degree scenario.

2.2. Vision and ambitions of the Clean Hydrogen for Europe partnership

Clean Hydrogen for Europe's main goal is to enable European hydrogen technologies (mature and developing) to live up to their potential as the missing link in achieving a sustainable and decarbonised energy system, fully integrated with consuming sectors, in particular those which are hard to electrify. Our common vision for the partnership is that it would accelerate the development of clean hydrogen technologies to the point where market and policy mechanisms can take over and continue deployment in a way that allows them to have a significant contribution to the European climate, environmental and economic objectives. The partnership would achieve this goal by leveraging technical and financial resources[4] from both private and public sources in pursuit of clearly defined objectives fully in line with the policies of the EU.

It is our view that continued support for hydrogen-based technologies in the framework of an IEP will bring an immense benefit for Europe in terms of climate as well as economic objectives. The seeds planted in the next decade could ensure that, by 2050, 560 Mt of CO_2 could be abated annually by hydrogen technologies in an industry that creates more than €5.4 million direct jobs and generates more than €800 billion annually.

Figure 6. Contribution of Hydrogen technologies in Europe in 2050

Source: Hydrogen Roadmap Europe, FCH2-JU, 2019

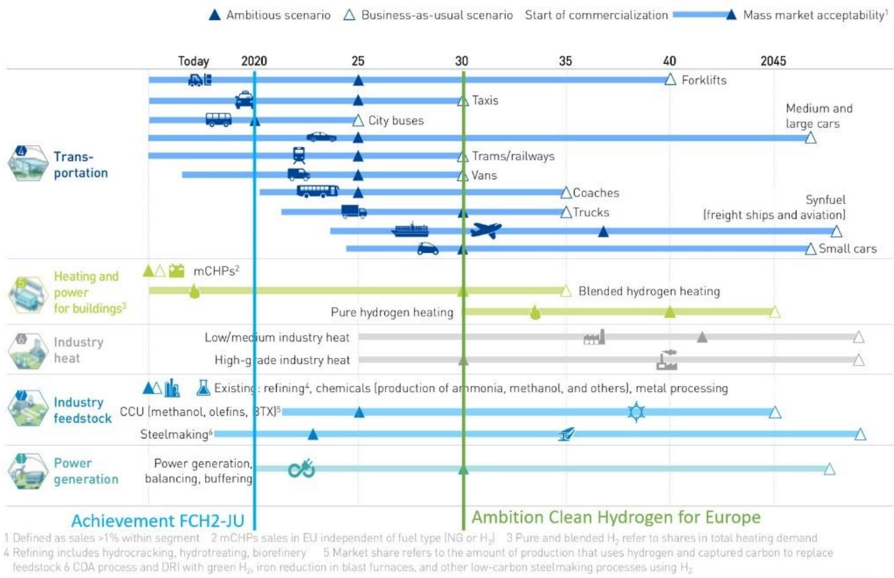
This vision cannot be achieved in the absence of strong commitment from industry, research and the public sector in Europe. And while the FCH JUs have had many achievements, much more remains to be done.

The evaluations of the FCH JUs have shown that the impact of the activities undertaken by the partnerships have been significant and far reaching. This chapter recounts the areas in which the FCH JU has been found to have been effective (in order to learn from the positives) while the subsequent section highlights the challenges that remain and the areas which require increased effort. As depicted in Figure 7, a series of technology/applications have been brought to technological maturity with the support of the FCH JU. For example, passenger cars, vans, material handling, domestic and commercial hydrogen-fed CHP and burners are now ready (or expected to be ready soon) for mass commercialisation. While technological building blocks should still be subject to improvement, no additional support for demonstration activities is required for these applications in the next financial period. For these applications, it is time that the market, industrial players and other policy instruments take over and continue (mass) deployment.

[4] A leverage effect which should go well beyond the leverage factor of similar programmes.

This success could not have occurred without the FCH JU, which is demonstrating thousands of light duty vehicles and which has kick started the deployment of the much-needed hydrogen refuelling requirements for further European uptake.

Figure 7. Status of maturity of various hydrogen applications



Source: Hydrogen Europe, adapted from Hydrogen Roadmap Europe, FCH2-JU, 2019

The FCH JU is also demonstrating more than 310 buses in 10 different cities based on a technology which is now close to commercial reality (at TRL8). Fuel efficiency has increased three-fold in 15 years and refuelling time has more than halved. In this period, the costs of fuel cell buses have decreased by almost 400%. All these impacts can be traced back to the efforts of the FCH JU[5]. While some work remains for hydrogen fuel cell buses to be fully competitive against diesel incumbents, it is not far off.

The progress achieved in cars and buses should now be replicated in other transport applications such as heavy-duty vehicles, ships, trains and aircrafts. These applications will require, in the next financial period, support from a future partnership, Clean Hydrogen for Europe (CHE), in order to follow the same success curve as the applications which reached maturity during the FCH JU.

As regards fuel cells (FC) for power production (stationary CHP), the relevant FC technology has been steadily demonstrated by FCH JU projects in real installations. In particular, FCs have shown great potential for residential micro-CHP[6] which allow users to produce much of their own electricity, heat and hot water. Technology leaders in this sector (most of them EU heating companies) are approaching commercialisation following extensive field trials in the range of 10,000s units of installed micro-CHP FC systems. Larger (industrial size) demonstrations[7] supported by the FCH JU have proven the viability of this application. In this field, maturity, as described above, is not far off.

The success registered so far by the FCH JU does not eliminate the need to continue the development of hydrogen infrastructure and improvement of core technological building blocks in all the applications presented above. It does not eliminate the need to invest in research, development and demonstration (including at scale) of applications which have not yet reached maturity, but it does show that public investments pays off in the long term and should be replicated, at scale, using those applications which

[5] Interim Evaluation of the FCH2-JU (2014-2016) operating under Horizon 2020 - Experts Group Report.
[6] Fuel cell micro Combined Heat and Power (µCHP) units.
[7] An example is project DEMCOPEM-2MW which uses hydrogen by-product to generate electricity, heat and water for the chlorine-alkali production process, lowering electricity consumption by 20%.

are now lagging behind and will require prioritisation in the next financial period.

As shown in Figure 7, while work still remains in some areas, a number of technology/applications are technologically mature and ready for mass commercialisation. The work of the FCH JUs over the past decade has brought hydrogen to the brink of widespread deployment, but **market failure and fragmentation prevent clean hydrogen from reaching its full potential as the missing link in an integrated, sustainable and clean energy system.**

The underlying core challenges which cause bottlenecks and market failures, preventing hydrogen technologies to reach mass market status, are diverse in nature and differ depending on the application and the technology they concern. These challenges can be summarised as followed:

1. Several technologies/applications do not exist yet or are not mature enough. For these applications, further Research & Innovation (R&I) is necessary to progress in Technology Readiness Levels (TRL).
   - Where R&I does take place (N.B. outside of the context of the current FCH JU) it is fragmented between various Member States and isolated companies.

2. For technologies/applications that are, technologically, ready for deployment, they face different challenges:
   - Hydrogen solutions remain more expensive for a good part due to the absence of volume (need for improved Industrialisation and Manufacturing Readiness Levels, MRL).
   - Unlike other technologies there is no first mover advantage: the first mover is not able to get such a market advantage where future profits can compensate for early losses.
   - The deployment of hydrogen applications is usually part of a broader system involving other hydrogen applications and/or other sectors therefore requiring a large coordination effort.
   - For these applications, the main challenge is to get policies that will push their introduction into the market and generate volume which will decrease the costs. However, beyond policies (which are out of scope of the objectives of the partnership), there is still a need for: (i) substantial R&I effort even for those technologies/application that are mature enough to enter the market to improve efficiency, cost, durability and manufacturability and (ii) coordinated roll-out and deployment of comprehensive systems, covering clean hydrogen production, transport and distribution and finally, end-use applications.

3. As it is very rapidly becoming necessary (and possible) to produce and use large quantities of clean hydrogen, transport, storage and distribution is at risk of becoming a bottleneck for the accelerated rollout of hydrogen technologies at scale. This central pillar between production and consumption requires new (pipelines, refuelling stations) and old (existing gas infrastructure, salt caverns) solutions to work together in a decarbonised energy system.

All applications, irrespective of TRL, MRL and scale suffer from the same horizontal problem: **low carbon and renewable hydrogen is not available cheaply and at scale in all regions** where it is destined to be consumed. This is directly linked to, among other factors, the cost of:

1. Renewable energy (out of scope of the IEP)
2. Electrolysers and
3. Low-carbon hydrogen production technologies (e.g. CCUS technologies).

The hydrogen sector, coordinated by Hydrogen Europe, Hydrogen Europe Research and the FCH2-JU, has carefully analysed the research and development needs and drafted a number of technology roadmaps, detailing the pathway towards mass market commercialisation of hydrogen-based technologies up to 2030 and beyond. The technological roadmaps are covering all applications under the scope of the partnership, with clear targets, milestones and indicators. **These roadmaps collectively make up our SRIA.**

This vision is shared by than 170 industry companies representing the entire hydrogen value chain, including OEMs, energy companies, as well as current and future end-users of hydrogen. Alongside Industry, 80 research organisations are committed to realising this vision and are ready to play their part. In addition to this clear commitment by the members of Hydrogen Europe and Hydrogen Europe Research, organisations representing sectors relevant to the energy transition are also included in a broad coordinated effort to maximise the outreach of the work of the partnership and further increase the achievement of clear, visible impacts for the EU and its citizens.

The SRIA of the next IEP has been organised around three equally important pillars, gathering the most important roadmaps into a coherent programme based on **3 convictions**[8]:

1. It is absolutely necessary to be able to produce massive amounts of clean hydrogen at affordable costs
2. These massive amounts need to be stored, transported and distributed
3. Additional large end uses applications need to be developed:
    - In transport, in particular, heavy duty, maritime and aviation.
    - In buildings, for providing clean heating and power.
    - In industry, in particular steel, refineries and the chemical sector.

All activities of the partnership should aim to maximise the leverage effect of the programme by ensuring that technical and financial resources from both the private sector are directed towards the policy objective pursued by the programme. This entails incentivising (even) more private R&D investment as well as the capitalisation of expertise held by private actors to fulfil tasks within the remit of the IEP (e.g. on annual programme implementation and development, RCS, safety, etc.).

As mentioned above, the core of the innovation programme should be structured along three, equally important, pillars:

1. **Production**
2. **Distribution**
3. **End-uses**

Within these pillars, seven specific objectives are to be pursued:

1. **Producing clean hydrogen at low cost**
2. **Enabling higher integration of renewable within the overall energy system**
3. **Delivering clean hydrogen at low cost**
4. **Developing clean hydrogen refuelling infrastructure**
5. **Ensuring the competitiveness of clean hydrogen for mobility applications**
6. **Meeting demands for heat and power with clean hydrogen**
7. **Decarbonising industry using clean hydrogen**

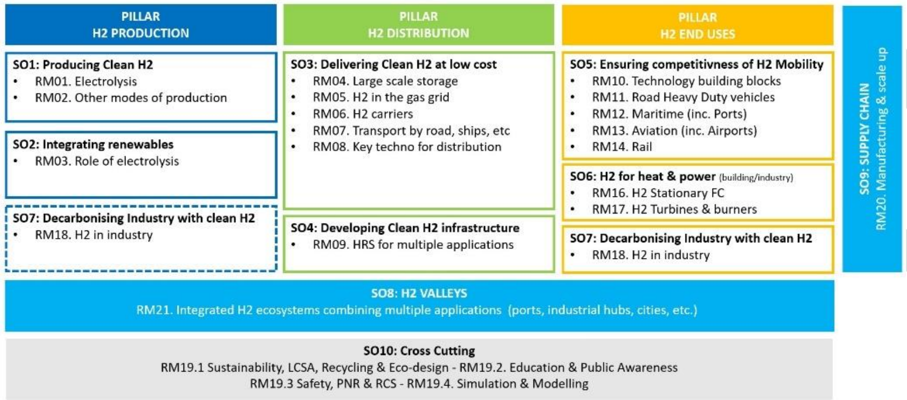
[8] These convictions reflect analytical results conducted internally, (e.g. the Hydrogen Roadmap Europe, available at: https://www.fch.europa.eu/publications/hydrogen-roadmap-europe-sustainable-pathway-european-energy-transition) as well as externally, by organizations such as the IEA (e.g. https://www.iea.org/hydrogen2019/)

The specific objectives within each of these pillars are, in turn, broken down in clearly defined, concrete, operational roadmaps. Each of these roadmaps is elaborated in the following chapters.

In addition to working within each of these pillars, mass deployment requires coordination action to be taken at system level. As a result of this, additional 3 horizontal and cross-cutting objectives have been defined:

1. Hydrogen Valleys that will aim to lay the groundwork for integrated hydrogen ecosystems combining multiple applications across the different pillars.
2. Development of supply chains and manufacturing scale-up.
3. Tackling of cross cutting issues related to RCS, training, safety, etc.

Figure 8. Pillars and specific objectives of the SRIA of Clean Hydrogen for Europe

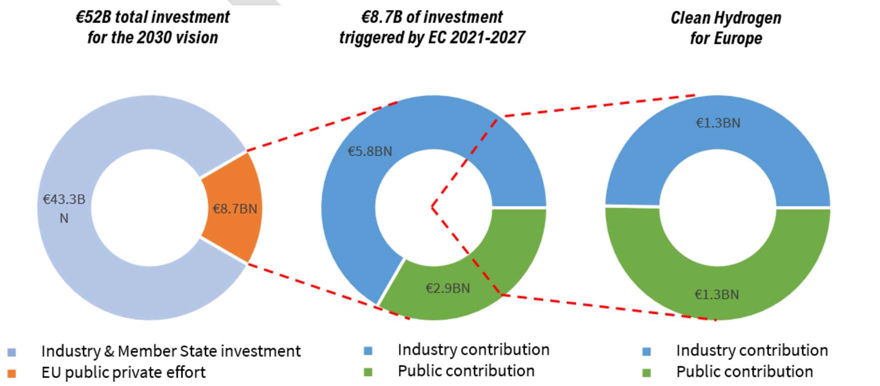


Source: Hydrogen Europe

2.3. Impact and private contribution

We estimate that an **EU public-private effort of €8.7 billion can trigger the €52 billion investment** needed to realise this vision. The €8.7 billion programme might in 70% be funded through existing or planned EU support funds like CEF Transport and Energy or the ETS Innovation Fund (mostly market deployment actions). The remaining 30%, i.e. €2.6 billion would be financed through the next IEP on hydrogen. As is expected in case of a public-private partnership the contribution will be shared equally by industry, research and the European Commission (EC).

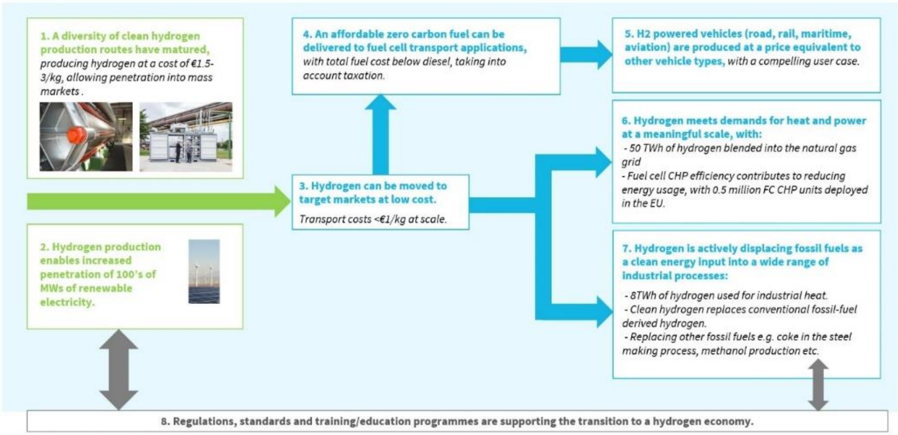
Figure 9. Clean Hydrogen for Europe budget in relation to total investments needed to realize the 2030 hydrogen economy vision



Source: Hydrogen Europe

We are confident that this level of public-private contribution through the Clean Hydrogen for Europe partnership will make it possible to reach a number of targets, that we are convinced are necessary for hydrogen to achieve the envisaged role in the 2030 energy system.

Figure 10. Main targets of the SRIA of Clean Hydrogen for Europe

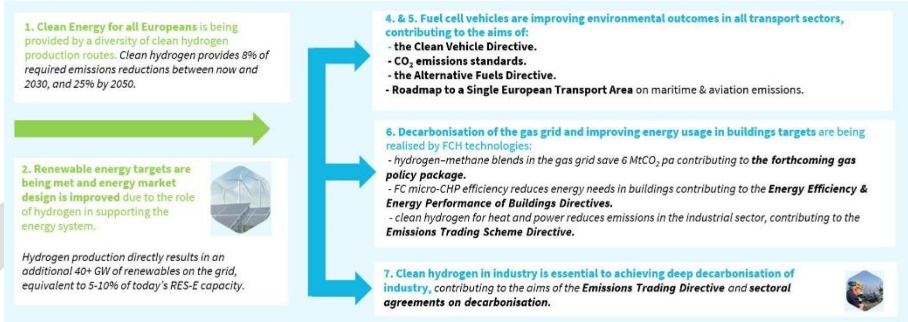


Source: Hydrogen Europe

By achieving these targets, clean hydrogen can be produced and distributed to markets at prices that are competitive in a range of applications that are key to decarbonising Europe's economy. Additionally, with the right support, the hydrogen option can not only be competitive and mature by 2030, but will be a vital tool to meet some of Europe's key policy aims:

- Deep cuts of CO_2 in hard to decarbonise sectors: heavy duty transport (road, rail, ship), heat and industry
- Reducing air pollution
- Ensuring energy security and sovereignty
- Providing energy to citizens at an affordable price

Figure 11. Impact areas of the IEP on hydrogen



Source: Hydrogen Europe

2.4. Instruments

Several instruments applicable to all pillars are to be deployed in order to maximise the benefit of the programme and ensure a strategic roll-out of clean hydrogen technologies which balance future needs with the impetus to deliver tangible results on the short and medium turn. These instruments are:

1. **Strategic research challenges** which focus on the long-term development of low TRL, on critical scientific and technological bottlenecks whose development will take several years and will require *inter alia* long-term (the whole programme period) research-led consortia performing basic theoretical and experimental research.
2. **Early stage Research and Development Research actions** will also focus on relatively low TRL applications (respectively TRL2-3 and TRL3-5), but whose development is achievable within a shorter timeframe.
3. **Demonstration actions**, which aim to achieve the incremental development (and demonstration) of clean hydrogen applications which have not yet reached technological maturity, but which are

expected to do so by the end of (or shortly after) the intervention. Innovation actions include actions which aim to strengthen the capabilities of mature clean hydrogen applications in terms of efficiency, durability, functionality, etc.

4. **Flagship actions** whose main role is to demonstrate the viability of clean hydrogen solutions at scale (large-scale hydrogen production must be achieved in order to reach competitive hydrogen prices of 2 to 3 € per kg, a sufficient amount of hydrogen must be produced to economically justify retrofitting an existing gas pipeline into a dedicated hydrogen pipeline and infrastructure system).
5. **Hydrogen Valleys** which seek to deploy, in a coordinated manner, entire systems which integrate all three pillars, proving the technical and economic readiness of a hydrogen ecosystem, including production, distribution and storage, and final use in transport and stationary applications.
6. **Industrialization action** aimed at enhancing the manufacturing and scale-up capacity of European clean hydrogen supply chains. Such actions have a strong component for SMEs, which are best placed to take advantage of the opportunities offered by new technologies and grow by creating new jobs requiring advanced skills.
7. **Cross cutting actions** which seek to address horizontal issues which risk delaying commercial roll-out, such as regulatory issues, standards, training and education, safety aspects as well as recycling and LCA.

We propose to distinguish different levels of TRL with decreasing funding rate corresponding to higher industry investment for the instruments outlined above:

Table 1. Funding rate of the different instruments proposed in Clean Hydrogen for Europe IEP

H2020 equiv.	Type of project	TRL	Ind.	Res.
RIA	1. Strategic research challenges Early stage Research Action	2-3	100%	100%
	2. Development Research Action	3-5	70%	100%
IA	3. Demonstration Action	5-7	50%	80%
	4. Flagship Action	7-8	30%	TBD
	5. Valley Action	7-8	30%	TBD
	6. Industrialization Action	2-8	30-70%	80%
RIA/CSA	7. Cross Cutting	n/a	70-100%	100%

Source: Hydrogen Europe

Together, these instruments address most of the core barriers which prevent clean hydrogen technologies from reaching their potential as key enablers of the decarbonized, sustainable energy system. These proposed funding rates are conditional on the consideration of the full CAPEX (equipment costs) rather than depreciation[9]. Otherwise the funding rates cannot be reduced to these levels.

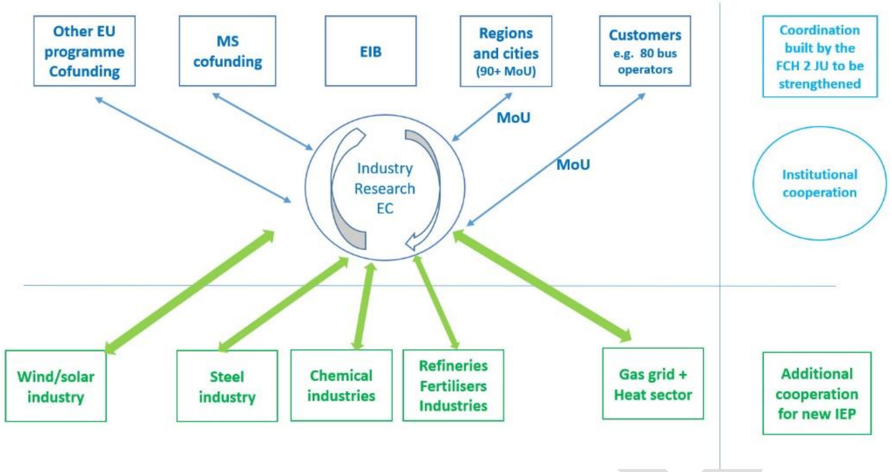
[9] This is the case when the partners build themselves the pilot that will be demonstrated. When the demonstrating partners purchase the pilot this is not automatically the case. When publishing the call, for Flagship and Demonstration projects, CHE should use the equivalent Horizon Europe to the H2020 option provided in the Grant agreement (Article 6.2.D.2 option 2) and explained in the Annotated Model Grant Agreement (p. 82 and following), to make the full purchase costs of capitalised equipment, infrastructure or other assets used for the action (not only the depreciation costs for the relevant periodic report) eligible for funding. This H2020 special clause was written specifically to cover this type of situations. The investment expenses will take place during the project and will be easily identifiable and auditable in the accounts (balance sheet and general ledger) of the project partner.

2.5. Synergies

2.5.1. Connected sectors and synergies other European Partnerships

Hydrogen Europe and Hydrogen Europe Research are in constant collaboration with other sectors that will use hydrogen for their decarbonisation, as shown in Figure 12. This further strengthens the outreach of the sector beyond the members of Hydrogen Europe and Hydrogen Europe Research and ensures coordination with related sectors which are either (i) essential for large scale production and distribution of clean hydrogen, (ii) can directly benefit from the deployment clean hydrogen technologies or (iii) are key actors supporting the funding and financing of projects.

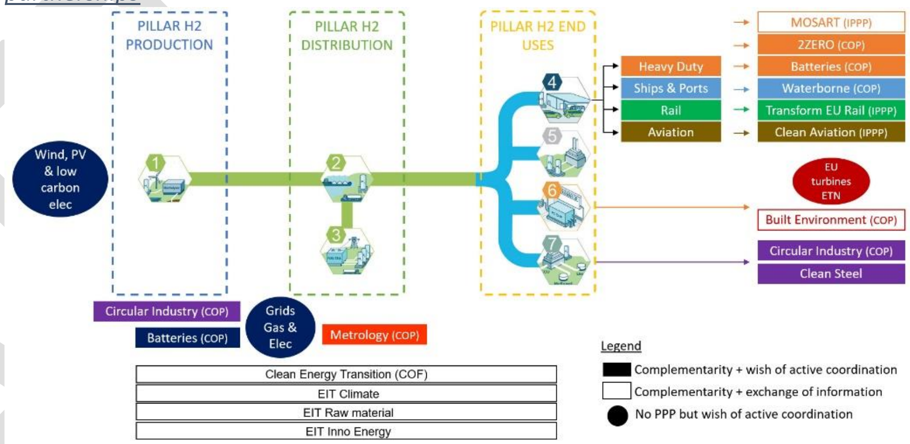
Figure 12. Established links between the FCH2-JU and the wider stakeholder community



Source: Hydrogen Europe

In additional with bilateral cooperation with connected sectors, significant potential for synergies with other EU partnerships has been identified. For this reason, a concerted effort was undertaken to align the EU partnership's SRIAs with the needs of those sectors contributing and/or benefitting from the development of Hydrogen technologies.

Figure 13. Cooperation efforts with connected sectors and synergies with other partnerships



Source: Hydrogen Europe

For most of the sectors which will be supported by a partnership in the next financial period with whom the hydrogen sector wishes to cooperate, (i.e. 2Zero, waterborne, EU rail, clean aviation, clean steel, clean and circular industry), regular meetings have been organised and aiming at:

- improving the quality of our technology roadmaps and strategic research and innovation agenda,
- proposing synergies and division of task between the partnerships,
- designing a process of regular mutual consultation.

We are at (or approaching) a stage where a MoU has been or can be signed, for most of them. This will be finalised in the course of 2020. For the specific cases of green vehicles, a more in-depth collaboration is expected, with the active involvement of the EC. The details of cooperation are explained in the relevant roadmaps. The state of play is shown on Table 2.

Table 2. State of Play June 2020 on synergies discussions with others private partners

Name	RM	Association	Contacts Identified	Association Contacted	Meeting done	Principles agreed	Draft agreement	Finalised agreement
Clean Steel	18	**ESTEP**	Yes	Yes	Yes	Yes	Yes	Yes
ZE Waterborne	12	**Waterborne TP**	Yes	Yes	Yes	Yes	Yes	Almost
2Zero	10,11	**EGVIA**	Yes	Yes	Yes	Yes	Yes	Almost
Clean Aviation	13	**CS-JU/members**	Yes	Yes	Yes	Yes	Almost	No
Battery	10	**EMIRI**	Yes	Yes	Yes	Yes	In progress	No
Transforming EU Rail	14	**ERRAC**	Yes	Yes	Yes	Yes	In progress	No
Circular industry	18	**SPIRE**	Yes	Yes	Yes	In progress	No	No

Source: Hydrogen Europe

Note: We are looking for checking synergies with the potential partnership on Metrology which could apply to the RM08 (see section 4.1.5). Contacts with the EMN Energy of EURAMET have been established, and further work is required.

In addition to the sectors which are supported through a partnership instrument, Hydrogen Europe has developed and strengthened formal cooperation with key sectors (i.e. wind, solar and gas sectors). In the absence of partnerships for these sectors, the discussions focus on the improvement of the quality of our technology roadmaps and SRIA and designing a process of regular mutual consultation.

2.5.2. Synergies with other EU, national, regional and international funding programmes

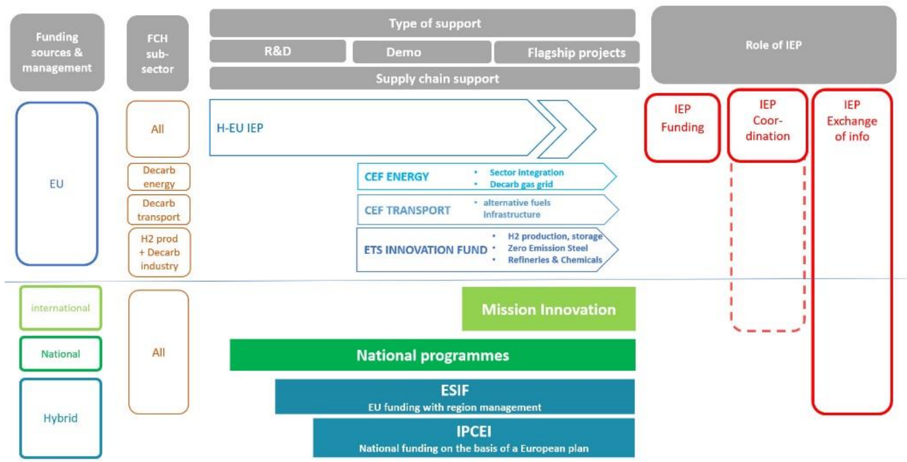
The current FCH2-JU has an excellent track record in facilitating the coordination with other EU funding programmes (in particular CEF and ESIF as well as other instruments managed by the EIB) and national programmes. Many projects benefited from the blending of financing instruments, where different instruments have funded complementary projects in a coordinated manner.

We suggest to further develop this role in the new financial period and, for this reason, we recommend the involvement of Commission DGs in charge of other EU programmes (R&I, MOVE, ENER, CLIMA, GROW) in the governing of the requested IEP. Furthermore, we propose that the next IEP is given, by the EU legislator, a mandate to play an active role of coordination with the other funding programmes in the field of hydrogen technologies in order to maximise the added value of EU funding, ensure synergies and avoid overlap.

As shown in Figure 14, in addition to the Horizon Europe funds directly managed by the IEP, Clean Hydrogen for Europe could play a coordination role when it comes to hydrogen technologies to be funded under CEF. This effort should extend to the ETS IF and EU invest were it is expected that continuation or expansion of projects funded by the FCH2-JU could be supported.

When it comes to other instruments (e.g. ESIF, national funding provided under the umbrella of Important Projects of Common European Interest (IPCEI), international funding with notably Mission Innovation and the key instrument "H_2 valley platform", other national or regional programmes), the IEP's role will be limited to knowledge and information sharing among relevant stakeholders.

Figure 14. Clean Hydrogen for Europe partnership to play a coordinating role for programmes funding hydrogen technologies



Source: Hydrogen Europe

Managing the fund: The IEP will manage the funds from Horizon Europe. If deemed appropriate, it could also be delegated the management of other EU funds like a fraction of CEF or the ETS innovation fund[10].

Actively coordinating: If the IEP is limited to the management of Horizon Europe budget, it should at least play a coordinating role between the activities supported by Horizon Europe, CEF and the ETS innovation funds. The IPPP with the unique expertise of its staff and its unique connection with the entire industry and research ecosystem is best place to ensure synergies between the different EU support instruments. The FCH2-JU has already experimented coordination with CEF Transport with complementary and synchronised projects (infrastructure funded by CEF and vehicles by FCH2-JU) or with demonstration projects of the FCH2-JU expanded in larger CEF deployment projects. The same can now be done also with CEF Energy and the ETS innovation funds and on a more systematic way.

Exchange of information: The connection that the IEP has with Member States, regions, and Mission Innovation enables it to build a soft coordination with their programmes through regular exchanges of information.

[10] This has been done in the previous financial period: SESAR joint undertaking has been delegated the management of a fraction of CEF budget.

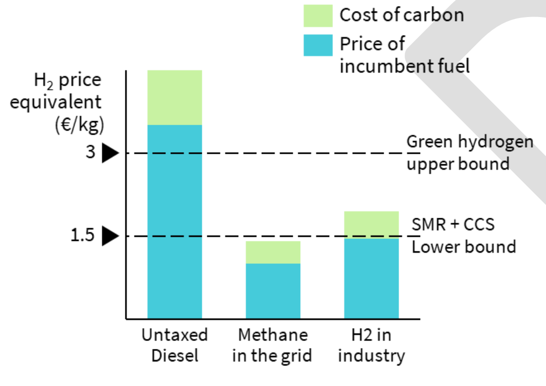
3. PILLAR 1: HYDROGEN PRODUCTION

3.1. Specific objective 1: Producing clean hydrogen at low cost

Most of the hydrogen that is currently being produced in the EU and worldwide is produced from fossil fuels – either by steam reforming of natural gas or gasification of coal. If hydrogen is to realise its potential to be an energy vector in a decarbonised economy, it needs to be produced on a mass scale in a sustainable way, but in order for that to happen, **clean hydrogen needs to become cost-competitive with conventional fuels**.

Hydrogen produced at a cost between **€1.5-3/kg** is competitive with conventional fuels for transport applications amongst others once a 2030 carbon price is considered. These prices are viable for both SMR with CCS and for electrolysis – assuming the targets of this SRIA are met. For example, fuel cell (FC) cars are projected to achieve cost parity with diesel at commercial production volumes at a hydrogen cost of €5/kg. Industry and gas – clean hydrogen as a feedstock can reach parity with fossil-based inputs once the cost of carbon is included.

Figure 15. SRIA objective for clean hydrogen production costs



Source: Hydrogen Europe

To reach the objective, some technology routes need further improvements – especially in the area of investment cost reduction and efficiency increase. But the cost decrease also strongly depends on the mass production, which means that the required low carbon hydrogen costs will not be possible if the production volume is not sufficiently large. Therefore, the SRIA focuses not only on facilitating technological breakthrough but also includes actions aimed at mass-scale deployment of clean hydrogen production.

3.1.1. Roadmap 01: electrolysis

Rationale for support

Water electrolysis has been used to produce industrial hydrogen for nearly a century. Electrolysis has the potential to be a low emissions form of hydrogen production, down to zero emissions if powered solely by renewables as embodied carbon is neglected. **Electrolysis is as a key mean for enabling renewable energy penetration into all sectors**, with electrolytic hydrogen being produced at, or transported to, the points of use. In so doing, electrolysis enables increasing amounts of intermittent renewable energy to be connected to electricity grids, and also for storing renewable energy which is difficult or prohibitively expensive to connect to the grid, by capturing the surplus of energy generation that will be increasing in time. However, considerable development of electrolyser technology, cost, performance and durability, connectivity to renewables and the scale of deployment is still needed to achieve this vision.

The roles of large-scale centralised systems with economies of scale, and hydrogen distribution to end uses, as well as distributed systems located at demand centres are key in the electricity distribution networks.

European manufacturers and supporting industries are well placed to keep Europe as the global leader on electrolysis technologies, securing high value jobs through manufacturing and supply chain.

Other technologies[11] such as reversible electrolysis and co-electrolysis will contribute to the innovation actions and technology progress, widening the impact to the energy and industrial sectors.

Current status of the technology and deployments

Water and Steam electrolysis demonstration projects for AEL, PEMEL and SOEL technologies[12] up to 10 MW scale are operational. Projects of c.20 to > 100 MW are under development. Current H_2 costs[13] are €5-8/kg.

Alkaline systems >100MW have been deployed worldwide in industry (typically in aluminium production, but historically in ammonia plants which pre-date cheap natural gas, and for chlorine production).

In Europe the currently largest operating electrolysers are:

- 9 MW AEL in Rjukan, Norway
- 6 MW PEMEL in Linz, Austria
- 0.7 MW SOEL in Salzgitter, Germany

In development are a series of FCH2-JU funded projects including:

[11] The application of these technologies for grid stabilization and carbon utilization are covered by RM03 and RM16

[12] AEL: Alkaline Electrolyser; PEMEL: Proton Exchange Membrane Electrolyser; SOEL: Solid Oxide Electrolyser; AEMEL: Anionic Exchange polymer Membrane Electrolyser; PPCEL: Proton Conducting Ceramic Electrolysis.

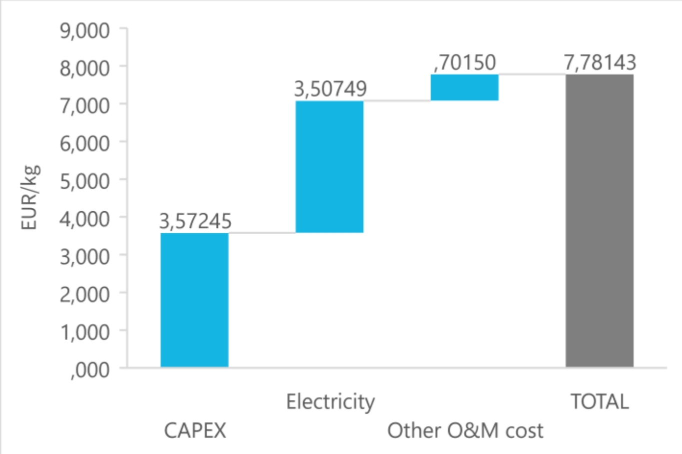
[13] Assumptions detailed in the KPIs section

- DJEWELS, a 20 MW AEL to be installed at Nouryon's Delfzijl site, The Netherlands, to produce green methanol,
- REFHYNE, a 10 MW PEMEL electrolyser to be installed at Shell's Cologne refinery,
- MULTIPLHY, a 2.6 MW SOEL to be installed at NESTE's Rotterdam biorefinery,
- DEMO4GRID and HYBALANCE, 4MW AEL and 1.25 MW PEMEL, respectively, for grid balancing.

Vision for 2030 and proposed areas for support

Hydrogen production via electrolysis is currently more expensive than via other methods – due to the capital costs and dependence on electricity costs.

Figure 16. Breakdown of hydrogen production cost via electrolysis



Source: Hydrogen Europe
Note: costs calculated with the following assumptions: capital costs – 8%, CAPEX – 1,200 EUR/kW, O&M costs – 2% of CAPEX, electricity consumption – 58 kWh per kg of H_2, renewable electricity price of 60 EUR per MWh, capacity factor of 2,000 hours per annum.

Vision 2030

- ***Up to 40 GW of electrolysis is installed in Europe***
- ***Commercially available electrolysis is capable of producing sustainable net-zero hydrogen at a cost of < €3/kg.***
- ***European players are global leaders in electrolyser sales.***

The key steps needed to realise the 2030 vision are reducing electrolyser cost and improving efficiency, with high durability and reliability, by increasing the scale of deployments or through production in series, for both water and steam electrolysis. The capital and fixed operational costs of electrolysers have been reduced considerably since 2012, yet additional improvements are needed.

Especially when operated exclusively on renewable electricity, limited utilisation increases the impact of these two cost factors on commercial viability. A second objective is to improve the efficiency of electrolyser systems to reduce the cost of hydrogen production.

By the end of 2030 the aim should be for **40 GW of electrolysis installed in Europe**. Together with improvements in efficiency, the resulting cost reductions should make it possible for electrolysis to be capable of producing net-zero hydrogen at a cost of below **€3/kg**. In order to achieve this goal, we propose the following development roadmap for electrolysis.

Early Stage Research Actions (TRL 2-3)

Future cost reductions and increased lifetime in the different electrolysis technologies may be realised through new materials/manufacturing processes/concepts. Priorities are identified for Europe as follows.

- Generic for all electrolysis: Develop new electrodes and membranes as well as novel cell designs to increase the current density without harming lifetime and efficiency; Develop low-cost metallic materials, coatings and seals
- AEL: develop more compact stack design, reach high current density without noble metals
- PEMEL: Reduce precious metal content in catalysts and consider recycling, develop PGM-free catalysts, develop new/advanced membranes
- SOEL: pressurised stack
- Emerging technologies: anionic exchange polymer membrane electrolysis (AEMEL) and proton conducting ceramic electrolysis (PCCEL)
- Others: investigate the possibility of non-pure water electrolysis

Development Research Actions (TRL 3-5)

Several concepts for reducing electrolyser costs and improving technical KPIs have been demonstrated in the laboratory. This area can support promising applications identified through the research programme suggested above as well as:

- Improve cell design for high performance and increase cell/stack robustness through improved thermal and process-flow management
- Develop larger area cells/stacks components with adequate manufacturing quality for high power systems.
- Consider innovative system designs and Improved balance of plant components to reduce parasitic losses and reduce cost (e.g. purpose-built rectifiers, integrated cooling systems, electrical heaters and heat-exchangers…).
- Develop Tools and methods for monitoring, diagnostics and control of electrolyser systems
- Develop High pressure stacks to avoid/reduce the need for downstream compression or alternative compression techniques (e.g. electrochemical).
- Consider original concepts like reversible operation (electrolysis/fuel cell) and co-electrolysis (to produce syngas)
- Explore the options for utilising by-product oxygen and waste heat

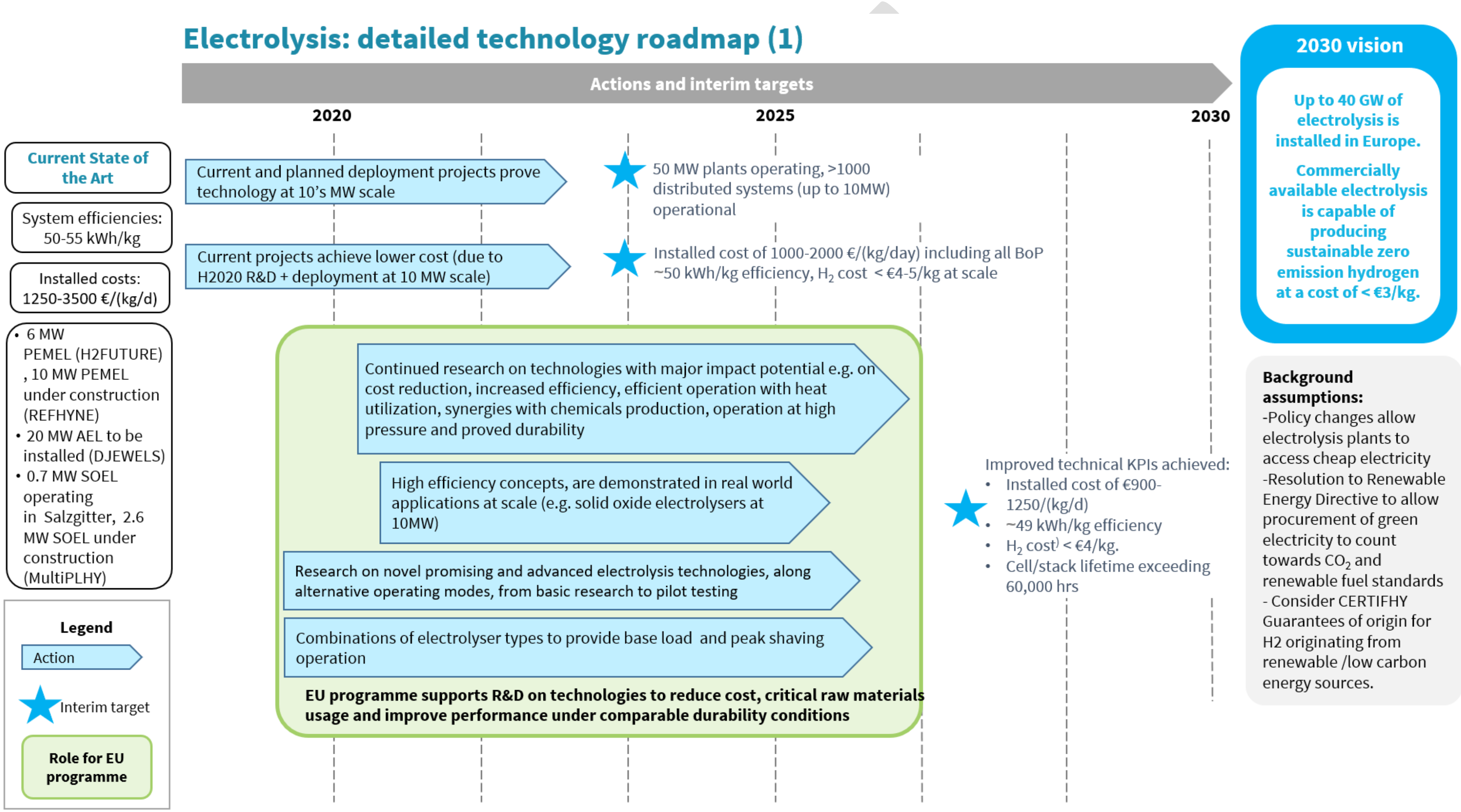
Demonstration Actions (TRL 5-7)

- Projects are needed to demonstrate that electrolysis technology, when deployed at scale, has the potential to meet cost and performance KPIs.
- Develop automation and quality control processes for continuous production of large volume of cell/stacks components
- Demonstrate at the MW range the alternative electrolysis technologies
- Provide a compelling economic and environmental case for key applications e.g. feedstock for industries, transport, energy storage, heat and power.
- Operate with variable load and adequate flexibility to be coupled with renewable energies, including offshore.

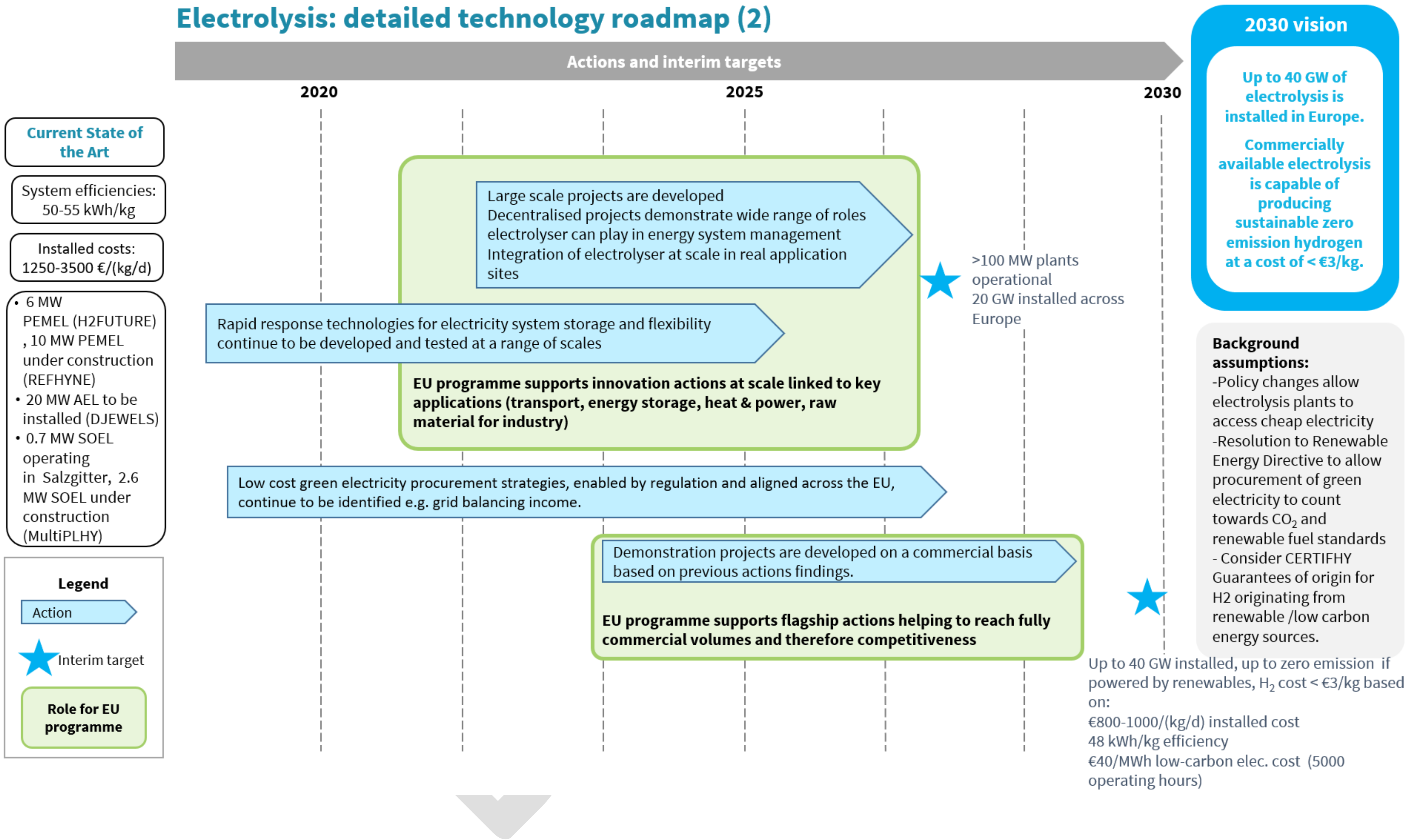
Flagship Actions (TRL 7-8)

Support for flagship projects recognises the environmental advantages of electrolysis and helps them to realise further cost reductions by creating true demand at scale (e.g. 100 x 10 MW systems per year per manufacturer). The support could stimulate the deployment of 0.5 GW of electrolysis.

Dedicated roadmap



Electrolysis: detailed technology roadmap (2)



KPIs

Most KPIs are sourced from the current MAWP of the FCH2-JU. Where KPIs are not available, we propose early suggestions based on expertise of the membership of Hydrogen Europe and Hydrogen Europe Research, as an outcome of initial reflections. Any input written in black indicates a good level of confidence and consensus on the KPI, while input in red flags a need for greater attention.

Table 3. KPIs AEL

No.	Parameter	Unit	SoA		Targets		
			2017	2020	2024	2027	2030
System*							
1.	Electricity consumption @ nominal capacity	kWh/kg	51	50	49	49	48
2.	Capital cost	€/(kg/d) (€/kW)	1,600 (750)	1,250 (600)	1,000 (480)	900 (440)	800 (400)
3.	O&M cost	€/(kg/d)/yr	32	26	20	18	16
4.	Hot idle ramp time	sec	--	60	30	10	10
5.	Cold start ramp time	sec	--	3,600	900	600	300
6.	Footprint	m^2/MW	--	100	60	60	40
Stack							
7.	Degradation	%/1,000hrs	0.13	0.12	0.11	0.11	0.10
8.	Current density	A/cm^2	0.4	0.6	0.7	0.8	1.0
9.	Use of critical raw materials as catalysts	mg/W	--	0.6	0.3	0.1	0.0

Notes:
*Standard boundary conditions that apply to all system KPIs: input of AC power and tap water; output of hydrogen meeting ISO 14687-2 at a pressure of 30 bar and hydrogen purity 5.0. Correction factors may be applied if actual boundary conditions are different.
1) Electrical energy demand at nominal hydrogen production rate of the system at standard boundary conditions.
2) Capital cost are based on 100 MW production volume for a single company and on a 10-year system lifetime running in steady state operation, whereby end of life is defined as 10% increase in energy required for production of hydrogen. Stack replacements are not included in capital cost. Cost are for installation on a pre-prepared site (fundament/building and necessary connections are available). Transformers and rectifiers are to be included in the capital cost.
3) Operation and maintenance cost averaged over the first 10 years of the system. Potential stack replacements are included in O&M cost. Electricity costs are not included in O&M cost.
4) Time required to reach nominal capacity in terms of hydrogen production rate when starting the device from hot idle (warm standby mode - system already at operating temperature and pressure).
5) Time required to reach nominal capacity in terms of hydrogen production rate when starting the device from cold standby mode.
6) Average specific space requirement of a MW system comprising all auxiliary systems to meet standard boundary conditions in 1) and built up as indoor installation.
7) Stack degradation defined as percentage efficiency loss when run at nominal capacity. For example, 0.125%/1,000h results in 10% increase in energy consumption over a 10-year lifespan with 8,000 operating hours per year.
8) Mean current density of the electrolysis cell running at operating temperature and pressure and nominal hydrogen production rate of the stack.
9) The critical raw material considered here is ruthenium for the cathode (mostly as RuO_2).

Table 4. KPIs PEMEL

No.	Parameter	Unit	SoA		Targets		
			2017	2020	2024	2027	2030
System*							
1.	Electricity consumption @nominal capacity	kWh/kg	58	55	52	50	48

2.	Capital cost	€/(kg/d) (€/kW)	2,900 (1,200)	2,100 (900)	1,550 (700)	1,250 (600)	1,000 (500)
3.	O&M cost	€/(kg/d)/yr	58	41	30	25	21
4.	Hot idle ramp time	sec	10	2	1	1	1
5.	Cold start ramp time	sec	120	30	10	10	10
6.	Footprint	m^2/MW	60	50	40	35	25
Stack							
7.	Degradation	%/1,000hrs	0.25	0.19	0.15	0.125	0.12
8.	Current density	A/cm^2	2.0	2.2	2.4	3.0	3.5
9.	Use of critical raw materials as catalysts	mg/W	5.0	2.7	1.25	0.5	0.3

Notes:
1) to 8) Similar conditions as for alkaline technology (see Table 3) and applying ISO 14687-2.
9) These are mainly iridium as the anode catalyst and platinum as the cathode catalyst.

Table 5. KPIs SOEL

No	Parameter	Unit	SoA		Targets		
			2017	**2020**	**2024**	**2027**	**2030**
System*							
1.	Electricity consumption @ nominal capacity	kWh/kg	41	40	39	38	37
	Heat demand @ nominal capacity	kWh/kg	n/a	9.9	9.0	8.5	8
2.	Capital cost	€/(kg/d) (€/kW)	12,000 (6,950)	3,550 (2,130)	2,000 (1,250)	1,200 (760)	800 (520)
3.	O&M cost	€/(kg/d)/yr	600	180	100	60	40
4.	Hot idle ramp time	sec	--	600	300	250	180
5.	Cold start ramp time	h	--	12	8	6	4
6.	Footprint	m^2/MW	n/a	--	150	75	50
Stack							
7.	Degradation @ U_{TN}	%/1,000hrs	2.8	1.9	1.0	0.7	0.5
8.	Current density	A/cm^2	0.3	0.6	0.85	1.0	1.5
9.	Use of critical raw materials as catalysts	mg/W	n/a	n/a	n/a	n/a	n/a
Technology related KPIs							
10.	Roundtrip electrical efficiency	%	41%	46%	52%	55%	59%
11.	Reversible capacity	%	20%	25%	30%	35%	40%

Notes:
*Standard boundary conditions that apply to all system KPIs: input of AC power and tap water; output of hydrogen meeting ISO 14687-2 at atmospheric pressure and hydrogen purity 5.0. Correction factors may be applied if actual boundary conditions are different.
1) Electrical energy demand similar as for AEL systems (see Table 3). Heat demand is the heat absorption of the system at nominal capacity (mostly provided by steam).
2) to 6) Similar conditions as for AEL systems (see Table 3).
7) Degradation at thermo-neutral conditions in percent loss of production rate (hydrogen power output) at constant efficiency. Note this is a different definition as for low temperature electrolysis, reflecting the difference in technology.

8) Same definition as in Table 3
9) Non applicable - No noble PGM-based materials are used as catalyst in SOEL.
10) Roundtrip electrical efficiency is defined as energy discharged measured on the primary point of connection (POC) divided by the electric energy absorbed, measured on all the POC (primary and auxiliary), over one electrical energy storage system standard charging/discharging cycle in specified operating conditions.
11) Reversible capacity is defined as ratio of the nominal rated power in fuel cell mode to the electric power at nominal capacity in electrolyser mode of the SOEL system.

Table 6. KPIs AEMEL

No.	Parameter	Unit	SoA		Targets		
			2017	2020	2024	2027	2030
System*							
1.	Electricity consumption @ nominal capacity	kWh/kg	n/a	55	53	50	48
2.	Capital cost	€/(kg/d) (€/kW)	n/a	--	1,440 (650)	1,100 (520)	900 (450)
3.	O&M cost	€/(kg/d)/yr	n/a	34	27	25	21
4.	Hot idle ramp time	sec	n/a	30	10	1	1
5.	Cold start ramp time	Sec	n/a	1,800	300	20	10
6.	Footprint	m^2/MW	n/a	90	80	60	50
Stack							
7.	Degradation	%/1,000hrs	> 1.0	> 1.0	0.9	0.4	0.15
8.	Current density	A/cm^2	0.5	0.5	0.6	1.0	1.5
9.	Use of critical raw materials as catalysts	mg/W	--	1.7	0.4	0.15	0.0

Notes:
1) to 7) Similar conditions as for alkaline technology (see Table 3) and applying ISO 14687-2.
8) Only data from scientific papers available, target values for KOH based electrolyte < 1.0 %mol.
9) This is mainly IrOx as the anode catalyst and Pt/C as the cathode catalyst.

Table 7. KPIs PCCEL

No	Parameter	Unit	SoA		Targets		
			2017	2020	2024	2027	2030
System*							
1.	Electricity consumption @ nominal capacity	kWh/kg	n/a	n/a	41	38	37
	Heat demand @ nominal capacity	kWh/kg	n/a	n/a	--	--	--
2.	Capital cost	€/(kg/d) (€/kW)	n/a	n/a	--	--	--
3.	O&M cost	€/(kg/d)/yr	n/a	n/a	--	--	--
4.	Hot idle ramp time	sec	n/a	360	360	280	200
5.	Cold start ramp time	h	n/a	n/a	--	--	--
6.	Footprint	m^2/MW	n/a	n/a	--	--	--
Stack							
7.	Degradation @ U_{TN}	%/1,000hrs	n/a	2.0	1.7	1.5	1.2
8.	Current density	A/cm^2	n/a	0.30	0.50	0.75	1.00
9.	Use of critical raw materials as catalysts	mg/W	n/a	n/a	n/a	n/a	n/a

Technology related KPIs							
10.	Roundtrip electrical efficiency	%	n/a	--	--	--	--
11.	Reversible capacity	%	n/a	--	50	55	60

Notes:
*Standard boundary conditions that apply to all system KPIs: input of AC power and tap water; output of hydrogen meeting ISO 14687-2 at atmospheric pressure and hydrogen purity 5.0. Correction factors may be applied if actual boundary conditions are different.
1) to 11) Same definitions and comments as stated in Table 5 for SOEL technology.

3.1.2. Roadmap 02: other modes of hydrogen production

Rationale for support

There are a range of H_2 production options, in addition to electrolysis, which could be environmentally neutral or even positive.

Producing H_2 from biomass and/or waste yields green hydrogen. Technologies currently at the early stages of development will provide breakthroughs in terms of cost and environmental impacts – like direct solar production from water, or biologically produced hydrogen from biogenic resources which are net-zero technology. New technologies using fossil sources but capturing the CO_2 (such as pyrolysis) are also included. However, well established techno such as SMR and coal gasification are not in the remit of this PPP. Their combination with CCS makes sense however the funding of CCS infrastructure is expected to fall under other support programmes.

Most hydrogen produced today is made by steam-methane reforming (SMR) or autothermal reforming (ATR) of natural gas, referred to grey hydrogen. SMR/ATR are mature technologies but produce CO_2 emissions. Those emissions can be avoided by using biomass and biogas as feedstock. Biomass and bio-waste gasification are methods of net-zero hydrogen production currently at the sub-MW demonstration stage. If it can be combined with CCS it has the potential to be a negative emission technology. Similarly, carbon can be stored as solid if the input gas is pyrolysed to provide hydrogen and carbon, where both can be valorised in the market. There are also promising developments in other novel production methods such as using sunlight to split water into hydrogen and oxygen by thermochemical, photochemical and photoelectrochemical means, and biological methods of H_2 production.

European companies are well placed to capitalise on hydrogen production technology – global gas and engineering companies as well as utilities, innovative SMEs supported by research organisations are capable to build up supply chains for all necessary key components of the technologies targeted for 2030. This is possible through adapting existing methods as well as through novel methods of production.

Current status of the technology and deployments

SMR/ATR are currently the cheapest methods of hydrogen production with production cost at <€2/kg. In Europe Air Liquide operate an SMR+CCU (carbon capture and utilisation) plant at Port-Jérôme, producing refinery H_2 and CO_2 for local industrial markets. The main developments needed in this sector are those linked to the required transfer of the technology towards bio-derived feedstocks plus combination with other renewable energy sources allowing net-zero hydrogen production.

Gasification of biomass and biowaste is an area being actively pursued by several SMEs worldwide. Some small-scale demonstration plants have operated successfully (e.g. gogreengas in the UK), yet there are no MW scale plants operating.

The FCH2-JU supported HYDROSOL-PLANT project is constructing a demonstration plant for solar thermo-chemical hydrogen production in a 750 kW_{th} scale. There are a range of technologies being explored at the laboratory scale for using solar energy to split water by photochemical and photoelectrochemical means.

Vision for 2030 and proposed areas for support

Considering the current state of development of other hydrogen production technologies other than electrolysis, we feel that the role of the IEP should be primarily to support R&D&I on the most promising technologies and concepts like waste gasification, direct solar production from water and biologically produced hydrogen. At the same time, we acknowledge that there is a case for European and Member States support for deploying SMR+CCS but given relative maturity of this technology support for its development may be provided by instruments such as the ETS IF or even be purely market-driven and would not be suitable for management under the CHE programme.

The objective of the R&D&I support provided by CHE will be to ensure that by 2030, a range of technologies which can produce low-carbon, low cost (**€3/kg**) hydrogen are operating either at industrial scales or close to industrial scales (**100'MW scale installations with over 10 GW of capacity installed in the EU**). In order to achieve this goal, we propose the following set areas to support:

Vision 2030

- ***A range of technologies which can produce net-zero hydrogen, at low cost (<€3/kg) and scale, are operating either at industrial scales or close to industrial scales.***
- ***Fossil based routes including CCS achieve cost below €2/kg.***

<u>Early Stage Research Actions (TRL 2-3)</u>

- *<u>Biomass & waste gasification:</u>* Novel reactors design, materials and processes improving feedstock flexibility and hydrogen yields, novel solutions and methods for syngas cleaning and upgrade
- *<u>Pyrolysis:</u>* New concepts of hydrogen production from pyrolysis, separating solid carbon
- *<u>Biological production:</u>* New concepts of bio reactors with a high rate of production for middle and large size plants.
- *<u>Direct solar:</u>* Range of photolysis, photo(electro)catalysis and thermo-chemical cycles developed and tested (simulation and experiment), novel architectures and system designs for collector/reactor integration, new materials and solutions for lower-temperature thermo-chemical cycles.

<u>Development Research Actions (TRL 3-5)</u>

- *<u>Biomass & waste gasification:</u>* Scaling up of most promising technologies (including e.g. hybrid systems, solar gasification).
- *<u>Pyrolysis</u>*: Development of concepts of hydrogen production from pyrolysis and methods of solid carbon handling
- *<u>Biological production:</u>* Development of medium-scale bio-reactors.
- *<u>Direct solar:</u>* Scaling up of most promising technologies.

<u>Demonstration Actions (TRL5-7)</u>

Demonstration projects of most promising technologies:

- Demonstration-scale plant for waste & biomass gasification.
- Demonstration-scale plant with hydrogen production from biogas
- Full sized biological reactor demonstration project.
- Medium-sized pilots of most promising direct sunlight technologies.

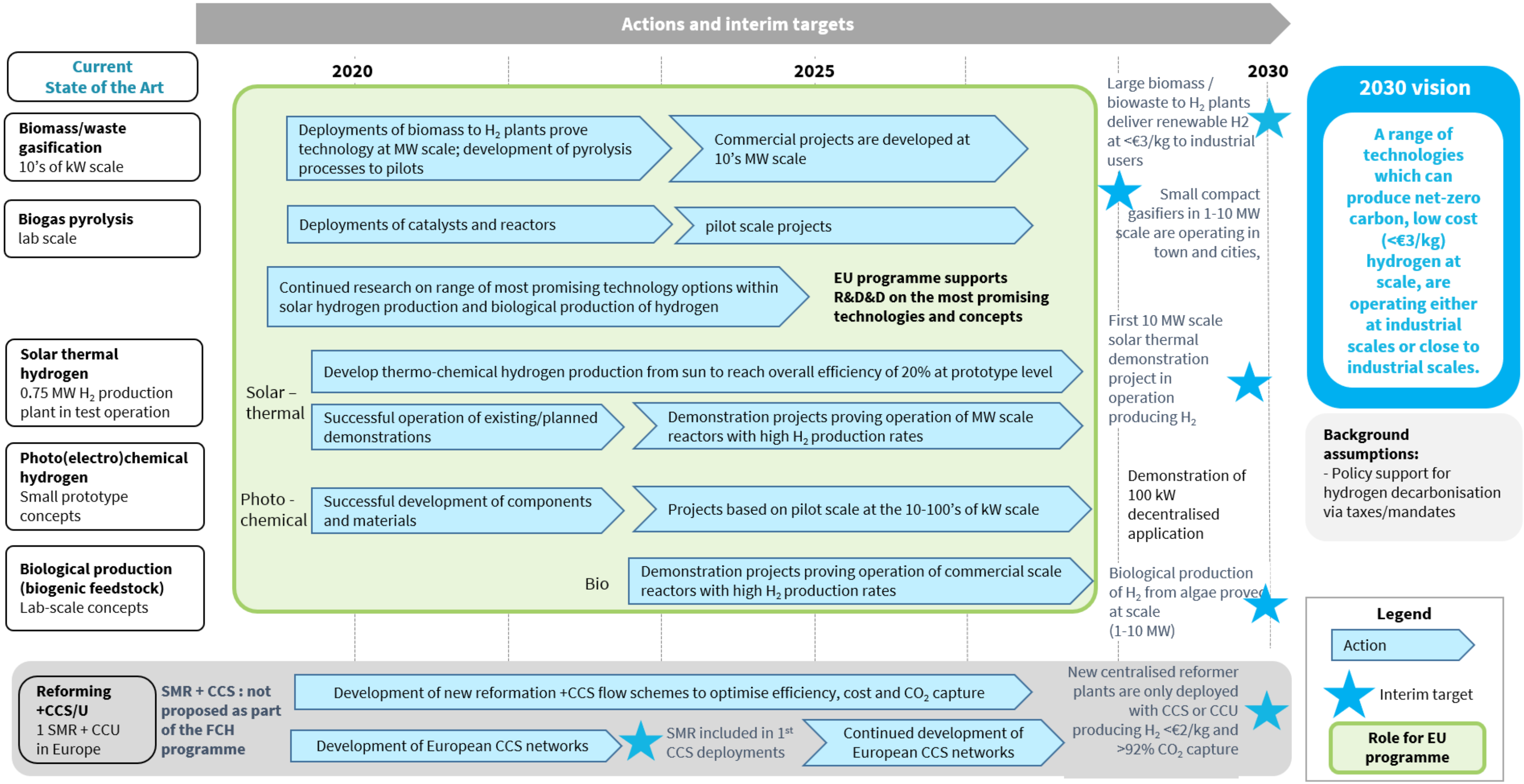
Funding not proposed here: Fossil-based reforming with CCS. There is a separate case for European and Member State support for deploying new reformer concepts if combined with CCU/CCS. European support for prototyping and testing of specific components (TRL7 stage) will act as a pre-cursor to novel designs. This type of support may be provided by instruments such as the ETS-IF and would not be managed under the CHE programme, though support will be promoted, and synergies sought.

Flagship Actions (TRL 7-8)

Support for decarbonised hydrogen in all deployment schemes are available from policy and regulation. There is a case for supporting one very large-scale deployment of the most promising direct sunlight technology, given the potential for this technology to revolutionise the energy system.

Funding not proposed here: Fossil-based reforming with CCS. Given the scale of the systems that will need to be deployed, it is likely that new reformer concepts with CCS will be deployed under commercial contracts, with the support of Member States + European support (e.g. from ETS-IF and the EIB). This type of support is not included here, though support will be promoted by CHE and synergies sought.

Dedicated roadmap



KPIs

Most KPIs are sourced from the current MAWP of the FCH2-JU. Where KPIs are not available, we propose early suggestions based on expertise of the membership of Hydrogen Europe and Hydrogen Europe Research, as an outcome of initial reflections. Any input written in black indicates a good level of confidence and consensus on the KPI, while input in red flags a need for greater attention.

Table 8. KPIs Hydrogen production from raw biogas

No	Parameter	Unit	SoA		Targets		
			2017	2020	2024	2027	2030
1	System energy use	kWh/kg	56	56	55	54	53
2	System capital cost	€/(kg/d)	3,800	3,100	2,400	2,000	1,550
3	System operational cost	€/kg	1.35	1.35	1.32	1.30	1.28

*Table 9. KPIs Photocatalytic water splitting**

No	Parameter	Unit	SoA		Targets		
			2017	2020	2024	2027	2030
1	H_2 production by energy**	kWh / (m^2year)	-	30	100	300	500
2	System cost	€ / m^2	-	300	210	185	110
3	System capital cost	€ / m^2	-	125	40	20	12
4	System lifetime	Years	-	0,3	3	5	10

* photo electrochemical cell

** These values are valid for a global solar irradiance of 2000 kWh/(m2a)

Table 10. KPIs Biological production

No	Parameter	Unit	SoA		Targets		
			2017	2020	2024	2027	2030
1	System carbon yield	H_2/C	0.62	0.64	0.65		0.65
2	Reactor production rate	€ / m2	10	40	100		200
3	Reactor scale	€ / m2	0.5	1	10		>10

Table 11. KPIs Solar thermal

No	Parameter	Unit	SoA		Targets		
			2017	**2020**	**2024**	**2027**	**2030**
1	Hydrogen production rate	kg/m^2	0.8	1.13	2.16	3.26	4.11
2	System capital cost	k€/kg/d	33.9	29.9	15.2	9.7	7.4
3	System operational cost	€/kg	1.39	1.17	0.59	0.38	0.30
4	Hydrogen prod. cost	€/kg		8.42	4.26	2.71	2.07

Table 12. KPIs Hydrogen production via pyrolysis

No	Parameter	Unit	SoA		Targets		
			2017	**2020**	**2024**	**2027**	**2030**
1	Hydrogen conversion rate*, [a,b,c,f,h]	kgH_2/kg	0.262	0.29	0.32	0.34	0.355
		% HHV	49%	50%	52.%	54%	56%

2	System carbon yield**, [c,b,f]	H_2/C (kg/Kg)	0.27	0.28	0.30	0.31	0.32
3	System capital cost***[a,b,e,d]	€/(kg/d)	1550	1442	1299	1192	1085
4	System overall operational cost****	€/kg	1.6	1.5	1.4	1.3	1.2
5	System operational cost*****	€/kg	0.01	0.01	0.009	0.008	0.008

Table 13. KPIs Hydrogen production via waste/biomass gasification

No	Parameter	Unit	SoA		Targets		
			2017	2020	2024	2027	2030
1	System carbon yield** [g]	H_2/C (kg/kg)	0.11	0.15	0.22	0.27	0.32
2	System capital cost*** [g]	€/(kg/d)	7654	7124	6417	5887	5357
3	System overall operational cost****[g]	€/kg	4.2	3.9	3.5	3.2	2.9
4	System operational cost***** [g]	€/kg	0.057	0.053	0.048	0.044	0.040

Notes

References:

(a) A comparative overview of hydrogen production processes Pavlos Nikolaidis, Andreas Poullikkass Renewable and Sustainable Energy Reviews 67 (2017) 597–611

(b) Di Marcoberardino, D. Vitali, F. Spinelli, M. Binotti, and G. Manzolini, "Green hydrogen production from raw biogas: A techno-economic investigation of conventional processes using pressure swing adsorption unit," Processes, vol. 6, no. 3, 2018.

(c)J. M. Encinar, J. F. González, G. Martínez, and M. J. Martín, "Pyrolysis and catalytic steam gasification of olive oil waste in two stages," Renew. Energy Power Qual. J., vol. 1, no. 6, pp. 697–702, 2008.

(d) D. Paper, Z. Erdgas, and M. Consulting, "Hydrogen from natural gas – The key to deep decarbonisation," Poyry. July, 2019.

(e)P. Size, G. Price, and H. Cost, "Supporting Information," vol. 57, pp. 1–17, 2018.

(f) H. F. Abbas and W. M. A. Wan Daud, "Hydrogen production by methane decomposition: A review," Int. J. Hydrogen Energy, vol. 35, no. 3, pp. 1160–1190, 2010.

(g) K. Nath and D. Das, Hydrogen from biomass,task 33 IEA, vol. 85, no. 3. 2003.

(h) S. Timmerberg, M. Kaltschmitt, and M. Finkbeiner, "Hydrogen and hydrogen-derived fuels through methane decomposition of natural gas – GHG emissions and costs," Energy Convers. Manag. X, vol. 7, no. May, p. 100043, 2020.

Methodology:

* estimated by linear fitting of the value available in the literature

**For 2017, the carbon yield was estimated as mass ratio based on the outlet composition reported in "Hydrogen from biomass gasification" IEA Bioenergy: Task 33: December 2018. To estimate the expected increase of the carbon yield by 2030 it has been assumed that 50% of conversion would be reached by 2030. This assumption is considered reasonable with respect to the maximum theoretical conversion is 88%. A conversion of 50 % results in a carbon yield of 0.32. Therefore, given the carbon yield estimated for 2017 and the value expected by 2030, the time evolution of the parameter was considered to be linear.

*** Gasification: the capital cost has been estimated from the data reported in "Hydrogen from biomass gasification" IEA Bioenergy: Task 33: December 2018. The capital cost has been estimated as (total investment)/(kgH_2/d) considering the lower heating value (LHV) of hydrogen for the 1MW plant. The system capital cost for the 50 MW plant @ 2017 was 1806 €/(kg/d) and @ 2030 it was estimated to be 1200 €/(kg/d)

Pyrolysis: capital cost from ref [a] for the plant 2.7 of ton H_2/day.

The temporal evolution of the capital cost (gasification and pyrolysis) was estimated using a learning curve and assuming a linear doubling of the number of plants by 2030. The "Learning Curve" approach with the doubling of power plants by 2030 shows a reduction of the capital cost of approximately 15%. Moreover, taking into account the breakthrough of new technologies by 2030, an additional 15% of capital cost reduction is expected by 2030, resulting in the overall reduction by 30% by 2030. Therefore, assuming the goal of reaching a reduction by 30% of the capital cost by 2030, a linear reduction from 2017 to 2030 was hypothesized.

**** The overall OPEX was estimated based on the data reported in the "Hydrogen from biomass gasification" IEA Bioenergy: Task 33: December 2018 for the 1 MW plant. The feedstock cost was included in the estimation. The decrease of the OPEX by 2030 was estimated with the same approach used for the capital cost by hypothesizing 30% CAPEX reduction by 2030.

***** The OPEX was estimated considering a plant life of 20 years and including only operation and maintenance costs.

3.2. Specific Objective 2: Enabling higher integration of renewable within the overall energy system

3.2.1. Roadmap 03: role of electrolysis in the energy system

Rationale for support

Green hydrogen production via electrolysis offers unique advantages: it can convert electricity into a **storable form for long periods via gas grids and/or underground storage**, so this clean energy can be transferred into other sectors. Hydrogen offers a locally produced clean and alternative energy vector for various applications (e.g. transport, industry, buildings), ensuring energy security for the EU and providing a complete solution towards sustainability for European islands, and also considering integration within digitization to optimize uses of infrastructure and resources towards a safer supply of energy for the final uses. Electrolysis enables the production of green hydrogen when coupled with renewable energy resources, either via the electricity grid or off-grid.

Increasing levels of renewable electricity generation brings a range of challenges. **Hydrogen produced via electrolysis can play a vital role in solving many of these challenges**:

- Increasing renewable generation on the grid to defer upgrades to T&D infrastructure, reducing curtailment, enhancing cross-sectoral flexibility (connecting power and gas networks) and for applications where direct electrification is complex.
- Boosting off-grid renewable generation in off-shore installations and areas adjacent to underground storage, islands and remote areas, by H_2 production and storage
- Providing a range of energy storage and grid services to help match supply and demand.

Current status of the technology and deployments

Hydrogen production via electrolysis is currently more expensive than via other methods – due to the capital costs and dependence on electricity costs. The key steps needed to achieve the 2030 vison is producing carbon-free hydrogen by **more than 40 GW of renewable energy resources, providing flexibility to the entire energy system** as programmable distributed loads and using this hydrogen by implementing a fully integrated model of hydrogen production, storage, transportation and utilization for heat, power and mobility, with avoidance of 16Mt CO_2 per annum.

A series of FCH2-JU funded projects ranging from kW to MW scale are being developed to demonstrate complementarity with renewable energy sources. Few examples:

- **ELY4OFF**: 50kW PEMEL system directly linked to an off-grid PV field
- **BIG HIT**: 1.5MW (0.5+1) PEMEL systems connected to nearly-off-grid wind and tidal energy converters, where produced hydrogen is used for mobility, power and heat applications.

- **HYBALANCE**: 1MW PEMEL system enabling the storage of cheap renewable electricity from wind turbines for grid balancing
- **HAEOLUS**: 2,5 MW PEMEL system using stranded wind resources from a wind farm in a remote area
- **DJEWELS:** 20MW AEL system is being developed to convert renewable electricity into 3,000 tons of green hydrogen per year, in real-life industrial and commercial conditions.

The projects done in the past years and those currently active shows that Europe counts with entities covering the spectrum of the whole supply chain required to achieve the 2030 vision. From electrolyser and key component suppliers, from system integrators and system operators (TSO & DSO) to companies with great expertise in large scale storage, Europe is in a strong position to produce electrolysers, to store large quantities of hydrogen, and to transfer hydrogen to other sectors (industry, gas and mobility).

Vision for 2030 and proposed areas for support

The bulk of specific areas of support have already been included in previous roadmaps (e.g. electrolysis). Yet there is still further research to be done on modelling to demonstrate potential value in a variety of electricity system roles.

Demonstration Actions (TRL5-7)

- Provision of flexibility services to grid operators (simulation & demonstration) at Distribution System level, helping to balance distribution system and enable increased use of local renewables as well as better utilisation of existing electricity grid assets.
- MW scale direct coupling to renewable generation (both on and off-grid) including operations at sea, aiming at identifying the best system configuration to reach competitiveness.

Vision 2030

More than 40GW of renewable generation accommodated as a result of hydrogen production by electrolysis on-grid and off-grid, resulting in the transfer of 140TWh of Europe's renewable electricity to other sectors (transport, industry, gas), avoiding at least 16Mt of CO_2 emissions per year to the atmosphere.

In addition, attention is given to digitisation aspects:

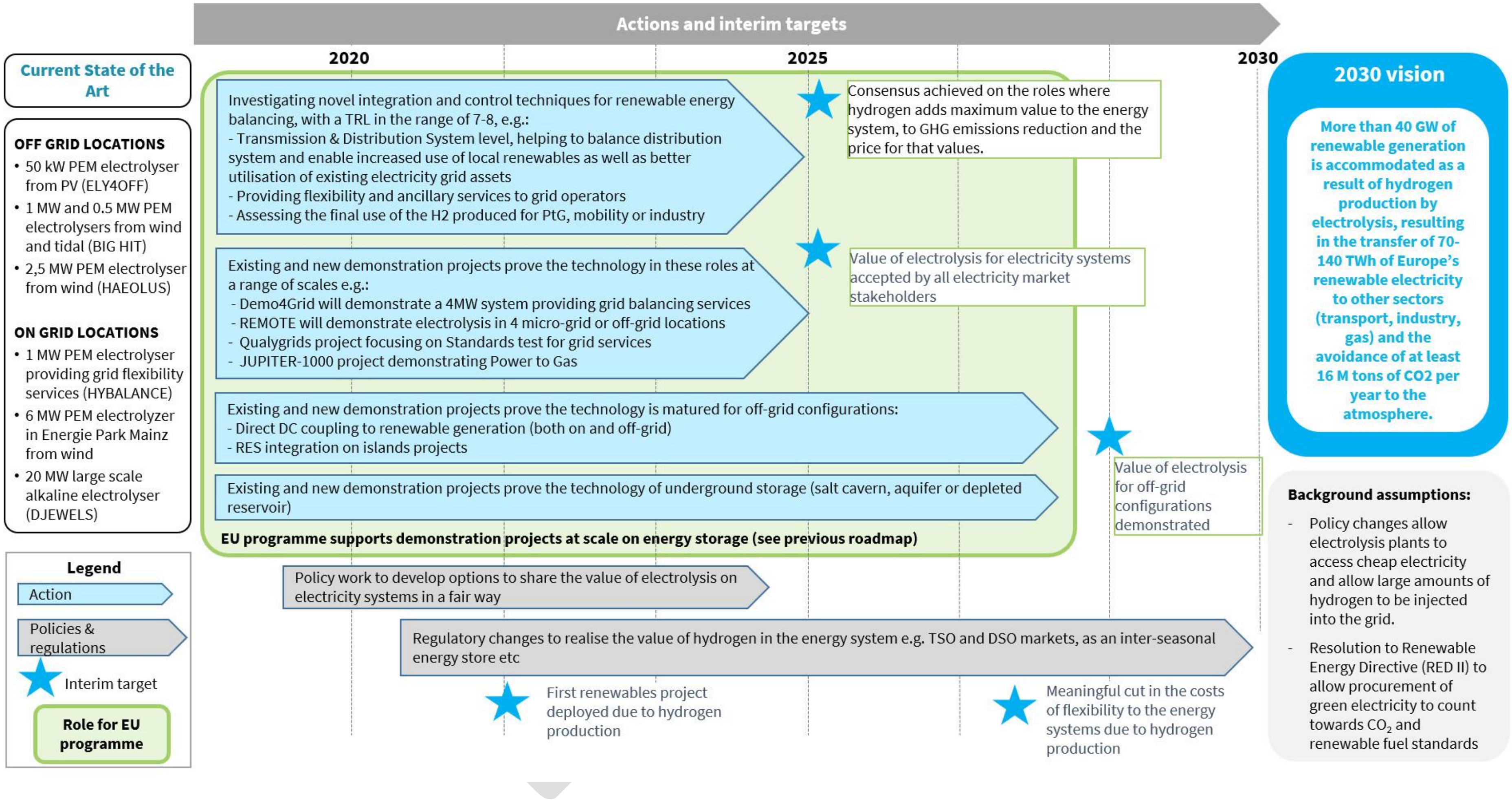
- Utilizing emerging digital technologies like blockchain and AI, to integrate distributed renewable energy generation, µCHP, electrolysers, BEV charging and other distributed energy supply/demand points into a highly flexible and resilient energy system. Using big data, machine learning and other digital methods, predictive models and self-learning tools could enhance the multi objective optimization of the energy system itself.
- Using Distributed Ledger Technologies (Blockchain trading) to establish a trusted sector coupled co-creating eco-system, with the participation of Financial Investment Partners, generation, transmission & distribution, as well as off-takers
- Building up and using a Digital Twin (an Energy System Design and Modelling) of the Energy Infrastructure, for remaining life calculations, failure and reliability forecasts, grid stabilization, system optimization, risk assessment, renewable energy integration impact. Digital twins can serve as well as solid discussion base for new business models, testing the economic and ecologic feasibility of new concepts, hand in hand with the regulatory ambitions at the political stage.

More specific actions will be developed in cooperation with other partnerships, including the Clean Energy Transition partnership (in direct coupling to renewable generation) and the Smart Networks and Services partnership (providing flexibility services to grid operators).

It should be noted though that for this vision to materialise, the proposed research and innovation actions would need to be accompanied by a series of policy and regulation changes. Policy studies should be used to develop the underpinning evidence on the need for bulk energy storage using hydrogen and hence the case for policy and regulatory support for market activation.

Dedicated roadmap

Role of electrolysis in the energy system: detailed technology roadmap



KPIs

Most KPIs are sourced from the current MAWP of the FCH2-JU. Where KPIs are not available, we propose early suggestions based on expertise of the membership of Hydrogen Europe and Hydrogen Europe Research, as an outcome of initial reflections. Any input written in black indicates a good level of confidence and consensus on the KPI, while input in red flags a need for greater attention.

Table 14. KPIs electrolysis in on-grid

			SoA		Targets		
No	**Parameter**	**Unit**	**2017**	**2020**	**2024**	**2027**	**2030**
1	Amount of Green H_2 produced	Gt/y			0.5	1.2	3.2
2	Capacity of EU electrolysis suppliers	GW/y		1	5	10	30
3	Penetration of electrolysers in on-grid	GW		< 1	5	12	32
4	Quantity of grid services provided	MWh, MW					

Notes on Table 14 (on-grid):
1) Technical parameters regarding technology (e.g. cost, durability, efficiency, etc.) are included in RM01.
2) Estimation: 1 GW produces 100,000 tonnes/y of H_2.

Table 15. KPIs electrolysis in off-grid

			SoA		Targets		
No	**Parameter**	**Unit**	**2017**	**2020**	**2024**	**2027**	**2030**
1	Unit size (single stack)	MW		1	2	2	5
2	Capital cost	€/(kg/d)					
3	Degradation	%/1000 h		0.5	0.5	0.2	0.2
4	Load factor	%			40	40	40
5	Operational efficiency (system level)	kWh/kg		56	53	51	49
6	Amount of Green H_2 produced	Gt/y			0.07	0.2	0.57
7	Capacity of EU electrolysis suppliers	Same as on-grid					
8	Penetration of electrolysers in off-grid	GW		<10 MW	1	3	8

Notes on Table 15 (off-grid): Considered PEMWE technology

Table 16. KPIs electrolysis (other KPI)

			SoA		Targets		
No	**Parameter**	**Unit**	**2017**	**2020**	**2024**	**2027**	**2030**
1	Amount of Green H_2 produced	Gt/y			0.5	1.2	3.2

Notes on Table 16 (other KPI): Other general parameters are included in complementary RM: hydrogen storage in RM04 (section 4.1.1), FCs in RM16 (section 5.2.1), turbines and burners RM17 (section 5.2.2).

3.3. Specific Objective 7: Decarbonising industry using clean hydrogen

3.3.1. Roadmap 18: industrial applications

Rationale for support

Clean hydrogen is an essential component of efforts to decarbonise industry. Approximately 7 Mt/year of hydrogen is currently used in Europe in a wide range of industrial processes (mainly refining & ammonia manufacturing). These quantities are largely produced by SMR from fossil natural gas, referred as grey hydrogen, and can be replaced by clean hydrogen. Furthermore, clean hydrogen can replace fossil fuels as a feedstock in other industrial process (e.g. coke as a reducing agent in the steel manufacturing process) and can be used in combination with CO_2 producing liquid fuels, synthetic natural gas and important petrochemicals as well as an energy source for heat and power generation. Clean hydrogen can be produced through different routes, such as the conversion of renewable electricity through electrolysis, biomass through gasification and pyrolysis or other forms of net-zero hydrogen generation. To achieve this transformation to clean hydrogen in industry, large quantities of clean hydrogen at globally competitive conditions as well as appropriate conversion technologies and process adaptions are needed. **Developing these applications and providing appropriate frameworks could put Europe at the forefront of a green industrial revolution.**

[14] Specific activities on the technologies for energy production and cogeneration are included in the programme of TC4

Current status of the technology and deployments

1-20 MW scale projects integrating clean hydrogen conversion technologies into refineries, steel and chemical plants are being planned/under construction or start running first demonstration phases.

Hydrogen has been used as a feedstock for industrial processes for many years, most importantly in ammonia production and refining operations. There is now increasing interest in producing and using clean hydrogen in a wide variety of industrial applications, including replacing natural gas for heat and power generation[14], as well as substituting fossil-fuel based inputs in industrial processes such as chemical plants, iron & steel making as well as in transportation such as shipping. There remains a cost premium for clean hydrogen, which will need to be overcome for its use to become widespread. This will involve both cost reductions in production and in large scale storage, and regulatory pressures or incentives. Multiple projects are underway to highlight the use, with associated benefits, of green H_2 as a feedstock for industry and its potential to cross link different sectors such as power & gas, industry and transportation. Below are some examples across different industries:

- Carbon Recycling International – Located in Iceland, the George Olah Plant is the world's largest CO_2 methanol plant. The plant uses renewable electricity from geothermal and hydropower sources to produce green H_2 and combines it with captured carbon in a catalytic reaction to produce methanol. With a capacity of 4,000 tonnes per annum of methanol, the plant recycles 5,500 tonnes of CO_2 per annum. The production and use of this low-carbon methanol as an automotive fuel releases 90% less CO_2 than a comparable amount of energy from fossil fuel.

- GrInHy, GrInHy2.0 & SALCOS – Projects demonstrate the design and manufacturing of a high-temperature electrolyser (HTE) and scale it to megawatt class. Based on Solid Oxide Cells, the first unit in GrInHy achieved >7,000 hours of operation in June 2017. By 2022, the up-scaled 720kW unit in GrInHy2.0 operating with an efficiency of ~84% LHV will supply 100 t of clean H_2 to annealing processes in the steel plant. GrInHy2.0 represents the most energy-efficient hydrogen pathway for Salzgitter's hydrogen-based steelmaking project SALCOS

- Refhyne – Project to install a 10MW electrolyser at the Shell Rhineland refinery complex in Germany to produce H_2 for processing and upgrading products at the refinery, as well as regulating the electricity use of the plant. When operational in 2020 this will produce 1,300 tonnes of H_2 per year, reducing CO_2 emissions and proving the polymer membrane technology on a large industrial scale.

- HyBrit – In 2016, SSAB, LKAB and Vattenfall formed a joint venture with the aim of replacing coking coal in ore-based steel making with H_2. In 2018, a pilot plant was planned and designed in Lulea and the Norbotten iron ore fields to provide a testing facility for green H_2 (produced by electrolysis) to be used as a reducing agent in steel-making (1 t/h direct reduced iron). Project partners state that using this production method could make steel-making technology fossil-free by 2035, reducing Sweden and Finland's CO_2 emissions by 10% and 7% respectively.

- DJEWELS – Project to install a 20 MW electrolyzer at Nouryon site in Delfzijl, the Netherlands, to produce H_2 for production of green methanol from 2022. The produced 3 kta H_2 will be reacted with biobased CO_2 to yield 16 kta of green methanol.

- Other notable projects on clean H_2 – H_2 Magnum, H21 UK, Shell Quest, Demo4Grid, Waste2Chemicals

With multiple demonstration projects taking place in Europe, those involved will have unrivalled expertise in the integration of clean H_2 as a feedstock for industry. **Europe could become a market leader in the use of clean H_2 in industry, producing revenues of €13.5 billion and 202,000 jobs by 2030.**

Synergies with Clean Steel partnership

Following discussions held with ESTEP and EUROFER, a MoU has been signed. This MoU describes envisioned responsibilities for each partnership. The MoU can be provided on demand. It described the following high-level principles:

- any technological development or innovation dealing with clean hydrogen production, distribution and storage be within the scope of CHE,
- any development of a new steel production plant or process will be within the scope of CS-LCS
- the integration of the production, distribution and storage of hydrogen in the steel making process is an area for cooperation between the 2 partnerships.

Synergies with Circular and Climate neutral Industry partnership

Initial discussions with SPIRE have already taken place, discussing high-level principles. Further discussions are required, and it is expected to reach a full common understanding on repartition of activities leading to a MoU in the course of 2020.

Vision for 2030 and proposed areas for support

The goals of this R&D&I agenda are to:

- Successfully demonstrate the use of clean hydrogen in steel and petrochemicals
- Replace grey hydrogen with clean hydrogen in industrial uses, saving c.60 $MtCO_2$ pa.

As these ambitious goals would require significant investments to become reality, it is unrealistic that Clean Hydrogen for Europe partnership alone will be able to provide the necessary funding. Therefore, it is crucial that in the area of the transformation of existing industrial processes to low CO_2 will require additional substantial public and private investment, particularly for largescale demonstration projects, which are a necessary prerequisite before a wide scale roll-out.

It will therefore be an area of intense focus of the Clean Hydrogen for Europe partnership to look for potential synergies with other potential funding sources that could allow to fund large scale demonstration projects and then to bridge the last step between demonstration and first industrial deployment of technologies. These synergies might be more easily found with:

- ETS IF,
- Support provided by other EU programmes and by the Member States (e.g. in the context of a possible IPCEI),
- Investment support in the form of loans and guarantees (e.g. InvestEU Fund),
- Financing of infrastructure elements of the projects (e.g. via coordinated investments in CEF and ESIF).

Vision 2030

Clean hydrogen introduced in industrial processes (steel, petrochemical, ammonia production) and in industrial heat and power generation replaces fossil-fuel derived hydrogen and fossil fuels in industrial uses, saving 60 $MtCO_2$/year.

Early Stage Research Actions (TRL 2-3)

Any early stage development projects for clean H_2 in industry relate to electrolysis, covered in section 3.1.1.

Development Research Actions (TRL 3-5)

Industrial heat and power
There is a case for development work on prototypes for the smart cogeneration of industrial heat and electricity by FC CHP at 1, 10 and 100 MW scales (relevant to TC4, see section 5.2).

Industrial processes
A suite of projects should demonstrate technology concepts which could be used to produce synfuels (i.e. improvements in catalytic reactions) and chemical processes (i.e. improvements in catalytic reactions, use of renewable carbon feedstock, use of oxygen from electrolysis, dynamic operation capability).

Demonstration Actions (TRL 5-7)

Industrial heat and power:
Demonstration projects could include a number of demonstration projects on cogeneration of industrial heat and electricity by FC CHP in a variety of application environments, e.g. food, biotech (relevant to TC4, see section 5.2).

Industrial processes:
Demonstration projects could include:

- Integrating large scale electrolysers (50-200 MW) into industrial production plants, demonstrating dynamic operation.
- Clean H_2 for refining crude oil into complex fuels (e.g. kerosene/jet fuel).
- Ammonia and methanol production with clean H_2 to decrease GHG emissions and managing energy loads.
- Production of synthetic petrochemicals (e.g. olefins, BTX and syngas) using clean H_2 from electrolysis and renewable carbon feedstock (captured carbon, biomass etc).
- Demonstrate the ability of H_2 as a reducing agent in iron and steel production (replacing fossil fuels such as coke and natural gas).

Flagship Actions (TRL7-8)

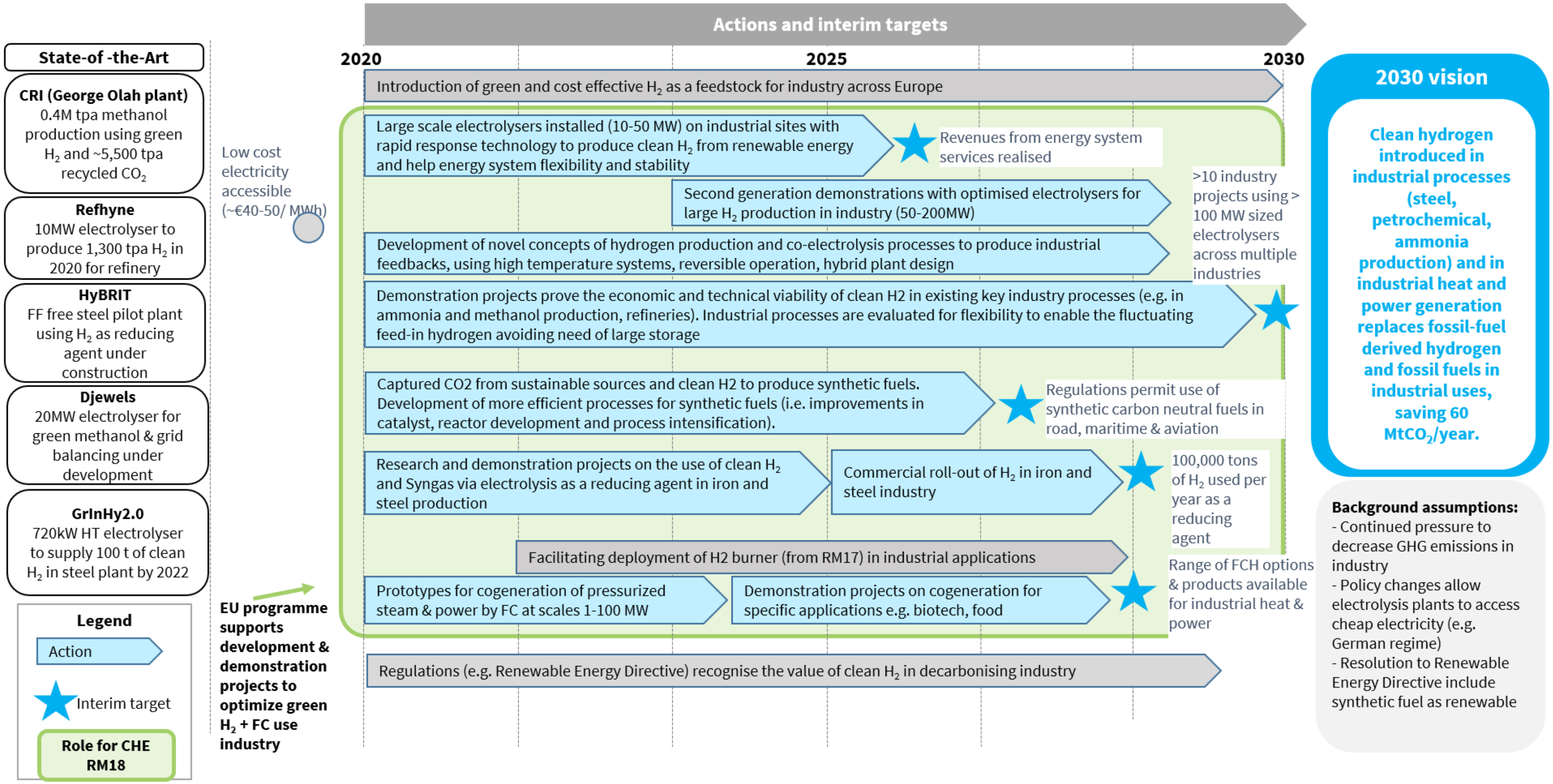
Application flagship support will be needed to:

- Begin the widespread roll-out of integrating clean H_2 into industry processes
- Begin the widespread roll-out of hydrogen-based FC CHP for power & low/medium grade heat requirements in industry, aiming to deploy at least 100 MW (relevant to TC4, see section 5.2).

They should consider GO schemes and integration with the electrical grid.

Dedicated roadmap

Hydrogen in industry: detailed technology roadmap



KPIs

Most KPIs are sourced from the current MAWP of the FCH2-JU. Where KPIs are not available, we propose early suggestions based on expertise of the membership of Hydrogen Europe and Hydrogen Europe Research, as an outcome of initial reflections. Any input written in black indicates a good level of confidence and consensus on the KPI, while input in red flags a need for greater attention.

Table 17. KPIs Hydrogen in Industry

No	Parameter	Unit	SoA indus. Ref.	SoA techno	Targets	
			2020	2020	2024	2030
Technical						
1	Scalability of the Project	%				
2	Flexibility of process	%				
3	Integration into process	%				
4	Lifetime of a process	h				
5	Availability of a process	%	95		97	99
Environmental						
6	ΔGHG emissions avoidance	%				
7	ΔReduction of fossile based feed	%				
Economical						
8	ΔCAPEX	%				
9	ΔOPEX	%				
10	ΔLevelized product cost	%				

Notes

1. The KPI measures the size of a project on industry relevant scale and its potential to scale up in the future
2. The KPI measures the possibility for a process to be flexible in demand and supply both theoretically as well as practically. There are multiple general principles that apply here:
- Load balancing: Possibility to fluctuate processes to match for example energy or material supply
- Grid support: Fast response by (part of) the process to respond quickly to support the grid
3. The KPI measures the overall energy/material efficiency of a project. A way to create an industry standard on integration is to define an overall efficiency of a process. Also, usable byproducts such as heat, when applied elsewhere, should be factored into the KPI
4. Operating hours until the first component within the process reaches end-of-life
5. The KPI measures the availability of a process, measured in: SUM of all hours with availability as % of max capacity for each hour / (total number of hours in the year x max capacity)
6. The KPI measures the avoidance of emissions compared to an industrial reference process (emissions reference process - emissions stated process) / emissions reference process
7. The KPI measures the avoidance of fossil-based feed compared to an industrial reference process (feed reference process - feed stated process) / feed reference process
8. The KPI measures the investment cost of the new process compared to an industrial reference process (investment cost industrial reference process - investment cost stated process) / investment cost industrial reference process
9. The KPI measures the operational cost of the new process compared to an industrial reference process (operational cost industrial reference process - operational cost stated process) / operational cost industrial reference process
10. The KPI measures the levelized product cost (cost fossil-based product - cost "green" product) / cost fossil-based product

Table 18. KPIs in Industry

No	Parameter	Unit	SoA	Targets		
			2020	2024	2027	2030
Clean H_2 integration in existing chemical plants (methanol, ammonia, refineries) and steel plants						
1	Electrolyzer (or equivalent) size	MW	10	50	250	1000
2	% of H_2 input	%	0	10	25	50

3	Flexibility	%	n/a	90-100	75-100	50-100
4	Reliability	%	95	98	99	99
Clean H_2 combined with new downstream plants						
5	Electrolyzer (or equivalent) size	MW	10	50	250	1000
6	Operational range	%	80-100	50-100	25-100	10-100
7	Reliability	%	95	98	99	99

Notes

2 The KPI measures % of green H_2 intake with respect to total hydrogen intake of plant.

3 The KPI measures the ability of existing plants to adjust production to flexible supply of green H_2

4 The KPI measures the reliability of total value chain (green H_2 plant + following plant). Indicated by % of available production hours with respect to total hours. Excludes scheduled maintenance.

6 Related to operational flexibility of H_2 plant and downstream plant. Aimed at minimizing intermediate H_2 storage

7 The KPI measures the reliability of total value chain (green H_2 plant + following plant). Indicated by % of available production hours with respect to total hours. Excludes scheduled maintenance.

General: For technical KPIs referring to specific technologies see sections 3.1.1, 3.1.2, 5.2.1, 5.2.2

4. PILLAR 2: HYDROGEN STORAGE, TRANSPORT & DISTRIBUTION

4.1. Specific Objective 3: Delivering clean hydrogen at low cost

4.1.1. Roadmap 04: large scale hydrogen storage

Rationale for support

For hydrogen production to become a significant part of energy storage, there needs to be an available and low-cost form of bulk storage. Additionally, the fluctuations in renewable electricity generation and hydrogen demand could require flexibility in the form of hydrogen storage. Potential stores include gas grids (see 4.1.2), and bulk storage above and below ground. Large-scale seasonal energy storage can be achieved by putting hydrogen in underground salt caverns (mostly dedicated to dedicated to daily adjustment) and/or underground reservoirs (mostly dedicated to to seasonal management), which are located in many places in Europe. Some of the salt caverns which are used to store natural gas today could be repurposed to store hydrogen. Hydrogen has been successfully stored at a large scale for industrial applications for many years. For example, underground gas stores in salt caverns were used to store hydrogen in the Teesside chemical complex in the UK for many years, and it has already been stored in depleted gas reservoirs and aquifers as well. Hydrogen can also be stored in large pressurised cylinder farms for aboveground storage of small quantities of hydrogen.

On the longer term, if hydrogen pipelines are introduced, the "line-pack" storage available by varying pressure in the pipelines represents a significant intra-day storage mechanism.

All these solutions are validated in the field, but they will need to be adapted to **a role in supporting the overall energy system**. For example, the rate at which salt caverns can be depleted is constrained by geology (to avoid cracking the caverns), which will make them suitable for long term storage, but could constrain their value for short term inter-day storage. Research will be needed in this field because due to the intermittency of renewable electricity, it is clear that caverns will be operated in daily cycling. Additionally, monitoring ground response to gas injection/extraction will be of key relevance for improving the rate of recovery, ensuring a sustainable storage for the environmental and public acceptance. Furthermore, there is potential for improved cost and efficiency, for example by hybridising the pressurised vessels with hydride solid-state storage materials and adsorbents, e.g. carbons and MOFs, and for further options such as depleted gas reservoirs and aquifers.

Finally, there is a challenge that these large-scale systems are needed for an energy system of the future when **sector coupling is a key element**, but in order to be ready in time, they need to be developed and proven now. This means there is a need to work to define the role of these large-scale stores in the future energy system to justify policy which accelerates their uptake in real world projects today. Development of adapted RCS is of key importance for enabling this technology.

Current status of the technology and deployments

Europe's industrial and chemicals sector is very experienced in handling and storing large quantities of H_2 in porous media (depleted gas fields and aquifers), as well as possessing the required geological knowledge to build new salt caverns. Circular economy can be organized with chemical industry using the existing salt caverns after the brine production to store H_2 and to use the brine for chlor-alkali electrolysis. Large-scale stores are associated with the pipeline networks in the Benelux region and in Teesside, UK. These companies are well placed to design, engineer and install the large-scale bulk H_2 storage systems of the future. Bulk pure hydrogen storage options have been deployed for large industrial activities with cost <€35/kg of underground H_2 storage capacity[15] and €500/kg for aboveground H_2 storage. The store of H_2 blending is also being tested in Europe in aquifer and depleted gas reservoirs.

Vision for 2030 and proposed areas for support

The ability to store very large quantities of hydrogen at low costs is key to realising the vision of hydrogen as a clean energy vector and for sector coupling. **Hydrogen offers the lowest cost option for large-scale energy storage**. The underground storage cost target of <€30/kg of hydrogen storage capacity (>1,000 ton) is much lower than the cost of battery stores.

Still, R&I efforts are needed to reach objectives of the vision. These efforts are presented below:

Early Stage Research Actions (TRL 2-3)

The bulk of the early stage work on storage techniques is covered by other roadmaps (e.g. hydride carriers, adsorbents, improved pressure vessels). There is however merit in researching novel concepts which can reduce the cost and improve the efficiency of hydrogen storage at a bulk level. This includes the use of lower pressure (lower cost) vessels in concert with low-cost hydride or adsorbent storage materials (with high reversibility (>90% of original storage capacity over at least 1,000 cycles) using lower targets for weight density than needed for other applications. Other examples include novel concepts for underground storage and line pack strategies for hydrogen gas grids.

Vision 2030

- ***Hydrogen storage is established and incentivised in European and Member State energy policy.***
- ***Large-scale underground storage demonstrated at <€30/kg of hydrogen storage capacity. Distributed above- ground stores for <€300/kg.***

Development Research Actions (TRL 3-5)

Development projects are required to develop the maturity of new concepts for aboveground and underground storage and their integration into the energy system including energy system modelling. Examples of areas for development are:

Aboveground

- Development of low-cost materials for above ground storage tanks, targeting optimised pressures.
- Novel designs and hybrid solutions for storage containers.

Underground

- Sustainable and safe designs for underground storage and the associated aboveground infrastructure more suited to energy system applications, including improving discharge rates and increasing pressure ranges within the underground storage.

[15] R.K. Ahluwalia et al., Argonne NL, 2019 [cavern with a 500ton capacity; CAPEX incl. survey, engineering, drilling, casing, brine transportation and disposal, piping, compressor]

Demonstration Actions (TRL 5-7)

A demonstration phase is necessary to highlight the readiness of hydrogen storage for integration within the overall energy system. There is the need for demonstrations of projects for both aboveground and underground operation, aiming to reduce cost and improve efficiency, including:

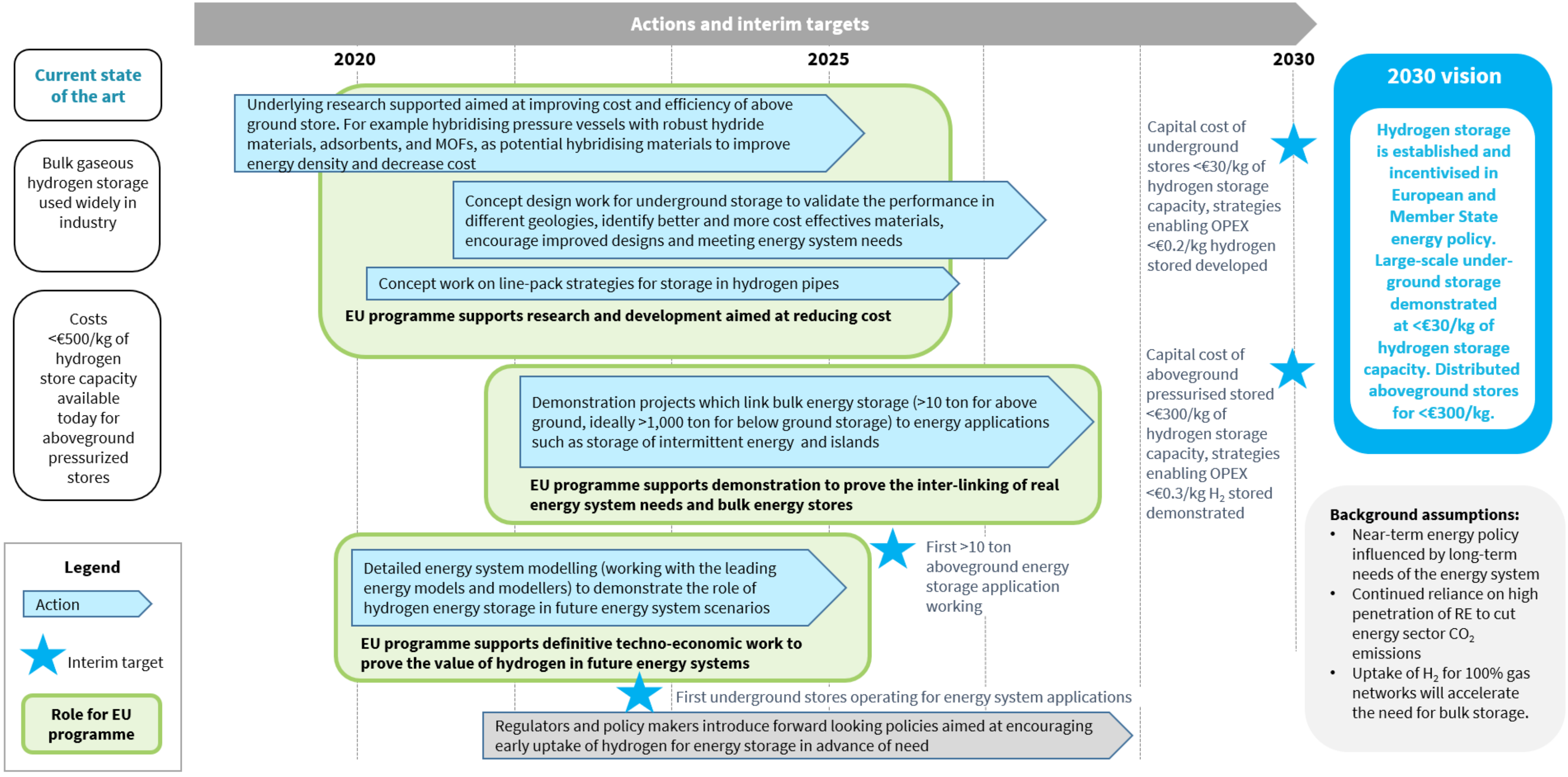
- Two medium-scale projects to both prove and optimise aboveground hydrogen storage solutions
- A large-scale demonstration project for underground H_2 storage, e.g. salt cavern, with high capacity and volumetric density

Flagship Action

- Flagship action for a bulk storage for a 250,000 m^3 underground large-scale storage. Alternatively, future projects should focus on including large-scale storage within large-scale projects.
- Policy studies should be used to develop the underpinning evidence on the need for bulk energy storage using hydrogen and hence the case for policy and regulatory support for market activation.

Dedicated roadmap

Bulk hydrogen storage: detailed technology roadmap



KPIs

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Note: pure hydrogen is considered here, not blending.

Table 19. KPIs Underground storage - Gas fields

No.	Parameter	Unit	SoA*	Targets	
			2020	2024	2030
1	Gas field size	m3	-	1,000,000	4,000,000
2	Capital cost**	€/kg	-	10	5
3	Levelised cost of hydrogen storage***	€/kg	-	0.19	0.17

Table 20. KPIs Underground storage - Caverns

No.	Parameter	Unit	SoA****	Targets	
			2020	2024	2030
1	Gas field size	m3	<200,000	< 400,000	>500,000
2	Capital cost*	€/kg	35	32	30
3	Levelised cost of hydrogen storage**	€/kg	0.21	0.19	0.17

Table 21. KPIs Aboveground storage

No.	Parameter	Unit	SoA****	Targets	
			2020	2024	2030
1	Storage size	ton	< 5	< 50	>50
2	Capital cost*	€/kg	500	400	300
3	Levelised cost of hydrogen storage**	€/kg	0.75	0.5	0.25

* R. Gerwen et al., Hydrogen in the electricity value chain, DNVGL position paper, 2919 (https://www.dnvgl.com/publications/hydrogen-in-the-electricity-value-chain-141099)
** based on the working mass of hydrogen stored
*** based on the mass of hydrogen produced from the storage

**** R.K. Ahluwalia et al., Argonne NL, 2019 [cavern with a 500 ton capacity; CAPEX incl. survey, engineering, drilling, casing, brine transportation and disposal, piping, compressor]

4.1.2. Roadmap 05: hydrogen in the gas grid

Rationale for support

With hydrogen and the continued use of the gas infrastructure **the enormous storage potential of the existing gas infrastructure will play a vital role in a low carbon future**. There are two ways hydrogen can be used to directly decarbonise gas infrastructure:

- Blending H_2 with natural gas: Blends of hydrogen up to 20% by volume may be possible without pipeline or appliance conversion although this should be determined case by case. The use of green hydrogen injection brings the important benefit of providing energy system flexibility and enabling sector coupling (Power to Gas).
- Conversion to 100% hydrogen grid: conversion programme of the network and appliances needed including related standards and procedures, similar to town > natural gas conversions of the last century. Purification advances (see section 4.1.5) would allow a 100% hydrogen grid to deliver fuel for heat, power, mobility, industry including feedstock.

Hydrogen is one of the most promising options for decarbonising demand segments, including industry, mobility, power production and domestic heat. Power-to-gas systems (using electrolysis of renewable electricity) have the potential to sector couple electricity and gas, transferring clean energy from constrained electricity networks, storing and using it in the gas networks. 50-80 TWh of hydrogen would be equivalent to approximately 1%-2% of the total European gas network demand (2019), or a 3%-5% volume blend.

Injecting hydrogen into the natural gas distribution networks is technically feasible today often up to 10-20% by volume, without major overhaul of pipelines or appliances. High pressure transmission pipelines have more uncertainties. In all cases safety must be assessed. There is significant energy system benefit in using existing gas assets as they have large seasonal storage potential and can also readily manage large swings in daily demand.

For deeper decarbonisation, 100% hydrogen is possible. Conversion of parts of the gas T&D infrastructure to 100% hydrogen is under serious consideration in the UK (H21, H100, HYNET) and plans are developing in countries such as the Netherlands, Germany, Belgium (Fluxys) and France. In these cases, existing transmission infrastructure could be repurposed for hydrogen (it is not referred to dedicated hydrogen pipeline here, they are covered in RM07, see section 4.1.4). Existing pipelines need to be cleaned and often compression needs to be changed. Not all steel pipes across Europe are equally compatible. Using existing infrastructure means a conversion can be executed in this decade.

Innovations are needed to ensure accurate measurement and billing including digitalisation. Network components need to be assessed to ensure they can support increasing the levels of hydrogen in the gas infrastructure, both for transmission and distribution.

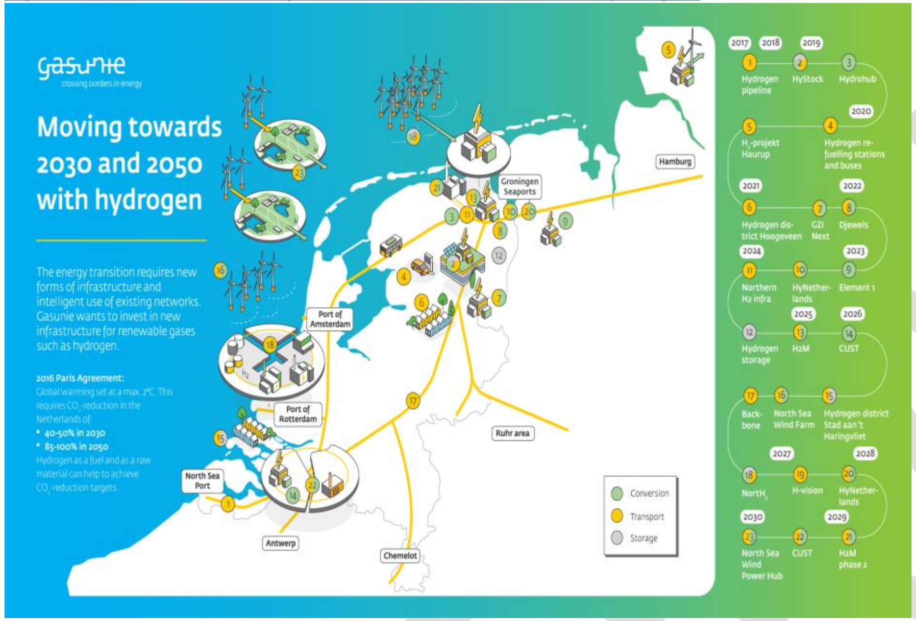
Current status of the technology and deployments

There are several demonstration projects injecting hydrogen into natural gas distribution grids, generally at <20% by volume. Limited demonstrations of conversions of steel pipes to 100% H_2 are commencing.

- Hydeploy (UK) and GrHyd (France) projects injecting 20% H_2 by vol. into gas distribution networks
- Gasunie has offered to bring a dedicated hydrogen grid in the Netherlands, based on the existing natural gas grid and into operation by around 2030. This network could have a capacity of approximately 15GW by that time. In order to achieve this goal,

Gasunie is developing several projects with partners in the Eemshaven, North Sea Canal, Rotterdam, Zeeland and Limburg industrial clusters

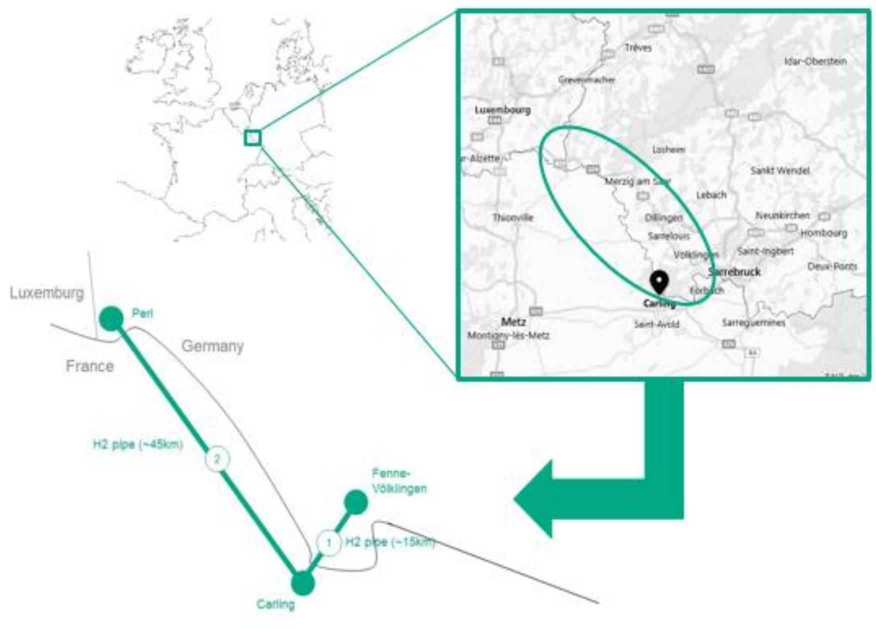
Figure 17. Gasunie: moving towards 2030 & 2050 with hydrogen



Source: Gasunie

- GRTgaz SA and Creos Deutschland GmbH are collaborating to create a 100% pure hydrogen infrastructure. MosaHYc (Mosel Saar Hydrogen Conversion) will focus on the conversion of two existing pipelines into a 70-km pure hydrogen infrastructure, connecting Völklingen (Germany), Carling (France), Bouzonville (France) and Perl (Germany), capable to transport up to 20,000 m³/h (60 MW) of pure hydrogen.

Figure 18. Project MosaHYc



Source: GRT Gaz

- The H21 Leeds City Gate study aimed to determine the technical and economic feasibility of converting the existing natural gas network in Leeds, UK, to 100% hydrogen. The first phase of the project reported in 2016[16] and concluded that the conversion is feasible. As well as supporting decarbonisation, 100% conversion of the gas network could be an enabler of other markets – hydrogen for transport or industry. The project is continuing to attract very

[16] H21 Report, July 2016, see www.northerngasnetworks.co.uk

significant political interest in the UK. Funding has been secured and a project team assembled to deliver c. €60 million of further work on detailed feasibility, FEED studies, demonstration scale tests, regulatory change, financing, etc. The partners estimate that 2025 is the earliest feasible date for conversion to natural gas.

- Beyond these three examples, there is much wider range of power-to-gas (and power-to-x) projects happening in Germany and Europe, including hydrogen injection into the gas grid.

Vision for 2030 and proposed areas for support

While the ultimate goal is to have entirely decarbonized gas grids, by the end of 2030 we should strive to at least achieve:

- 50 to 80 TWh pa of hydrogen to be blended into the natural gas grid.
- >10 EU regions in EU Member States implementing 100% hydrogen for residential & industrial sectors.

For that to happen innovations are needed to:

- improve metering accuracy to accommodate variable volumes of hydrogen in the gas grid.
- improvement of hydrogen pipeline components, to support increasing the levels of hydrogen in the gas grid.

While there is a need for EU programmes to support development of the above-mentioned components in order to increase the percentage of hydrogen in the gas grid, much of the activity to realise this roadmap will occur in the gas sector and with mature components, yet there is an essential role for CHE programme to play.

Specific topics and areas for support will be further developed in cooperation with the Built Environment and Construction Partnership and also with input from stakeholders like natural gas TSOs and DSOs and major gas end users for heat and power and industrial applications.

Vision 2030

- ***50 to 80 TWh pa H_2 is blended into the natural gas grid.***
- ***>10 European regions implementing 100% H_2 industrial and mobility sectors, with some residential use appearing.***

Early Stage Research Actions (TRL 2-3)

- Precisely map the influence, with testing techniques developed, of hydrogen on:
  - grades of steel in pipes and their welded joints and induced phenomena (embrittlement, crack propagation, etc.). Develop mitigation techniques based on testing to reduce any barriers. Develop mitigation techniques (including oxygen passivation)
  - metallic materials existing on the distribution network (cast iron, copper, brass, lead, aluminium) and induced phenomena (embrittlement, propagation of cracks, fatigue, etc.). Develop mitigation techniques
  - materials of elastomer types present mainly in equipment in the distribution network (regulator membranes, meters, etc.)
  - cathodic protection and external coatings
- Precisely model the influence of hydrogen including blends on identified safety and risk areas in order to update design and operating methods, and ensure safe operation
- Develop rehabilitation technologies to limit the impact on hydrogen on the existing network using an internal coating and in situ robotic application or others solutions (pipe in pipe)
- Development of real time energy content tracking for energy billing

- Develop insight in the effects of contamination in existing networks on the purity of the hydrogen at the exit point
- Techno-economic analyses of >20% concentrations in future scenarios and temporal and spatial mapping of P2G plant impacts on gas networks.

Development Research Actions (TRL 3-5)

- Identification and development of new materials (steels, joints, components, …) optimized for hydrogen transport
- Accelerate development and testing of scalable separation technologies
- Specify, develop and adapt our leak detection tools in the presence of hydrogen
- Compact blending and mixing units for hydrogen injection
- Check the metrological response and the potential drift of metering at different levels of hydrogen rate under dynamic network conditions
- Qualify the impact of hydrogen on network compressors in the presence of hydrogen and develop new compatible components

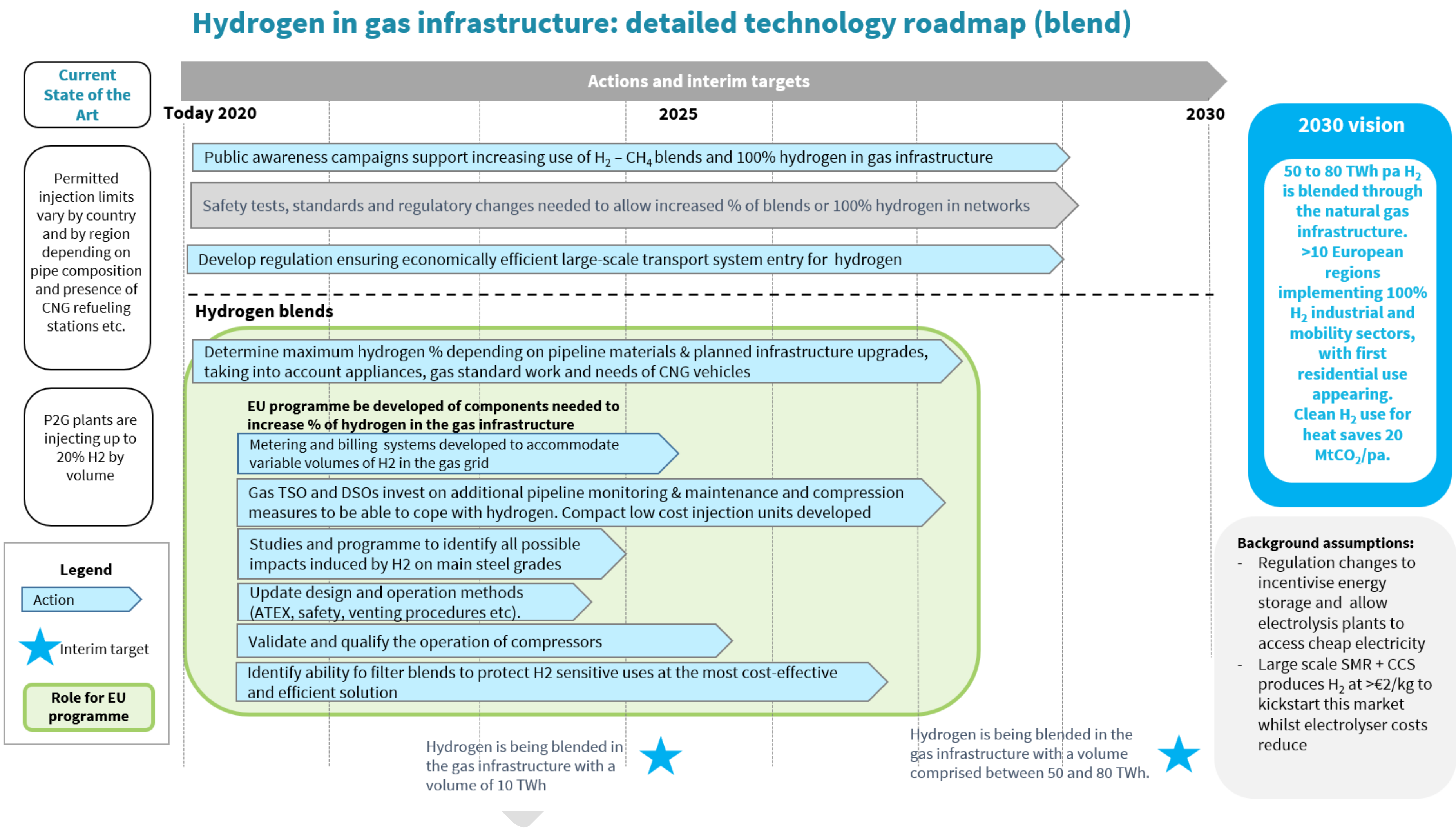
Demonstration Actions (TRL 5-7)

- Develop methods for connecting current off-grid projects to the gas market
- Construct local demonstration projects for blending and 100% with cross border participation, also developing programmed timings for a move to 100%

Flagship Actions (TRL 7-8)

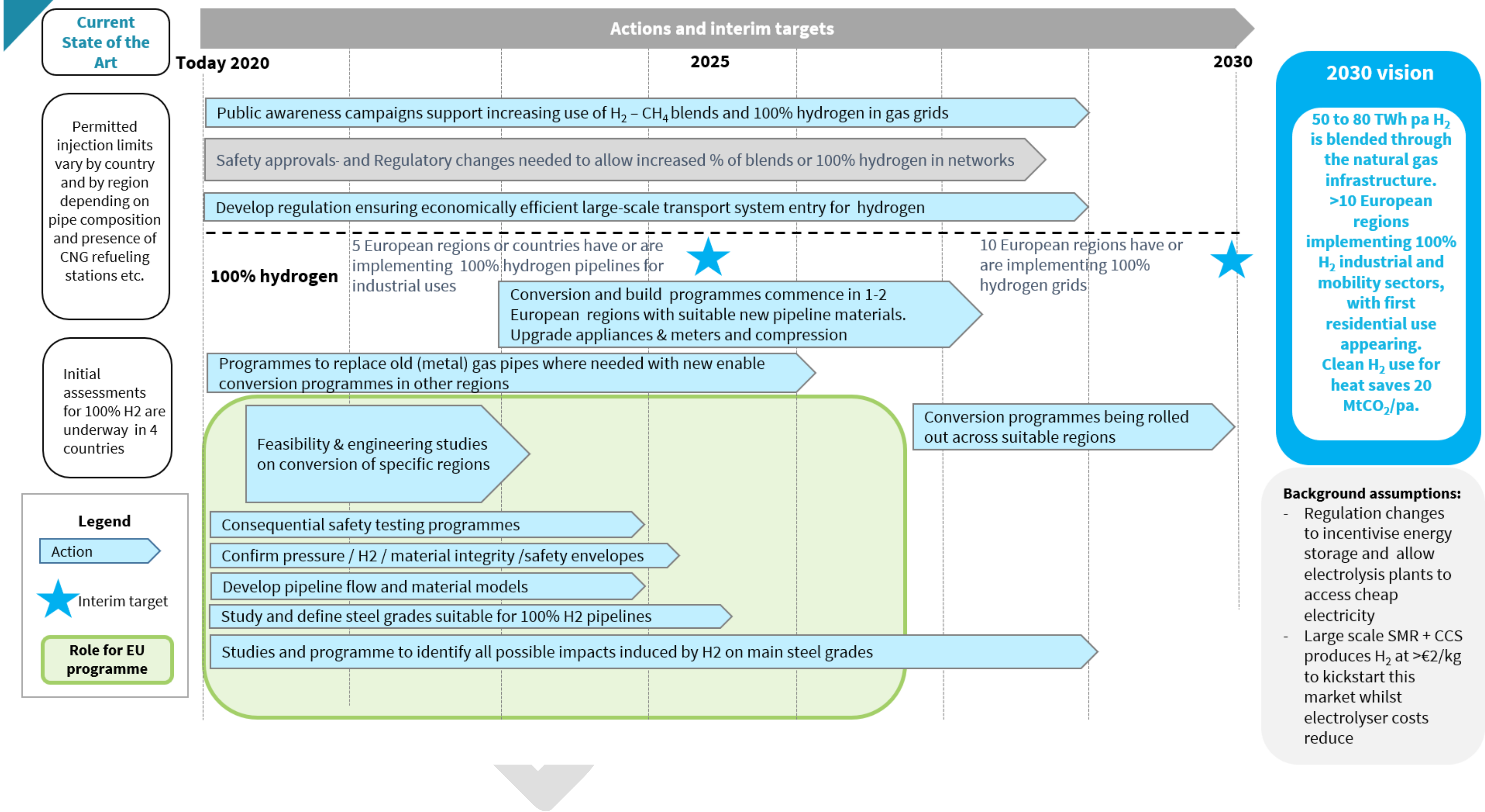
- Flagship cluster projects demonstrating cross border transmission, blending and industrial / mobility / residential use. Current example is the HyNet / H100 project in the UK

Dedicated roadmap



RM05 Gas Grid

Hydrogen in gas infrastructure: detailed technology roadmap



KPIs

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Table 22. KPIs Hydrogen in gas grids

No	Parameter	Unit	SoA	Targets	
				2024	2030
1	Blending percentage allowed gas distribution networks (Europe wide target), without detrimental asset integrity issues	%	2 -20	6-20	20
2	Blending percentage *compatible* with existing Gas Transmission networks (Europe wide target) without detrimental asset integrity issues	%	3 (turbines, underground storage)	6	10, up to 20 (based on potential for some deblending)
3	Extent of mapping of H_2 compatibility of materials and equipment in gas distribution and transmission networks	%	50	75	100
4	Energy content of hydrogen blended in gas network	TWh	<1	10	50-80
5	European regions planning or implementing 100% H_2 in gas infrastructure	#	4	6	10
6	H_2 incorporated in standards through CEN technical committees		Ad hoc process ongoing with standardisation request	complete	
7	Scalable separation technology	TRL	2-4	5-6	8

4.1.3. Roadmap 06: liquid hydrogen carriers

Rationale for support

Hydrogen is one of the most energy dense fuels by mass, but it is extremely light and so the volumetric energy density in standard conditions is very low. Conventional hydrogen delivery solutions solve this problem by either compressing and delivering a pressurized gas, or by liquefaction and delivery of a liquid. These methods of transportation are currently SoA but require sophisticated technical solutions to handle high pressure and boil off management. Alternative mode should naturally be investigated to reduce handling and transportation costs. Such hydrogen carriers include for example liquid organic hydrogen carriers (LOHCs), ammonia, CO_2 based hydrogen carriers (e.g methanol, dimethylether, formic acid) as long as they remain carbon neutral or carbon negative (atmospheric capture) or inorganic hydrogen carriers (e.g borohydrides, polysilane). Because there is the possibility for improvement of conventional liquefaction of hydrogen, it is included here. The transport of liquid hydrogen is covered in another roadmap (see section 4.1.4).

Hydrogen carriers store hydrogen by hydrogenating a chemical compound at the site of production or onboard and then possibly dehydrogenating either at the point of delivery or potentially onboard the fuel cell vehicle for transport applications. They are largely at the research stage and have yet to be proven to be cost, energy / roundtrip efficient.

Large industrial gas companies have expertise in liquefaction technologies and are well placed to exploit this market. European SMEs are active in developing hydrogen carriers and could capitalize on this with the continued research and development in this market.

Current status of the technology and deployments

Conventional liquefaction of hydrogen is a mature technology but has not been subject to significant innovation in recent decades. There is therefore scope to improve cost, scale and efficiency.

Several companies are developing hydrogen carrier as well as technology to recover pure hydrogen out of these carriers, some of which, however, have not yet been deployed at an industrial scale.

There is interest in a range of hydrogen carriers which could provide energy efficient, safe and practicable solution to transport hydrogen. They give the opportunity to be used directly or to allow pure hydrogen recovery for enabling safe and affordable mid-size to large scale energy storage and dispatch hydrogen storage. Few examples are:

- **Liquefaction**: Liquefaction is a conventional means of transporting hydrogen. Hydrogen is cooled to -253°C. After liquefaction, liquid hydrogen is transported in super-insulated “cryogenic” tankers. At the distribution site, it is vaporised to a high-pressure gaseous product. During LH_2 transfer some hydrogen is evaporated (boil-off) and needs a special molecule management to avoid losses. The same phenomenon happens during storage but at a far lower level.
- **LOHCs**: LOHCs are typically hydrogen-rich aromatic and alicyclic molecules, which are said to be safe to transport. The hydrogenation reaction occurs at elevated hydrogen pressures of 10-50 bar and is exothermic. Dehydrogenation is endothermic and occurs at low pressures. The unloaded carrier is returned to the production site for reloading with possible degradation of the carrier happening depending on chemistries, operating conditions and number of cycles.

- **Ammonia**: Ammonia production via renewable hydrogen is receiving increasing interest as costs of solar energy drop. Conventional ammonia production via the Haber-Bosch process must be adapted for proper integration with renewables. Ammonia cracking is done in the presence of a catalyst and can possibly generate back pure hydrogen, Innovative processes for hydrogenation (e.g. electrochemical) and hydrogen carriers cracking/reforming must be developed.
- **CO_2 neutral/negative carriers**: Methanol production from renewable hydrogen has received a large attention for years and has reached commercial stage in some area. Particular attention must be provided to the sourcing of CO_2 and its management in order to remain carbon neutral or even carbon negative (using for instance atmospheric capture). Dehydrogenation is done via reforming under pressures and temperatures of c. 200°C. Beside methanol, Other CO_2 neutral/negative hydrogen carriers, like dimethylether or formic acid can be considered. Dimethylether can be produced directly from hydrogen and CO_2 or out of methanol. Hydrogen recovery from dimethylether is performed through reforming.

Vision for 2030 and proposed areas for support

Considering elements mentioned above, we propose to focus on R&D actions developing a range of hydrogen carriers are being used to transport and store hydrogen at low cost:

Early Stage Research Actions (TRL 2-3)

- **Liquefaction**: Energy efficiency improvements and cost reductions could come from next generation materials for liquefaction, e.g. cryogenic vessels. Support would target innovations with the potential to reduce energy cost of liquefaction, reduce boil off losses, improve efficiency and improve reliability.
- **Hydrogen carriers**: More research is needed to develop novel chemistry, catalysts and reactor technologies, reduce both the amount of expensive raw materials needed in hydrogenation / dehydrogenation reactions, and the CO_2 equivalent footprint (including carrier supply chain and potential degradation)

Development Research Actions (TRL 3-5)

- **Liquefaction**: No development work proposed here – instead the innovations identified in early stage projects will be demonstrated (see TRL 7-8)
- **Hydrogen carriers**: Most promising concepts from early stage work will be developed into working prototype systems, with a focus on new technologies with improved safety, cost and performance

Demonstration Actions (TRL 5-7)

- **Liquefaction**: One demonstration project will be supported, based on the solutions validated in the early stage R&D projects
- **Hydrogen carriers**: Most promising concepts which have been developed will be deployed in a real-world application.

Vision 2030

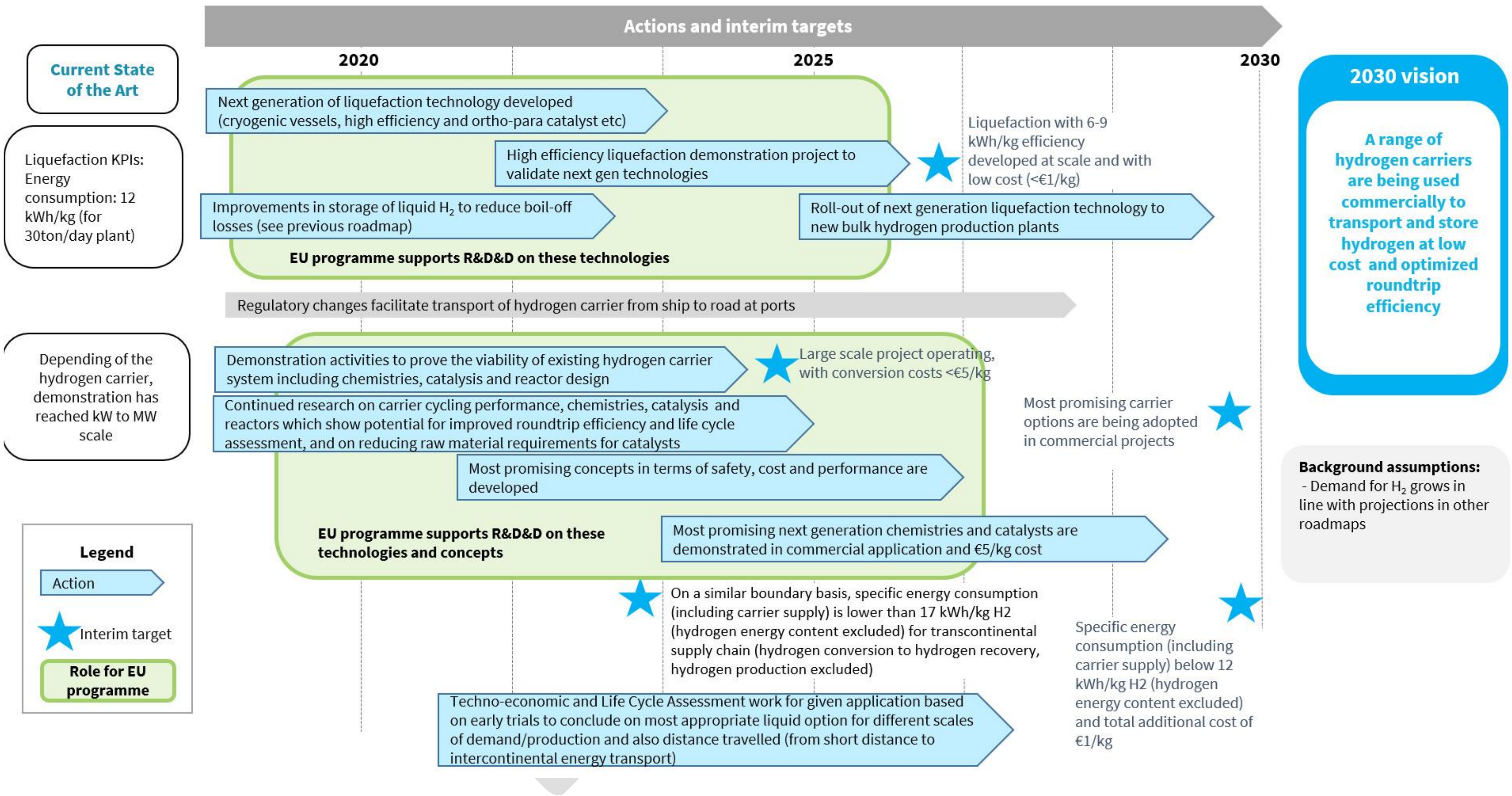
- ***A range of hydrogen carriers are being used commercially to transport and store hydrogen at low cost and optimised hydrogen roundtrip efficiency.***

Flagship Actions (TRL 7-8)

- Application flagship may be required once the technology readiness has improved and the costs have been lowered, though in practice the various hydrogen transport options would be expected to compete for end-use markets established by the end-use specific market activation work which is defined in this SRIA.

Dedicated roadmap

Hydrogen carriers: detailed technology roadmap



KPIs

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Table 23. KPI Hydrogen carriers

No	Parameter	Unit	SoA	Targets	
				2024	2030
1*	H_2 liquefaction energy intensity	kWh/kg	10-12	8-10	6-8
2*	H_2 liquefaction cost	€/kg	1.5	<1.5	<1.0
3**	Hydrogen carrier delivery cost (for 3000km ship transfer)	€/kg	5	4.5	<4
4**	Hydrogen carrier specific energy consumption***	kWh input/kg H_2 recovered	53 (20 + H_2 LHV)	50 (17 + H_2 LHV)	45 (12 + H_2 LHV)
5	CO_2 equivalent footprint related to conversion and dispatch****	gCO_2eq/kWh transported)	8% SOA CCGT	6% SOA CCGT	<5% SOA CCGT
6	Scalability	(g/kWh transported)	Current	100 tH_2/day	1000 tH_2/day
7	Safety		No very high concern molecules (Reach)		

* Hydrogen liquefaction has its own set of targets. LH_2 shipping and storage is covered by other roadmaps. As such, full supply chain evaluation not straightforward, or not feasible without close collaboration with other roadmaps

** Number will be defined for a relevant bulk energy storage and dispatch by ship: 1000-ton H_2/day, distance set to be 3000km. economic figures related to ship and other distribution infrastructure will be taken from another roadmap. H_2 recovered will have a purity compatible with PEM fuel cell for mobility application (ISO 14687 :2019). Energy requirement related to H_2 ship transport will be taken from another roadmap. The considered element takes into account the conversion of hydrogen into a dispatchable of energy up to the recovery of hydrogen. For the sake of comparison, carrier supply chain (e.g. Nitrogen for ammonia is considered.

*** with similar boundaries - from hydrogen conversion into a dispatchable form to the hydrogen recovered, including carrier supply chain/degradation, except hydrogen production)

**** including carrier supply chain

4.1.4. Roadmap 07: developing existing hydrogen transport means

Rationale for support

H_2 presents unique challenges for transportation and distribution due to its low volumetric density. If H_2 is to become a widespread energy carrier, distributed from centralized production facilities in high volumes across large geographic areas, these obstacles must be overcome in a cost-effective and efficient way. The development of novel transportation methods optimized for large scale H_2 delivery is therefore needed.

- **Pipelines** – for delivering large volumes of hydrogen over land pipelines are a leading option. In Europe there is already >1000 km dedicated hydrogen pipelines serving the industry. This network should be expanded by new build pure H_2 pipelines. Development of new high strength materials resistant to H_2 cracking can increase the pressure and capacity of H_2 pipelines, decreasing the cost of transportation. Note that under RM05 (see 4.1.2) the transport of H_2 blended with natural gas through the existing gas grid is developed as an alternative, as well as conversion of the gas grid for transport of pure H_2.
- **Road transport of gaseous hydrogen** – most tube trailers in operation today deliver small quantities of compressed H_2 gas (<300kg of H_2 per delivery) at a low pressure (<200bar). The development of a tube trailers at increased pressure and capacity will reduce costs per kg H_2 delivered. A good example is the Linde tube trailer which has a 1,100kg H_2 capacity with 500 bar pressure. The ambition is the development of a 700 bar tube trailers (c. 1,500kg) in the coming years.
- **Road transport of liquid hydrogen** – H_2 in liquid form is the most conventional means of transporting bulk hydrogen on the road. The H_2 is stored at -253°C in super-insulated 'cryogenic' tankers. However, liquefaction is energy intensive and storage/transport of the LH_2 results in heat ingress and losses due to evaporation. "Boil-off" losses can be reduced by improved insulation concepts or, as illustrated by NASA, by an integrated refrigeration and storage system. It should be noted that most of the boil-off happens during transfer phase (Storage to Trailer, Trailer to local storage), far above the vaporization inside storage tanks.
- **Shipping of bulk liquid hydrogen** – Oversea transport and global trading of renewable energy between regions rich and short in energy will become essential at some point in time. Overall, Europe is expected to import renewable energy. Shipping of bulk LH_2 follows in essence the business model of today's LNG shipping and trading. KHI has built a first LH_2 vessel for prove of principle. Further technology development is required for scale-up of the LH_2 containment, systems integration and overall ship design.

Current status of the technology and deployments

Current SoA: Multiple methods for delivering H_2 are available but at high cost. Novel concepts for pressurised hydrogen transport are maturing (e.g. 500 bar tube trailers). Liquid H_2 transport and H_2 pipelines are commonly applied in the industry but require further development to bring down the cost.

EU supply chain: With expertise throughout the entire production and distribution chain European companies will play a leading role in the development and distribution of H_2 globally. Large industrial gas companies such as Linde and Air Liquide have already developed novel H_2 transport and storage solutions and will continue to pave the way in the distribution and transport of H_2. Smaller companies are also developing solutions, e.g. Hexagon composites.

Vision for 2030 and proposed areas for support

The vision for this roadmap is to ensure that by the end of 2030 road transport networks will offer efficient solutions to deliver hydrogen across Europe together with new large hydrogen pipeline networks (different from gas grid retrofitting, covered by RM05, see section 4.1.2) serving hydrogen energy users with clean hydrogen. **Hydrogen transport costs across all transportation methods will be below €1/kg**.

Vision 2030

- ***H_2 transport costs < €1/kg across all transportation methods.***
- ***Road transport networks offer efficient solutions to deliver hydrogen across Europe.***
- ***New high capacity H_2 pipeline networks are serving industrial users with clean hydrogen.***
- ***Shipping of bulk liquid H_2 is used to import clean H_2 into Europe.***

Early Stage Research Actions (TRL 2-3)

- The transport of H_2 by road (compressed gas tube trailers and liquid H_2) is a relatively advanced sector. Due to this, no early phase projects are proposed to further these technologies.
- Early phase development of new high strength and lightweight materials (both steel and FRP) resistant to pure H_2 can increase the pressure and capacity of H_2 pipelines, decreasing the cost of transportation. This includes welding processes consistent with a high or 100% H_2 content and research into H_2 embrittlement / permeation.

Development Research Actions (TRL 3-5)

- Development of very high capacity pressurised tube trailer concepts (e.g. at 700bar)
- Development work to optimise the transport and storage of liquid hydrogen for road transport. The aim is to minimise/eliminate H_2 losses by evaporation. Potential areas for development are improved insulation concepts and the implementation of an integrated refrigeration and storage systems.
- For the scale-up and cost reduction of shipping of bulk LH_2, the development of new thermal insulation concepts and the integration with the containment tank is essential. The development of H_2 based propulsion as a potential means of boil-off handing and loading facilities is covered under RM12 (see 5.1.3).

Demonstration Actions (TRL 5-7)

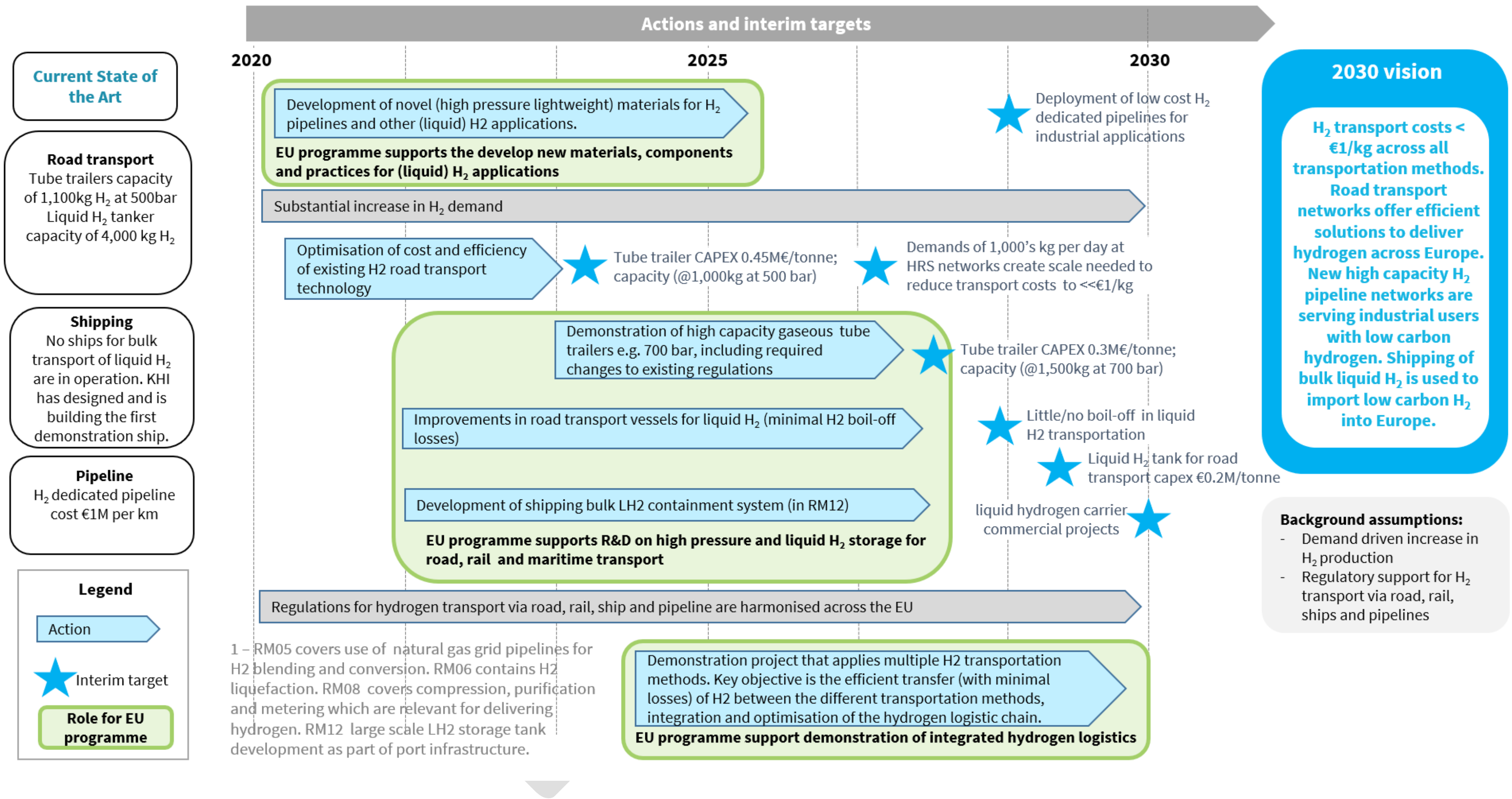
- A demonstration project that applies multiple H_2 transportation methods is required. Key objective is the efficient transfer of H_2 (with minimal H_2 losses) between the different transportation methods, integration and optimisation of the hydrogen logistics as a whole.

Flagship Actions (TRL 7-8)

- Growing markets for hydrogen and hydrogen applications should provide the pull needed to reach volumes for distribution methods. In some places there may be an argument for Member State/European support for e.g. optimised gas networks as part of programmes like CEF. No funding from the programme is proposed here.

Dedicated roadmap

Developing existing means of H2 transport: detailed technology roadmap[1]



1 – RM05 covers use of natural gas grid pipelines for H2 blending and conversion. RM06 contains H2 liquefaction. RM08 covers compression, purification and metering which are relevant for delivering hydrogen. RM12 large scale LH2 storage tank development as part of port infrastructure.

KPIs

Most KPIs are sourced from the current MAWP of the FCH2-JU. Where KPIs are not available, we propose early suggestions based on expertise of the membership of Hydrogen Europe and Hydrogen Europe Research, as an outcome of initial reflections. Any input written in black indicates a good level of confidence and consensus on the KPI, while input in red flags a need for greater attention.

*Table 24. KPIs Hydrogen pipelines**

No	Parameter	Unit	SoA	Targets	
				2024	2030
1	Total capital investment**	MEUR/km	1.1	1.0	0.7
2	Transmission pressure	bar		100	120
3	H_2 leakage	%***		<0.5%	<0.5%
4	Lifetime	years		50	50

* KPIs for H_2 pipelines should be developed further based on expected H_2 transport in Europe by 2030 (e.g. pipeline capacity, pipeline diameter and cost of transport)
** for an 8-in. diameter pipeline, excluding right-of-way
*** of hydrogen transported

Table 25. KPIs road transport of compressed hydrogen

No	Parameter	Unit	SoA	Targets	
				2024	2030
5	Tube trailer payload	kg H_2	850	1,000	1,500
6	Tube trailer capex	€/kg H_2	650	450	350
7	Operating presure	bar	300	500	700
8	Tubes gravimetric capacity	%	5-5,3	5,7	6
9	Lifetime	years		30	30

Table 26. KPI road transport of liquid hydrogen

No	Parameter	Unit	SoA	Targets	
				2024	2030
10	LH_2 tank trailer payload	kg	3500	4000	4000
11	LH_2 tank trailer capex	EUR/kg	>200	200	100
12	LH_2 tank trailer boil-off	%/d	0.3-0.6 %	?	near to 0
13	Lifetime	years		30	30

Table 27. Shipping of bulk liquid hydrogen

No	Parameter	Unit	SoA	Targets	
				2024	2030
14	LH_2 containment tank capacity	t	75*		1400**
15	LH_2 containment tank - capex	€/kg			<10
16	LH_2 boil-off	%/d			<0.3
17	LH_2 containment tank -safety performance		Class approval		

* 1250 m3
** 20,000 m3

4.1.5. Roadmap 08: Key technologies for hydrogen distribution

Rationale for support

The ability to move, measure and compress clean hydrogen will be an important part of the transition to using hydrogen more widely in the energy system. Today, a limited range of equipment exists to move hydrogen, and there is **considerable scope for optimisation of the efficiency and cost of these components**. More specifically:

- **Compression** – for the transport sector hydrogen needs to be pressurised above 700 bar to enable refuelling of high pressure storage tanks and 200 bar for injecting in pipelines. Furthermore, hydrogen refuelling stations have intermittent usage which means compressors are subject to stop-start loads. There is a need to create purpose designed compressors with a lower cost than today and with high efficiency. Several options are under development including liquid piston compressor, metal hydride-based compression and electrochemical compression.
- **Metering, piping and instrumentation** – the accuracy of current hydrogen meters needs to be sized up and improved. There is a need for more accurate, larger and cheaper meters and sensors with an accuracy sufficient for weights and measures standards and suitable piping, valves, spare parts compatible with H_2 or mixture blend, as well as safety aspects and communication protocols. Potential synergies with potential partnership on Metrology are yet to be identified. European manufacturers (e.g. KEM Küppers Elektromechanik) have now developed systems with the required accuracy but work is still required to produce cheaper systems and monitoring protocols. Piping and instrumentation have a critical role in the H_2 distribution chain, so they are considered in the present roadmap.
- **Purification and separation** – hydrogen for use in low temperature fuel cells requires a very high purity, as much as 99.999%. Current purification techniques are costly and inefficient, novel methods to purify hydrogen at lower cost would improve the overall supply chain. The separation of hydrogen from other gases will be valuable for a range of future industrial uses (e.g. separation from ammonia, methane or CO_2 streams). A range of new membrane, electrochemical and thermochemical techniques are being developed to improve processes for both purification and separation of hydrogen from different gas streams.

Current status of the technology and deployments

Current state of the art

- **Hydrogen compressors** are available but are the main source of failure in hydrogen stations. Novel techniques only available at lab scale (hydride, electrochemical).
- **Metering** accuracy prevents approved custody transfer for hydrogen in filling stations.
- **Purification** based on energy intensive PSA. Membrane-based purification technologies improving efficiency of hydrogen production from hydrocarbons and intermediate carriers (e.g. ammonia) are being developed and first field tests start to appear.

European companies are undoubtedly leading in the field of hydrogen logistics and handling for hydrogen applications. Companies such as Nel, Linde, HyET Hydrogen and Hystorsys (developing novel compressors) are global leaders, two of the main industrial gas companies are strongly positioned in Europe (Linde and Air Liquide) and there is considerable experience within the European oil and gas and chemicals industries. In addition, emerging companies in the development of key novel hydrogen production and purification systems such as H_2SITE strengthen the **leading position that Europe holds** in terms of innovation and exploitation required in these areas.

Vision for 2030 and proposed areas for support

Key technologies for distribution are the building blocks of the distribution of hydrogen at large scale. Development of these technologies is critical. The objectives will be to make sure that by the end of 2030 **a range of compression and purification techniques are available and cost competitive** enough to enable further decrease of hydrogen storage costs and that European companies supply world leading components which remove the existing technical barriers to the hydrogen distribution. The necessary actions and instruments to achieve this goal are as follows:

Early Stage Research Actions (TRL 2-3)

Due to the relative immaturity of the hydrogen sector there remain several challenges to address with regards to hydrogen infrastructure, including the storage, distribution and dispensing of hydrogen. Whilst systems exist today which allow the system to function, there is considerable scope for optimisation through new components and techniques. Outlined below are several areas where technology could benefit from research efforts:

H_2 compression

- Development of novel and hybrid technologies for compression, including chemical compression (hydride thermal cycles) and electrochemical compression.
- Testing of electrochemical, thermal and hydride compression at low, medium and high temperatures and pressure.
- Novel cryogenic impression approaches.

Vision 2030

- ***Range of compression and purification techniques develop and compete.***
- ***European companies supply world leading components which remove the existing technical barriers to the hydrogen distribution.***

H_2 purification and separation

- Development of low or free content PGM solutions
- Concepts to increase H_2 purity levels to 99.999% with a reduction in energy wastage.
- The purification of H_2 with medium and high temperature electrochemical processes.
- Development of new purification/separation technologies (i.e. membranes, electrochemical and thermochemical processes)

Material compatibility / resistance in contact with H_2 and blend

- Testing of the materials involved in the key technologies (compression and purification).

Development Research Actions (TRL 3-5)

Validation projects need to be commissioned to optimise storage and distribution technologies for hydrogen. Development efforts should focus on the following areas:

- Producing compression units with higher performance levels (reliability, efficiency) and in-field testing.
- Development of large compression technologies for injection of H_2 into gas pipelines (<5 bar to 100-200 bar).

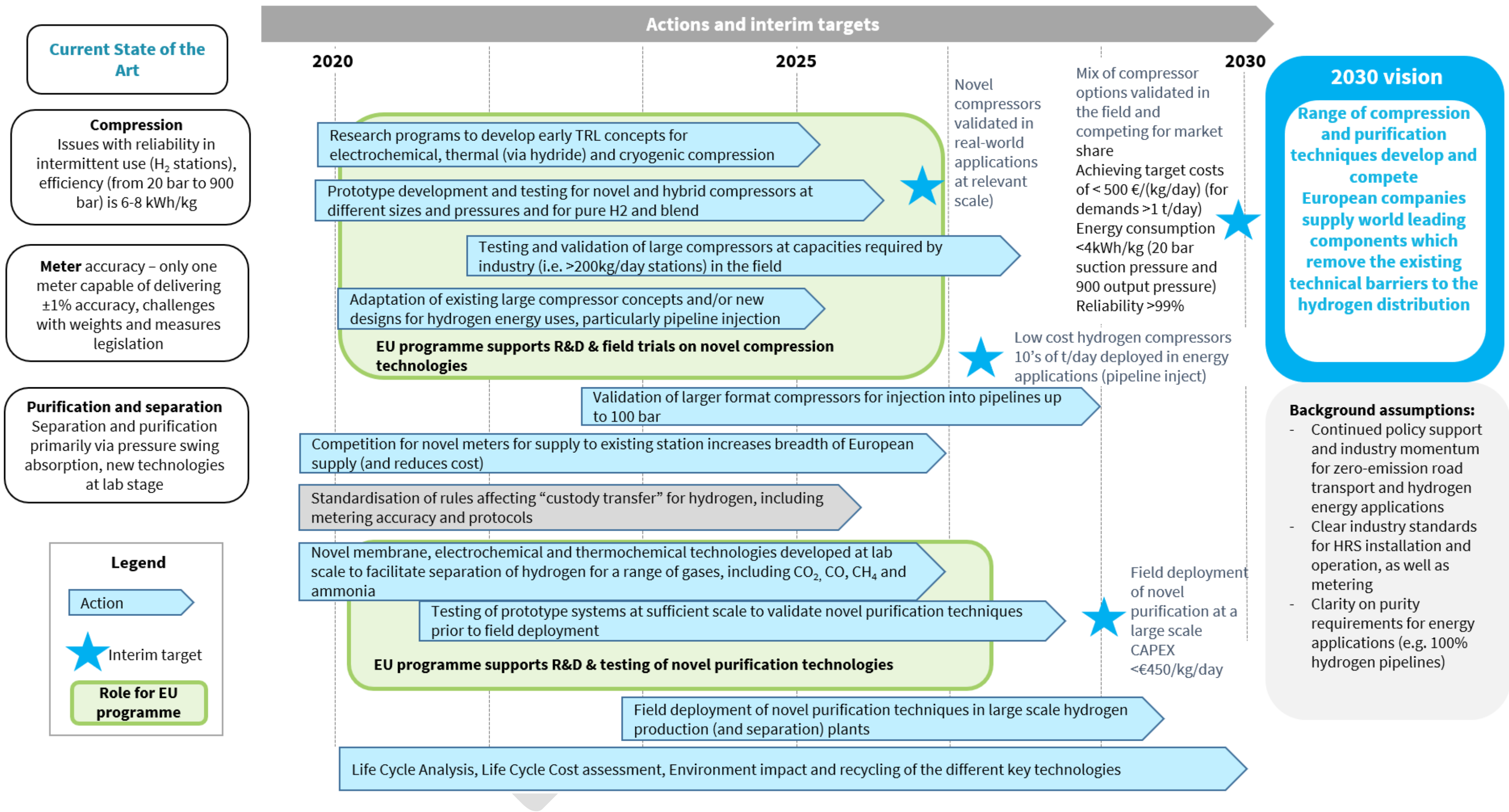
- Development of a greater accuracy within hydrogen sensors and flow meters.
- Projects which could reduce the cost of H_2 separation and increase poisoning resistance.
- Methodologies for separating H_2 from blended natural gas.
- Reducing the energy intensity for purification through improved flow sheets for purification system (better integration with production processes) and/or use of novel membranes and other components.

Demonstration Actions (TRL 5-7)

- Demonstration of novel and hybrid concepts for compression (pure H_2 or blended H_2/NG mixture) at a real-world scale (i.e. >200kg.day for hydrogen stations 10's of ton/day for pipeline injection).
- Demonstration of novel concepts for hydrogen purification and separation (i.e. H_2 purification, H_2 separation from blended H_2/NG mixture)
- Integration of innovative metering, piping and instrumentation technologies into the overall hydrogen innovation actions.

Dedicated roadmap

Key technos for distribution: detailed technology roadmap



KPIs

Most KPIs are sourced from the current MAWP of the FCH2-JU. Where KPIs are not available, we propose early suggestions based on expertise of the membership of Hydrogen Europe and Hydrogen Europe Research, as an outcome of initial reflections. Any input written in black indicates a good level of confidence and consensus on the KPI, while input in red flags a need for greater attention.

Table 28. KPIs Compression

No.	Parameter	Unit	SoA	Targets	
				2024	2030
1	Technical lifetime*	Years	10	14	20
3	Energy consumption**	kWh/kg	6	4	3
4	Energy consumption***	kWh/kg	8	6	4
5	Availability	%	95	98	99
6	MTBF****	hours	25,000	40,000	60,000
7	Maintenance cost	€/kg	0.12	0.07	0.06
8	CAPEX for the compressor	€/(kg/day)	1800	1000	500

* compressor system
** PH_2 from 5 to 400 bar
*** PH_2 from 5 to 900 bar
**** Mean time between failures/maintenance

Table 29. KPIs Purification

No.	Parameter	Unit	SoA	Targets	
				2024	2030
9	Lifetime	Years	1-5	5-10	20
10	Energy consumption**	kWh/kg	4	3.5	3
11	Energy consumption***	kWh/kg	3.5	3	2.5
12	Maintenance cost	€/kg	0.12	0.07	0.06
13	Hydrogen Recovery factor	%	80	90	95
14	H_2 levelized cost purification	euro/kg	2.0-7.4	2	1.5
15	CAPEX for the purifier	€/(kg/day)	1800	800	450

* purification system
** (molar fraction H_2 from 0.1 input to 0.99995 output) at a recovery of 95%
*** molar fraction H_2 from 0.75 input to 0.99995 output) at a recovery of 95%

4.2. Specific Objective 4: developing hydrogen refuelling infrastructure

4.2.1. Roadmap 09: hydrogen refuelling stations

Rationale for support

The hydrogen refuelling station is an essential part of the hydrogen mobility proposition. For widespread hydrogen mobility to be viable, it will be essential that there is a **nationwide network of publicly accessible hydrogen refuelling stations** for passenger cars, trucks and vans. Furthermore, the larger heavy-duty fuelling applications such as buses and trains will require **very reliable, high capacity stations capable of delivering many tonnes each day**, usually in short overnight refuelling windows. Today (May 2020), we see about 200 refuelling stations around Europe. These stations demonstrate the ability to completely refuel hydrogen vehicles quickly and with an equivalent experience to refuelling a conventional vehicle. There are however significant issues with publicly accessible stations, which can all be resolved over the coming years:

- The costs of the stations are high (both CAPEX and OPEX) which creates a challenge in creating a viable refuelling station business model, particularly in the early years when utilisation is low.
- The station reliability (particularly for passenger cars) is too low – The refuelling station networks for passenger cars have struggled to reach availability levels in excess of 95%, whilst at least 98% is required for a viable network. This creates issues for customers who cannot rely on their hydrogen supply. This situation will be partly resolved through increased throughput at the stations but will also benefit from improved components (particularly compressors and dispensers).
- The network is not sufficiently widespread to allow sale of hydrogen cars to the private customer – this leads to a requirement for new business models based on targeting fleet customers who are "captive" to a specific region with a geographically limited network coverage
- The permitting and construction process is too long – leading to a need to improve standardisation, technical certification and also levels of education and awareness amongst regulators.
- The design of the HRS is heavily influenced by the respective fuelling protocols which need to be jointly developed with vehicle manufacturers to allow a safe and reliable refuelling. Regarding maturity, refuelling protocols for Light Duty will be in place more readily, while Heavy Duty ones may not be well developed until 2030.
- In addition, there is technical work which needs to be done to develop and optimise concepts for high capacity refuelling for heavy duty vehicles & vessels, as well as to facilitate the use of green Hydrogen, e.g. produced onsite by electrolysis or biomass. Heavy duty transport is expected to be a relevant driver for HRS deployment.
- Finally, there is a lack or limited availability of existing cross-border infrastructure and cooperation.

Current status of the technology and deployments

Hydrogen refuelling stations are being deployed across Europe at an accelerating pace. Viable HRS have been deployed in limited national networks (~200 stations across Europe). HRS availability in excess of 99% achieved for bus stations, <95% for passenger cars stations.

Yet further deployment programs focussing on publicly accessible stations will be required to allow mainstream deployment of hydrogen passenger cars, vans and trucks. There is scope for improvements in the reliability, cost and footprint of stations through novel design concepts and the introduction of new components[17] (e.g. liquid hydrogen pumps for liquid hydrogen stations).

In addition, novel station designs are required for the very high hydrogen capacity needed for the heavy-duty applications in bus depots and for trucks, rail and ships, where the supply and form in which the hydrogen comes from (liquid, gas pipe, on-site production) also has to be considered. In any case, the use of green hydrogen should be supported, e.g. by enabling onsite production via electrolysis or biomass.

European supply chain

European manufacturers dominate the global supply of hydrogen stations. Companies such as Linde, Air Liquide, Nel and McPhy create an unrivalled ecosystem of hydrogen station development, deployment and worldwide export. Furthermore, Europe has a larger deployment of hydrogen stations compared to any other region, which provides greater experience in the operation and support of these stations than elsewhere. This positions Europe to be a long-term leader in the supply of stations worldwide.

Vision for 2030 and proposed areas for support

Early Stage Research Actions (TRL 2-3)

- Despite HRS being demonstrated in the field, there is scope for advancement to improve the efficiency, reduce footprint, noise disturbance and cost of refueling stations. Better interfacing technology is required between hydrogen vehicles and HRS to ensure optimal (and safe) filling protocols. Increase flexibility and enable low inlet pressure are necessary to support the use of green H_2 produced locally.

Vision 2030

- ***A network of HRS installed across Europe, achieving continent wide coverage and enabling sales to heavy-duty vehicles and private car customers.***
- ***HRS cost decreased by >50% compared to today***
- ***>99% availability.***

Development Research Actions (TRL 3-5)

As HRSs have reached the phase of commercial deployment, development efforts should focus on optimising station design (to reduce footprint, improve efficiency and decrease cost) and increasing station size (to allow FCEV sales to all use cases, including ships, fleets of trains and airplanes). Below are some examples of development projects which could be targeted:

- Development of new approaches to decrease overall HRS footprint.
- Develop high throughput stations for large scale vehicles (ships, fleets of trains, large fleets of buses or trucks), including > 1,000kg/day capacity and individual fills in excess of 200kg (in less than 20 minutes).
- Reduction in the CAPEX and OPEX of HRS through integrating innovative technological components – development work here would focus on how to integrate those components.

[17] New components such as novel compressors are already covered in the key technologies for distribution roadmap, see 4.1.5

- Facilitate the use of locally produced green H_2, e.g. by enabling low inlet pressure and flexible operation for intermittent RE.

Demonstration Actions (TRL 5-7)

Demonstration projects are key to optimising HRS technologies and testing their operational ability in real-world use cases. It is suggested that the programme focusses demonstration efforts on actions which:

- Aim to standardize and industrialise HRS equipment and components.
- Have a specific goal to increase the reliability, safety and availability of HRS equipment and infrastructure.
- The deployment of high throughput stations (multi-ton/day) for large scale ships, fleets of trains or large fleets of buses and trucks.
- Support improved efficiency and zero boil off during H_2 transfer and H_2 distribution at a HRS based on liquid hydrogen.
- Explore novel business models, for example, on-demand hydrogen refuelling and compact hydrogen mobile stations.

Application Flagship (TRL 7-8)

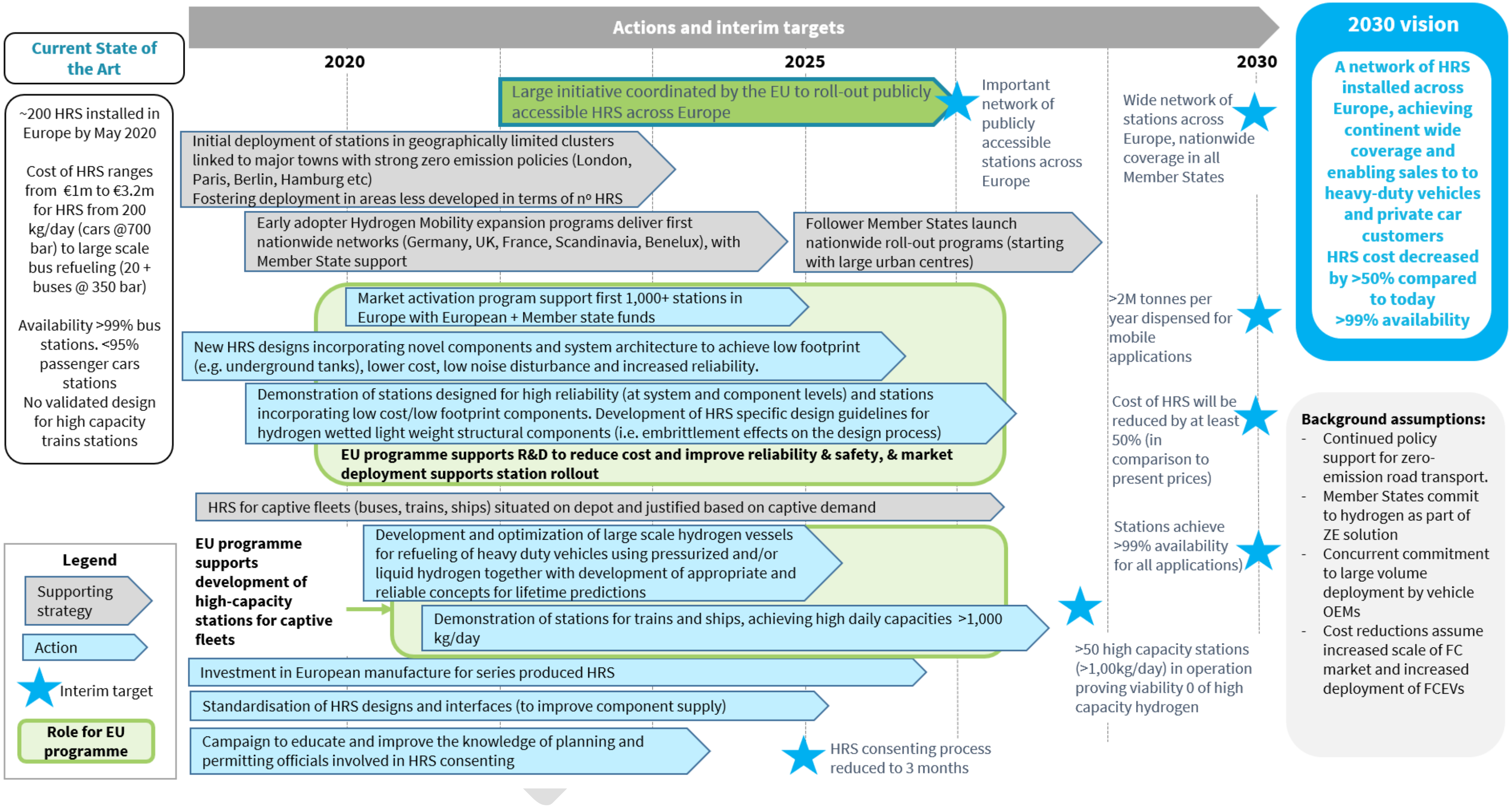
Funding through application flagship will help encourage HRS operators to invest in hydrogen technology by lowering the initial capital cost of HRSs and hence helping to create the initial networks required to deploy hydrogen vehicle technologies. European support (25% funding rate) is envisaged alongside Member State support (25%) for a large HRS deployment in Europe.

Others (Cross-cutting)

Educating and improving the knowledge and understanding of planning and permitting officials involved in HRS consenting.

Dedicated roadmap

Multi-use hydrogen refuelling stations: detailed technology roadmap



KPIs

Most KPIs are sourced from the current MAWP of the FCH2-JU. Where KPIs are not available, we propose early suggestions based on expertise of the membership of Hydrogen Europe and Hydrogen Europe Research, as an outcome of initial reflections. Any input written in black indicates a good level of confidence and consensus on the KPI, while input in red flags a need for greater attention.

Table 30. KPIs Hydrogen refuelling stations

No	Parameter	Unit	SoA	Targets	
			2020	2024	2030
1	Energy consumption 700 bar	kWh/kg	5	4	3
	Energy consumption 350 bar	kWh/kg	3.5	2.5	2
	Energy consumption LH_2	kWh/kg	0.5	0.5	0.3
2	Availability 700 bar	%	<95	98	99
	Availability 350 bar	%	97	98	99
	Availability LH_2	%	n/a	97	99
3	Mean time between failures 700 bar	days	48	72	168
	Mean time between failures 350 bar	days	96	144	336
	Mean time between failures LH_2	days	n/a	216	504
4	Annual maintenance cost 700 bar	EUR/kg	1.0	0.5	0.3
	Annual maintenance cost 350 bar	EUR/kg	0.66	0.35	0.15
	Annual maintenance cost LH_2	EUR/kg	n/a	0.5	0.3
5	Labour 700 bar	person h/kh	70	28	16
	Labour 350 bar	person h/kh	42	17	10
	Labour LH_2	person h/kh	n/a	28	16
6	CAPEX for the HRS 700 bar (200-1000kg/d)	kEUR/(kg/day)	2-6	1.5-4	1-3
	CAPEX for the HRS 350 bar (200-1000kg/d)	kEUR/(kg/day)	0.8-3.5	0.65-2.5	0.5-2
	CAPEX for the HRS LH_2 (200-1000kg/d)	kEUR/(kg/day)	2-6	1.5-4	1-3
7	HRS contribution in hydrogen price 700 bar	EUR/kg	4	3	2
	HRS contribution in hydrogen price 350 bar	EUR/kg	2.5	2	1.25
	HRS contribution in hydrogen price LH_2	EUR/kg	4	3	2
8	TCO (Total Cost of Ownership)	EUR/kg	>15	~10 for LD FCV	10 for LD FCV 6 for HD FCV

Notes:

1. Station energy consumption per kg of hydrogen dispensed when the station is loaded at 80% of its daily capacity – For HRS which stores H_2 in gaseous form, at ambient temperature, and dispense H_2 at 700bar in GH_2 from a source of >30 bar hydrogen.
2. Percent number of hours that the hydrogen refuelling station is able to operation versus de total number of hours that it is intended to be able to operate (consider any amount of time for maintenance or upgrades as time at which the station should have been operational).
3. Mean time between failures (MTBF). How long the HRS will run before failing.

4. Parts and labor based on a 200 kg/day throughput of the HRS. Includes also local maintenance infrastructure. Does not include the costs of the remote and central operating and maintenance centre.
5. Person-hours of labor for the system maintenance per 1,000 h of operations over the station complete lifetime.
6. Total costs incurred for the construction or acquisition of the hydrogen refuelling station, including on-site storage. Exclude land cost & excluding the hydrogen production unit. Target ranges refer to stations' capacity between 200-1000 kg/d.
7. Contribution of the HRS to the final cost of the hydrogen dispensed, therefore hydrogen production and transport is not considered. Included amortization and O&M costs.
8. TCO = (Depreciation + ROI + Energy + O&M (Operation & Maintenance) + G&A (General & Administrative)) / kg of hydrogen produced. Depreciation: 10years. ROI: business reference. Energy: estimated between 50 to 80 €/MWh. O&M = Man hours cost for Operation. G&A = 15-20% of total cost incurred. kg of hydrogen produced: considering availability / MTBF / Time of maintenance.

5. PILLAR 3: END-USES

Clean Hydrogen and renewable electricity are the two secondary energies and both versatile energy vectors suited to cover Europe's end energy needs in complementary way. They offer pathways leaving the fossil route and its associated emissions.

At this early stage of the energy transition, the electricity production is already substantially decarbonised, while large pans of the transport and industrial sector as well as heat and power in winter times still have significant emission footprints. Pillar 3 "end-uses" addresses solutions in the hard to abate sectors like heavy-duty vehicles, trains, shipping, aviation, industrial process, as well as in power and heat, where renewable energy sources are over constraint if they are to provide continuous supply. Early solutions based on hydrogen are already available in most of those sectors. By scaling and by process integration, cost reductions and higher efficiencies will enlarge the economic use cases in an avalanche manner, e.g. by platform approaches of FC modules across sectors or by the cogeneration of power and heat in the building and industrial sector. Pillar 3 supports the objectives of ensuring the competitiveness of clean hydrogen for mobility applications and for clean hydrogen to meet demand for heating & power.

5.1. Specific Objective 5: ensuring the competitiveness of clean hydrogen for mobility applications

On the end use side there are already some hydrogen applications that have, to some degree, proven to be on the verge of being ready for market deployment. FC material handling vehicles, FC buses and - to a lesser degree - FCEV passenger cars, have been successfully developed, demonstrated and, within the scope of activities of the FCH JUs, have are already been deployed with limited subsidies needed.

Yet a number of technology routes still need further improvements to reduce costs and increase efficiency in order to be competitive with incumbent technologies. Those include:

- Improvement of main technology building blocks that can be applied across a range of different applications like fuel cell stacks and hydrogen tanks;
- Adapting fuel cell systems from other vehicles (urban buses / cars) for long distance coaches and HDV;
- Components for freight and shunting locomotive applications;
- Marinization of FC components;
- Development of tanks and FC technologies specifically adapted for aviation

It should be also stressed that, especially in the case of hydrogen-based vehicles potential cost reductions are in equal measure dependant on research and innovation breakthroughs as they are on mass production of vehicles and components. It is therefore crucially important that the strategic agenda of the next partnership on hydrogen also includes actions aimed at stimulating a broad rollout of FC vehicles around Europe. On the other hand, the Total Cost of Ownership (TCO) of the FC vehicles depends not only on the costs of the vehicles themselves but also on the price and availability of hydrogen as a fuel. Only when all of those (hydrogen production push and demand pull) will be addressed together will there be a chance for hydrogen application to enter mass market.

5.1.1. Roadmap 10: FCEV technology building blocks

Rationale for support

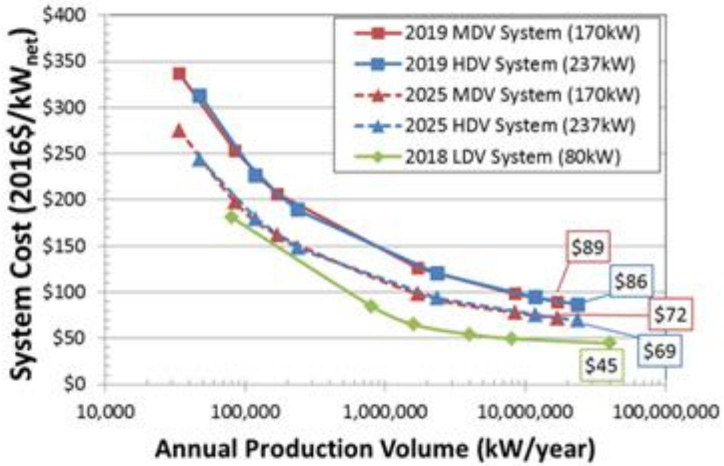
The EU Commission Green Deal target is net-zero greenhouse gas emissions by 2050. This objective requires a carbon-neutral and affordable on-road vehicle fleet. To achieve this ambitious objective, all available technologies should be considered and specifically all zero-emission technologies are needed for mobility. Hydrogen and fuel cell technology has great potential to offer zero emission mobility for a range of transportation uses without compromising the way vehicles are refuelled today (same refuelling time, similar range), especially for Heavy-Duty vehicles.

For this to be a realistic target, the vehicle prices will need to tend towards the prices of vehicles in use today. This in turn requires a reduction in the cost of the powertrain components – the "technology building blocks" – the fuel cell stacks, the supporting balance of plant which makes up the "fuel cell system" and the hydrogen storage tank. **Cost reduction in these components will be driven by a combination of technology development and volume of deployment**.

Fuel Cell systems

The Figure 19 shows the impact of production rate on the cost of the key fuel cell components. It is clear that increasing production will, already today, have a very significant impact on price. LD and HD components will likely be similar until 2025 but will become HD specific after 2025.

Figure 19. Evolution of HD system costs depending on production volumes



Source: DOE cost analysis 2019

This view is shared by the H_2 Council which is expecting an impact of the annual production volume on the reduction of the Fuel Cell System cost (including the PEM stack and the BoP) with 70-80% or 60-65% reduction expected for respectively 150,000 or 10,000 heavy duty trucks. In addition, *"the impact is higher for trucks than for passenger vehicles at the same volumes because of the larger fuel cell systems needed"*[18].

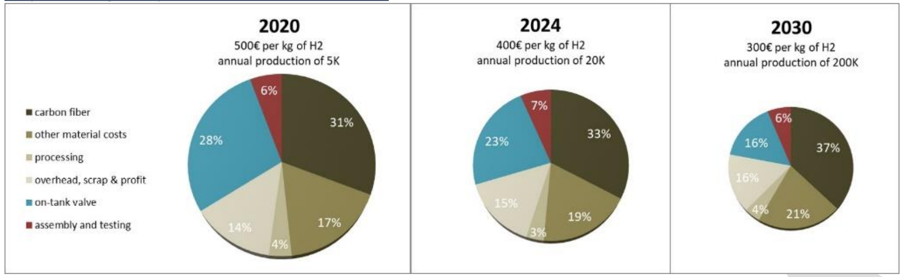
Hydrogen tanks

Volume production and technology developments will also play a similar role for hydrogen tanks. The importance of volume is that to develop the components themselves to the correct prices, market deployment programmes to stimulate the market and allow the technology to mature along the cost curve are crucial. In parallel, technology development

[18] Report of the Hydrogen Council - Path to hydrogen competitiveness - A cost perspective

programmes are required to ensure the core technology progresses towards the lower bound of the cost targets.

Figure 20. Hydrogen Tank – Cost breakdown for the high-pressure technology depending on production volumes[19]



Source: TAHYA, 2019 FCH JU Project Review days

It should be noted that due to the specific requirements of the Maritime (for larger ships) and Aviation sectors, the development of dedicated high-power fuel cells at MW scale and larger energy storage systems are covered in these dedicated roadmaps.

Current status of the technology and deployments

Researchers have developed these components to the point where they have the operational reliability to allow them to be deployed in small series production to mainstream vehicle customers (1,000s of unit in the US and Asia); the main driver for fuel cell technology in Europe is heavy duty applications (over 1,600 buses to be deployed). The fuel cell stacks operating in London's buses since 2010 have lasted for over 25,000 hours, thereby proving their possible longevity in a heavy-duty vehicle at least for this specific usage. The challenge now is to reduce cost through a combination of increased production volume as well as technology development to improve and automate production techniques, reduce material costs per unit of output (specifically costs of precious metals used as catalysts in fuel cells and carbon fibre in tanks) and improve designs at stack (e.g. catalyst layers) and system BoP components level (e.g. air loop). Spillovers in terms of technology and upscaling will be considered regarding LDV systems and are expected for other fields of HDV applications like rail, marine or aviation (where power ranges are comparable to HDVs).

The technology is now validated in numerous European trials and cost reduction is the key challenge e.g. current FCEV system costs > €200/kW for passenger cars but need to fall below €50/kW for mass market.

The European supply chain for PEM FCEV has evolved considerably within the last decade and it is highly competitive compared to other market areas, although there are still gaps, particularly in the supply of BoP components. The involvement of Tier1 and Tier2 suppliers indicates that the European product portfolio is starting to broaden for stacks, FCEV systems and hydrogen tanks; however, it is necessary to incentivise further suppliers to enter the market in order to increase competitiveness and innovation. There are a limited number of OEMs currently offering fuel cell vehicles to the market. With expertise at each stage of the FCEV supply chain, including FCEV integration and PEM stack components, Europe could play a vital role

[19] Calculation based on a single tank system architecture for 5.3 kg H2 at 70 MPa

in the FCEV market. The level of deployment of European vehicles manufacturers is slightly behind leading companies from Asia.

Synergies with the Battery partnership

Synergies with the Battery partnership are relevant when considering hybridisation aspect of both batteries and hydrogen technologies. Following discussion held with EMIRI (jointly with 2Zero) it is generally understood that hybridisation aspects should fall under the area of powertrain integration (see Table 31 below), within the remit of 2Zero. There are no significant synergies expected between CHE and the Battery partnership. We however encourage exchange of information, under the leadership of 2Zero.

Synergies with 2Zero

Building on existing links between HE and EGVIA[20], synergies and respective perimeters for both partnerships to cover have been extensively discussed, resulting in a fully aligned understanding between HE/HER & EGVIA and which should lead to a MoU between the associations in the course of 2020. The Table 31 below describes the envisioned repartition of responsibilities, focus being on Heavy-Duty vehicles:

Table 31. Envisioned distribution of responsibilities CHE-2Zero (view HE/HER-EGVIA)

Area	Partnership	Collaboration	Roadmap HE
Fuel cell stack	CHE		10
Fuel cell module	CHE		10
Fuel cell system	CHE	Medium	10
Onboard storage	CHE	Strong	10
Powertrain integration	2Zero	Strong	10-11
Prototype demo	2Zero	Strong	11
Large demo	CHE	Medium	11
End of life	CHE		19.1
H_2 infrastructure	CHE		09

[20] https://egvi.eu/mediaroom/battery-and-hydrogen-electric-vehicles-for-zero-emission-transport/

Vision 2030

High level R&D, demonstrated for manufacture, has enabled next generation fuel cell systems and hydrogen tank components to be optimised to allow FCEVs to be offered on a cost competitive basis from light to heavy duty markets.

It should be noted that only technical aspects are mentioned in the SRIA, the cooperative process being out of scope of this document.

Vision for 2030 and proposed areas for support

The technologies required for hydrogen fuel cell based automotive systems have matured rapidly, to the point that commercial sales of hydrogen passenger cars (in volumes of 1,000's/year) and heavy-duty vehicles (in volumes of 100's/year per manufacturer) are observed.

The main issue now is to **drive down cost and develop manufacturing technology to be able to increase production volumes** whilst maintaining low ppm process failure and an acceptable level of durability and efficiency. This will be driven by two factors:

- **Scale** – economies of scale will be critical in taking costs out of the supply chain for fuel cell system components and moving from today's volumes to 100,000 units/year.

- **Technology** – new lab-based technologies need to progress through the TRL levels and into final products to further reduce cost.

The goal of the programme will be that by the end of 2030 fuel cell system and hydrogen tank components would be developed to allow FC vehicles to be offered on a **cost competitive basis for both light and heavy-duty markets** and FCEVs would offer the lowest ownership cost for zero-emission vehicles in many classes. As a result, there should be at least 5 million FCEVs operating in the EU by 2030 (1.5% of total stock) and 1 in 5 new taxis will be a FCEV.

Below we have described a series of potential areas of support that should help achieving this goal, with developped synergies with 2Zero.

Early Stage Research Actions (TRL 2-3)

Fundamental improvements are available for all the FC components. Key areas of research include:

Fuel cell stack technology

- Development of new disruptive technologies towards improved areal and volumetric power density, increased reliability and extended lifetime (validation at single cell and short stack level).

Fuel cell system technology

- Improvement or development of strategic BoP components and design of HDV systems for low cost and scaled-up manufacturing
- Development of disruptive concepts towards improved volumetric and gravimetric density and increased durability of HDV systems

On board storage technology

- Development of new materials for high-pressure tanks enhancing the properties of the liner and targeting cost reduction of the reinforcement
- Development of novel storage concepts to improve storage density, including solid carrier, pressurised tank and liquid hydrogen.

Development Research Actions (TRL 3-5)

Development projects will work on existing technologies deployed in real systems, including:

Fuel cell stack technology

- Stack level improvements for higher HDV system performance, durability and reliability (incl. game changing concepts on core components)
- Developing low cost concepts and improving manufacturability (processes, automation, quality control tools, in-line and end-of-line diagnostics).

Fuel cell system technology

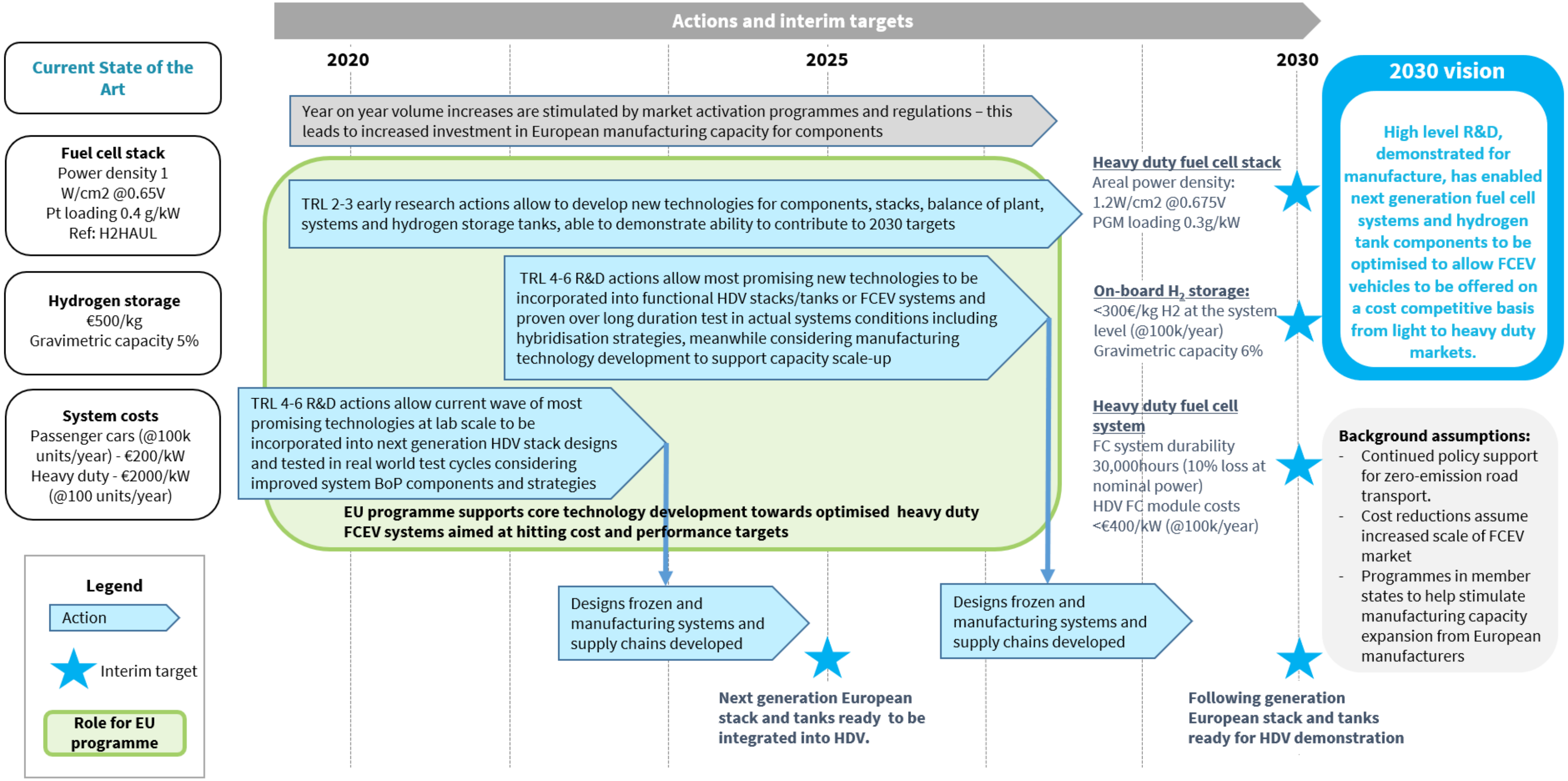
- Improving HDV system manufacturability.
- Optimisation of the HDV system to different use cases targeting improved performance and durability (e.g. hybridised powertrains, range extender, advanced tools and methods for improving control and strategies).

On board storage technology

- Development and validation of integrated mounting concepts, safety by design and innovative manufacturing issues.
- Integration of low cost and reliable safety sensors for structural health monitoring and fire detection

Dedicated roadmap

FCEV Building blocks: Detailed technology roadmap



KPIs

Most KPIs are sourced from the current MAWP of the FCH2-JU. Where KPIs are not available, we propose early suggestions based on expertise of the membership of Hydrogen Europe and Hydrogen Europe Research, as an outcome of initial reflections. Any input written in black indicates a good level of confidence and consensus on the KPI, while input in red flags a need for greater attention.

Table 32. KPIs FC for Heavy-Duty vehicles

No.	Parameter	Unit	SoA	Targets	
				2027	2030
1	FC module cost CAPEX	€/kW	n/a	n/a	n/a
2	FC module availability	%	85%	95%	98%
3	FC stack durability	h	15,000	20,000	30,000
6	FC stack cost	€/kW			< 50
7	FC stack efficiency	%			
8	Areal power density	W/cm^2 @ V	1.0 @ 0.650	High TRL 1.2 @ 0.675 Low TRL >1.5 @ 0.650	
9	PGM loading	g/kW	0.4	High TRL 0.3 Low TRL < 0.25	
10	Start-up, Turn-off and Reaction time				
10.a	Number of starts	-			30,000
10.b	0-50% Output Power time Cold start (-20C) Hot start (> 0C)	[s]	300 10	60 5	30 5
11	CO_2 footprint (FC system)	g/kW		*to be defined & compatible with RM HDV and cross-cutting*	
12	Recycling (FC system)	%			>85%

Notes:

1. FC module is defined as FC stack plus BoP, excluding tanks, cooler, filters and DCDC (cf. roadmap 11 Heavy Duty vehicles, section 5.1.2). Values for this KPI require further elaboration at this stage.

3. The durability target account for less than 10% performance loss at nominal voltage.

8. 9. This roadmap aims at supporting low and high TRL actions to allow disruptive developments with highest performance and technology ready for integration.

10. For information and in line with KPIs for FC modules and systems defined in RM11 Heavy Duty vehicles, section 5.1.2

Table 33. KPIs hydrogen storage for Heavy-Duty vehicles

No.	Parameter	Unit	SoA	Targets	
				2027	2030
1	CAPEX – Storage tank	€/kg H_2	500	400	300
2	Gravimetric capacity	%	5%	5.7	6

Notes:

1. Total cost of the storage tank, including one end-plug, the in-tank valve injector assembly assuming 200,000units/year in 2030.

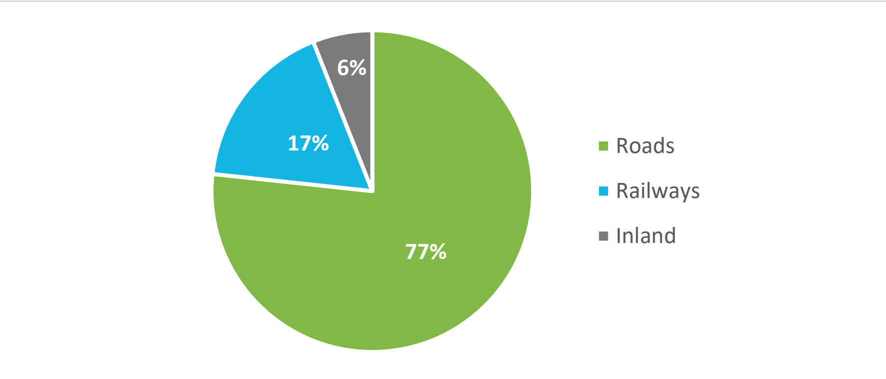
2. At tank system level

5.1.2. Roadmap 11: Road Heavy-Duty Vehicles

Rationale for support

Road freight transport is a fundamental component in the integrated freight transport system of the European Union – making more than 3 quarters of the EU freight transport – thus being a significant contributor to greenhouse gas emissions and air pollution.

Figure 21. Freight transport modal split in the EU in 2017



Source: Eurostat

Given that trade and freight developments forecast suggest that freight demand might triple by the end of 2050 it becomes clear that addressing the road freight transport emissions should be a top priority.

Hydrogen fuel cells are well suited to applications where long range and/or high payloads are required due to the relatively high energy density of compressed hydrogen. In its *Hydrogen Scaling Up* study[21], the Hydrogen Council identified the truck sector (along with buses / coaches and large cars) as being a key market for FC technology over the period to 2050. In much the same way as fuel cell buses provide a no compromise zero emission solution for public transport operators, fuel cell trucks are a potential drop-in replacement for diesel trucks as they can be refuelled in minutes and achieve a range of hundreds of kilometres, while having no impact on the payload. Furthermore, there is growing interest in zero emission logistics in Europe, particularly from major retailers and their transport solutions providers given the versatility of hydrogen (for ex. On-site renewable hydrogen used to develop a hydrogen logistics hub with trucks, forklifts, automated guided vehicles etc. (e.g., in ports areas) – this helps to provide an early market.

The FC truck sector is composed of a wide range of segments; the most promising for FCs are:

- Long haul heavy duty for logistics applications
- Refuse collection trucks

In addition, coaches present the same goals and requirements of long-haul trucks are set/to be pursued and are therefore covered in this area.

Hydrogen is the only viable zero emission option for much of the long-distance trucking market (e.g. capable of offering sufficient range and payload for long-haul HGVs) **without major infrastructure investment** (e.g. installation of overhead lines on major arterial routes).

There has been limited OEM activity and there are currently no fully demonstrated fuel cell trucks on the market in Europe. This is set to change with the FCH2-JU project H2Haul, involving two major European truck OEMs along with other developments.

[21] https://hydrogencouncil.com/wp-content/uploads/2017/11/Hydrogen-scaling-up-Hydrogen-Council.pdf

The most promising applications are in long-haul, heavy duty (26-40 tons) applications and logistics, including refrigerated food transport, where FC options can provide the range and flexibility required. Others options such as mining trucks or garbage trucks are foreseen to play a role as well.

Many European OEMs have relevant experience in this area and are well placed to respond to the growing demand for zero emission HDV. This includes Daimler (also in JV with Volvo), IVECO, MAN, Scania (VW) and VDL. Several European FC system or module suppliers are also active in this sector, e.g., Bosch-PowerCell, ElringKlinger, Plastic Omnium (provider of the FC system for the ESORO / MAN truck), Proton Motor and Symbio.

Current status of the technology and deployments

A small number of vehicle OEMs have developed FC HDV to a TRL of 5/6 via prototyping and demonstration activities. Examples include:

- Trials by La Poste in France of a Renault Maxity electric truck (4.5t) equipped with a 5kW range extender system;
- A conversion of a 34t MAN truck by engineering and prototyping company ESORO;
- Trials with COOP in Switzerland and the testing of a 40t truck by GreenGT/KAMAZ (GOH project) in Geneva.
- Four 27t FC trucks from Scania for use by ASKO in Norway
- VDL's developments of a 27t FC truck in the H2-Share project used by different operators around Europe plus a 44t truck for Colruyt in Belgium.
- It is also worth mentioning Hyundai's deployment plans of a 34t trucks for the Swiss market.
- The FCH2-JU project REVIVE and the HECTOR project are currently respectively testing 15 and 7 FC refuse trucks in different locations across Europe.
- The FCH2-JU funded project H2Haul started in 2019 and will develop and demonstrate 16 FC HDVs, up to 44t. These vehicles will run for a minimum of two years in real world operations, with the intention of reaching a TRL of 8 by the end of the project and thus preparing for wider uptake in the 2020's.

Despite a growing number of small-scale FC truck development and demonstration projects underway in Europe, vehicles are yet to be fully tested and validated in real world operations. Today there is no FC HDV OEM available on the market with a commercial offer on a regular basis.

Synergies with 2Zero

Building on existing links between HE and EGVIA[22], synergies and respective perimeters for both partnerships to cover have been extensively discussed, resulting in a fully aligned understanding between HE/HER & EGVIA and which should lead to a MoU between the associations in the course of 2020. The below describes the envisioned repartition of responsibilities, focus being on Heavy-Duty vehicles:

Table 34. Envisioned distribution of responsibilities CHE-2Zero (view HE/HER-EGVIA)

Area	Partnership	Collaboration	Roadmap HE
Fuel cell stack	CHE		10
Fuel cell module	CHE		10
Fuel cell system	CHE	Medium	10
Onboard storage	CHE	Strong	10
Powertrain integration	2Zero	Strong	10-11

[22] https://egvi.eu/mediaroom/battery-and-hydrogen-electric-vehicles-for-zero-emission-transport/

Prototype demo	2Zero	Strong	11
Large demo	CHE	Medium	11
End of life	CHE		19.1
H_2 infrastructure	CHE		09

Vision for 2030 and proposed areas for support

To have a meaningful impact on road transport GHG emissions and to get the sector on the road to future full decarbonisation, we have set out a goal that by the end of the next decade there should be **10,000's of new sales of FC trucks per year (c. >7% of annual sales), and the share of FC trucks in European fleet should approach 2% (~95,000 trucks).**

With that goal in sight it is proposed to support the following actions:

Development Research Actions (TRL 3-5)

Building on the development work already underway in this sector, a targeted programme of support can help to cover the costs of further development activities and attract a growing number of suppliers. There is a case for funding to support non-recurring engineering costs and prototyping / development activities, including:

- Establishing FC HDV specifications required to meet users' needs and regulation constraints for a range of truck sizes, duty cycles and auxiliary units (e.g., refrigerated food transport) power demand. Modelling, optimisation and life cycle cost analysis tools are essential to suitably address optimal HDV and coaches powertrain design and energy management, as well as FC-related recycling potential.

- Prototyping activities, development of control, diagnostic and prognostic procedure, interfaces between sub-systems and integration of FC systems and on-board hydrogen storage into FC HDV. investigation of future usage of liquid hydrogen. Development of health of state monitoring concepts for service and maintenance.

Vision 2030

- ***A European fleet of 95,000 FC HDVs on the road.***
- ***Sales ramp-up after 2030, due to new CO_2 regulations and FC-HDV's TCO competitiveness.***
- ***FC HDV will be worthy of up to 40 % of annual sales by 2050.***

Note: It is mutually understood and agreed with EGVIA that these activities should be performed by the 2Zero partnership. They are also indicated in this SRIA as well to ensure and highlight a consistent and integrated approach from development of building blocks to demonstration including powertrain integration.

Demonstration Actions (TRL 5-7)

Given the similarities and synergies between the FC HDV/coaches and maritime and railway sector, demonstration projects in this area can learn from previous real-world trials. Further demonstrations in the post-2020 period should focus on:

- Validating the performance of the technology in a range of real-world operations, specifically KPIs such as availability, lifetime, efficiency and ownership costs.

- Preparing the market for wider roll-out, e.g. by training technicians to maintain the vehicles etc.

- Collecting and analysing empirical evidence on performance (technical and commercial) of vehicles and associated refuelling infrastructure. Exploiting the promising synergies between hydrogen-based renewable distributed energy systems and transport sector.

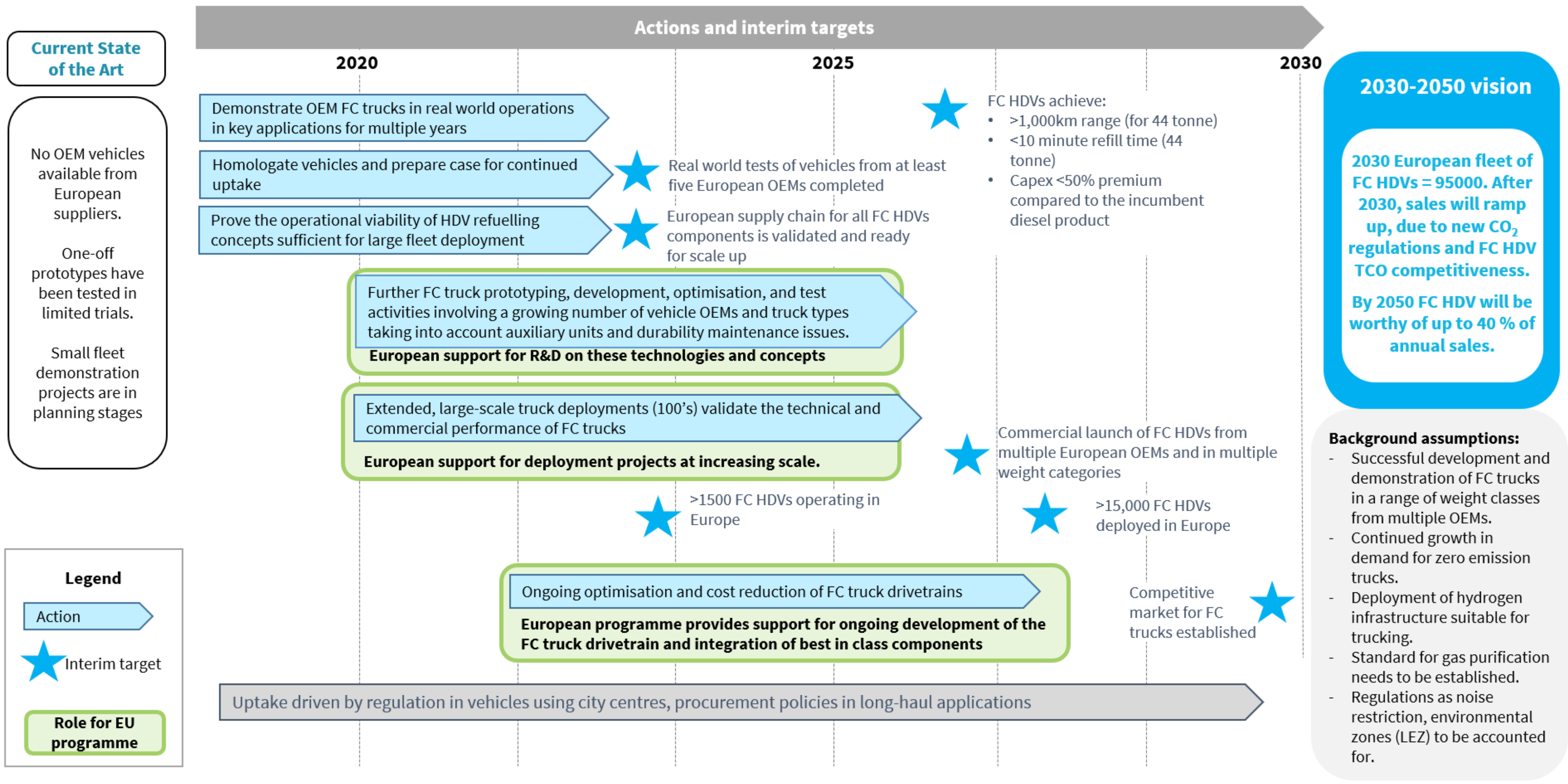
- Ensuring the range of truck types are trialled (i.e. different weight classes, niches such as refuse trucks).
- Ensure fully addressing the safety issues associated to the significant amount of on-board stored pressurized hydrogen.

Flagship Actions (TRL 7-8)

With a growing need to decarbonise all areas of the transport sector, and a high focus on air quality issues in cities arising from traffic emissions, the demand for zero emission vehicles in all segments is anticipated to continue to grow over the next decade. The development and demonstration activities outlined above will lay the foundations for a larger scale FC HDV roll-out programme in the mid 2020's. Funding of around €100k per vehicle is anticipated to be sufficient to catalyse the uptake of around 500 FC HDV, creating the scale required for this sector to reach a commercial footing. Key priorities in the market activation phase include developing and implementing innovative commercial models to manage risk appropriately and supply chain development to ensure that the vehicles are fully supported throughout their operational lives. Supporting such priorities entails guaranteeing customer expectations in terms of FC system reliability and driving range.

Dedicated roadmap

Road HDV: detailed deployment roadmap



KPIs

Most KPIs are sourced from the current MAWP of the FCH2-JU. Where KPIs are not available, we propose early suggestions based on expertise of the membership of Hydrogen Europe and Hydrogen Europe Research, as an outcome of initial reflections. Any input written in black indicates a good level of confidence and consensus on the KPI, while input in red flags a need for greater attention.

Table 35. KPIs Heavy Duty Vehicles

No	Parameter	Unit	SoA	Targets 2027	Targets 2030
1	FC module costs CAPEX	[€/kW]	n/a	n/a	n/a
2	FC module maintenance costs OPEX	[€/km]	0,35-0,30	0.15	0.10
3	FC module durability	[h]	15,000	20,000	30,000
(3)	Range (Long Haul 45-50km/h)	[km]	712,500	950,000	1,425,000
4	FC module efficiency	[%]	50%		
5	FC system availability (Uptime)	[%]	85%	95%	98%
6	Hydrogen consumption system	[kg/100km/ton]	0.30	0.27	0.24
7	TCO HDV in % (FC-20XX/Dsl-20XX)	%	200%	125%	100%
8	FC module volumetric density	[kW/m3]	80-120	200	250
9	FC module gravimetric density	[kW/ton]	150-200	300	350
10	Start-up, Turn-off and Reaction time	[s]			
10a	Number starts	[-]	20,000	25,000	30,000
10b	Cold start (-20C) 0-50% Output Power	[s]	300	60	30
10c	Hot start (> 0C) 0-50% Output Power	[s]	10	5	5
11	CO_2 footprint FC system	[g/kW]			
12	Recycling system	[%]			>85%
13	Noise HDV	dBa	81	76	74
14	Size and Interfacing	[]	All kinds	Kind of Standard	

Notes

1. Module is defined as FC plus BoP. It excludes tanks, cooler, filters and DCDC. Values for this KPI require further elaboration at this stage.
2. Spare parts and Maintenance per km travelled and related to FC module
3. Durability until 10% power degradation
4. To be defined
5. Percent of time vehicle is in operation against planned operation and related to FC system
6. Real operation and 100% on hydrogen. This KPI also depends on operation.
7. Excluding drivers' costs. Hydrogen costs per kg are very crucial in the TCO calculation
8. Figures are related to stack goals (Autostack Core)
9. Figures are related to stack goals (Autostack Core)
10. To be defined
11. To be defined
12. To be defined
13. Noise measured at 7.5m distance and at full power. This is for rated power engine >250kW. Based on -3dBa compared with diesel regulations
14. To get demand from OEM's, which are not making their own FC System, any kind of Standard would be preferable

5.1.3. Roadmap 12: Maritime

Rationale for support

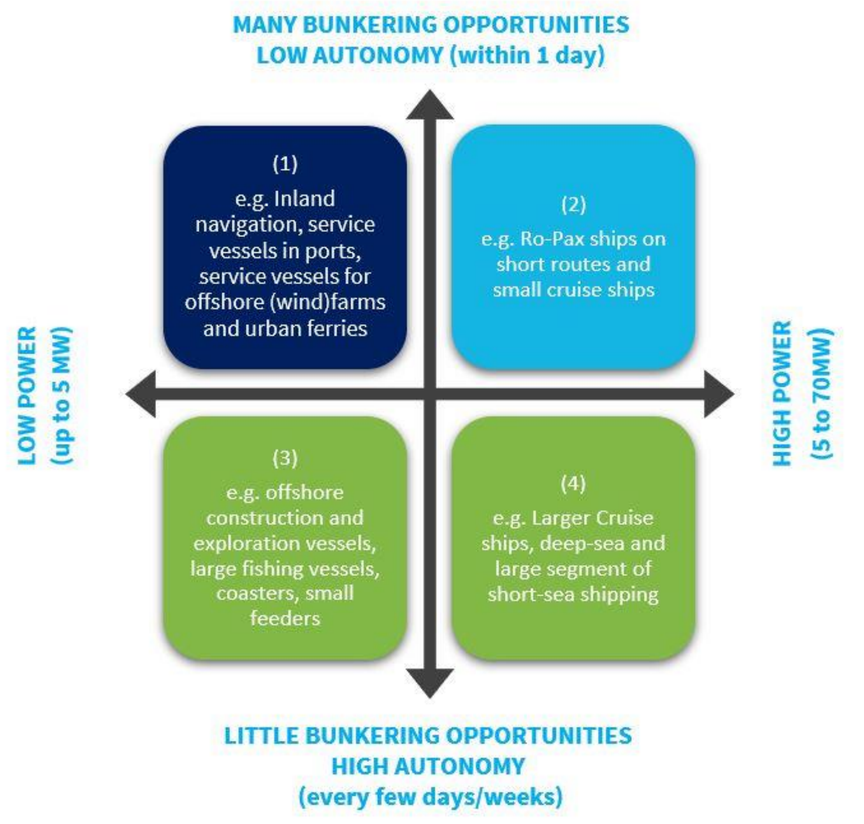
To put global climate change to a hold, the International Maritime Organization (IMO) adopted a Greenhouse Gases (GHG) reduction strategy in 2018. With projected growth of the shipping industry, the IMO estimated that the overall GHG contribution from shipping could double in a business-as-usual scenario. The IMO set a target to reduce CO_2 emissions by 50% in 2050. As ships are generally in service for over 30 years, the maritime industry faces an enormous task to achieve this goal. Hydrogen and fuel cells are an important piece of the puzzle, as they provide 0% GHG emissions and can therefore **contribute to a rapid decrease of the average GHG emissions for shipping**. As the target requires the transition of a worldwide and complex sector, providing technology will not be enough. Therefore, CHE will closely cooperate with Zero Emission Waterborne Transport (ZEWT) to research, develop and demonstrate urgently needed hydrogen and fuel cell-based technology. One of the most important factors to decarbonize shipping is **the availability of carbon-free fuels in ports**, which will also be addressed in this roadmap.

Development work will focus on improving access to the market for H_2 and FCs on smaller vessels and advancing the components and fueling systems required for larger ship types. This will strengthen and consolidate the European maritime hydrogen value chain.

The shipping sector involves a wide range of use cases, with both the autonomy and power requirements of small vessels and large cruise ships differing by three orders of magnitude. This highlights the importance of defining different strategies for zero emission propulsion for each vessel type.

To simplify, in the marine sector, four different users can be distinguished due to different implications for on board power and refueling:

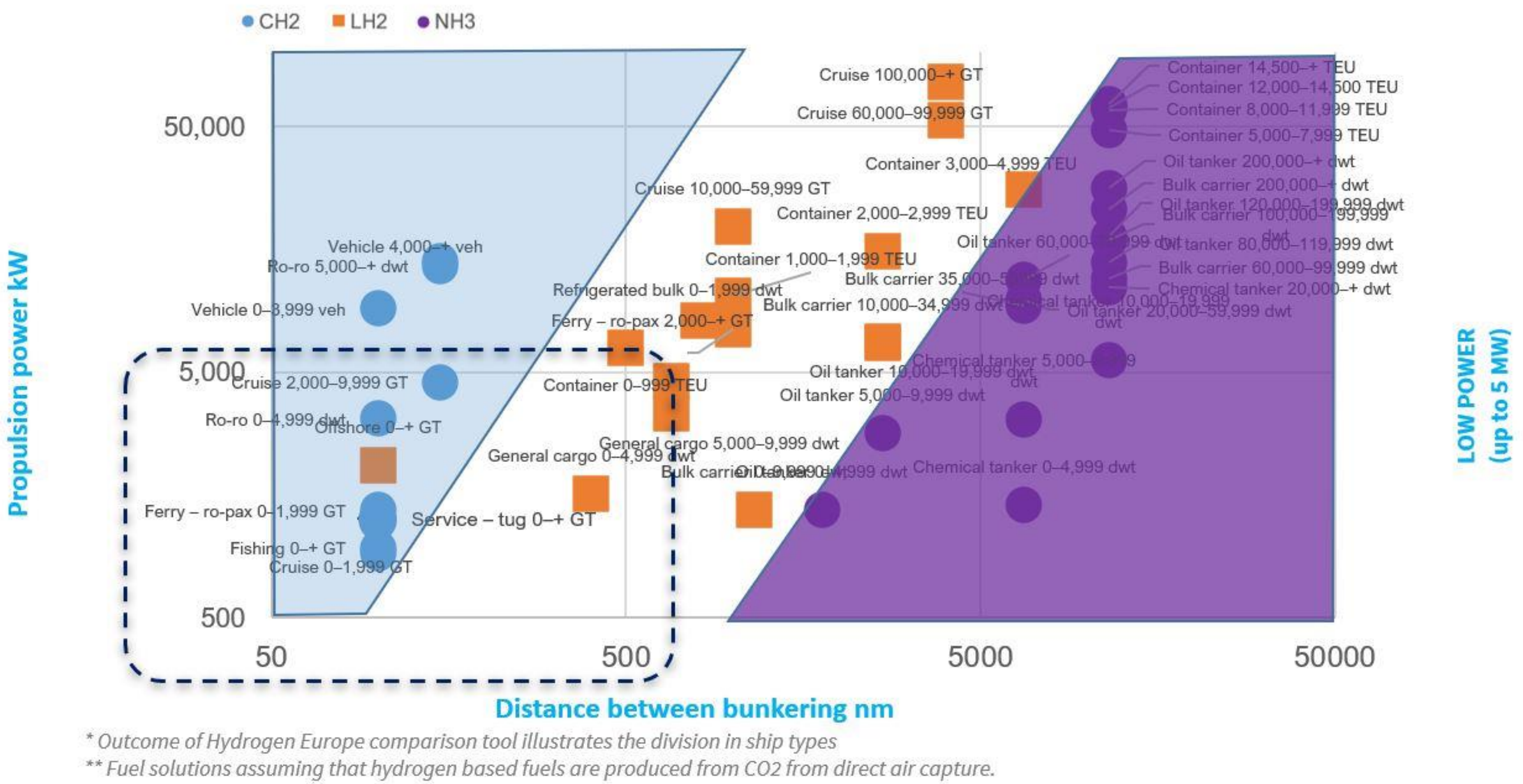
Figure 22. Simplified segmentation of the maritime sector



Source: Hydrogen Europe

A comparison tool was developed by Hydrogen Europe indicating the fuel option based on power and distance between bunkering (level of autonomy). Based on this research done within its Maritime Working Group, possible fuel options and engine options based on power and autonomy requirements show that, depending on the vessel's characteristics and its operational profile there is potential for both **pure hydrogen as a fuel** (either compressed or liquefied – for ship types 1 and 2) and **hydrogen derivative fuels**, such as e-ammonia, e-LNG or e-methanol for ship types 3 and 4.

Figure 23. Optimal zero emission solution vs ship type



Source: Hydrogen Europe

Four categories of commercial ships can be distinguished with different implications:

Fuel Cells and Internal Combustion Engines in combination with decarbonized- or carbon-neutral fuels will provide a viable power alternative in all maritime applications and are key to enabling future reductions in GHG emissions in the marine transport and shipping sector

Technology development

CHE
R&I + demo

Synergies with existing on shore applications

Cooperation with **ZEWT**

CHE: building blocks (see next slides)

ZEWT: integration and demonstration

Completely new technology development

(1) e.g. Inland navigation, service vessels in ports, service vessels for offshore (wind)farms and urban ferries

Small ships navigating on fixed routes and urban ferries will be the sequential adopters, due to the possibility of relying on fixed bunkering points along their routes. On board storage will not be an issue because of shorter/fixed routes. In many cases, **onshore fuel cell technology and Hydrogen Refuelling Stations (HRS) can be used or adapted.** Fuel distribution networks will enable the introduction of new and retrofitted ships. Also service vessels in ports and vessels bringing crew to offshore windfarms can be served with a dedicated “back to port” fuelling infrastructure and thus do not require large on-board energy storage. Power ranges in general start at 50kW for auxiliary loads up to 5MW for propulsion and hotel loads in more demanding applications.

(2) e.g. Ro-Pax ships and small cruise on short routes

The acronym ROPAX (roll-on/roll-off passenger) describes a RORO vessel built for freight vehicle transport along with passenger accommodation. Although regulatory issues need to be addressed, the development of Type 1 hydrogen powered vessels will demonstrate the reliability of these solutions, both ashore and onboard, before further up-scaling is undertaken. Larger power generation units will be required (from 1MW to 15-20MW), however with limited autonomy. Upscaling to these high-power generation units, **will require new technology development**. Innovation will be driven by the demonstration and development of Type 1 vessels.

(3) Offshore vessels, coasters, small feeders, …

Offshore (exploration and construction) vessels are ships that specifically serve operational purposes such as research and construction work at the high seas. These ships are generally characterised by reduced hull dimensions and a very high number of systems and equipment on-board. Power needs are therefore dominated by propulsion and the operation of on-board equipment. These vessels could be served in distinct clusters (e.g. from a fishing port) to minimise infrastructure costs. Nevertheless, these ships will still require considerable on-board energy storage. Coasters have a higher autonomy need and main engine power than inlands ships but they are shallow-hulled allowing them to trade also on inland waterways. Feeders transport containers over a predefined route on a regular basis.

(4) Large Ships with high autonomy

Ships requiring large power (up to 50-70MW) and large autonomy constitute this category. Intercontinental transport and a large segment of short-sea-shipping fall under this category. They will be the most complex vessels to power with fuel cells, and initial development will focus on hotel loads, before increasing to partial power, these ships are likely to be one of the final adopters of a full technology switch in the maritime sector. There will need to be international agreement with respect to fuel choice to ensure bunkering is available in all the ports served along the shipping routes.

Choice of fuel

H_2 as a fuel

Choice of fuel still open

Current status of the technology and deployments

FCs and H_2 have been demonstrated in e.g. submarines, small in-land and near coastal vessels, proving the viability of the technology. In addition, demonstration projects on small ferries are under construction. Larger vessels are generally at the design study stage and a range of fuels and fuel cell types are currently being tested. The European hydrogen and fuel cell supply chain is scaling up, with formal cooperation's and joint ventures between FC manufacturers and maritime power train providers.

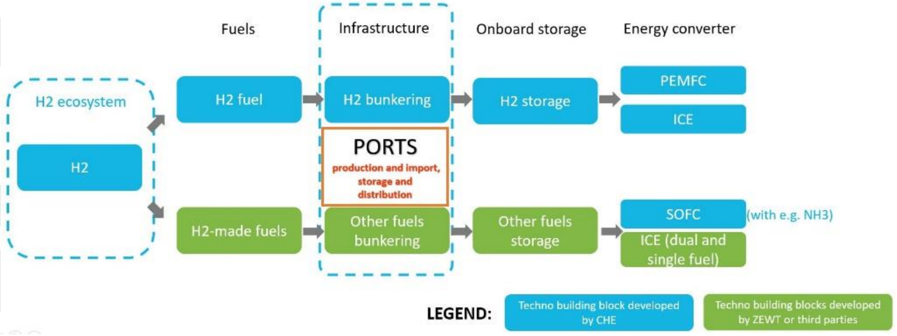
Demonstration projects are underway to highlight the viability of H_2 to power ships using FCs and modified combustion engines. For certain use types (in-land, near coastal), there is **an emerging consensus that FCs, using H_2 are the most promising ZE option**.

Several design projects are ongoing to test the applicability of FCs to larger vessels. However, due to the magnitude of energy storage and power required in these use cases, **no consensus on the optimal strategy for fuel and propulsion has been reached**.

Synergies with Zero Emission Waterborne Transport

As presented, the shipping sector encompasses a wide range of ship types each with their advantages and disadvantages for hydrogen technology. This variety highlights the importance of defining different strategies for hydrogen as a fuel for each vessel type. The most crucial bottleneck with hydrogen as a fuel, is likely not the production of renewable hydrogen or the end-point use but rather the **storage both onshore and onboard** the vessels. Power and autonomy are the key determining factors in this regard. Clean Hydrogen for Europe is the expert for the hydrogen ecosystem, including production, storage, infrastructure and energy converters and has been for many years in onshore applications. Therefore, to develop hydrogen technology in an effective way, **CHE will focus on hydrogen technology building blocks**, which will be used in ZEWT. To prove the technology readiness of production, storage and distribution, and power generation from hydrogen are inevitable. Therefore, CHE will research, develop and demonstrate technology to incorporate operational experience, but will do so for applications which are **suitable for first movers** and create synergies with for instance mobility and stationary sectors to increase impact. These first movers and opportunities are primarily found in type 1 vessels.

Figure 24. Synergies with ZEWT



Source: Hydrogen Europe

Vision for 2030 and proposed areas for support

FC and hydrogen technologies can provide a **commercially viable option for zero-emission marine transport** in certain use cases. For small ships (Type 1 and 2), hydrogen and fuel cells have the potential to become the **mainstream option** for zero emission ships. For larger vessels selecting **FCs can be a preferred zero emission propulsion solution**, using a range of fuel types. In order for that to happen, future development work will focus on improving access to the market for hydrogen and FCs on smaller vessels and advancing the components and fuelling systems required for larger ship types. More specifically we propose that the following areas should be supported by the Clean Hydrogen for Europe partnership.

Early Stage Research Actions (TRL 2-3)

The early TRL stage work will be carried out as part of the work defined in the “technology building blocks” roadmap. Special attention will be paid within these tasks to the specific needs of FCs in maritime applications, focussing on novel FC stacks and systems and the modular scale up of technology. Furthermore, development of alternative hydrogen carriers and on-board reforming will be part of the work. First demonstrations will uncover potential weaknesses in FCs and associated fuel infrastructure which need to be analysed and require further development.

Development Research Actions (TRL 3-5)

The maritime sector has a diversity of use cases with different demand profiles. Existing technology used in demonstration projects for type 1 vessels will indicate area`s for innovation and provide the basis for substantial development work on new technologies to expand the use of FCs to all maritime use cases (i.e. Type 2, 3 & 4). In addition, it will be important to undertake studies to determine how to provide low cost H_2 at ports/harbours. This will create opportunities for a shipowner's economic viable business case.

For ships in category 1, development projects should focus on optimising FC modules for maritime use cases, including work on the balance of plant and fuel storage.

- Design studies for type 1 ships using different combinations of fuel cells (or modified IC engines), a novel balance of plant configurations and different hydrogen carriers and possible reforming options to increase operational flexibility and FC durability.

Vision 2030

- ***FC passenger ships reach mass market acceptance for small in-land and coastal vessels, using hydrogen as a preferred fuel.***
- ***Larger vessels select FCs as a preferred zero emission propulsion solution, using a range of fuel types***
- ***Europe has become market leader for ZE technology for shipping***

For Type 2, 3 & 4 ships, which require higher autonomy and power, extensive development of existing technology for both FC and fuel is required. Integration of such systems will be executed within the ZEWT. Development projects could include:

- New technologies developments with increased scalability and power density of FC stacks and BoP, enabling the scale up of technology required for application in Type 2, 3 & 4 ships. This will involve LT and HT PEM fuel cells, as well as SOFC and MCFC systems capable of using a range of fuels and will include maximization of overall efficiency.
- Projects should investigate how to store and bunker very large volumes of energy in ports, either as pure hydrogen (LH_2) or as hydrogen carriers. This should be accompanied by a full costing and business case development exercise to test the viability of progressively larger and more autonomous zero emission vessels (and the associated refuelling infrastructure required). Furthermore, transporting of large quantities of LH_2 and other hydrogen carriers must be considered.

Demonstration Actions (TRL 5-7)

For vessels indicated in type 1 and to a limited extend in type 2, limited demonstration activity is already underway to prove the technology and associated refuelling infrastructure. However, further demonstration projects will be required to strengthen and consolidate the European maritime hydrogen value chain. Projects should work on applying hydrogen FCs and H_2 storage into new and existing vessels and installing the associated high capacity refuelling infrastructure into ports.

For larger ships, as of type 2, projects will be needed to validate the technical readiness of novel FCs and to determine the preferred fuel option for large vessels. Integration of FCs and applicable hydrogen carriers will be developed in the ZEWT.

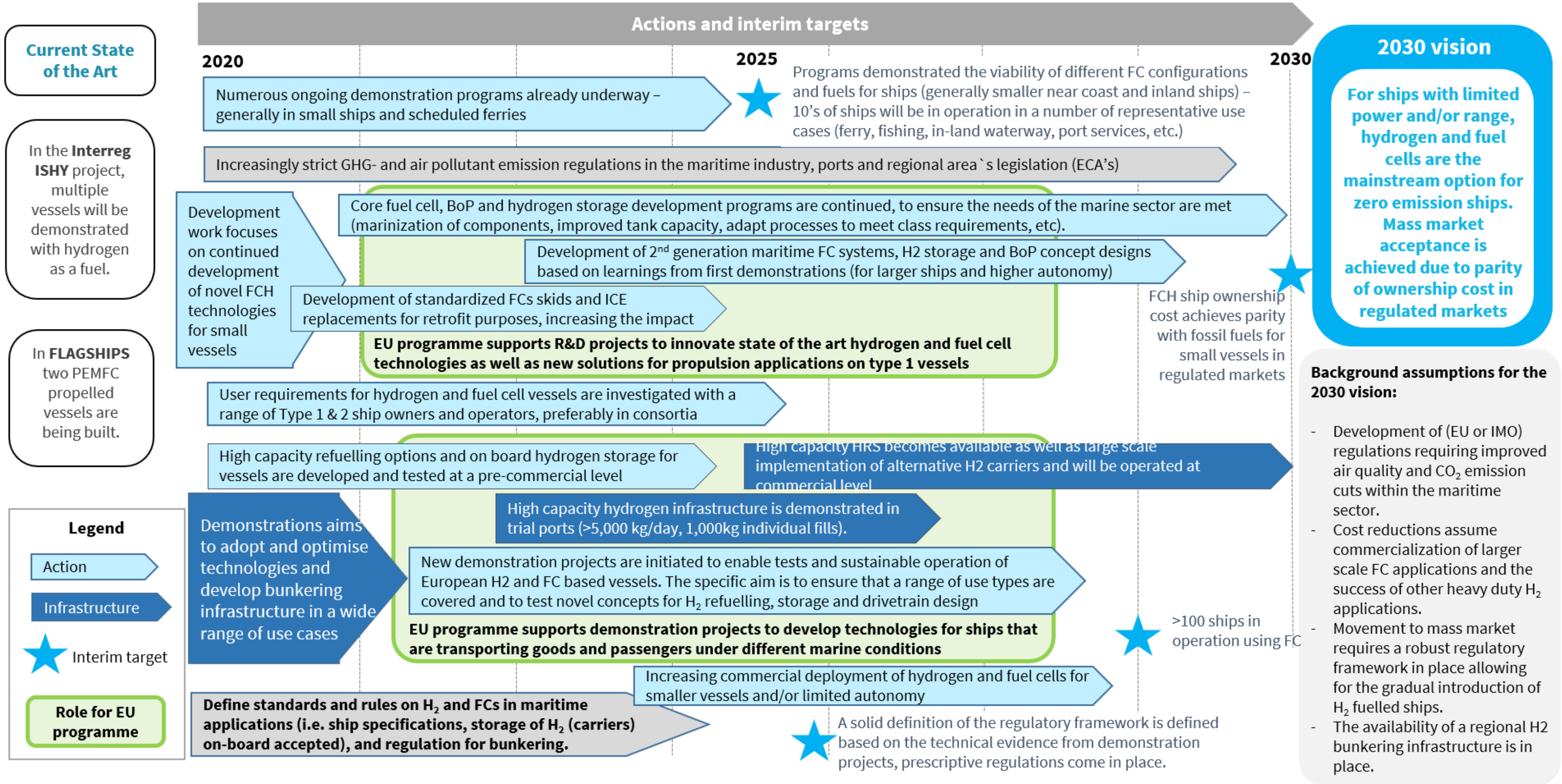
Flagship Actions (TRL 7-8)

Application flagship actions will be required by the FC maritime industry once technological readiness has been established, fuel costs are lowered, and a port infrastructure is available. This is mainly expected to come through a combination of regulation, a widely spread bunkering infrastructure and commercial pressure on ship operators to offer cleaner solutions.

Dedicated roadmap

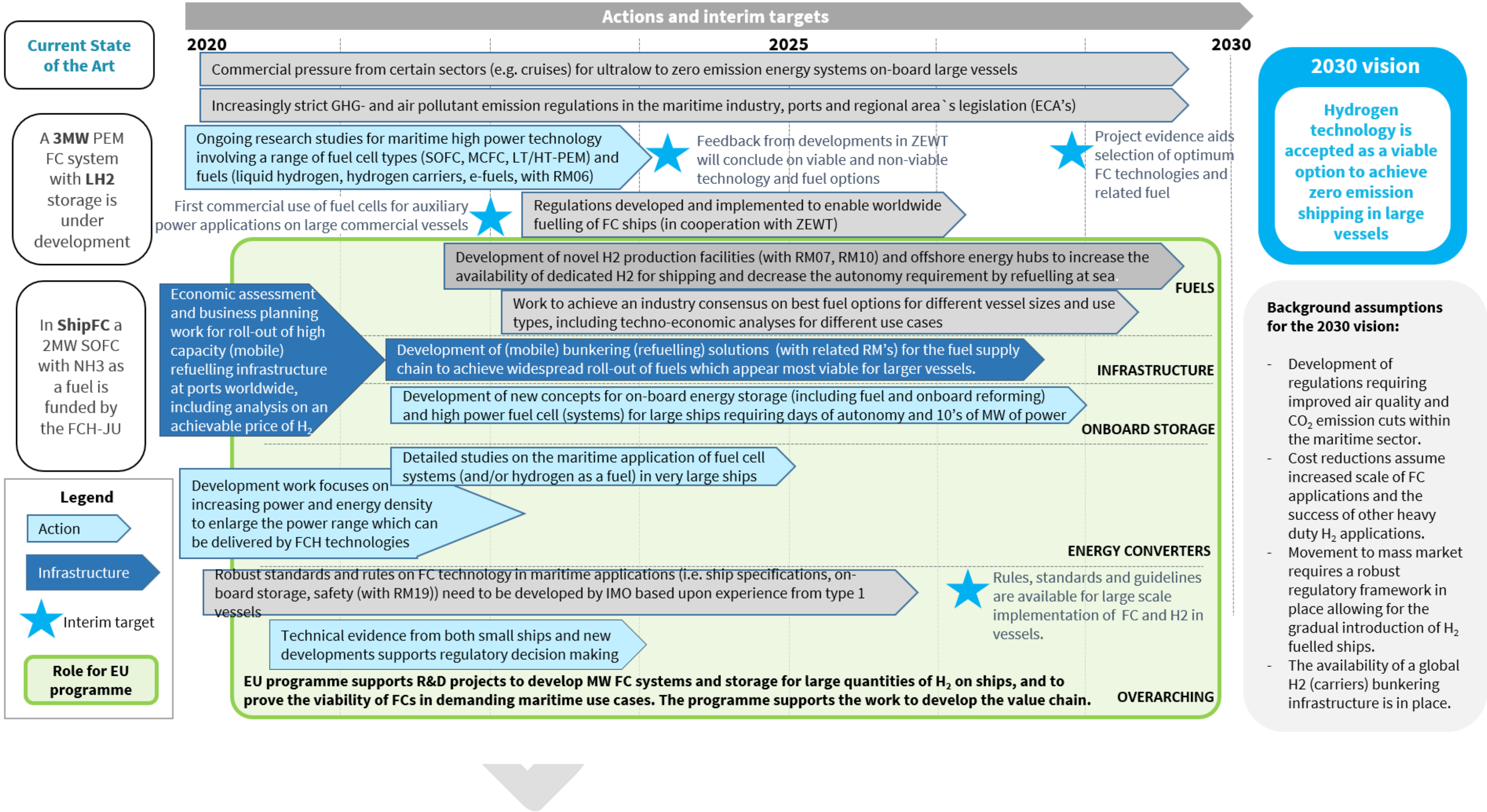
Detailed technology roadmap: Vessels in category 1

Propulsion and auxiliary loads can be replaced by clean hydrogen technologies



Detailed technology roadmap: Vessels in category 2, 3 & 4

Multi MW, clean hydrogen technologies to propel large ships as of 2030



KPIs

Further discussions are required between Hydrogen Europe and Waterborne TP to define a set of KPIs that should be in the remit of each partnership. Consequently, no KPIs are available yet.

5.1.4. Roadmap 13: Aviation

Rationale for support

The target of carbon neutrality of aviation in 2050 will be reached only by a combination of all available levers, such as technology, ATM, but also sustainable alternative fuels.

Hydrogen presents a strong potential, used in fuel cells or in dedicated turbines. Nevertheless, key technologies remain to be developed and demonstrated within the framework of Clean Hydrogen and Clean Aviation partnerships.

High power FC (1.5 MW) are yet to be developed in order to address the propulsion of small commercial aircrafts, as well as key technologies such as tanks and fuel systems.

Current status of the technology and deployments

The use of FCH in aviation applications is already being tested in demonstration projects across different use cases. However, due to the unique challenges posed by aviation (i.e. extremely large energy demands) projects to date focus on light, small-scale UAVs and passenger airplanes (<5 passengers). For example, the Hy4 project is the world's first four-seat passenger aircraft powered by FC technology. Demonstration projects are progressively targeting larger applications, yet very few demonstrations of hydrogen for propulsion (FC and turbine) have been performed.

APUs in aviation applications have also been tested through the HYCARUS project (2013-2018). Supported by the FCH JU, this project aimed to develop a Generic Fuel Cell System (GFCS) for use as auxiliary power on larger commercial aircrafts and business jets. Flight tests of the GFCS will be carried out in 2018 on-board the Dassault Falcon. Over time, as this technology is advanced and matured, FC applications will be deployed on progressively larger and heavier aircrafts and become operable in real-world service.

Aeronautics is one of the EU's key high-tech sectors on the global market. With world leading aircraft companies (i.e. AIRBUS, SAFRAN, Rolls-Royce and research institutes such as DLR) and expertise in fuel cell technologies, **Europe could play a vital role in driving the transformation of aviation** to reduce emissions. The potential economic gains of this area are large - in the UAV market alone, the EU could have a market share of c. €1.2 billion pa by 2025. In the civil aviation, the global market is estimated to be > 38 000 airplanes by 2034.

Synergies with Clean Aviation

Hydrogen is seen in Clean Aviation as a potential key enabler in the decarbonisation roadmap. Hydrogen use through:

- Fuel cell with Liquid / gaseous storage for Regional flights
- High power fuel cell (1MW+) using liquid hydrogen for the propulsion of short range SMR
- Dedicated turbine using Liquid hydrogen for SMR/LR
- Non-propulsive energy through fuel cell or turbo-electric architecture (as synergy for requirement work, but a different approach to propulsion)

Strong links with Clean Hydrogen initiative should therefore be established for key technological bricks and infrastructures, such as:

- Onboard storage of liquid hydrogen
- Fuel cell technology
- Low TRL hydrogen combustion research (synergy with stationary turbine developments)
- Airport infrastructure and refuelling tech / procedures

Hydrogen can also be envisaged as a base for liquid fuel through (for instance) Power-to-Liquid pathways.

Synergies proposal between the two partnerships are presented in the Table 36 below.

Table 36. Proposed synergies between CHE and CA

Area	Hydrogen Europe	Clean Aviation
LH_2 logistics	▪ Production ▪ Logistics to the airport (including synergies between aircraft usage and ground usage)	▪ Refueling technology
Storage in the aircraft	▪ Development of dedicated LH_2 tanks, in link with other applications	▪ Definition of fuel line and tank integration in the aircraft
Fuel cell (including dedicated fuel system)	▪ Follow-up of FC fundamental developments for non-propulsive applications ▪ Development of a dedicated fuel cell for propulsive applications, with a target of 1+MW ▪ Adaptation of the FC stack to aviation requirements	▪ Adaptation of the FC stack to aviation requirements, including heat management ▪ Integration in the aircraft and in-flight demonstration
Hydrogen combustion turbine (including dedicated fuel system)	▪ Low TRL research on low emissions combustion chamber with hydrogen (synergy with stationary turbine developments)	▪ Development of dedicated turbine (including fuel lines) ▪ Integration in the aircraft ▪ Ground and in-flight demos
Safety / Regulations	▪ All aspects linked to fuels logistics	▪ All aspects linked to aircraft operations
Environmental aspects	▪ WtW GHG balance	▪ Non-CO_2 effects

Vision 2030

- ***FCs are increasingly used for auxiliary power units & ground power units but also propulsion in civil aircraft***
- ***A selection of FCH aviation models achieve full certification and are in real-world operation, including small passenger planes (<50 seats)***
- ***First demonstration (ground, in-flight) of a LH_2 propulsion aircraft (Fuel cell / turbine)***

Vision for 2030 and proposed areas for support

Following discussions held between the two partnerships, an considering the study commissioned jointly by Clean Sky and FCH2 JUs[23] recently published, the following set of actions is being proposed.

Early Stage Research Actions (TRL 2-3)

- Special FC MEA Components for Aircraft applications
- Aviation dedicated technological bricks: evaporation unit LH_2 Tank, Gaseous H_2 compressors, valves and sensors (gauging)

Development Research Actions (TRL 3-5)

- Development of 250 kW FC stack and scalability of FC System and components to 1,5+ MW

[23] https://www.fch.europa.eu/publications/hydrogen-powered-aviation

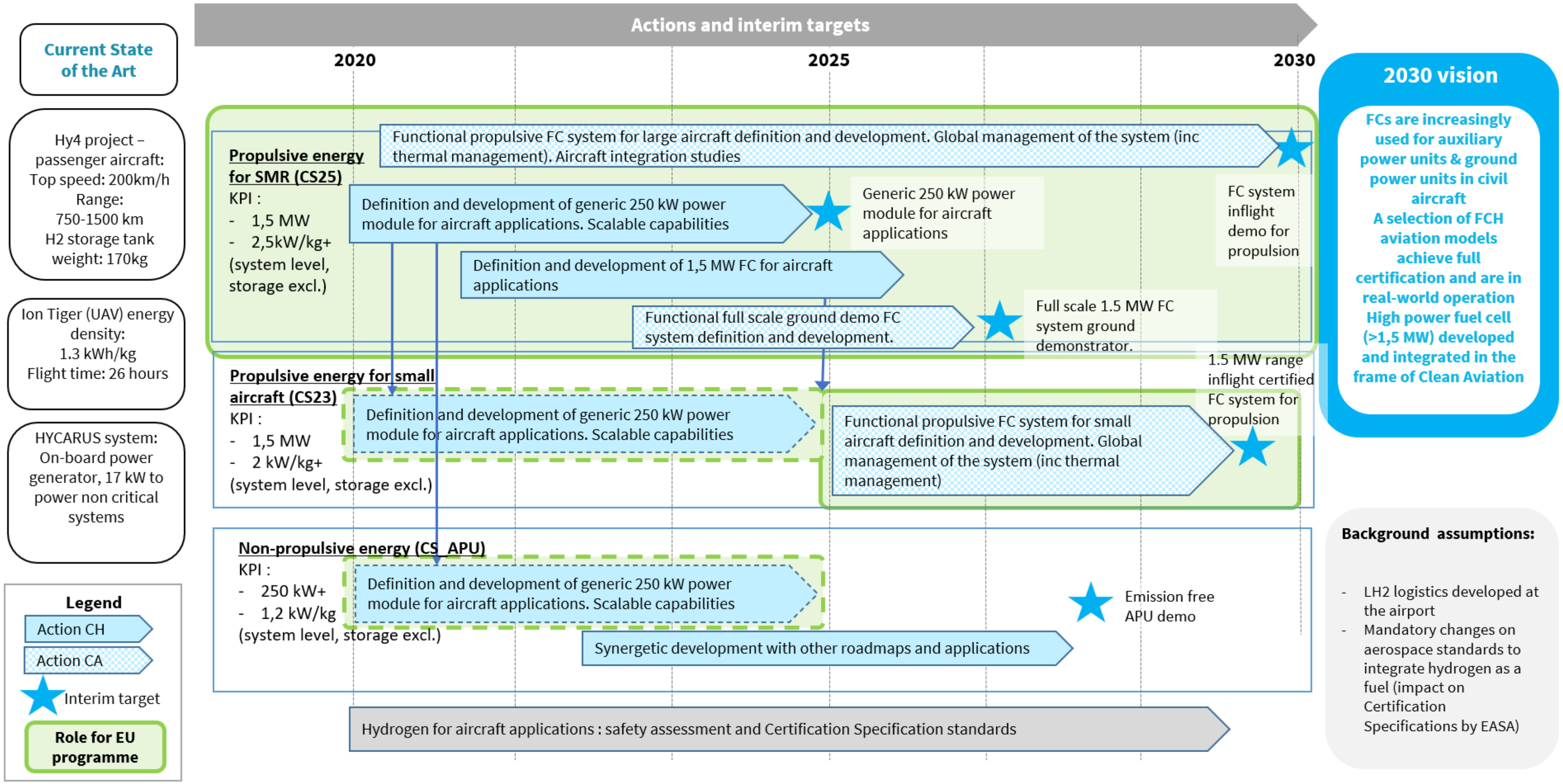
- High gravimetric BoP Research and Development
- Fuel handling LH_2 (including aircraft refuelling)
- New development of components and system controls
- Development of a low NOx / high efficiency hydrogen combustion chamber for aviation, in synergy with stationary applications

Demonstration Actions (TRL 5-7)

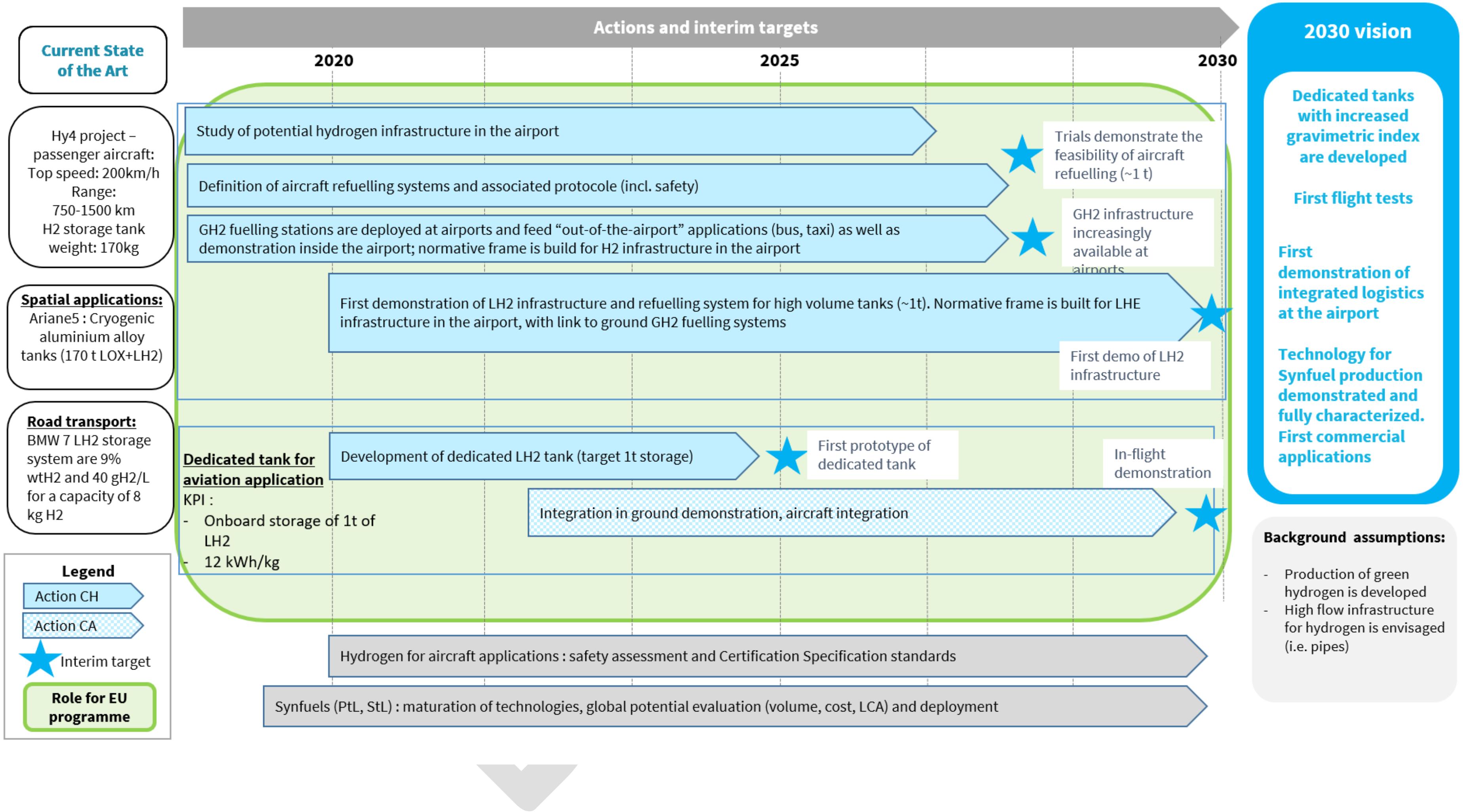
- Safety related system architecture of FC, LH_2 system
- Preparation of LH_2 System and FC System for integration for Demo in Clean Aviation
- Infrastructure challenges

Dedicated roadmap

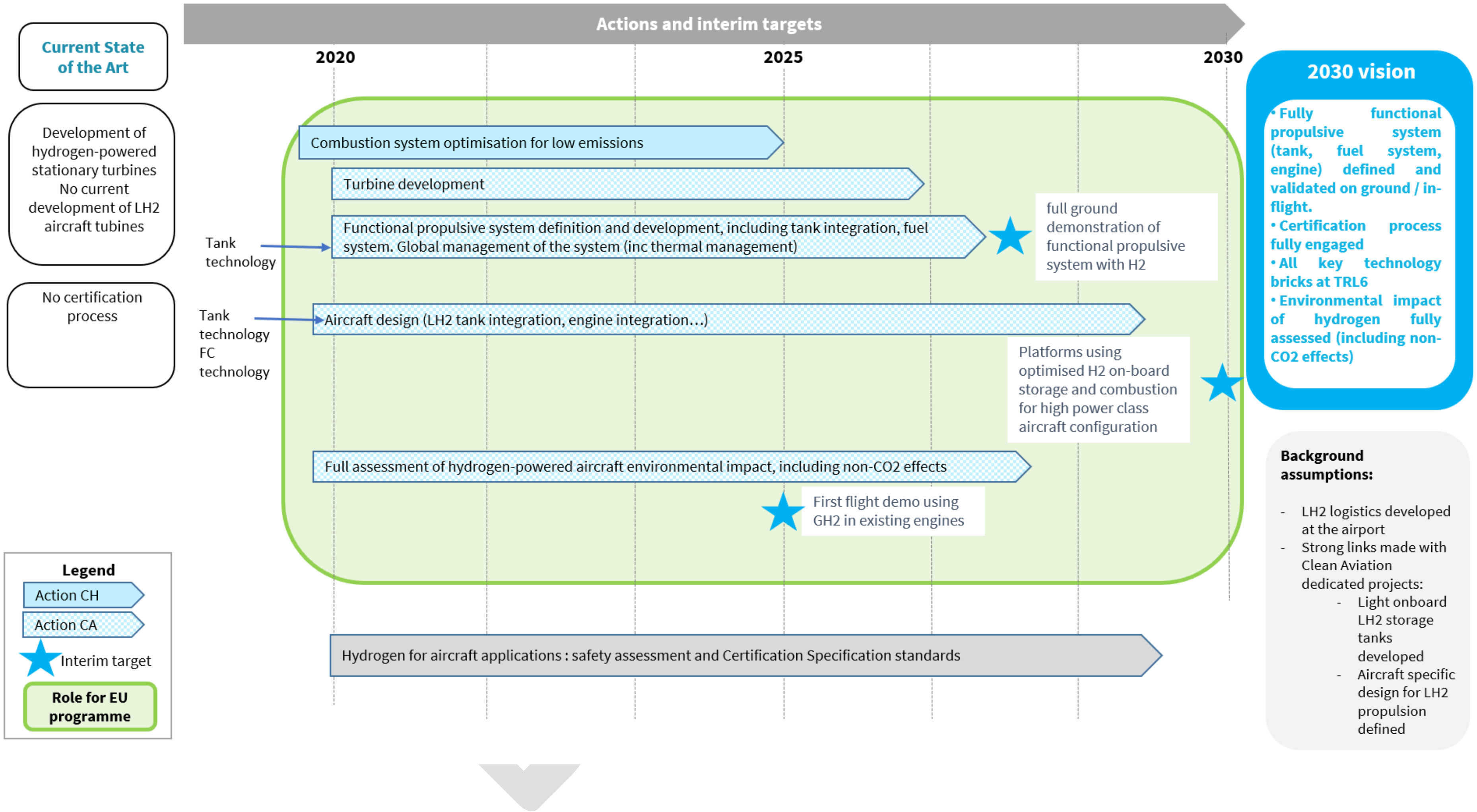
Aviation: detailed deployment roadmap



Aviation: detailed deployment roadmap



Aviation: detailed deployment roadmap



KPIs

Further discussions are required between Hydrogen Europe and stakeholders in the preparation of the Clean Aviation PPP to define a set of KPIs that should be in the remit of each partnership. Consequently, no KPIs are available yet.

5.1.5. Roadmap 14: Rail

Rationale for support

The majority of trains operating today are either diesel powered or electrified via overhead lines. Whilst electrification offers zero emissions at the point of use, overhead lines of traditional electric locomotives are expensive and logistically complex (so limited to higher capacity lines). Hydrogen offers several advantages over electric locomotives, e.g. freedom of the locomotives to roam, relatively little infrastructure required and the option to secure a zero-carbon fuel supply. **Hydrogen is key enabling technology to decarbonising rail transport as it can provide the most cost-effective solution** for certain lines that are still operated with diesel trains, by revamping diesel units or replacing existing trains with new hydrogen-powered ones. As well as **regional passenger trains**, FCH trains could provide viable zero emission options for **freight trains** and **shunting locomotives**. The technology requires further demonstration and optimisation of integrated FCH components into trains, development of flexible FC systems, and market deployment support to increase volumes and reduce costs. There is also considerable **effort required around regulation** for the use of hydrogen on railways.

Current status of the technology and deployments

A study of Shif2Rail and FCH2 JUs[24] pointed out a good potential for fuel cells in the railway environment for the replacement of diesel rolling stock. Some of the cases evaluated already show a positive Total Cost of Ownership (TCO) for fuel cells, while in others this technology is recognized **as the most adequate zero-emission alternative**.

Europe has adopted a leading position on the integration and assembly of FCH trains thanks to the innovative work from Alstom and Siemens. Whilst there is passenger train demonstration activity in Asia and Canada, it appears that Europe has the lead in this area especially with regards to the integration of the fuel cell drivetrain, the provision of large-scale infrastructure and regulation to allow the use of hydrogen on the railways.

Three European companies are developing new hydrogen fuelled fuel cell trains. Use cases based on this technology indicate that TCO be within 5-20% more of conventional options (depending on cost of hydrogen).

- The Alstom iLint FCH train has a 400 kW FC, and a max range of 1000 km (350 bar hydrogen, 260 kg stored on board) and can accommodate up to 300 passengers. Capital costs are c. €5.5M (excluding H_2 infrastructure). It has been approved for commercial operations in Germany, and 2 prototype trains have been in operation since 2018 with passenger service. 41 trains have been ordered for delivery in 2021/2022, and letters of intent for a total of 60 trains have been signed.
- Siemens are also working on a fuel cell version of their Mireo train, and there are plans to convert freight locomotives to use hydrogen (e.g. Latvian Railways). In the UK a number of train operators are exploring conversion of existing rolling stock to use hydrogen (e.g. Eversholt with Alstom).
- The hydrogen-powered FLIRT H_2 train from Stadler is planned to be introduced in 2024. The train is expected to have seating space for 108 passengers and in addition standing room, with a maximum

[24] https://www.fch.europa.eu/publications/use-fuel-cells-and-hydrogen-railway-environment

speed of up to 130 km/h. A first contract has been signed to supply a hydrogen-powered train to run in the United States.

Synergies with transforming Europe's rail system partnership

Initial discussions with UNIFE have already taken place, discussing high-level principles. Further discussions are required, and it is expected to reach a full common understanding on repartition of activities leading to a MoU in the course of 2020.

Vision for 2030 and proposed areas for support

The areas singled out for support have been selected with the end goal in sight of enabling hydrogen to be recognised as the leading option for trains on non-electrified routes, with **1 in 5 trains sold for non-electrified railways are powered by hydrogen**.

In order to make that objective a reality Clean Hydrogen for Europe needs to work in close collaboration with the Transforming Europe's Rail System Partnership as well as look for synergies with other funding sources – most notably CEF transport and CEF transport blending facilities for mass deployment of FC trains and the required hydrogen refuelling infrastructure.

Early Stage Research Actions (TRL 2-3)

Due to the FCH trains already achieving a high TRL (6) no early phase development projects will be funded.

Development Research Actions (TRL 3-5)

There is potential to reduce costs of FCH systems for trains through technological developments such as:

- Designing new concepts for on board bulk hydrogen storage e.g. cryo-compressed hydrogen or liquid storage.

Vision 2030

Hydrogen is recognised as the leading option for trains on non-electrified routes, with 1 in 5 new hydrogen-powered trains in 2030.

- Developing novel hybrid systems to optimise component sizing – Fuel cell specific train architecture. To date train architecture has been based on retrofit of existing components – there is space to optimise (e.g. space for hydrogen storage, use of waste heat) in purpose-built designs.
- Ensuring performances of very high capacity refueling stations (i.e. hydrogen infrastructure) meets railway technical, operational and safety specific constraints, in order to optimize production & distribution costs.

Demonstration Actions (TRL 5-7)

Projects need to be implemented across Europe to demonstrate that FCH trains could create cost-savings in comparison to diesel and electric trains. Demonstration projects will help to illustrate the technology's potential to:

- Ensure early deployment of trains of different types including local freight and shunting locomotives.
- Validate the commercial and environmental performance of the trains (and hence the claim of being the lowest cost zero emission option for non-electrified routes).
- Test very high capacity refuelling stations.

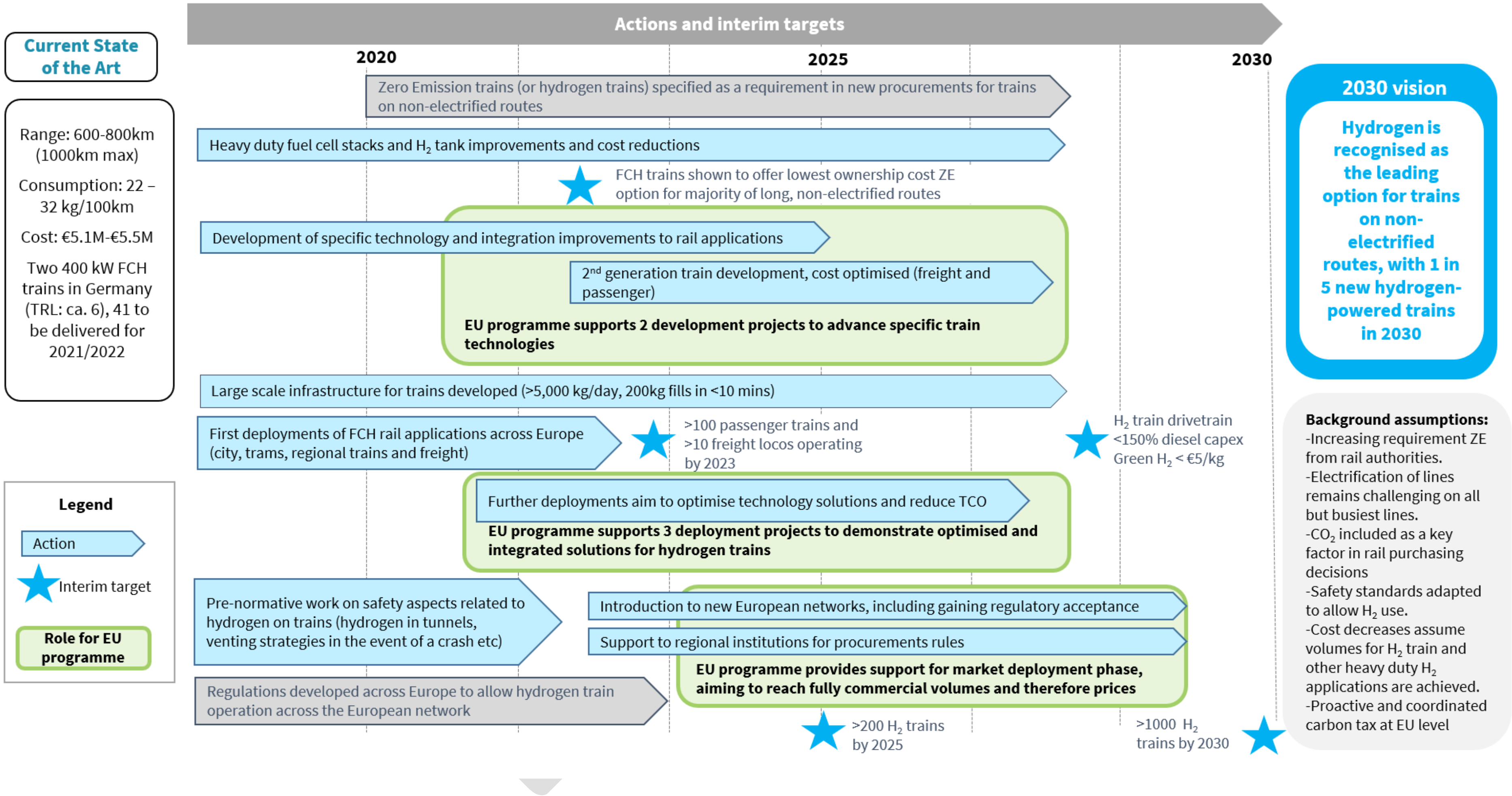
Such projects could also help to develop maintenance and support strategies for the vehicles and provide a basis to develop regulations to enable FCH trains and hydrogen use across Europe.

Flagship Actions (TRL 7-8)

Support to promote the deployment of ~100 trains across Europe to enable OEMs to begin standardised production and establish the technology as a mainstream option for Europe's train specifiers. Initial financial aid will help increase the scale of the technology across Europe as well as support the integration of hydrogen refuelling infrastructure across the continent.

Dedicated roadmap

Hydrogen fuel cell trains: detailed technology roadmap



KPIs

Most KPIs are sourced from the current MAWP of the FCH2-JU. Where KPIs are not available, we propose early suggestions based on expertise of the membership of Hydrogen Europe and Hydrogen Europe Research, as an outcome of initial reflections. Any input written in black indicates a good level of confidence and consensus on the KPI, while input in red flags a need for greater attention.

Table 37. KPIs FCH Trains

No	Parameter	Unit	SoA	Target	
				2024	2030
1	Fuel cell system durability	h	20,000	25,000	30,000
2	Hydrogen consumption	Kg/100 km	22 – 32	21 – 30	20 – 28
3	Availability	%	94	97	>99

1) Durability of the fuel cell system subject to EoL criterion output voltage at maximum power
2) Hydrogen consumption for 100 km driven under operations using exclusively hydrogen feed
3) Percent amount of time that the train is able to operate versus the overall time that it is intended to operate

5.2. Specific Objective 6: Meeting demands for heat & power with clean hydrogen

Hydrogen as a mean of decarbonisation for the power and heat demand of the residential, commercial and industrial sectors is in focus of TC4. The strategy relies on technologies whose high efficiency will guarantee the minimum emissions compared to conventional energy systems. The implementation of the proposed solutions is the most effective way to decrease the impact of the heat & power consumption, pathways for the clean and efficient exploitation of hydrogen by final users.

The direct conversion of chemical energy into electricity is achieved with fuel cells. If the hydrogen is generated from RES the FC is the unique technology able to generate silently clean energy (i.e. zero emissions). **Cost targets follow the market requirements and offer more and more economic opportunities to stationary FCs with increasing reliability and reducing operational costs**. Micro-CHP systems offer high flexibility in the residential and commercial sector and support the realisation of the distributed energy generation paradigm, able to ensure the balancing of the grid transmission lines. Electrochemical conversion has been envisaged also for surplus energy storage for medium/small size installation with reversible fuel cell. This will contribute to the improvement micro/medium sized grids, where smart management solutions could be easily accomplished by the installation of reversible Fuel Cells.

On large grids, the balancing demand is increasing due to the intermittency of RES, expected to be become even more critical as nuclear and coal-fired plants will be phased out. On this level, **gas turbines fed with clean hydrogen will complete the options for the full decarbonization providing stable energy supply**. Gas turbines ensure high-grade thermal energy generation as sub-product of the electrical energy generation for both industry and large CHP installations. Adaptation of existing gas turbines to gradually increasing levels of hydrogen will reduce the overall costs of the energy transition, as investments in new dedicated assets can be postponed. The transition towards a whole decarbonization is completed with the actions foreseen for burners and furnaces to accommodate these technologies for full hydrogen feeding.

The two roadmaps “Stationary fuel cells” (RM16, section 5.2.1) and “Hydrogen turbines & burners” (RM17, section 5.2.2) envisage actions to guarantee the progress of the research to solve the limiting bottleneck to improve performance, durability, cleanliness and availability. The subsection referring to industrial CHP in “Industrial Application” (RM18, section 3.3.1) also refers to the objective of decarbonisation of power and heat. Moreover, other measures will support the pace of deployment by cost reduction via advancement of production technologies and standardisation.

5.2.1. Roadmap 16: stationary fuel cells

Rationale for support

Fuel cells have a high electrical generation efficiency compared to most other generator technologies (reciprocating engines, gas turbines without combined condensing cycles). They can be used for distributed power generation eliminating electrical grid losses. They are proposed for a wide range of applications:

- CHP - Fuel cells (typically gas fuelled) can be installed in a Combined Heat and Power (CHP) system to provide heat for buildings as well as electricity at high efficiency - fuel cells have been designed for “Micro-CHP” applications, powering residential, commercial and light industrial buildings, for medium sized applications and for very large scale applications at power levels over 1MW. High-temperature stationary fuel cells can be fed directly with biogenic gases from anaerobic digestion or waste gasification for clean CHP on site.

- Back-up power and gen-sets (typically hydrogen or methanol fuelled) – because of fast response times and low maintenance needs compared to diesel systems, fuel cells are an ideal component of back-up and temporary power systems. Key markets are telecom towers and data centres, where there is a premium on reliable and clean power, and where pollutants and noise in urban and low emission zones are critical.
- Prime power (gas or hydrogen fuelled) – fuel cells can also be used as prime power providers. In Europe there have been limited prime power applications, but in the US and Asia, applications such as data centres and large corporate campuses have seen significant uptake. There is also a niche market associated with the use of waste hydrogen from chemical process plants (e.g. chlor-alkali and petrochemical plants).
- Energy system coupling and flexibility Reversible fuel cells and systems are under development which could operate in prime power and electricity system markets, using surplus electricity for hydrogen production and utilizing produced hydrogen in combination with natural gas or biogas for power supply.
- High-temperature fuel cells can separate CO_2 from effluent streams while generating power, leading to pure CO_2 for downstream use. In the USA, two companies are demonstrating large-scale CO_2 separation with support from European research institutes.

Current status of the technology and deployments

Deployment of stationary fuel cells in Europe has been limited compared to e.g. Japan where over 300,000 fuel cell CHP systems have been installed (targeting 5M systems by 2030), strongly supported by government subsidy. In the US and Korea, incentive programs have led to deployment of several >1MW fuel cell systems, whilst in Europe there are less than 5 MW-scale systems installed to date. The largest FC power plant operating in Europe is 1.4 MW.

Most installations in Europe have been supported by incentive programs, notably the FCH2-JU funded Ene.field project which has installed ~1,000 fuel cell CHP units and the PACE project as follow-up with 2,800 planned installations by 2021, with a view to decrease costs by >30%. German Government support for small fuel cells is also now encouraging increased pace of uptake. Currently the cost of fuel cell micro CHP is €10,000/kW, with >2,000 systems installed in Europe in 2020 and another 2,500 by 2021.

There is a strong European based supply chain for fuel cell CHP, which has been developed also thanks to FCH JUs' funded projects. It includes micro-CHP system integrators such as; Bosch, SOLIDpower, Viessmann, SOLENCO Power, as well as stack developers such as Elcogen, Serengy, Ceres Power, Sunfire, HELION, Bosch and mPower/Hexis. For larger systems there is more limited experience, though companies such as Convion (solid oxide fuel cells), AFC (alkaline FCs for waste hydrogen), PowerCell, NedStack (polymer FCs) and HELION are expanding, and European carbonate FC technology is being developed in Poland.

Vision for 2030 and proposed areas for support

In order to facilitate a widespread uptake for domestic and commercial buildings (with the aim of 2.5GW FC CHP units deployed and numerous European manufacturers producing 500MW sales/year by the end of 2030), the most immediate focus of the research agenda should be put on R&D on **new stack technologies and components to reduce costs and improve flexibility in operation**. Next step should be the development of **reversible**

fuel cell concepts leading to deployment of distributed commercial systems capable of linking electricity and gas grids at medium and low voltage levels.

Additional support for mass market activation can be provided through funding of flagship projects (or Hydrogen valley).

Early Stage Research Actions (TRL 2-3)

- Research into new cell materials, stack technologies, components and manufacturing processes for stationary fuel cell systems to improve system flexibility, durability and increase robustness of components under flexible operation.
- Research to develop advanced reversible cell concepts, based on both oxide ion and proton conductors.
- Fuel cells operating on alternative fuels, also considering opportunities for effluent capture and utilisation.

Development Stage Research Actions (TRL 3-5)

- Support to drive standardisation and cost reductions in the balance of plant components and in-operation processes such as predictive maintenance and development of fuel cell systems that are integrated with (smart) power grids, off-grid and decentralised renewable energy sources. Innovative manufacturing methods suitable for mass-production and enabling cost reductions. Develop a commercial/industrial scale CHP unit (100 kW – 1 MW) to demonstrate this.

- Integration work on reversible cell concepts, in particular to integrate a range of gas inputs (hydrogen – methane blends, biogas, syngas, ammonia), to improve the round-trip efficiency to above 50% and to develop concepts at a range of scales.

Demonstration Actions (TRL 5-7)

Vision 2030

- ***Widespread uptake for domestic and commercial buildings, with over 2.5GW FC CHP units deployed.***
- ***Numerous European manufacturers producing >500MW sales/year.***

- Demonstrate the deployment of the next generation of commercial/industrial scale fuel cell CHP and/or prime power units from European suppliers (100 kW – 1 MW).

- Demonstrate reversible cell concepts at sites with renewable generation and/or biogas/syngas inputs.

- Automated production, Quality assurance tools and techniques during production and End-of-Line testing (see also section 6.2.1)

Flagship Actions (TRL 7-8)

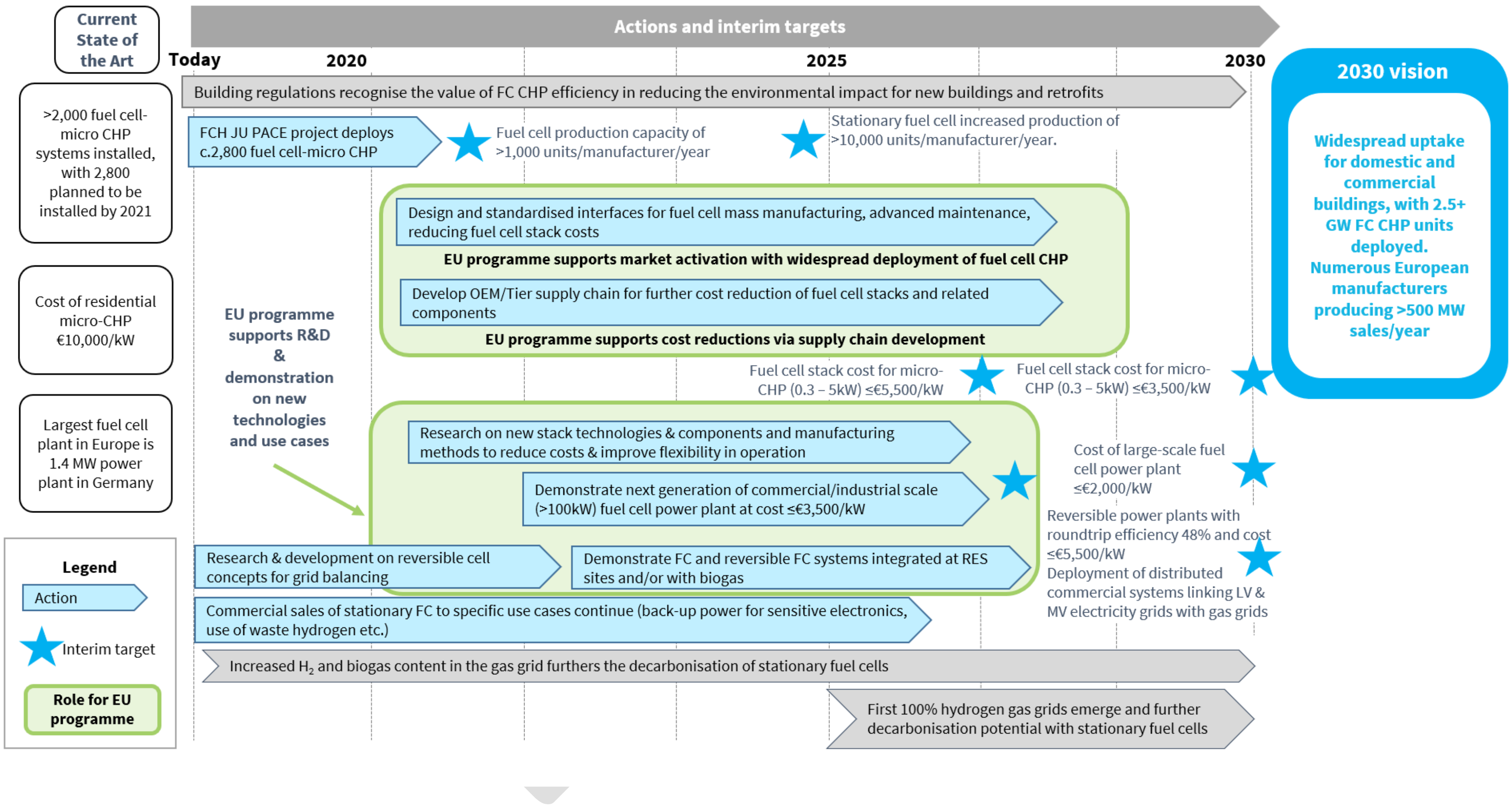
European support for the roll-out of fuel cell CHP, in concert with activities in other Member States (notably Germany). This type of programme, along with supply chain support has the potential to ensure European dominance in FC-driven CHP markets.

Where possible, support should be aimed at gas grids with a program to maximise the concentration of clean hydrogen or biogas, to build on the decarbonisation benefits of gas fired fuel cell CHP.

As 100% hydrogen gas grids are developed, the market activation support program should look to ensure a role for fuel cell CHP on these gas grids.

Dedicated roadmap

Stationary fuel cells: detailed technology roadmap



KPIs

Most KPIs are sourced from the current MAWP of the FCH2-JU. Where KPIs are not available, we propose early suggestions based on expertise of the membership of Hydrogen Europe and Hydrogen Europe Research, as an outcome of initial reflections. Any input written in black indicates a good level of confidence and consensus on the KPI, while input in red flags a need for greater attention.

Table 38. KPIs SOFC

No	Parameter	Unit	SOA		Targets		
			2017	**2020**	**2024**	**2027**	**2030**
	System*						
1.	Capital cost <5 kW_{el} 5-50 kW_{el} 51-500 kW_{el}	€/kW	16,000 12,000 12,000	10,000 10,000 10,000	8,000 8,000 7,500	5,500 4,000 3,500	3,500 2,500 2,000
2.	O&M cost 1-5 kW_{el} 5-50 kW_{el} 51-500 kW_{el}	€ct/kWh	20 17 15	10 12 10	8 7 5	4 3.5 3	2,5 2.0 1,5
3.	Efficiency @ BOL, **CH_4**: η_{el} (η_{tot}) <5 kW_{el} 5-50 kW_{el} 51-500 kW_{el}	% LHV net AC	**30** (85) **50** (80) **50** (80)	**35-55** (90) **55** (85) **55** (85)	**55** (90) **58** (85) **60** (85)	**55** (90) **60** (85) **62** (85)	**55** (90) **62** (85) **65** (85)
4.	Warm start time	min	20	15	10	5	2
5.	Specific system volume <5 kW_{el}	l/kW_{el}	230	220	210	205	190
6.	Tolerated H_2 content in CH_4	vol. %	n/a	0-15	0-20 or 100	0-25 or 100	0-30 or 100
	Stack						
7.	Degradation @ CI & FU=75%	%/1000h	0.8	0.6	0.4	0.3	0.2
8.	Production cost	€/kW_{el}	8,000	4,000	2,000	1,000	≤800
	Technology related KPIs						
9.	System roundtrip electrical efficiency in reversible operation	%	n/a	32	38	43	48

Notes:

*Standard boundary conditions that apply to all SOFC system KPIs: input of (bio-)methane, tap water (if necessary) and ambient air; output of electrical power and heat. Correction factors may be applied if different fuel is used.

1) Capital cost are based on 100MW/annum production volume for a single company and on a 10-year system lifetime running in steady state operation, whereby end of life (EOL) is defined as 20% loss in nominal rated power. Stack replacements are not included in capital cost. Cost are for installation on a prepared site (fundament/building and necessary connections are available). Balance of plant components are to be included in the capital cost. Capital costs doesn't include margins, distribution and marketing costs.

2) Operation and maintenance cost averaged over the first 10 years of the system. Potential stack replacements are included in O&M cost. Fuel costs are not included in O&M cost.

3) Electrical efficiency (ηel) is ratio of the net electric AC power (IEV 485-14-03) produced by a fuel cell power system (IEV 485-1818 09-01) to the total enthalpy flow (fuel LHV) supplied to the fuel cell power system. Heat recovery efficiency is ratio of recovered heat flow of a fuel cell power system (IEV 485-09-01) to the total enthalpy flow (fuel LHV) supplied to the fuel cell power system. Total efficiency of fuel cell power system (ηtot) is a sum of electrical efficiency and heat efficiency.

4) Time required to reach the nominal rated power output when starting the device from warm standby mode (system already at operating temperature).

5) Average volume requirement per kW of system comprising all auxiliary systems to meet standard boundary conditions in * and built up as indoor installation
6) Maximum allowable content of H_2 in (bio-)methane.
7) Stack degradation defined as percentage power loss when run starting at nominal rated power at BOL for fuel composition specified by stack manufacturer at constant current (density) and fuel utilization of 75%. For example, 0.125%/1000h results in 10% power loss over a 10-year lifespan with 8000 operating hours per annum
8) Stack production cost are based on 100MW/annum production volume for a single company. Stack production costs doesn't include margins, distribution and marketing costs.
9) Roundtrip electrical efficiency is energy discharged measured on the primary point of connection (POC) divided by the electric energy absorbed, measured on all the POC (primary and auxiliary), over one electrical energy storage system standard charging/discharging cycle in specified operating conditions. Only valid for rSOC systems.

Table 39. KPIs PEMFC

No	Parameter	Unit	SoA		Targets		
			2017	2020	2024	2027	2030
System*							
1.	Capital cost <5 kW_{el} 5-50 kW_{el} 51-500 kW_{el}	€/kW	n/a n/a 3200	6000 2500 1900	5000 1800 1200	4000 1200 900	3200 874 633
2.	O&M cost <5 kW_{el} 5-50 kW_{el} 51-500 kW_{el}	ct/kWh	n/a n/a 8	10 10 5	8 7 3	6 5 3	4 3 2
3.	Efficiency @ BOL, **H_2**: η_{el} (η_{tot}) <5 kW_{el} 5-50 kW_{el} 51-500 kW_{el}	% LHV net AC	n/a n/a 50(n/a)	50(n/a) 45(n/a) 50(n/a)	50(n/a) 50(n/a) 52(n/a)	53(n/a) 53(n/a) 53(n/a)	56(n/a) 56(n/a) 58(n/a)
4.	Warm start time	sec	350	60	15	10	10
Stack							
5.	Degradation @ CI	%/1000h	0.8	0.4	0.2	0.2	0.2
6.	Production cost	€/kW_{el}	(900)	400	240	180	150
Technology related KPIs							
7.	Non-recoverable CRM as catalyst	g/kW_{el}	n/a	0.1	0.07	0.03	0.01

Notes:
*Standard boundary conditions that apply to all PEMFC system KPIs: input of hydrogen, tap water (if necessary) and ambient air; output of electrical power and heat. Correction factors may be applied if different fuel is used.
1) Capital cost are based on 100MW/annum production volume for a single company and on a 10-year system lifetime running in steady state operation, whereby end of life (EOL) is defined as 20% loss in nominal rated power. Stack replacements are not included in capital cost. Cost are for installation on a prepared site (fundament/building and necessary connections are available). For PEMFC the EBOP (Power Conversion System or electrical balance of plant components) have not been included in capital costs. Capital costs doesn't include margins, distribution and marketing costs.
2) Operation and maintenance cost averaged over the first 10 years of the system. Potential stack replacements are included in O&M cost. Fuel costs are not included in O&M cost.
3) Electrical efficiency (ηel) is ratio of the net electric DC power (IEV 485-14-03) produced by a fuel cell power system (IEV 485-1818 09-01) to the total enthalpy flow (fuel LHV) supplied to the fuel cell power system. Heat recovery efficiency is ratio of recovered heat flow of a fuel cell power system (IEV 485-09-01) to the total enthalpy flow (fuel LHV) supplied to the fuel cell power system. Total efficiency of fuel cell power system (ηtot) is a sum of electrical efficiency and heat efficiency.
4) Time required to reach the nominal rated power output when starting the device from warm standby mode (system already at operating temperature).
5) Stack degradation defined as percentage power loss compared to nominal rated power at BOL for fuel composition and utilization specified by stack manufacturer at constant current (density).
6) Stack production cost are based on 100MW/annum production volume for a single company. Stack production costs doesn't include margins, distribution and marketing costs.
7) The critical raw material considered here is Platinum.

Table 40. KPIs High Temperature PEM fuel cells (HT-PEMFC)

No	Parameter	Unit	SoA		Targets		
			2017	2020	2024	2027	2030
System*							
1.	Capital cost <5 kW_{el} 5-50 kW_{el}	€/kW	17,000 n/a	15,000 n/a	10,000 n/a	8,000 n/a	6,000 n/a

2.	O&M cost <5 kW_{el} 5-50 kW_{el}	ct/kWh	20 17	10 12	8 7	4 3.5	2.5 2.0
3.	Efficiency @ BOL, **H_2**: **η_{el}** (η_{tot}) <5 kW_{el} 5-50 kW_{el}	% LHV net AC	**42** (90) **42** (90)	**45** (92) **45** (92)	**48** (94) **48** (94)	**50** (95) **50** (95)	**52** (96) **52** (96)
4.	Warm start time	min	10	5	4	3	2
5.	Specific system volume (≤5 kW_{el})	l/kW_{el}	n/a	300	150	75	30
6.	Tolerated H_2 content in CH_4	vol. %	15	15	0-20 or 100	0-25 or 100	0-30 or 100
Stack							
7.	Degradation @ CI	%/1000h	0.4	≤0.3	≤0.2	≤0.15	≤0.1
8.	Production cost	€/kW_{el}	n/a	1,200	<1,000	<800	<500
Technology related KPIs							
9.	Use of critical raw materials as catalysts	g/kW_{el}	8-12	4-8	< 4	< 2	< 0.5

Notes:
*Standard boundary conditions that apply to all HT-PEMFC system KPIs: input of (bio-)methane, tap water (if necessary) and ambient air; output of electrical power and heat. Correction factors may be applied if different fuel is used.
1) to 6) Similar conditions as for Table 38)

7) Stack degradation defined as percentage power loss when run starting at nominal rated power at BOL for fuel composition and utilization specified by stack manufacturer at constant current (density)
8) Stack production cost are based on 100MW/annum production volume for a single company. Stack production costs doesn't include margins, distribution and marketing costs.
9) The critical raw material considered here is Platinum.

Table 41. KPIs Proton Conducting Ceramic FC (PCFC)

No	Parameter	Unit	SoA		Targets		
			2017	**2020**	**2024**	**2027**	**2030**
Stack							
1.	Degradation @ CI & FU=75%	%/1000h	n/a	n/a	0.8	0.6	0.4
2.	Production cost	€/kW_{el}	n/a	n/a	8,000	4,000	2,000
Technology related KPIs							
3.	System roundtrip efficiency by reversible operation	%	n/a	n/a	n/a	35	40

Notes:
1) Stack degradation defined as percentage power loss when run starting at nominal rated power at BOL for fuel composition specified by stack manufacturer at constant current (density) and fuel utilization of 75%. For example, 0.125%/1000h results in 10% power loss over a 10-year lifespan with 8000 operating hours per annum
2) Stack production cost are based on 100MW/annum production volume for a single company. Stack production costs doesn't include margins, distribution and marketing costs.
3) Roundtrip electrical efficiency is energy discharged measured on the primary point of connection (POC) divided by the electric energy absorbed, measured on all the POC (primary and auxiliary), over one electrical energy storage system standard charging/discharging cycle in specified operating conditions. Only valid for systems designed for reversible operation.

5.2.2. Roadmap 17: hydrogen turbines & burners

Rationale for support

Turbines

Gas Turbines (GT) use natural or synthetic gas to provide dispatchable power and heat following the system and market requirements. In a system with an increasing share of variable electricity production from non-dispatchable renewable energy sources, **the high flexibility of gas turbine-based power plants can effectively ensure the grid stability and security of supply**. Used also in cogeneration systems, they can flexibly provide the necessary amounts of power and heat for industrial settings or district heating.

Their main advantage lies in the **power density**, which enables large amounts of power being available within a very short time and with a small footprint. Moreover, GT have a **significant fuel flexibility**, being able to burn a large variety of different fuel and with varying fuel composition.

GTs can reach thermal efficiencies up to ~43% as Open Cycle Gas Turbine (OCGT) and up to ~63% in Combined Cycle Gas Turbine (CCGT) configurations. In cogeneration mode, the fuel conversion rate reached is above 90%.

With the increasing admixture of decarbonised and renewable gases in the gas network, such as hydrogen, gas turbines increasingly become a source of sustainable dispatchable power and heat that deliver at any time according to the system needs. This in turn allows for additional amounts of variable renewables to be integrated into the system, supporting therefore Europe's energy system decarbonisation pathway. **A fuel switch to hydrogen aims to retain all present strengths of gas turbines while ensuring carbon-free energy conversion.**

Yet, the use of diluents or WLE[25] combustion (legacy technology) provides today only a sub-optimal solution to hydrogen firing of GTs and the aim of future R&D is to achieve **100% H_2 firing by DLE[26] combustion, still complying with NOx emissions targets (< 25 ppm) without the use of diluents and with minimal thermal efficiency penalty**.

Burners

Many processes such as drying, hot quenching or painting in the industry have a demand for high temperature heat that is today satisfied by gas boilers and burners. In commercial applications the use of alternatives such as heat pumps is often limited due to the need for high temperatures and the lack of adequate heat sources (temperature level and space restrictions).

As blends of hydrogen increase in the gas grid and conversion programmes for 100% hydrogen in the grid appear, there will be a need for commercial and industrial fuel flexible hydrogen boilers and burners to provide high temperature heat. **Gas burners and entire boiler units must be 100% hydrogen ready and fulfil the same NOx emissions standards as gas boilers by 2030**.

Both gas turbine and burner technologies provide **a unique opportunity to reutilise existing infrastructure**, reducing investment costs in new infrastructure and ensuring a cost-competitive transition to renewable gases and zero-carbon power generation. They do not pose strict requirements to fuel gas purity and are able to handle unproblematically

[25] Wet Low Emission

[26] Dry Low Emission

traces species, enabling therefore the adoption of cost- and energy-effective production and handling technologies for renewable and low-carbon fuel blends at large scale.

Current status of the technology and deployments

Turbines

Gas turbines are operating with renewable gases generated from carbon-neutral sources or synthetic fuels, like synthetic methane, and mixtures of natural gas up to 5% mass / 30% vol hydrogen with DLE. Currently higher hydrogen contents can only be claimed by use of dilution that can significantly affect GT NO_x emissions, efficiency, lifetime and cost (WLE).

Thermal efficiency (fuel conversion rate to electricity) depends on GT size (class). Indicative State-of-the-Art OCGT (Open Cycle) and CCGT (Combined Cycle) efficiency figures are:

- Heavy Duty GTs ~43%/63% (100-500 MW_e)
- Industrial GTs ~40%/55% (30-100 MW_e)
- Aeroderivative GTs ~35% (1-30 MW_e)
- Micro GTs ~30% (0.1-1 MW_e)

While the reduction of firing temperature has a positive impact in reducing flame stability issues and NOx emissions in hydrogen firing of GTs, it also negatively affects thermal efficiency, posing a considerable challenge. GTs of all classes (0.1-500 MW_e) are presently used in a wide range of applications typically using gaseous fuels (natural gas or syngas):

- CHP
- Back-up and peak demand power
- Prime power

[27] https://www.iea.org/data-and-statistics/charts/installed-power-generation-capacity-by-source-in-the-stated-policies-scenario-2000-2040

Vision 2030

100% hydrogen ready gas turbines & burners fulfilling emissions standards, for zero-carbon sustainable dispatchable power and high temperature heat.

- Energy system coupling and flexibility
- Energy supply chain

Europe has a strong turbine industry, notably Ansaldo Energia, Baker Hughes, Doosan Skoda Power, GE Power, MAN Energy Solutions, Mitsubishi Hitachi Power Systems, Siemens Gas & Power and Solar Turbines.

Vision for 2030 and proposed areas for support

Turbines

In long-term perspective, the installed electrical capacity increases for VRE and GTs only (IEA WEO 2019[27]) whereas GTs represent key assets to stabilize the energy system. By 2040, GTs will play a significant role in the European electrical capacity (25%, 431 GW_e i.e. 1043 TWh/year) implying that a yearly CO_2 reduction potential >450 Mt can be realized by increasing the content of hydrogen to 100% in the gas turbine fuel.

Burners

Today there are no hydrogen burners available on the market for commercial and industrial applications. Only for industrial applications (>1MW) the first custom made boilers have been shown. The next generation of boilers will be H_2 ready to be later retrofitted with hydrogen burners. No hydrogen surface burners are available today. The UK's project Hy4Heat represents an important milestone and potential synergy with the

CHE activity in this context, providing a precious source of data useful in the development of domestic and industrial hydrogen gas appliances.

Taking it into account, we propose the following areas to be covered by Clean Hydrogen for Europe:

Early Stage Research Actions (TRL 2-3)

- Combustion physics, flame stability and combustion dynamics in gas turbine operation with pure hydrogen and hydrogen-blends (including ammonia), focussing on development of new DLE combustion models for H_2 content up to 100%.

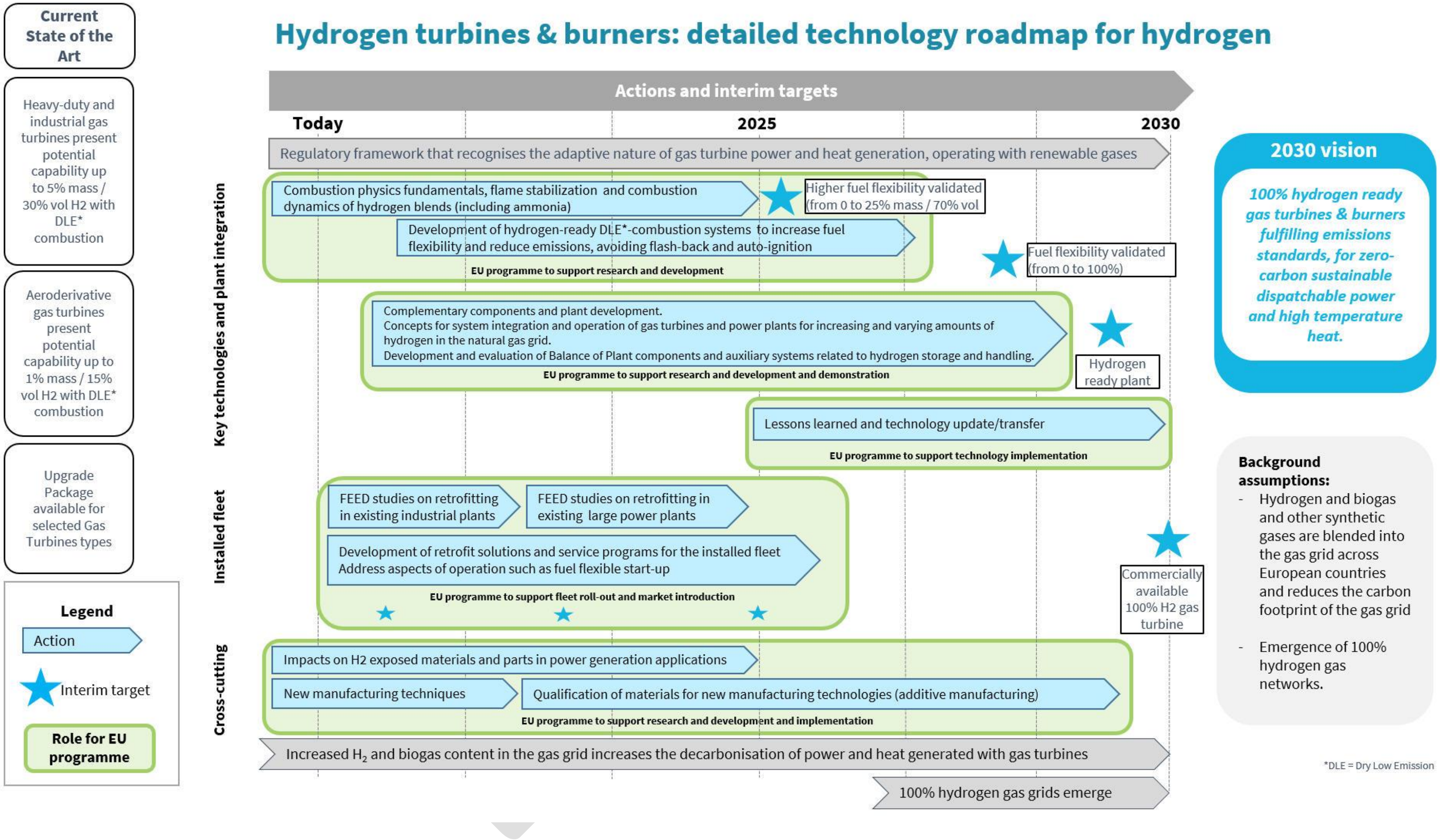
Development Stage Research Actions (TRL 3-5)

- Development of plant integration concepts, business models and value chains, incl. retrofitting
- Safety concepts, Standards and Norms (linked to cross-cutting activities, see section 6.3.3)
- Qualification and development of advanced material and manufacturing technologies of turbine hot path components
- Development of material exposed to H_2 and parts in power generation applications
- Development of a fuel flexible or pure H_2 burner for boilers, capable of accepting a growing percentage of H_2 in natural gas and with compliant NOx emissions (domestic & commercial scales). Research areas should focus on flame monitoring, optimal mixture formation, impact of buoyancy effects, flame stability & flashback, reduction of emissions and life-time analysis of thermally high stressed materials.
- Investigation of the influence of hydrogen and higher gas supply pressures on component tightness and thermal aging behavior.

Demonstration Actions (TRL 5-7)

- Demonstration of operation with wide fuel flexibility (up to 100% H_2) in selected industrial sites in Europe (different plant sizes, from tens to hundreds of MWs) using advanced gas turbines-based power and heat generation technologies
- Upgrade existing plants to safely utilise hydrogen enriched fuels

Dedicated roadmap



KPIs

Most KPIs are sourced from the current MAWP of the FCH2-JU. Where KPIs are not available, we propose early suggestions based on expertise of the membership of Hydrogen Europe and Hydrogen Europe Research, as an outcome of initial reflections. Any input written in black indicates a good level of confidence and consensus on the KPI, while input in red flags a need for greater attention.

Table 42. KPIs Turbines (DLE combustion)*

No	Parameter	Unit	SoA	2030 Target
1.	H_2 range in gas turbine fuel	*% mass (% vol.)*	0 - 5% (0 - 30%)	0 - 100%
2.	NO_x emissions	*ppmv@15% O_2*	< 25	< 25
3.	Maximum H_2 fuel content during startup	*% mass (% vol.)*	0 - 1% (0 - 5%)	0 - 100%
4.	Maximum efficiency reduction in H_2 operation	*% points*	2	2
5.	Minimum ramp rate	*% load / min*	10	10
6.	Ability to handle H_2 content fluctuations	*% mass / min (% vol. / min)*	±2% (±10%)	±5% (±30%)

* Applicable only to DLE (Dry Low Emission) technology. WLE (Wet Low Emission) technologies are not in scope.

2. A fuel switch to hydrogen aims to retain all present strengths and ensure carbon-free energy conversion. NOx emissions increase considerably as the hydrogen content in the fuel is increased, because of the higher reactivity of hydrogen and the consequences on flame stability, temperature etc. Keeping the same low-NOx emissions level from 5% (by mass) to 100% H_2 may not seem ambitious but is a serious challenge.

4. Evaluated at FSFL (Full Speed Full Load) condition.

6. Evaluated with respect to nominal H_2 content in fuel composition.

6. CROSS-CUTTING & HORIZONTAL ACTIVITIES

6.1. Specific Objective 8: creation of Hydrogen Valleys

6.1.1. Roadmap 21: Hydrogen Valleys

Rationale for support

The H_2 Valley concept has gained momentum in the last couple of years and is now one of the main priorities of industry and the EC for scaling-up hydrogen deployments and creating interconnected hydrogen ecosystems across Europe.

The aim of supporting the creation of Hydrogen Valleys is to **demonstrate interoperability and synergies between the three pillars** (production, storage & distribution, end use applications), to identify the best business-cases and showcase the value proposition of hydrogen with emphasis on sectorial-integration.

By contrast with the other roadmaps, emphasis is therefore not put on the technology development of an application but on an **integrated system-level approach** towards the production of renewable hydrogen, its distribution and storage, and its subsequent valorisation as energy vector in transport, industrial feedstock and electricity/gas grid.

A Hydrogen Valley can not only demonstrate how the hydrogen technologies work in synergies, it should also work in synergies with (or reuse of) other elements: renewable production, gas infrastructure, electricity grid, batteries, etc.

A key objective is to demonstrate the notion of **"system efficiency and resilience":** it is not only the energy efficiency of a single application that matters but the overall energy and economic efficiency and resilience of the integrated system.

A supported project could use low carbon and/or green hydrogen; however, production investment in CCS, SMR, coal gasification, are excluded from partnership funding.

Criteria for selecting H_2 valleys

In terms of innovation

The H_2 Valley topics should require unprecedented achievement in the following fields:

- System integration: what is assessed is not the innovation in developing one technology but in integrating several elements together to overall efficiency.
- System efficiency: what is assessed is the overall energy and economic efficiency of the integrated system.
- Market creation: demonstration of new market for hydrogen, especially when applications are used in synergies.
- Complementarity with RES + recycling + reuse/integration with other technologies, existing infrastructures, etc.
- Mutualisation of production or distribution and storage, assuming decentralisation as key parameter.
- Regulation

In terms of scope and budget

- The H_2 valleys should combine the three pillars (at least two should be in the project).
- The H_2 valleys should involve a total investment in the magnitude of **€ 80-100 million or more**.

- The H_2 valleys could receive a funding support from the partnership that does not exceed 30% of the total investment. Project promoters should be invited to search for other financial supports (see section on synergies). Project promoters must show political commitment at regional and national level at proposal stage.

In terms of impact

- Replicability (EU impact): the project demonstrates the economic and technical feasibility of an archetype of H_2 valley that can then be replicated in many other locations/integrated value chains.
- Continuity and expansion (local impact): the H_2 valley will continue to develop after the project and will further expand the market.

Depending on the budget of the partnership, a H_2 valley could be supported every year or every other year to reach different synergic solutions.

Process to prepare H_2 valleys throughout the programme

This roadmap defines the basics of Hydrogen valleys: rationale, scope, criteria, examples, etc. It is necessary to extend this work on a continuous basis. Throughout the CHE programme a working group will:

- Firstly, it further defines generic criteria applicable to all H_2 valleys.
- Secondly, it defines criteria for an archetype of H_2 valley that can then become a topic for the call for proposals:
    - Archetype/topic should bring a clear innovation by comparison with previous H_2 valleys and projects.
    - Archetype/topic should be defined in such a generic way that several consortia can apply proposing different approaches on synergies.
    - See examples of archetype in the next section.
- At the same time being aware of the portfolio of industrial projects in preparation to ensure that the topic can trigger several solid applications for optimisation of the funding chain.

Preparing projects of this size with the integration of many applications, partners and several funding sources requires long preparation, much longer than the 3 months between the publication of the call for proposals and the deadline for application. For this reason, it might be useful to consider publishing the topic 6 months in advance or in the previous call for proposals.

Examples of H_2 valleys

Here are a few examples of Hydrogen valleys that could be supported:

A port with combined production, transport and use of hydrogen for

- Ship fuel.
- Ports operation (material handling/power use at berth…).
- Transport (possibly import/export) and storage.
- Usage of H_2 in the port industrial hinterland.
- Port as logistical hub (truck or trains).

An airport with combined production, transport and use of hydrogen for

- Aviation fuel (H_2 as a fuel or H_2 made fuels).
- Airport operation (material handling/power use at airport).
- Airport as logistical hub (buses, cars, trucks, or trains).

An industrial hub with

- Mutualised H_2 production.
- Mutualised H_2 transport and/or storage.
- Multiple H_2 uses: H_2 for steel, refineries, chemicals, glass, industrial heat and power.

An H_2 infrastructure backbone

- A hydrogen pipeline and/or storage and/or a large liquefier which is mutualised.
- To accept production from several plants.
- To distribute H_2 to several locations and creating a first H_2 shared infrastructure serving a network of refuelling stations and/or uses for building and industry.

A logistical hub with combined production and use of hydrogen for

- Mutualised and decentralised production
- Multiple H_2 mobility uses: trains, HDVs, last mile, forklifts, etc.
- Uses in buildings and industrial heat and power

A H_2 city (or area) combining:

- Production.
- Distributions.
- Uses in buildings and transport.

Combinations of the above, for example:

- An industrial scale production hub on a port.
- Filling of ships, and bleeding H_2 into the local natural gas pipelines.
- Transportation of the generated H_2 inland via waterways.
- Transported H_2 used in large city applications (passenger car HRS supply, University hydrogen R&D facility feed).

Synergies and cooperation with other initiatives and role of the partnership

On this topic, the partnership and its members cannot work in isolation. Cooperation and synergies with

- Other funding instruments:
  - **IPCEI**. An Important Project of Common European interest is a specific possibility to overcome the first market and industrial deployment difficulties from R&D&I disruptive and ambitious projects, beyond the state of the art in the hydrogen sector, offering flexible funding schemes as much higher and closer to the market is.
  - **ETS Innovation fund**. Highly innovative European value added clean hydrogen technologies and big flagship clean hydrogen projects are suitable to be proposed to t he IF as one of the world's largest funding programmes for demonstration of innovative low-carbon technologies and energy intensive industrial processes by helping investment in the next generation of technologies needed for the EU's low-carbon transition, boosting growth and EU competitiveness, and supporting reaching the market.
  - **Regional, national, ERDF**. The European Regional Development Fund (ERDF) is one of the main financial instruments of the EU's cohesion policy. Its purpose is to contribute to reducing disparities between the levels of development of European regions and to reduce the backwardness of the least favoured regions by focusing on four strategic priorities: Research and innovation, Information and Communication Technologies, Small and Medium-sized Enterprises, and Promotion of a low-carbon economy.
  - **Green Deal Just Transition Mechanism**. Overall, coal infrastructure is present in 108 European regions and close to 237,000 people are employed in coal-related activities. Some of these regions' economies are highly dependent on coal so they have already developed strategies to reindustrialise their economies by designing regional hydrogen roadmap. The scale of the transition challenge - reindustrialisation process - of the highest greenhouse gas intensive regions as well as the social challenges in the light of potential job losses in this industry should be considered.

- **Other PPPs**; notably the notion of Clean and circular industrial hub developed by the homonymous PPP. EU Circular Economy Action Plan for a Cleaner and More Competitive Europe. This new Circular Economy Action Plan adopted by EC is one of the main blocks of the European Green Deal.
- **A New Industrial Strategy for Europe.** The EU must build on its strengths, including a robust industrial base, high quality research, skilled workers, a vibrant start-up ecosystem, mature infrastructure and a leading position in the use of industrial data. The EC has set up different priority areas, including energy and environmental as creating certainty for EU industry to become more competitive globally and enhance Europe's strategic autonomy.
- **CEF**. The Connecting Europe Facility is a key EU funding instrument to promote growth, jobs and competitiveness throughout targeted infrastructure investment at European level. It supports the development of high performing, sustainable and efficiently interconnected trans-European networks in the fields of transport, energy and digital services, in order to match the Europe's energy, transport and digital backbone at one stage.
- **European Investment Bank (EIB)** throughout InnovFin Energy Demonstration Projects. They provides loans, loan guarantees or equity-type financing typically between EUR 7.5 million and EUR 75 million to innovative demonstration projects in the fields of energy system transformation, including but not limited to renewable energy technologies, smart energy systems, energy storage, CCS and CCU, helping them to bridge the gap from demonstration to commercialisation.
- **Enhanced European Innovation Council (EIC)** pilot. It supports top-class cutting-edge innovations, entrepreneurs, small companies and scientists with bright ideas and the ambition to scale up internationally.
- Creating interconnected hydrogen ecosystems across Europe by bringing successful experiences and stories from previous projects, interested EU regions, EU and overseas acknowledge and monitoring the portfolio of H_2 valleys in preparation can be in good cooperation with
    - S3 Smart Specialization Platform - H_2 Valleys Partnership (S3P-EHV)
    - FCH2-JU initiatives to monitor H_2 valleys in the context of Mission Innovation, such as Hydrogen Valley Platform (H2V), PDA regions, etc.
    - The cooperation between HE and IEA in tracking preparation of industrial scale hydrogen projects.

Relevant members of Hydrogen Europe and Hydrogen Europe Research are also taking an active role in these other initiatives; therefore links could be facilitated.

Remark: H_2 valleys projects are part of a broader categories of projects called flagship projects: i.e. project of such a size and maturity that after their completion they can be replicated at scale and on a commercial basis. Flagship projects include H_2 valleys but also mono-application projects (e.g. the existing JIVE and JIVE 2 projects that are demonstrating 300 buses). In view of the size of the required investment (80-100M or more), the grant is limited to a modest share of the investment, and the projects' promoters are invited search other feasible support.

6.2. Specific Objective 9: supply chain development

6.2.1. Roadmap 20: Supply chain & industrialisation

Rationale for support

Whilst the benefits of fuel cells and hydrogen (FCH) may be achieved irrespective of the geographical origin of the technologies used, the benefits to Europe could be greater if the European industrial supply chain for components for hydrogen production and its use were to play a strong role. While Europe has a very strong research and technology base, and strong supply chain actors in some areas, Japan, Korea and some parts of the US have been the early movers in the actual deployment of FCH technologies, and they are now being joined (and are likely to be overtaken) by China.

Supply chain development is key to securing inward investment and maintaining competitiveness. The FCH sector includes a series of highly successful SMEs that have developed products and are eager to move to **massive large-scale manufacturing** to enable cost reductions and market penetration to match the growing demand, which tends to 40 GW of electrolysis installed in Europe by 2030. This typically requires investments higher than €50 million. Despite the former lack of private European investors, funding mechanism can be found now. This paradigm change leads to a relevant bottleneck issue at FCH component and (sub)system suppliers' level. To provide funding for suppliers that'd like to improve and increase their capacity manufacturing at cost reduction with a clear focus on innovation in new machines and new manufacturing processes, will give a chance to those numerous companies that have technologies and skills that can be useful in the FCH field. However, they do not have contacts or know little about the sector, so they are hesitant in offering their products. Therefore, **constant monitoring** of the evolution of the overall supply chain as well as **raising industry awareness** are key to stimulate greater numbers of supply chain players in the FCH field.

Current status of the technology and deployments

The sector is diverse, complex and interlinked. The 'pure-play' FCH sector is fragmented and consists mainly of relatively small organisations, specialists either in final application assembly or in components, but rarely in both which tend not to be profitable. Major companies are gradually increasing their stakes in FCH technologies, but it only represents a small part of their activities still largely viewed as investment for the future. Focus must be put in **developing new manufacturing technologies** at cost reduction and up-scaling efficiency increase to mitigate technology and raw material bottlenecks.

Europe has strengths in key components of fuel cell stacks: catalysts, membrane electrode assemblies, bipolar plates and gas diffusion layers. Over 30 European companies sell these products worldwide today and are well positioned to take a significant share of the growing markets.

Europe has further international strength in the hydrogen production, distribution, storage and handling technologies. Europe is a global leader in electrolysis in all technology types, from component supply to final product manufacturing and integration capability. About 20 European companies offer or develop electrolysis systems while 10 European companies offer hydrogen refuelling stations, creating an unrivalled ecosystem of HRS development, deployment and worldwide export.

In terms of mobility (HDV, rail, buses), Europe has adopted a leading position on the integration and assembly. It is well placed to respond to the growing demand for zero emission applications. Nevertheless, there is still significant potential for other European companies in this area.

Unlike in most world regions, Europe has smaller, specialised integrators developing and launching new products and concepts in addition to the major manufacturers. These still bring additional supply and purchasing opportunities. If European production focuses mostly on components, exports are offset by imports of systems and subsystems whereas a stronger participation in the whole FCH value chain - from specialised materials or (sub)components all the way through to subsystems and system integration - will lead to stronger export performance. Given the right support, regulations and frameworks, substantial portions of these supply chains would be European, and these deployments would also strongly support local economic development in installation and servicing.

Knowledge-based actors - EU universities, research institutes, etc. - are strong across many FCH related fields, from fundamental research through engineering to social science and business studies. They are vital in developing the human resources needed for the FCH sector to succeed and in the fast identification of technology and raw material risks of bottlenecks to prepare potential mitigation plans, develop PNR, disseminate, etc.

Vision for 2030 and proposed areas for support

To achieve this objective, it is necessary to **identify and promote key value chains of strategic importance to Europe**. Focus must be put on up-scaling and innovations within component and equipment manufacturing but maintenance/after-sale assistance must also be undertaken as well as to strengthen EU leadership on research and manufacturing of product components by reinforcing the integrators' role. To keep high quality products, it is fundamental in a massive industrial production to develop capable processes and quality control systems in the various production phases and at the end of the line.

The following proposed actions build on the recent work by the FCH2-JU in mapping of the EU FCH value-chain , including the supply-chain, that was prepared with the aim to identify the main bottlenecks/and weaknesses and put in place well-targeted actions in order to address those.

Vision 2030

- ***European manufacturers are global leaders***
- ***At least 2 European suppliers on the most critical components***
- ***Non-FCH mature supply chain has adapted. Supplier capacity enlargement at reduction cost***

We propose to support:

Early Stage Research Actions (TRL 2-3)

- Developing new manufacturing technologies, innovative sensors and actuators, production processes including automation and semi-automation, production equipment, defect detection, technical cleanliness, etc. to improve production speed, process capabilities and yield, real-time quality control in the manufacturing process (2021-2024). Targeted R&D programmes already exist, so additional support would require co-ordination with these programmes.

Development Research Actions (TRL 3-5)

- Mapping and monitoring critical components and subsystems, bottlenecks, etc. to advise the EC/FCH2-JU on key FCH value chains in Europe that require joint, well-coordinated actions and investments. Identifying changes in manufacturing approach that will lead to step changes in production speed and labour costs. Build a common European vision for key FCH value chains. Raising industry awareness to stimulate greater numbers of supply chain players and increased production rates.

- Manufacturing training (qualified people, technicians, maintenance and after-sales, etc.), linked with cross-cutting activities (see section 6.3.2)
- Supporting EU companies to access export markets
- Integrating of new manufacturing technologies, innovative sensors and actuators, production processes and equipment, defect detection, technical cleanliness, etc. to improve production speed, process capabilities and yield, real-time quality control in the manufacturing process. Targeted R&D programmes already exist, so additional support would require co-ordination with these programmes.
- Non-FCH mature supply chain adaptation to FCH. Medium size scale experiments.
- Non-FCH mature supply chain adaptation to FCH. Big size scale experiments.

In terms of digitisation, we propose:

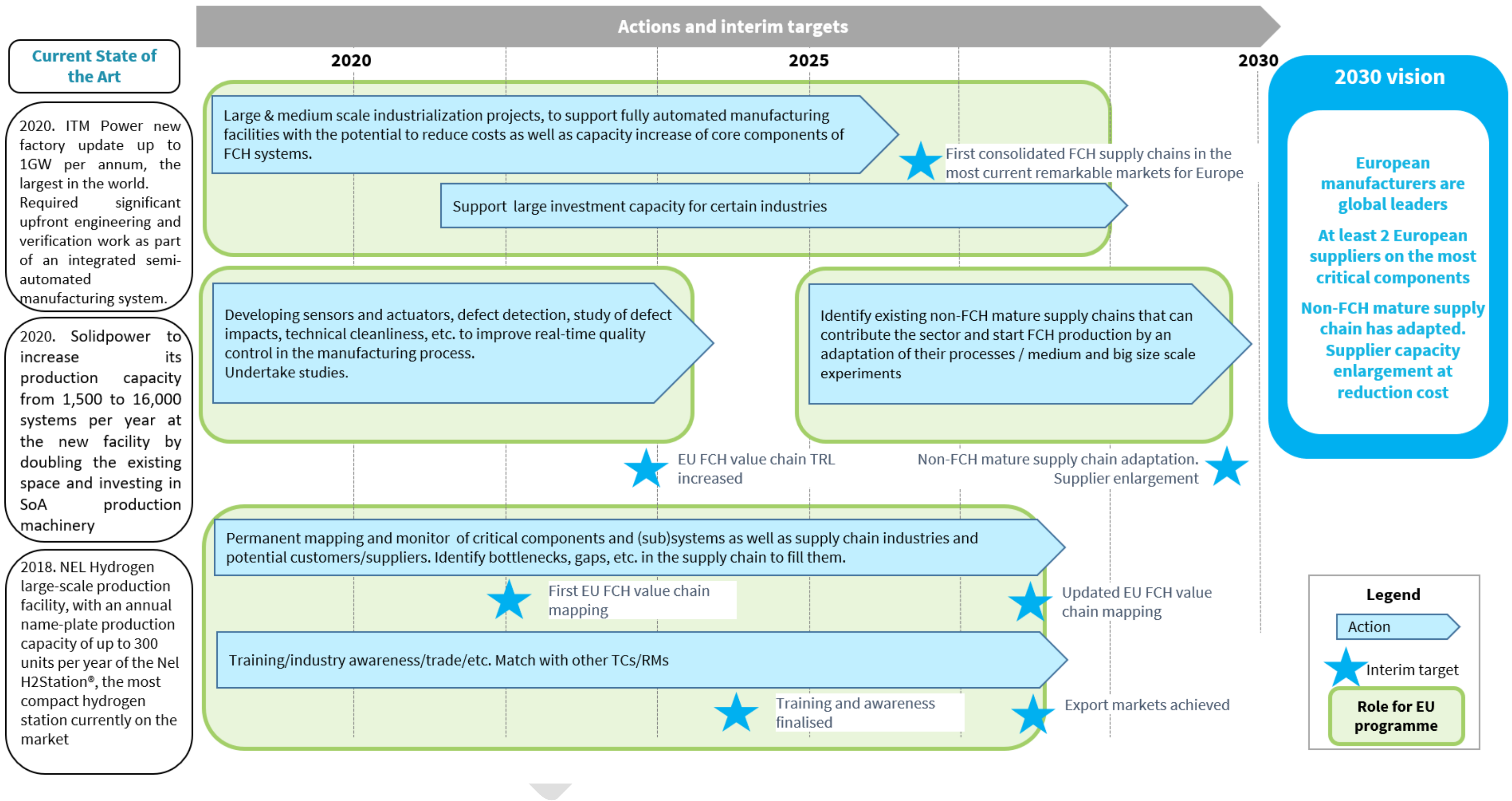
- Exploring the possibility of using AI and other emerging digital technologies to improve the manufacturing and /or maintenance of fuel cells, electrolyser components or other crucial equipment
- The creation of Digital Twin tools, for failure and reliability forecasts, grid stabilization, system optimization, risk assessment, renewable energy integration impact, as well as virtual testbeds for new business models, and economical feasibility of new concepts.
- Exploring the Distributed Ledger Technologies to establish a trusted sector coupled co-creating eco-system.

Demonstration Actions (TRL 5-7)

- Supply chain innovation to FCH within medium manufacturing capacity
- Supply chain innovation to FCH within large manufacturing capacity
- Implementation of quality measures

Dedicated roadmap

Supply chain: detailed roadmap



KPIs

Most KPIs are sourced from the current MAWP of the FCH2-JU. Where KPIs are not available, we propose early suggestions based on expertise of the membership of Hydrogen Europe and Hydrogen Europe Research, as an outcome of initial reflections. Any input written in black indicates a good level of confidence and consensus on the KPI, while input in red flags a need for greater attention.

- Value-added % increase
- Number of EU suppliers by component/(sub)system
- Direct employment impact
- Indirect employment impact
- Trade balance impact
- Current production capacity and planned production capacity in 2024 and 2030
- Technology, manufacturing and commercial readiness levels
- Industry value, M€/year
- System production capacity per company, units/year

6.3. Specific Objective 10: cross-cutting issues

6.3.1. Roadmap 19.1: Sustainability, LCSA, recycling and eco-design

Rationale for support

Aligned with the EU strategy, the FCH sector should ensure its circularity, which is covered within this roadmap with the aim of **minimizing the impacts of the products from its design; ensuring its recovery, reuse and recycling with emphasis on the recovery of materials (Platinum Group Metals - PGMs and Critical Raw Materials - CRMs); and supplying the assessment tools required**:

- Life cycle thinking tools (LCA, LCC, SLCA, LCSA) are methodologies to assess the environmental, economic and social impacts associated with all the stages of a product's life cycle. Such an assessment of hydrogen systems will prove their sustainability through Life Cycle Sustainability Assessment based on Standards (LCA + LCC + SLCA).
- Recycling is the most sustainable solution not only from an environmental and social impact perspective but also in terms of resource and economic efficiency. The recovered materials can serve the production of new products sold into global commodity markets, hence, increasing the security of future raw material supply, especially CRMs/PGMs. Recycling industry requires the balancing of several factors such as high collection rate, high recovery, and recycling targets, which are primarily driven by policy (regulations and policies), economic (cost savings), and market initiatives (balancing demand and supply), considering also social (reducing health risks, new jobs creation) and environmental (reducing energy payback time, appropriate EoL (End of Life) chain) drivers. Furthermore, recycling of CRMs/PGMs will reduce the external European dependency throughout a better design.
- Eco-design and sustainable design are focused on (re)designing the product to minimize its environmental and social impacts in each stage of its life cycle, from the extraction of raw materials to production, distribution, use and end-of-life. The products are redesigned to ease its reparability, re-use, recovery of pieces and materials (CRMs/PGMs/Storage), and recycling. It also supports industrial competitiveness and innovation by promoting the better environmental performance of products throughout the internal market.
- Eco-efficiency is also focused on the FCH processes in order to be economically and environmentally sustainable from a life-cycle perspective, aiming to cover all the different hydrogen technologies available today.

FCH market is ready to start its deployment in different applications and levels. It is necessary to develop **sustainable approaches in all the cases to fully comply with environmental principles and goals**. LCA tools have been developed to cover environmental, social, and economic aspects. Also, **strategies for recycling** have been proposed, as well as the adaptation of processes for other non-FCH devices. There is not any specific development for FCH products (eco-design) or processes (eco-efficiency) as such, or any corporative responsibility guidelines or sustainability indicators database. To improve FCH sustainability, key focus areas for development are **complete and integrated LCSA tools, enhanced recovery of PGMs/CRMs, development of recycling integrated processes, and development of eco-design guidelines and eco-efficient processes.**

Current status of the technology and deployments

LCSA framework for FCH systems to be developed (FCH-04-5-2020) going beyond previous project outcomes (the FC-HyGuide guidance documents) as well as past international initiatives such as the IEA Hydrogen Task 36 on LCSA of Hydrogen Energy Systems (including harmonization of life-cycle indicators for comparative studies).

Prepar-H_2 Preparing socio and economic evaluations of future H_2 lighthouse projects. The final outcome was systematic social and economic datasets providing grounds for accompanying measures in future hydrogen lighthouse projects.

For FCH technologies' recycling, the project HyTechCycling has delivered reference studies and documentation to pave the way for future actions. Currently, there are materials in FCH technologies that lacks recycling technologies, meanwhile for other materials as PGMs, used in other industries or sectors as catalysts, companies as UMICORE have technology available. Novel recycling processes that provides added values (e.g. suitable for more than one material present in FCH technologies, able to work with CRMs recycling) and that solve the lack of recycling process for specific components needs to be addressed, to increase the circularity of hydrogen technologies.

Two eco-design guidelines to be developed under the call FCH-04-3-2020, however more guidelines for other products families are lacking.

Expertise and capabilities from European institutions throughout the entire FCH value chain will play a leading role in the development of different tools for H_2 globally. Corporate social responsibility will be essential to offer a great added value to key European players. Different European institutions have already developed LCA tools, as well as eco-design and recycling approaches. Adaptation and further development of the current circularity solutions will ensure the commitment with the sustainable development goals.

Vision 2030

- ***FCH is recognised as a sustainable and circular sector with recycling as part of the value chain, and as main contributor to reach the European goals on decarbonisation, climate and clean cities.***
- ***LCSA tools and eco-design/eco-efficiency integrated in decision-making of FCH companies.***

Vision for 2030 and proposed areas for support

Sustainability, LCSA, recycling and eco-design activities will be strategically important by 2030. To address these issues, we propose the following actions:

Early Stage Research Actions (TRL 2-3)

Development work is needed to optimise the recycling technology for Solid Oxide FCH processes. Learnings from this work should be able to be scaled-up towards market deployment.

Coordination and Support Actions (CSA)

Building on the previous projects' development, the actions from Cross-cutting activities will be made throughout the following areas:

- EU Eco-design Directive preparatory study for future regulations
- Ten eco-design/sustainable design guidelines
- Eco-efficiency integrated in FCH manufacturing
- Development of PEFCRs
- Regionalised LCSA
- SLCA-LCC on supply chains

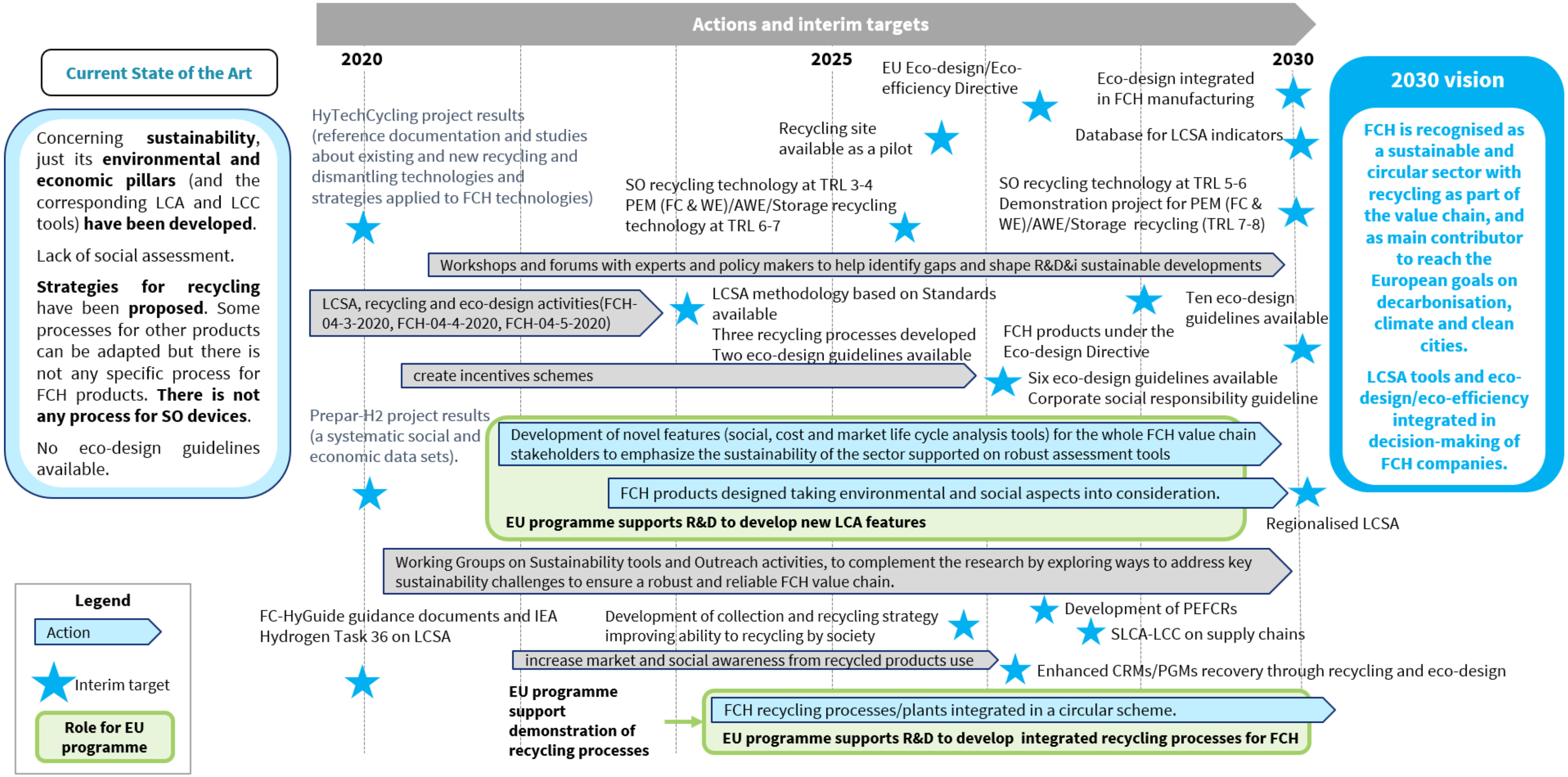
- Database for LCSA indicators
- Corporative social responsibility implementation guidelines

<u>Demonstration Actions (TRL 5-7)</u>

Polymeric and Alkaline Electrolysis (PEMEL, AEMEL, AEL), Polymeric Fuel Cells (PEMFC), and Storage materials recycling processes need to be developed by transferring current industrial processes already in place for other different value chains than FCH. The recycling of the different components of the FCH value chain needs to be addressed to optimise systems components and reduce hydrogen losses.

Dedicated roadmap

RM19.1 Sustainability, LCSA, Recycling and Eco-design detailed roadmap



KPIs

Most KPIs are sourced from the current MAWP of the FCH2-JU. Where KPIs are not available, we propose early suggestions based on expertise of the membership of Hydrogen Europe and Hydrogen Europe Research, as an outcome of initial reflections. Any input written in black indicates a good level of confidence and consensus on the KPI, while input in red flags a need for greater attention.

Table 43. KPIs Sustainability, LCSA, recycling and eco-design

No	Parameter	Unit	SOA	Targets		
				2024	2027	2030
1	Eco-design					
	- Guidelines developed	number	-	2	6	10
	- Eco-efficiency improvement	%	-	10	15	20
	- Cumulative cost reduction	%	-	3	5	10
	- Environmental cost reduction	%	-	10	15	20
2	Preparatory study for Eco-design Directive (200k units commercialised)	number	-	-	1	1
3	Harmonized and regionalized life cycle thinking tools (environmental, social, costs) for FCH technologies/products	number	-	1 (Har) *	-	1 (Reg) **
4	Product Environmental Footprint (PEF) pilots	number	-	-	-	3
5	Corporate social responsibility implementation guidelines	number	-	-	-	1
6	Recycling processes:					
	- Minimum CRMs/PGMs (other than Pt) recycled from scraps and wastes	%	-	30	40	50
	- Minimum Pt recycled from scraps and wastes	%	-	95	98	100
		%	-	75	78	80
	- Minimum ionomer recycled from scraps and wastes	%	-	-	-	20
	- Collection rate of devices (% Product collected vs Total Product commercialised)	number	-	-	-	3
	- Number of recycling pilots	number	-	3	5	6
	- Recycling technologies in the FCH value chain (Pyro, Hydrometallurgical, …)	%	-	-	35	50
	- Rate of secondary raw materials used within the FCH value chain					

Notes
* Harmonised
** Regionalised

6.3.2. Roadmap 19.2: Education & Public awareness

Rationale for support

When scientific results and innovative technologies are introduced into society, their social acceptance depends largely on their reliability; the introduction of hydrogen is not an exception. Hydrogen has particular characteristics that are different from existing energy technologies, as well as some historical prejudices as the "hydrogen bomb" and "Hindenburg disaster", and this makes it necessary to make an extra effort to **promote its social recognition and acceptance of the technology, in order to achieve its widespread use.**

Technical knowledge about hydrogen and its technology leads to greater acceptability through increased levels of confidence in the technology, and further work is needed to develop educational and training material. The more commercially advanced sectors, which are mobility and combined heat and power sector, especially needs to reach the same level in **professional accreditation for technical service**.

Moreover, social and environmental benefits at the business level (Corporate Social Responsibility (CSR)), other aspects such as public health and energy assurance, also have an impact on the level of acceptance and should be included in this roadmap. Public events, the provision of information adapted to different levels and languages, and demonstrative influential experiences related to technology is a way to increase public awareness and acceptance. For example, test-driving experiences have proven to be useful in greatly modifying barriers to the introduction and recognition of technology.

In the age of communication and openness, the strategy for the development of hydrogen technologies has to go together with the social sciences, in a strong and close collaboration between technicians and other knowledge-based experts to enable a robust and consistent deployment of hydrogen.

Several studies have been conducted on the social recognition and acceptance of hydrogen energy. According to the results of some of these survey-based studies, participants tend to have **lower levels of knowledge about hydrogen technology**, although confidence in the technology and acceptability of its use, in mobility for example, tend to be higher.

Educational materials for schools and universities have also been developed, as well as training programmes in areas such as safety. These aspects need to be further extended and must be rolled out in more languages to further strengthen the access of the public to such material. Thus, those materials can be used for education (schools, universities), for increase public awareness (individuals, institutions, NGO’s) etc.

Projects have gathered relevant information on administrative, legal and economic barriers to the implementation of hydrogen technologies, but **these findings have not been effectively transferred to groups of local**, regional or national authorities, which are ultimately responsible for integration. This activity must continue in selected deployment areas.

Current status of the technology and deployments

Base information about the awareness and social acceptance of the FCH technologies is available thanks to Hyacinth. According to the results of some of these survey-based studies, participants tend to have lower levels of knowledge about hydrogen technology, although confidence in the technology and acceptability of its use, in mobility for example, tend to be higher.

Educational material for the base schools has also been developed (FCHGo!), as well as training programmes at high level in areas such as safety (HyResponders), and university teaching (TrainHy, TeacHy, Joint European Summer School JESS), these aspects need to be further strengthened so that they are accessible to all communities and languages, and should have open access so that different educational institutions: teachers from schools, university readers can use them in their teaching practice.

Projects such as HyLAW have gathered relevant information on administrative and economic barriers to the implementation of hydrogen technologies, the scope of these projects should be also extended covering different precommercial applications, and their findings still need to be effectively transferred to groups of local, regional or national authorities, which are ultimately responsible for FCH technologies integration. This transference will be achieved thanks to an efficient dissemination of the FCH technologies, based on a collaboration between hydrogen stakeholders' technicians and social scientists to address a widespread communication, facilitated by the digital repository.

It is worth noting the following initiatives and projects:

- TeacHy2020: Specifically addresses the supply of undergraduate and graduate education (BEng/BSc, MEng/MSc, PhD etc.) in fuel cell and H_2 technologies across Europe.
- HYACINTH: The overall purpose is to gain deeper understanding of social acceptance of H_2 technologies.
- H2TRUST: Development of H_2 Safety Expert Groups and due diligence tools for public awareness and trust in hydrogen technologies and applications.
- KnowHY: Provision of a training offer for technicians and workers for the fuel cells and H_2 sector.
- HyResponse: European Hydrogen Emergency Response training programme for First Responders

Vision 2030

- ***Obtaining a professional and business network trained and updated in hydrogen technologies.***
- ***New communication and demonstration tools for reinforcing public awareness and education at multiple levels and types of education.***

- NET-Tools: Novel Education and Training Tools based on digital applications related to H_2 and Fuel Cell Technology.
- FCHgo!: develops activities to disseminate a set of tools for teachers and pupils in primary and secondary education, ensuring technical and pedagogical excellence.

Vision for 2030 and proposed areas for support

We propose the following activities:

Early Stage Research Actions (TRL 2-3)

- Integration aspects with social sciences and develop educational and public understanding and acceptance.
- Incorporation of CSR, integration of activities
- Design, development, technical realisation and maintenance of comprehensive digital repository for e-learning materials

Coordination and Support Actions (CSA)

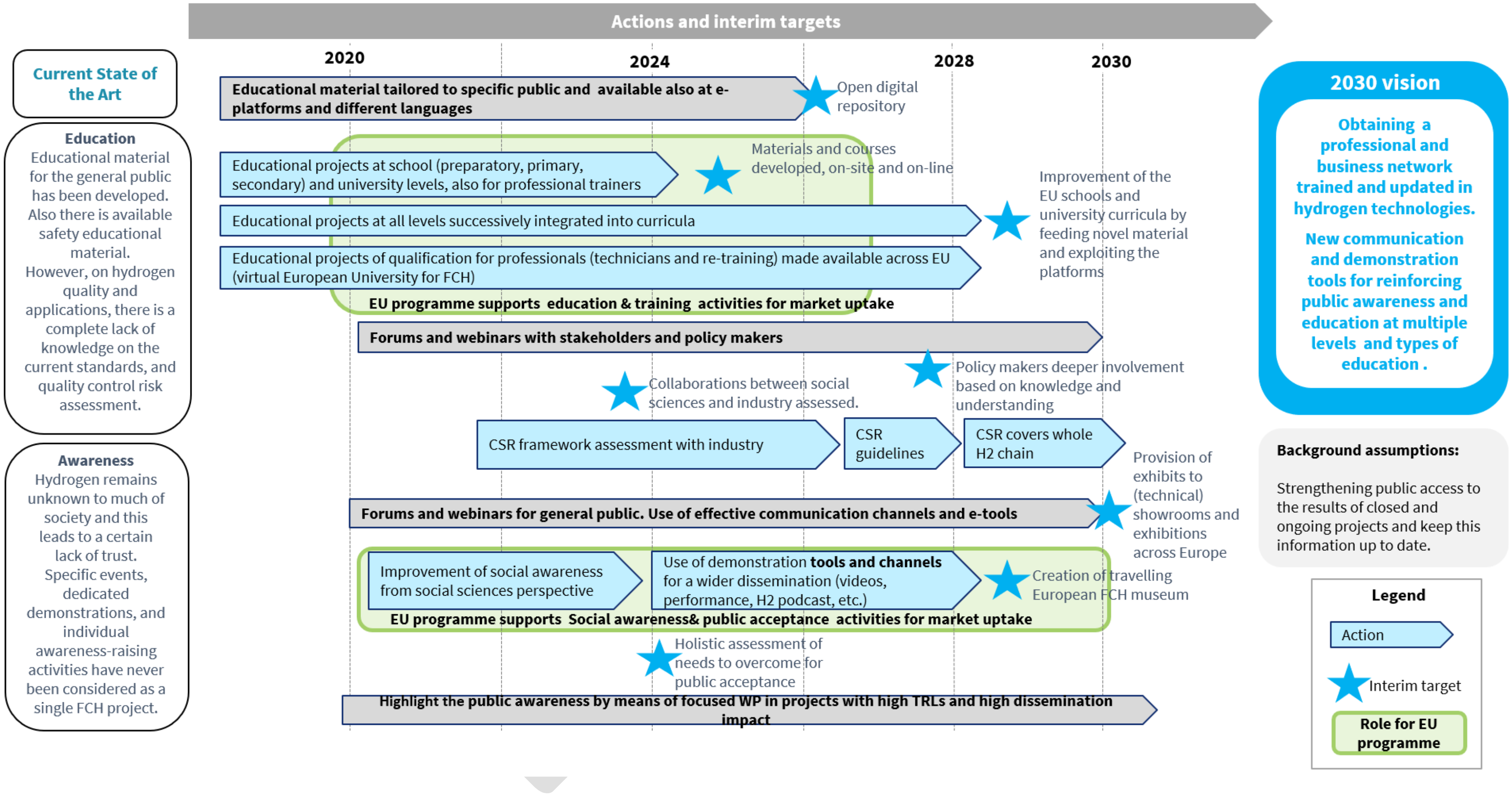
- Preparation and dissemination material for Education at all levels, included training for industries available in different languages.
- Events for training and education of different stakeholders
- Building Training Programmes for Young Professionals in the H_2 and Fuel Cell Field
- Travelling Hydrogen Technologies Museum Initiative

<u>**Demonstration Actions (TRL 5-7)**</u>

- Evaluation of social acceptance of H_2 technologies at the different levels of the value chain and looking at the different components of community acceptance, market acceptance and socio-political acceptance.
- Specific activities and demonstrative events to raise public awareness sufficiently according the benefits of FCH-technologies.
- Development and Installation of a virtual European University on FCH educational targets including service and specific events e.g. summer and winter schools

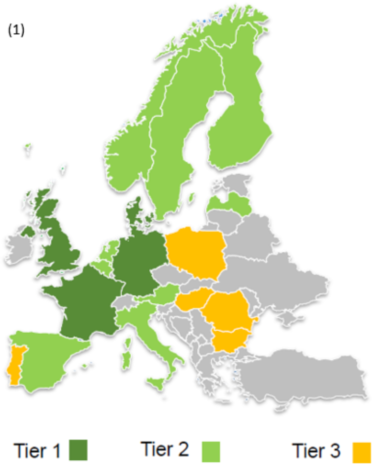
Dedicated roadmap

RM19.2 Education & Public Awareness



RM19.2 KPIs Education & Public Awareness

(1)



[(1)] Tier 1 : FCH front running EU countries
Tier 2 : FCH fast following EU countries
Tier 3 : FCH emerging EU countries

1 – Countries gathered by clusters. **Initial** classification obtained from HyLAW Project Presentation 2017. Grant Agreement No 737977.

	No	KPI	Unit	2024			2028			2030		
				TIER 1	TIER 2	TIER 3	TIER 1	TIER 2	TIER 3	TIER 1	TIER 2	TIER 3
Education	1	% of trained pupils and distribution by countries	%	40	25	15	70	50	30	100	70	50
Education	2	Numbers of trained professionals and distribution by countries	Number K	50	7,5	5	80	15	10	120	40	20
Education	3	Technical Universities/Institutes offering curses on hydrogen and distribution by countries	%	40	20	10	60	30	20	70	45	30
Education	4	Number of Educational events (summer schools, congress)	Number /year		15			25			35	
Education	5	Number of existing or novel documents uploaded in the digital repository (education, awareness, RCS, modelling)	Number		300 (2026)			500			700	
Public awareness	6	Number of large communication events for the general public based on learning by doing ("see, touch and try") and their distribution by country	Number /year	2	1	1	3	2	2	4	3	3
Public awareness	7	Number of information events for stakeholders, decision and policy makers and their distribution by country	Number /year	1	1	1	2	2	2	3	3	3
Public awareness	8	Number of webinars for general public awareness, covering from basic concepts and hydrogen benefits to all topics related to H2 technologies, performed by projects and other means.	Number /year		50			75			100	

6.3.3. Roadmap 19.3: Safety, PNR & RCS

Rationale for support

The deployment of the H_2 value chain requires assessing several important cross-cutting aspects that transversally affect all roadmaps considered in this exercise. Safety, PNR and RCS development require an open communication and knowledge transfer across project boundaries and beyond project terms. **Collaboration and coordination with international partners and stakeholders** is essential to ensure that this goal is achieved around the world, with CHE leading to help de-risk hydrogen technologies across the globe. Applying suitable instruments for those topics then provides a programmatic cohesion.

Safety

Consistent safety policies and intrinsic safety principles have to be applied in the whole value chain. The implementation of good practices and procedures facilitating the safe design, operation and management in the Production, Storage, Distribution and End Use of H_2 is of key importance. This applies in particular when new hydrogen technology with a small experience basis will come closer to the untrained end user. Only with a profound understanding over-conservative solution may be avoided and the costs for safety will stay acceptable. As risk scales with inventory and special hazards are associated with transfer of H_2, stationary and mobile storage, as well as interfaces and transfer protocols need special care. Obviously, homogenization of safety criteria will help to gain a common understanding at European level and beyond.

Safety is paramount for sustainable development, perception, acceptance of and trust in new technologies in a modern society. As such, it is necessary to make sure and demonstrate that the risks associated with hydrogen technologies are at least equivalent to, if not lower, than for established energy technologies. This represents a considerable challenge, as hydrogen and its hazards are quite different from currently used energy carriers and new applications require innovative solutions partly operated at unconventional conditions.

Pre-normative research and regulations, codes and standards.

Pre-normative research and demonstration projects will develop further the state-of-the-art and provide crucial input for recommendations to periodically review RCS. For performance-based RCS, critical knowledge gaps have to be closed and innovative solutions have to be evaluated with respect to performance and safety. Predictive approaches, based on lessons learnt, can guide the pathway to safer solutions. For the safety aspect, RCS will refer to validated risk assessment procedures, safety planning and management of change principles. The extended scientific basis will help building fit-for-purpose rules and ensure consistency across jurisdictions. PNR work should be conducted in synergy with technological development and market-readiness level of the various applications, so that, when a particular technology is ready for large-scale roll-out, **its deployment is not further delayed by regulatory gaps or hindered by the absence of commonly agreed standards**. The support to regulatory and international standardization bodies should be on a continuous basis and should be directed by a commonly derived prioritization of PNR activities, such as the ones proposed below.

Appropriate regulations and harmonised industry codes and standards are pre-requisites for a mature, commercial market for hydrogen technologies. Regulations and standards should be technically and/or scientifically based, they should ensure both safe rollout of the technology as well as certainty and stability for economic and industrial operators. In an EU context, it is particularly important that rules, legislation, codes and protocols are consistent across different jurisdictions. This requires a sound scientific basis steadily adapted and extended.

RCS, therefore, should be seen as both a necessary step in ensuring safety, as well as a tool that avoids regulatory barriers, enables economic efficiencies resulting from a robust European scientific grounding, clarity, harmonization and standardization.

Vision for 2030 and proposed areas for support

We propose the following areas for support:

Early Stage Research Actions (TRL 2-3)

- Improve understanding of accidental behavior of hydrogen for support the development of RCS in heat, maritime, railways, heavy duty and aerospace application (from TRL1 to TRL3 – i.e. from more fundamental phenomena to applied)
- Improved understanding of hydrogen embrittlement, thermal attacks and effects also in non-metallic materials
- Valorization and possibly development research for metering of hydrogen and hydrogen/methane blends
- Safe refueling, bunkering and storage protocols; in particular for large inventories and LH_2 (incl specific aspects associated with the maritime sector)
- PNR to support heavy duty crash standardization, including recognition of H_2 vehicles and health state of onboard storage by responders (road, rail, maritime), development of protocols for non-destructive testing of COPVs
- Review of refueling processes and quantification of over-conservatism in refueling and onboard storage
- PNR and benchmarking for hydrogen sensor selection, integration, installation and operation

Vision 2030

- ***H_2 specific, internationally harmonized RCS are in place and support the safe and efficient deployment of H_2 technologies and coin its perception as a sustainable solution.***
- ***Safety is understood and lived as a holistic, integrated and value adding approach at each stage of the implementation.***

- Improved understanding of effects of increased hydrogen content on combustion and performance of end-use gas appliances
- PNR to support performance testing standardization (H_2 production, distribution, storage and usage)
- Support for development of standards associated with introduction of hydrogen in residential and commercial buildings (incl. measurement systems, information for first respondents, etc.)

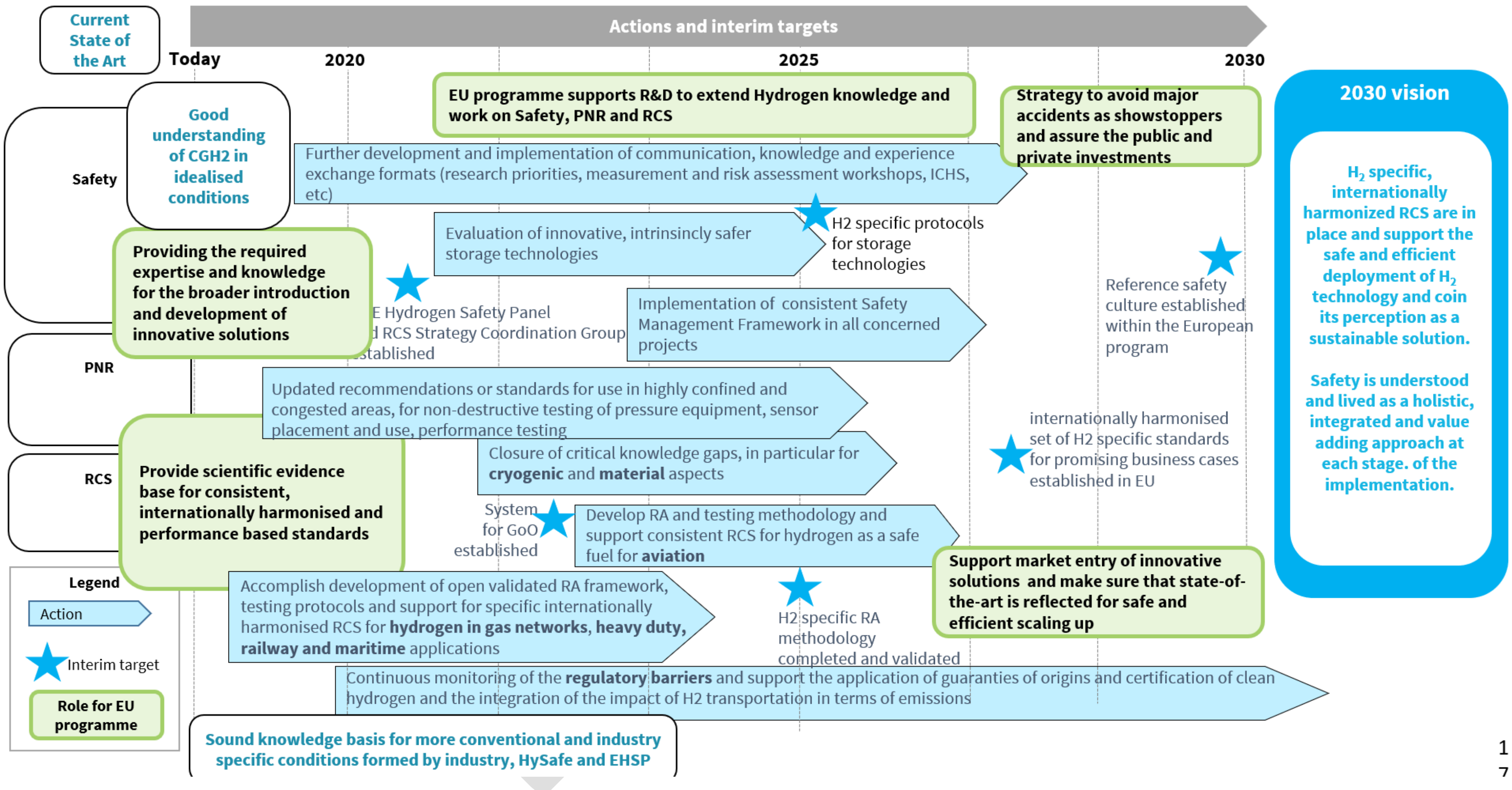
CSA and Networking Actions

- Establish and run Hydrogen Safety Panel with active participations in SDO working groups (ISO, IEC, CEN/CENELEC)
- Support the development of fact based legal and permitting regulations across Europe
- Establish and run RCS Strategy Coordination Group, with active participations in SDO working groups (ISO, IEC, CEN/CENELEC)
- Support the trainers of 1st and 2nd responders with regular updates from Early Stage Research, Development Research and Innovation actions
- Development of an open and validated risk assessment toolkit, suitable to serve as a reference in standards

- Support functioning of guaranties of origins and certification of clean hydrogen and methodologies for calculating the impact of H_2 transportation in terms of emissions
- Continuous monitoring of the regulatory barriers

Dedicated roadmap

RM19.3 Safety, PNR, RCS



KPIs

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Table 44. KPI Safety, PNR & RCS

No	Parameter	Unit	SoA	Targets	
				2024	**2030**
1	Frequency of Major Accidents in the CHE supported program	1/(a x project)	10-5	10-5	10-6
2	Percentage of relevant projects with an open and consistent safety communication and pro-active safety management	%	1	50	100
3	Number of Site Visits of the CHE HSP	1/a	0	10	20
4	Number of research priorities, risk assessment, measurement workshops	1/a	1	2	4
5	Reports of off-normal conditions and mishaps reported in HIAD / HELLEN	1/a	10	50	100
6	Number of guidance documents / input supporting the further development or revision of RCS (in any area, not just on safety)	1/project	0.75	0.9	1.25
7	Number of standards developed or reviewed with input from funded projects (PNR or demonstration) (in any area, not just on safety)	1/a	0.25	0.5	1

Notes

1. Major Accident defined here as an accident with human losses or with financial losses representing a considerable fraction of the CHE budget, inducing public concerns about the safe management of the CHE program and about the safety of hydrogen in general.

6.3.4. Roadmap 19.4: Modelling and simulation

Rationale for support

Modelling and simulation are fundamental tools used by engineers to design products, plants and complex systems. To accelerate the technological development of hydrogen and fuel cells technology it is necessary to have **reliable and validated models for "speeded up understanding, predicting and improving".** It is extremely important to push all model developers into **the same direction**: harmonized and open and thus to increase modeling reliability by improving the flow of information between modelers and experimenters bridging experimental and numerical research and ensuring sufficient feedback for experimental validation which for the moment is fragmented and insufficient

The availability of open studies will accelerate the development and update of the models and will offer a reference and validated block for complex systems studies.

The definition of rules and standards, in terms of model design, will facilitate the development of the technology. Moreover, new solutions are under development over the consolidated technologies. Trains, shipping, integrated systems, green hydrogen production chains, hydrogen eco-systems and valleys require new models with a system approach for Life Cycle Sustainable Assessment (LCSA) and Techno Economic Analysis (TEA) which go beyond single demonstration projects. In this way, also harmonized TEA is required, with common definitions of variables and scopes.

A gap analysis is needed to identify the missing models and push the scientific community to accelerate on developing "second generation" of models, both technological and economical. The harmonization of the studies, and the open access which is a research issue itself, will support both existing and new models to feed hydrogen community with high quality tools for to guided decisions.

Model and simulation are a wide typology of tools that vary from the component level up to the system or multi-system studies. Simulation is fundamental for the development of the technology since it allows for reduction of the development time, acceleration of the knowledge development, prevention of duplication and reduction the investment.

Simulation and modeling have been developed in the field of hydrogen and fuel cells by Accademia and private companies. Such studies were developed in the FCH-JUs' funded projects and independently from the European research groups.

The models are not fully disclosed and developed in different languages, both "open" and "closed", with no unified simulation codes. They are suffering from lack of available information sources for model validation experimental parameters. The new program has to push through open access model to open source. **This will allow consistently integrating different building blocks and creating consistent architype system evaluations for technology developers and decision makers.**

Current status of the technology and deployments

Scientific literature contains studies developing models and simulation. Research departments of private companies developed own models to support technology development. Some of these studies were developed in the frame of FCH-JUs projects. Main problems of the current state of the art are that models are not publicly available and developed in different languages, combined with lack of unified modeling thesaurus and simulation codes. Many of the studies are not in open access nor open source and although there is some harmonization between the project partners, it is locked and even lost after the project termination. The result is a low level of integration between different models and impossibility of building blocks to reach a multi-system level model necessary to support industry, decision makers and, in particular, policy makers. Moreover, new technologies and new systems are coming and there is the need of tools to analyze and evaluate innovations and their integration with the existing technological environment, including competing technologies. For example: how to integrate trains refilling and hydrogen production from renewable in a validated and integrated model? Thus, **the need of new modeling opportunities emerging with the deployment of hydrogen technologies, is urgently needed**.

Vision for 2030 and proposed areas for support

We propose the following areas of support:

Early Stage Research Actions (TRL 2-3)

- Develop harmonized procedures to collect, sort, systemize and share (open access) hydrogen and fuel cell models and model validation data base (from TRL2 to TRL 4)
- Provide new models, simulations and enrich experimental validation data base to cover existing gaps for the new technologies and archetype systems. (from TRL2 to TRL6)
- Integration of the models into open source environment for multi-system technical and techno-economic analysis (from TRL2 to TRL 5)

Coordination and Support Actions (CSA)

- Open Access repository for sorted physical models with harmonized thesaurus and experimental validation data base (TRL 5 – TRL 8)

Vision 2030

The vision of the activities is to have a harmonized and normalized procedures and interfaces and share open-source available models to support industry and decision makers in terms of technological and political design.

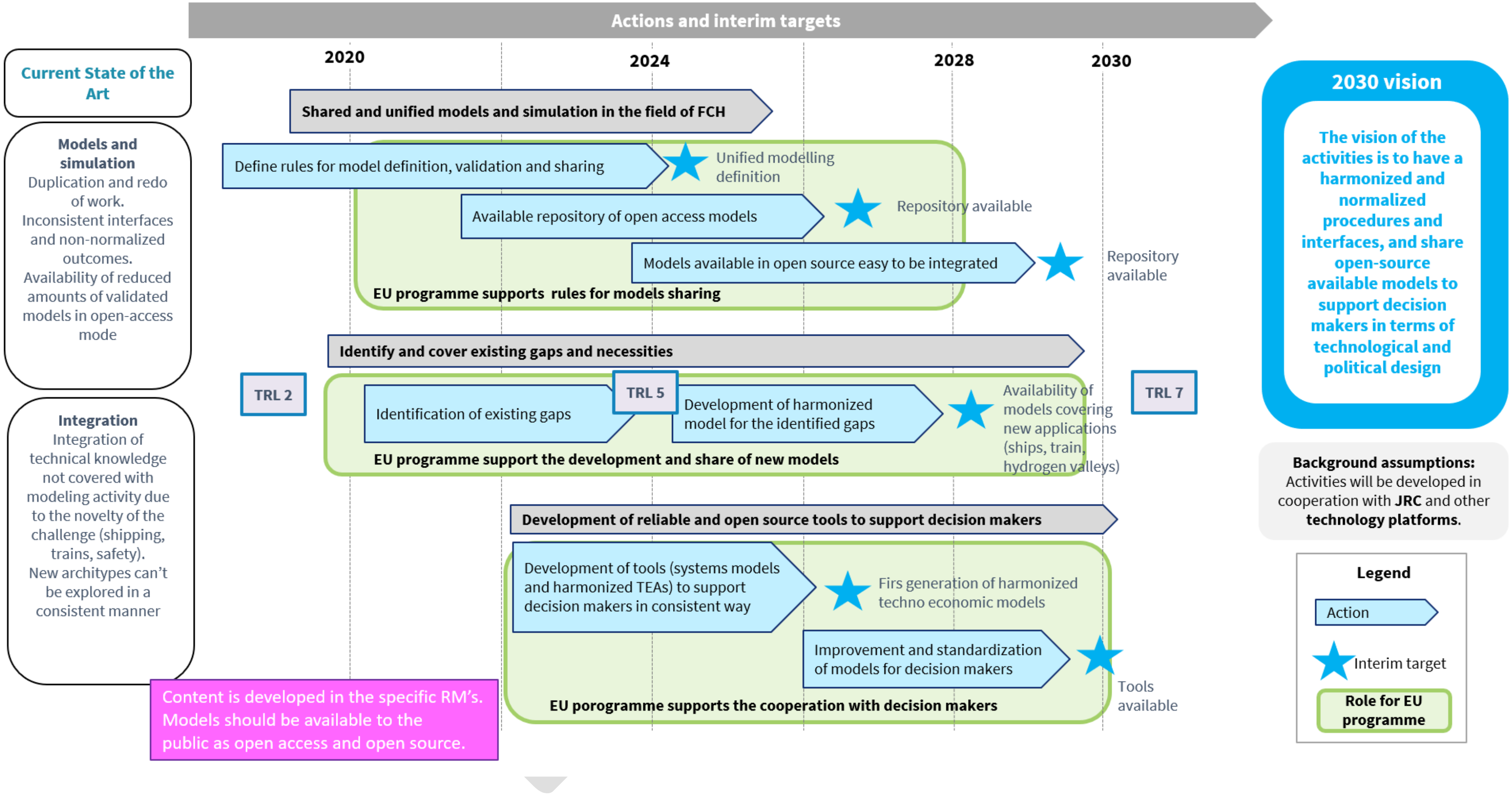
- Develop a simulation tool of hydrogen/fuel cell integrated systems for LCSA and TEA to support industry and decision makers (TRL 5 to TRL 8)

Flagship Actions

- Compilation of activities 1. Repository; 2. Recognized benchmarks; 3. Software product which can handle full value chains.

Dedicated roadmap

RM19.4 Simulation and Modelling



KPIs

No KPIs are available yet. However, a table of TRL has been defined:

Table 45. TRL Simulation & Modelling

No	Parameter
TRL2	Physical model defined
TRL3	Model implemented into an engineering tool
TRL4	Model validated over an experimental and thermodynamics database (from central repository)
TRL5	Model validated and implemented into harmonizes model procedures. Create benchmarks (in close collaboration with RM's) in central repository
TRL6	Model validated and shared as open access with defined API's and version control
TRL7	Model validated and shared as open source with modular web-based user interface and version control.
TRL8	Model implemented and open, customized to support industry and decision makers with we based user interface

7. STRATEGIC RESEARCH CHALLENGES

Addressing strategic research challenges is not a simple task. It needs investigations of **different disciplines, with different expertise, at different scales** (materials, component, cell, stack, system). It needs also to combine all the generated knowledge in such a way that allows comprehensive interpretations. The usual superposition of 3-year research projects does not really appear to be the optimum option to ensure a continuum in early stage research knowledge.

The proposed approach, already applied with success with national laboratories for several years by US DOE[28], considers gathering, **with a long-term vision covering the whole CHE partnership**, the needed capabilities and expertise from European research and technology organisations. Additional and complementary expertise will be ensured by project opportunities from AWPs open to universities and industry.

The alignment of European research and technology organisations' efforts in critical areas enables to complement the strengths of each by streamlining access to unique research tools across the organisations, developing missing strategic capabilities, and curating a public database of information. The result will lead to a **generally comprehensive strategy** investigating modeling, characterization and testing accelerating the further developments in classical research and innovation actions.

Following the early stage research action proposal in the different roadmaps, the following strategic research challenges appear:

- Low or free PGM catalysts and critical raw materials for electrolysers and fuel cells
- Advanced materials for hydrogen storage (e.g. carbon fibers, H_2 carriers…)
- Advanced understanding of the mechanisms of electrolysers and fuel cells performance / durability.

[28] https://www.hydrogen.energy.gov/pdfs/review18/2018_amr_05_fuel_cell.pdf

Membership Hydrogen Europe

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