Annex to GB decision no. CleanHydrogen-GB-2022-02

CLEAN HYDROGEN JOINT UNDERTAKING

Strategic Research and Innovation Agenda 2021 – 2027

Clean Hydrogen Partnership

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Acronyms and abbreviations

2Zero	Towards Zero Emission Road Transport Partnership
AC	Alternating Current
AE	Alkaline Electrolyser
AEL	Alkaline Electrolysis
AEMEL	Anion Exchange Membrane Electrolysis
AFIR	Alternative Fuels Infrastructure Regulation
APU	Auxiliary Power Unit
B4P	Built4People European Partnership
BoL	Beginning of Life
BoP	Balance of Plant
BPP	Bipolar Plates
BTX	Mixtures of Aromatic Hydrocarbons
CAPEX	Capital Up-front Expenditure (Investment)
CC	Combined Cycle
CCGT	Combined Cycle Gas Turbines
CCS	Carbon, Capture and Storage
CCUS	Carbon, Capture, Utilisation and Storage
CEF	Connecting Europe Facility
CEM	Clean Energy Ministerial
CEN	European Committee for Standardisation
CENELEC	European Committee for Electrotechnical Standardisation
CEAP	Circular Economy Action Plan
CETP	Clean Energy Transition Partnership
CGH_2	Compressed Hydrogen Gas
CHP	Combined Heat and Power
CO_2	Carbon Dioxide
COP	United Nations' Conference of the Parties
COPV	Composite Overwrapped Pressure Vessel
CRM	Critical Raw Materials
D&E	Dissemination and Exploitation
DC	Direct Current
DLE	Dry Low Emissions
DoE	United States Department of Energy. EERE is it's Office of Energy Efficiency &

	Renewable Energy.
DRI	Direct Reduced Iron
EC	European Commission, sometimes also shortened to just Commission
EoL	End of Life
ECH2A	European Clean Hydrogen Alliance
ED	Executive Director
EHS&CP	European Hydrogen Sustainability and Circularity Panel
EHSP	European Hydrogen Safety Panel
EIC	European Innovation Council
EERA	European Energy Research Alliance
ERA	European Research Area
ETS	Emission Trading System (also seen as EU ETS)
EU	European Union
EU ETS	EU Emission Trading System
EURAMET	European Association of National Metrology Institutes
FP	European Union's Framework Programmes for research and technological development. FP7 refers to the seventh programme (period 2007-2013), H2020 to the eighth (period 2014-2020), while Horizon Europe to the ninth (period 2021-2027).
FC	Fuel Cell
FCEV	Fuel Cell Electric Vehicle
FCH	Fuel Cell and Hydrogen
FCH (2) JU	Fuel Cells and Hydrogen Joint Undertaking. FCH 2 JU (2014-2020/Horizon 2020) succeeded FCH JU (2008-2014/FP 7) [1].
FCHO	Fuel Cell and Hydrogen Observatory, https://fchobservatory.eu/
GB	Governing Board
GDL	Gas Diffusion Layer
GH_2	Gaseous Hydrogen
GHG	Greenhouse Gases
GT	Gas Turbine
GW	Gigawatt. GW_e refers to GW electric.
H_2	Hydrogen
H2020	Horizon 2020

[1] FCH JU was replaced by FCH 2 JU, which has taken over all rights and obligations of its predecessor. FCH 2 JU is now in turn replaced by the Clean Hydrogen Joint Undertaking.

HDV	Heavy-Duty Vehicles
HDT	Heavy-Duty Transport
HFP	European Hydrogen and Fuel Cell Technology platform
HHV	Higher Heating Value
HRS	Hydrogen Refuelling Station
HTCP	Hydrogen Technology Collaboration Programme
IEA	International Energy Agency
IEC	International Electrotechnical Commission
IMO	International Maritime Organisation
IPCC	Intergovernmental Panel on Climate Change
IPCEI	Important Projects of Common European Interest
IPHE	International Partnership for Hydrogen and Fuel Cells in the Economy
IRENA	International Renewable Energy Agency
ISO	International Organisation for Standardisation
IT	Information Technology
JRC	Joint Research Centre of the European Commission
JU	Joint Undertaking. For the scope of this document this acronym is used specifically to refer to the Clean Hydrogen Joint Undertaking. In all other instances or when not obvious the longer name is used.
kg	Kilogramme
KOH	Potassium Hydroxide.
KPI	Key Performance Indicator
kW	Kilowatt; kW_{th} refers to kW thermal.
kWh	Kilowatt-hour; kWh_e refers to kWh electric, while kWh_{th} to kWh thermal.
LCA	Life-Cycle Assessment
LCSA	Life-Cycle Sustainability Assessment
LCC	Life-Cycle Costing
LDV	Light Duty Vehicles
LH_2	Liquid Hydrogen
LHV	Lower Heating Value
LNG	Liquefied Natural Gas
LOHC	Liquid Organic Hydrogen Carrier
m^2, m^3	Square Meters, Cubic Meters
MEA	Membrane Electrode Assembly
METI	Japan's Ministry of Economy, Trade and Industry. NEDO refers to its New

	Energy and Industrial Technology Development Organisation.
Mt	Million Tonnes
MTBF	Mean Time Between Failures
MTRR	Mean Time to Repair
MW	Megawatt. MW_e refers to MW electric.
NASA	National Aeronautics and Space Administration
NECP	National Energy and Climate Plans
NH_3	Ammonia
NO_x	Nitrogen Oxides
NRCan	National Resources Canada
NRRP	National Recovery and Resiliency Plans
O&M	Operation and Maintenance
OCGT	Open Cycle Gas Turbine
OEM	Original Equipment Manufacturer
OPEX	Operational Expenditure
OPS	Offshore Power System
P4P	Processes 4 Planet Partnership
PCCEL	Proton Conducting Ceramic Electrolysis
PEFCR	Product Environmental Footprint Category Rules
PEME	Proton Exchange Membrane Electrolyser
PEMEL	Proton Exchange Membrane Electrolysis
PEMFC	Proton Exchange Membrane Fuel Cell
PFAS	Per- and Polyfluoroalkyl Substances
PGM	Platinum Group Metals
PNR	Pre-Normative Research
PO	JU Programme Office
POC	Primary Point of Connection
PSA	Pressure Swing Adsorption
R&I	Research and Innovation
R&D	Research and Development
RCS	Regulations, Codes and Standards
RCS SC	Regulations, Codes and Standards Strategy Coordination
RES	Renewable Energy Sources
RFNBO	Renewable Fuels of Non-Biological Origin

RSMR	Regional and Short-Medium Range
RTO	Research and Technology Organisations
SBA	Single Basic Act; referring to the regulation establishing the Joint Undertakings under Horizon Europe.
SDG	Sustainable Development Goal
SDO	Standardisation Developing Organisations
SG	Stakeholder Group
SLCA	Social Life Cycle Analysis
SME	Small and Medium-sized Enterprise
SMR	Steam Methane Reforming
SoA	State-of-the-Art
SOE	Solid Oxide Electrolyser
SOEL	Solid Oxide Electrolysis
SOFC	Solid Oxide Fuel Cell
SRIA	Strategic Research and Innovation Agenda for 2021-2027 of the Clean Hydrogen Joint Undertaking (previously MAWP Multi-Annual Work Programme).
SRIA-HE/HER	Strategic Research and Innovation Agenda for 2021-2027 of Hydrogen Europe and Hydrogen Europe Research
SRG	State Representative Group
TC	Technical Committee
TCO	Total Cost of Ownership
TEN	Trans-European Network. TEN-E refers to Electricity, while TEN-T to Transport.
TIM	Tools for Innovation Monitoring
TRL	Technology Readiness Level:

TRL 1 –	*basic principles observed*
TRL 2 –	*technology concept formulated*
TRL 3 –	*experimental proof of concept*
TRL 4 –	*technology validated in lab*
TRL 5 –	*technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)*
TRL 6 –	*technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)*
TRL 7 –	*system prototype demonstration in operational environment*
TRL 8 –	*system complete and qualified*
TRL 9 –	*actual system proven in operational environment (competitive*

manufacturing in the case of key enabling technologies; or in space)

UAV	Unmanned Aerial Vehicle
UK	United Kingdom
US, USA	United States of America
WLE	Wet Low Emissions
ZEWT	Zero Emission Waterborne Transport Partnership

Executive summary

This document represents the Strategic Research and Innovation Agenda (SRIA[2]) 2021-2027 of the Clean Hydrogen Joint Undertaking (hereafter also Clean Hydrogen JU[3]). It covers therefore the duration of Horizon Europe and identifies the key priorities and the essential technologies and innovations required to achieve the objectives of the joint undertaking[4].

The Clean Hydrogen JU is the continuation of the successful Fuel Cell and Hydrogen Joint Undertakings (FCH JU and FCH 2 JU), under FP7 and Horizon 2020 (H2020) respectively. It is set up in the form of an institutionalised partnership under the Research and Innovation Framework Programme Horizon Europe.

The EU remains committed to the 2030 Agenda, by setting and implementing an ambitious policy programme to deliver on sustainability in the EU and beyond. As part of its policy agenda, on 11 December 2019 the European Commission presented the European Green Deal, a new growth strategy for Europe aiming to transform the Union into a modern, resource-efficient and competitive economy. The implementation of the Green Deal would set the EU on a course to become a sustainable climate-neutral and circular economy by 2050. To achieve these ambitious goals, the European Commission adopted the Fit-for-55 package with a set of policy proposals approaching the goal of emission reductions from many different angles, with both targeted and horizontal policy measures. In this set of proposals the role of clean energy technologies and carriers is prominent, becoming in essence the enablers for achieving EU's ambitious goals.

In this context and due to its multiple possible uses, hydrogen is expected to play a key role in a future climate-neutral economy, enabling emission-free transport, heating and industrial processes as well as inter-seasonal energy storage. To emphasise its importance and facilitate the scaling up of hydrogen applications, the Commission adopted in 2020 the EU hydrogen strategy, aiming to accelerate the development of clean hydrogen. To achieve this, it will require among others the improvement of its competitiveness against other energy carriers, research and innovation into breakthrough technologies and an infrastructure network that can bring it to a geographically spread market.

Focusing on research and innovation rather than deployment, the Council and the Parliament adopted the Single Basic Act, a regulation establishing the Joint Undertakings under Horizon Europe, including the establishment of the Clean Hydrogen Joint Undertaking. The Clean Hydrogen JU will have the leading role in research activities related to hydrogen, collaborating closely with most of the end-use European partnerships on hydrogen applications in the relevant sectors.

The Clean Hydrogen JU will contribute to the European climate neutrality goal by producing noticeable, quantifiable results towards the development and scaling up of hydrogen applications. This will help develop a number of hydrogen technologies, which are currently either not competitive or have a low technology readiness level, but are expected to contribute to the 2030 energy and climate targets and most importantly make possible climate neutrality by 2050.

[2] Previously known as Multi-Annual Work Plan (MAWP) for FCH 2 JU.
[3] For purposes of communication with the public, the name Clean Hydrogen Partnership is also used instead of the legal name of the JU. In the present document only the legal name is used.
[4] According to the Article 2-Definitions of the SBA

The scope of the research and innovation activities of the Clean Hydrogen JU will have a different scope compared to FCH 2 JU, shifting to areas related primarily to the production of clean hydrogen, as well as the distribution, storage and end use applications of low carbon hydrogen in hard to abate sectors. They will be guided to a large extent by EU's Hydrogen Strategy and the policy developments in this context, contributing to its implementation.

Planned research and innovation actions

The key component in the implementation of the Programme is the annual Call for Proposals, covering a number of the research and innovation actions described in the SRIA. They represent a set of prioritised actions, consistent with the objectives of the Clean Hydrogen JU, divided into the Pillars presented in Section 3.1.

The emphasis given to different actions in different pillars reflects the industry and research partners' assessment of the state of the technological maturity of the applications and their estimated importance to achieve critical objectives of the Clean Hydrogen JU.

Below the main scientific priorities and challenges for the different pillars and activities:

Hydrogen production

Further improvements are required especially in cost reduction and efficiency increase for a variety of renewable hydrogen production routes, the main workhorse being electrolysis, supported by other routes exploiting direct sunlight such as thermal dissociation of water using concentrated solar energy or through photocatalysis, biomass/biogas or other biological routes.

Water electrolysis will be the main technology supported, covering both high TRL types - Alkaline Electrolysis (AEL), Proton Exchange Membrane Electrolysis (PEMEL), Solid Oxide Electrolysis (SOEL) - and less mature types - Anion Exchange Membrane Electrolysis (AEMEL) and Proton Conducting Ceramic Electrolysis (PCCEL).

Hydrogen storage and distribution

As explicitly mentioned in the EU Hydrogen Strategy, it is essential that hydrogen becomes an intrinsic part of an integrated energy system. For this to happen, hydrogen will have to be used for daily and/or seasonal storage providing buffering functions, thereby enhancing security of supply in the medium term. The strategy also calls for an EU-wide logistical infrastructure that needs to be developed to transport hydrogen from areas with large renewable potential to demand centres across Europe.

A pluralistic approach with respect to the technologies that will be investigated and supported is envisaged, to have a complete set of technologies that can serve as building blocks of the EU-wide logistical infrastructure.

Hydrogen end uses - transport

The technology developments so far are not sufficient to meet the ambitious emission reductions in transport. A number of technology routes still need further improvements, especially in the context of reducing costs and increasing durability, in order to make them competitive with incumbent technologies.

It should be also stressed that, especially in the case of hydrogen-based transportation, the competitiveness of hydrogen technologies is dependent on research and innovation breakthroughs, on production volumes of vehicles and components and on the price and availability of hydrogen as a fuel. Therefore, actions aimed at stimulating a broad rollout of FC vehicles around Europe are equally important to research and innovation actions, in particular for hard to abate sectors, in order to drive the Total Cost of Ownership (TCO) of the FC vehicles down.

Hydrogen end uses - clean heat and power

Hydrogen offers a unique chance to decarbonise the power generation and heating sectors reliably and independently from weather or seasonal conditions. The overall goal of this pillar is to support European supply chain actors to develop a portfolio of solutions providing clean, renewable and flexible heat and power generation for all end users' needs and across all system sizes; from domestic systems all the way to large-scale power generation plants. Preferential support will be for solutions running on 100% hydrogen. However, there is still room to support solutions running on a hydrogen mixture in the gas grid (up to 20% within the context of the activities included in this support area) during the transition phase[5].

Cross-Cutting activities

Mass-market commercialisation of hydrogen-based technologies presents a number of systemic (or horizontal) challenges that need to be addressed to effectively kick-start a hydrogen ecosystem of significant scale throughout the EU in the coming decade.

Cross-cutting activities are structured around three focus areas: (i) Sustainability; (ii) Education and public awareness; and (iii) Safety, pre-normative research and regulations, codes and standards.

Hydrogen Valleys

Since 2014, FCH JU has pursued the concept of hydrogen territories, which have evolved into the most recent concept of Hydrogen Valleys. A Hydrogen Valley is a defined geographical area, city, region or industrial area where several hydrogen applications are combined together and integrated within an FCH ecosystem. The idea is to demonstrate how all the different parts of the use of hydrogen as an energy vector fit together in an integrated system approach. This concept has gained momentum and is now one of the main priorities of industry and the European Commission (EC) for scaling-up hydrogen deployments and creating interconnected hydrogen ecosystems across Europe.

Hydrogen Supply Chains

Hydrogen technologies and systems have been recently identified by the European Commission as an emerging and strategic value chain for Europe.[6] A set of actions are foreseen aiming at strengthening the overall supply chain of hydrogen technologies, from processing the raw materials into specialised materials (e.g. electro-catalysts), production of components and sub-system to system integration. The supply chain is complemented by the wider view of the value chain approach vis-à-vis creation of jobs, added value to economy and industry competitiveness.

Strategic Research Challenges

To ensure a continuous generation of early stage research knowledge, the above actions will be supplemented by multidisciplinary investigations, gathering expertise at different technology

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[5] According to the "Hydrogen strategy for a climate-neutral Europe", the blending of hydrogen in the natural gas network at a limited percentage may enable decentralised renewable hydrogen production in local networks in a transitional phase.

[6] Strengthening Strategic Value Chains for a future-ready EU Industry, EC, 2019.

scale (materials, component, cell, stack and system). All the generated knowledge needs also to be combined in such a way to allow further comprehensive interpretations. The proposed approach considers gathering, with a long-term vision and covering the whole Clean Hydrogen JU activities, the needed capabilities and expertise from European Research and Technology Organisations (RTO).

Other activities

Although the financial support to research and innovation actions is the main tool of the JU to achieve its objectives, it is not sufficient. A number of additional activities are necessary to fulfil its objectives, as follows:

Activities related to Synergies

In line with the SBA, the JU will develop close cooperation and ensure coordination with other European partnerships, including by dedicating, where appropriate, a part of the joint undertaking's budget to joint calls. Moreover, it will seek and maximise synergies with and, where appropriate, possibilities for further funding from relevant activities and programmes at Union, national and regional level.

Activities related to Regulations, Codes and Standards

The Clean Hydrogen JU will contribute to supporting the implementation of hydrogen-specific regulatory and enabling frameworks by a strategic and coordinated approach to RCS issues within the Programme, which will mostly be implemented through Pre-Normative Research (PNR) activities. Moreover, a RCS Strategy Coordination (RCS SC) Task Force will be set up to better coordinate these activities.

Activities related to European Hydrogen Safety

Independently of the research and innovation actions addressing hydrogen safety issues, the Clean Hydrogen JU will retain and further reinforce the European Hydrogen Safety Panel (EHSP), aiming to support the development and deployment of inherently safer hydrogen systems and infrastructure.

Activities related to Sustainability and Circularity

The Clean Hydrogen JU will set up a European Hydrogen Sustainability and Circularity Panel (EHS&CP) at the Programme level which will act as a focal point or "advisor" to the Programme in these matters in an independent, coordinated and consolidated way.

Activities related to knowledge management

The main goals of the Clean Hydrogen JU knowledge activities will be to support the collection and diffusion of high quality new knowledge and support evidence-based implementation of Union policies, while monitoring progress towards the achievement of the objectives of the Clean Hydrogen JU.

Activities related to SMEs

The Clean Hydrogen JU will continue to rely on the innovativeness of SMEs. To do this, it will need to deal with two of the largest obstacles that SMEs must overcome, the need to raise financing, especially in the early stages of growth, and to kick-start sales and thereby gain valuable field experience.

Activities related to international cooperation

The Clean Hydrogen JU will build on the actions undertaken by its predecessor and expand them accordingly, in order to support the European Commission under its coordination in the implementation of its international cooperation agenda in research and innovation.

Activities related to Communication

The JU will undertake a number of communication activities with the objective to promote the development of the hydrogen technologies sector, build public awareness and acceptance of the hydrogen technologies and ensure communication towards and between stakeholders. Such communication activities will be coordinated with the European Commission.

Programme Implementation and Governance

The budget of the Clean Hydrogen JU shall be formed of contributions from the Union and its members other than the Union – namely Hydrogen Europe and Hydrogen Europe Research. The financial contribution from the Union to cover administrative and operational costs of the Clean Hydrogen JU shall be 1 billion euro, with the private members contributing at least the same amount. In order to achieve its objectives, the Clean Hydrogen JU shall provide financial support mainly in the form of grants for research and innovation activities to participants, following open and competitive Calls for proposals.

In order to manage and implement its budget, the JU will retain a similar structure to the one of the FCH 2 JU. The Governing Board will be the decision-making body of the JU that decides on the long-term strategic orientation of the partnership, as well as its annual priorities. The Executive Director shall be the chief executive responsible for the day-to-day management of the joint undertaking in accordance with the decisions of the GB and, operating under his responsibility, the Programme Office will execute all the necessary tasks for the implementation of the mandate of the Clean Hydrogen JU. The Member States and associated countries will be represented through the States Representative Group, while the public and private stakeholders active in the field of hydrogen will also be able to provide input on the strategic priorities of the JU via the Stakeholders Group.

The Clean Hydrogen JU prepared a Strategy Map[7] in order to better map its objectives coming from the Single Basic Act and the Horizon Europe Regulation and assist in preparing its programme implementation strategy. The Strategy Map links the resources of the JU and the actions taken (operational objectives / indicators) towards concrete outcomes (specific objectives / indicators) and directly to one (or more) of the general objectives and intended impacts of the Clean Hydrogen JU, which would contribute in turn to one or more high-level objectives of the Union.

To facilitate the tracking of progress towards the objectives, the Clean Hydrogen JU has set up a monitoring framework that will allow it to continuously monitor its management activities and perform periodic reviews of the outputs, results and impacts of its projects, implemented in accordance with the Horizon Europe Regulation.

The successful implementation of all the above require a modern and effective administration. For this reason, Clean Hydrogen JU aims for an effective management of human resources in order to optimise the capacity to deliver on the Clean Hydrogen JU's objectives and core business. The Clean Hydrogen JU relies on a performance culture in which staff is motivated

[7] See Figure 3 Strategy Map of the Clean Hydrogen Joint Undertaking, Section 7.

and can deliver work of a consistently high quality, adding value. The Clean Hydrogen JU will ensure its organisational structure and staff allocation is adapted to its needs and priorities, allocating staff efficiently taking into account the talent and potential of staff and workload issues.

The above will be complemented by sound financial management and cost-effective controls, which give the necessary guarantees concerning the legality and regularity of underlying transactions. In line with the Commission's Digital Strategy, the JU continue its transition to the new digital era, on the basis of paperless procedures, improved access and use of data and IT systems permitting the efficient collaboration of staff independent of their location. Finally, the Clean Hydrogen JU will strive to improve its environmental impact in all its actions and will actively promote measures to reduce the related day-to-day impact of the administration and its work.

1. Introduction

This document represents the Strategic Research and Innovation Agenda (SRIA[8]) 2021-2027 of the Clean Hydrogen Joint Undertaking (hereon also Clean Hydrogen JU[9]). The overall goal of the Clean Hydrogen JU is to support research and innovation (R&I) activities in the Union in clean hydrogen solutions and technologies, under EU's new funding programme for research and innovation, Horizon Europe, established by the Horizon Europe Regulation[10], and in synergy with other EU initiatives and programmes. The Clean Hydrogen JU is the continuation of the successful Fuel Cell and Hydrogen Joint Undertakings (FCH JU and FCH 2 JU), under FP7 and Horizon 2020 (H2020) respectively.

1.1. The European Green Deal and the climate neutrality ambition of Europe

As part of the sustainable development agenda, the "2030 Agenda"[11] as summarised in the 17 Sustainable Development Goals (SDGs)[12], all countries are committed to develop strategies to address the global challenge for sustainable development. The aim is to support economic growth, while addressing in parallel a range of social needs and tackling climate change and environmental sustainability.

The EU remains committed to the 2030 Agenda, by setting and implementing an ambitious policy programme to deliver on sustainability in the EU and beyond. As part of its policy agenda, on 11 December 2019 the European Commission (also Commission or EC in the text) presented the European Green Deal[13], a new growth strategy for Europe aiming to transform the Union into a modern, resource-efficient and competitive economy. The implementation of the Green Deal would set the EU on a course to become a sustainable climate-neutral and circular economy by 2050.

At the core of the European Green Deal lies the need to fight climate change. The Intergovernmental Panel on Climate Change (IPCC) estimated that in order to be on a pathway to limit temperature increase to 1.5 °C by the end of the century, net-zero CO_2 emissions at global level need to be achieved around 2050 and neutrality for all other greenhouse gases somewhat later in the century. This would require the EU to become climate neutral by 2050.[14] Both the European Parliament and the European Council (also referred to as Parliament and Council, respectively) have endorsed the long-term EU climate-neutrality objective.[15, 16] On 4 March 2020, a European Climate Law was proposed by the Commission, capturing the climate-neutrality objective in EU law. At the same time, it underlined the need to review the Union's targets for 2030 and define a trajectory compatible with the climate neutrality objective by 2050. To this end, the Commission adopted on September 2020 the 2030 Climate Target Plan,[17] proposing the increase of the greenhouse gas emissions reduction ambition for 2030, from

[8] Previously known as Multi-Annual Work Plan (MAWP) for FCH 2 JU.
[9] For purposes of communication with the public, the name Clean Hydrogen Partnership is also used instead of the legal name of the JU. In the present document only the legal name is used.
[10] Regulation (EU) 2021/695 establishing Horizon Europe – the Framework Programme for Research and Innovation, OJ L 170, 12.5.2021, p. 1-68.
[11] https://sdgs.un.org/2030agenda
[12] https://www.un.org/sustainabledevelopment/sustainable-development-goals/
[13] European Green Deal Communication. COM(2019) 640 final.
[14] A Clean Planet for all Communication. COM(2018) 773 final.
[15] European Council conclusions, 12 December 2019.
[16] European Parliament resolution on climate change, 14 March 2019.
[17] 2030 Climate Target Plan Communication. COM(2020) 562 final.

40% to at least 55%, setting Europe on a cost-effective path for climate neutrality by 2050.

On 28 June 2021 the ambitious Commission proposals were adopted at EU level, writing into law the goals set out in the European Green Deal. The first European Climate Law[18] not only sets the goal of climate-neutrality and the aspirational goal for EU to strive to achieve negative emissions after 2050, but also includes a binding EU climate target of a reduction of net greenhouse gas emissions (emissions after deduction of removals) of at least 55% by 2030 compared to 1990.

To achieve these ambitious goals, the European Commission adopted on 14 July 2021 the 'Fit for 55' package[19] of policy proposals to make the EU's climate, energy, land use, transport and taxation policies fit for this target. It is a broad package, containing 13 different proposals approaching the goal of emission reductions from many different angles, with both targeted and horizontal policy measures:

- Increasing renewable energy, energy efficiency and member states' non-ETS targets;
- Strengthening the EU emission trading system (EU ETS), including creating a new ETS for buildings and road transport (ETS-2);
- Restructuring energy taxation in Europe, including the introduction of a carbon border adjustment mechanism;
- Revising the CO2 emission standards for new cars;
- Accelerating the development of alternative fuel infrastructure, while at the same time promoting the use of sustainable fuels in Aviation and Maritime;
- Creating a social climate fund and acknowledging the importance of forests and land use in achieving our climate goals.

In this set of proposals the role of clean energy technologies and carriers is prominent, becoming in essence the enablers for achieving EU's ambitious goals.

The Fit-for-55 package was complemented by a second package in December, the gas markets and hydrogen package.[20] The package consists of the Regulation and the Directive on common rules on the internal markets for renewable and natural gases and in hydrogen. The main scope of this massive redrafting is to enable the creation of a European hydrogen market, which would be fully regulated, as is the case for the current gas and electricity markets, from 2030 onwards.

1.1.1. The role of hydrogen technologies

Fighting climate change will require a deep energy transition. The energy sector – comprising the use of energy for power generation, transportation, heating and manufacturing – is responsible for more than 70% of the global GHG emissions. Achieving climate neutrality would require us to substantially restrict the use of fossil fuels in the energy sector, replacing them with renewable energy sources and other climate neutral or low carbon fuels, as much as possible.

As a direct consequence, the share of EU renewable electricity production and other

[18] Regulation (EU) 2021/ 1119 establishing the framework for achieving climate neutrality and amending Regulations (EC) No 401/2009 and (EU) 2018/1999 ('European Climate Law').
[19] 'Fit for 55': delivering the EU's 2030 Climate Target on the way to climate neutrality, COM(2021) 550, July 2021.
[20] https://ec.europa.eu/commission/presscorner/detail/en/IP_21_6682

decarbonised energy carriers are set to gradually replace all current fossil uses. Such an accomplishment would largely decarbonise electricity from the grid in 2030 and turn it climate neutral by 2050. This would also present a significant opportunity to make the demand sectors of our economy climate neutral (buildings, transport, and industry).

Nevertheless, energy transformation comes together with a number of challenges that need to be addressed. The significant deployment of renewable energy sources in the power sector will require also the deployment of energy storage and smart grid solutions capable to address its variable generation profile. At the same time, although electrification based on today's technology perspectives seems to be seen an increasingly cost-efficient solution for some sectors, this does not hold true for all.

Across different examined alternatives complementing electrification, almost all recent economic analyses indicate that hydrogen is an energy carrier that can play a critical role in filling the gap and addressing these challenges. Hydrogen can be used as a feedstock, a fuel, an energy carrier and an energy storage medium, and thus has many possible applications across industry, transport, power and buildings sectors. Most importantly, when produced sustainably, it does not emit CO_2 and does not pollute the air when used. It is therefore an important part of the overall solution to meet the 2050 climate neutrality goal of the European Green Deal.

Complementing other storage applications, including hydro pumps and batteries, as well as smart grid applications, it can act as a vector for seasonal storage of renewable energy. At the same time, low-carbon hydrogen can be used to replace fossil fuels in hard to abate sectors and complement renewable energy sources in the effort to transform our economy. Furthermore, there is also considerable potential to repurpose the current gas infrastructure to carry and store this hydrogen, helping achieve EU's climate goals much faster and more economically using existing infrastructure.

In its strategic vision for a climate-neutral EU presented by the European Commission on 28 November 2018, the share of hydrogen in Europe's energy mix is projected to grow from the current less than 2% to 13-14% by 2050. The projections were confirmed in the recent impact assessment for the 2030 Climate Target Plan[21], as well as the impact assessments supporting the various policy proposals of the 'Fit for 55' package, where the policy scenarios considered project a ramp up of the installed electrolyser capacity between 37-66 GW by 2035, while for 2050 all policy scenarios project the share for hydrogen in final energy consumption to be at least 9% across policy scenarios. The Fit-For-55 package also considers a 50% target (by 2030) for RFNBOs (which include renewable hydrogen) in industry and a target of at least 2.6% in transport. Blending hydrogen with natural gas in the pipelines is facilitated in the gas and hydrogen markets package, by allowing blends of up to 5% hydrogen volume into natural gas flows to be accepted and facilitated at cross-border points from October 2025, while voluntary agreements for higher blends at interconnection points between Member States remain possible.[22]

In order for hydrogen to claim this position in the energy mix, it will require among others the improvement of its competitiveness against other energy carriers, research and innovation into breakthrough technologies and an infrastructure network that can bring it to a geographically

[21] Commission Staff Working Document Impact Assessment accompanying the Communication Stepping up Europe's 2030 climate ambition. SWD(2020) 176 final.
[22] Proposal for Regulation "Internal markets for renewable and natural gases and for hydrogen (recast)". COM(2021) 804 final, December 2021.

spread market.

1.1.2. The EU hydrogen strategy for a climate-neutral Europe

On 8 July 2020, the Commission adopted the Energy System Integration[23] and Hydrogen Strategies[24]. Together they aim to address a vision on how to accelerate the transition towards a more integrated and clean energy system, in support of a climate neutral economy.

The Energy System Integration Strategy addresses the planning and operation of the energy system "as a whole", across multiple energy carriers, infrastructures, and consumption sectors. The Strategy sets out 38 actions to implement the necessary reforms, including legal, financial and research and development actions. The strategy is built on three complementary and mutually reinforcing elements:

1. A more circular energy system.
2. The use of cleaner electricity produced from renewable sources.
3. The promotion of renewable and low-carbon fuels, including hydrogen, for sectors that are hard to decarbonise.

Recognising the complexity of the hydrogen value chain and the need to act on different areas in order to promote low-carbon hydrogen, the Commission also adopted a Hydrogen Strategy, complementing the Energy System Integration Strategy. Its aim is to identify means to unlock the potential of renewable hydrogen, by decarbonising hydrogen production and expanding the use of low-carbon hydrogen in hard to decarbonise sectors, where it can replace fossil fuels.

Building on the Commission's New Industrial Strategy for Europe[25] and the Recovery Plan for Europe[26], the Strategy sets out a vision of how the EU can turn hydrogen into a viable solution to decarbonise different sectors over time. Most notably, it sets the ambitious goal of installing at least 6 GW of renewable hydrogen electrolysers in the EU by 2024 to produce 1 million tons of hydrogen and 40 GW of renewable hydrogen electrolysers by 2030 to produce 10 million tons of hydrogen.

Through the Hydrogen Strategy a first attempt to define the different types of hydrogen is made, based on their means of production. This document uses to the largest extent the terminology proposed in the Hydrogen Strategy[27]:

- *Renewable hydrogen* refers to either electricity-based hydrogen produced through the electrolysis of water and with the electricity stemming from renewable sources or through the reforming of biogas or biochemical conversion of biomass.
- *Clean hydrogen* refers to renewable hydrogen.

[23] Strategy for Energy System Integration. COM(2020) 299 final.
[24] A Hydrogen Strategy for a climate neutral Europe. COM(2020) 301 final.
[25] New Industrial Strategy for Europe. COM (2020) 102 final.
[26] Europe's moment: Repair and Prepare for the Next Generation. COM (2020) 456 final.
[27] According to the Energy System Integration Strategy, the Commission was planning to propose a comprehensive terminology for all renewable and low-carbon fuels and a European system of certification of such fuels by June 2021. Such a proposal has been included in the revision of the Renewable Energy Directive in the context of the 'Fit for 55' package, but only for renewable hydrogen. As stated in the impact assessment of the proposal, a political decision is required for the inclusion or not of the certification of low-carbon fuels in the same or different proposal, such as the Hydrogen and Decarbonised Gas Market Package planned for the fourth quarter of 2021. For this reason it was decided to remain with the Hydrogen Strategy terminology.

- *Electricity-based hydrogen* refers to hydrogen produced through electrolysis, regardless of the electricity source.
- *Fossil-based hydrogen* refers to hydrogen produced through a variety of processes using fossil fuels as feedstock, mainly the reforming of natural gas or the gasification of coal.
- *Fossil-based hydrogen with carbon capture* is a subpart of fossil-based hydrogen, but where greenhouse gases emitted as part of the hydrogen production process are captured.
- *Low-carbon hydrogen*[28] encompasses fossil-based hydrogen with carbon capture and low-carbon electricity-based hydrogen.

The Hydrogen Strategy identifies as the priority for the EU to develop renewable hydrogen, produced using mainly wind, hydro and solar energy. This should be the main form of hydrogen in the long-term, towards 2050, supported by the very high shares of renewable electricity. In the mid-term, other forms of low-carbon hydrogen will also be needed, both to support the uptake of hydrogen as energy carrier and feedstock, and to replace most polluting forms of producing hydrogen.

The Hydrogen Strategy describes a roadmap with three phases of development:

1st phase: 2020-2024 (activation)

- Install at least 6 GW of renewable hydrogen electrolysers to decarbonise existing hydrogen production, producing 1 Mt of renewable hydrogen in the EU;
- Scaling up of manufacturing of electrolysers;
- Planning of transmission and carbon capture infrastructure;
- Setting up the regulatory and enabling framework for a hydrogen market.

2nd phase: 2025-2030 (upscaling)

- Install at least 40 GW of renewable hydrogen electrolysers, producing 10 Mt of renewable hydrogen in the EU;
- Increasing cost-competitiveness of renewable hydrogen;
- New application for hydrogen, including steel making, trucks, rail and maritime transport applications.
- Electricity-based hydrogen offering flexibility services to the power system;
- Retrofitting of existing fossil-fuel production with carbon capture;
- Emergence of EU-wide logistical and transportation infrastructure for hydrogen;
- Development of Hydrogen Valleys;
- Financial support to stimulate investments;
- Completion of an open and competitive EU hydrogen market.

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[28] In the Gas and Hydrogen Market package, a newer definition is provided for low-carbon hydrogen. According to it, it refers to "*hydrogen the energy content of which is derived from non-renewable sources, which meets a greenhouse gas emission reduction threshold of 70%*".

3rd phase: 2031-2050 (market uptake)

- Low carbon hydrogen technologies reaching maturity, able to be deployed at large scale to reach all hard to decarbonise sectors.

Achieving the above targets will require significant research and innovation efforts, in particular for the second and third phases of the roadmap.

On the generation side, there is a need to optimise and develop specific renewable assets for the renewable hydrogen production and to upscale electrolysers in order to increase competitiveness compared to fossil-based hydrogen, but also develop solutions which are currently at a lower technology readiness level. On the distribution side, further developments are needed in relation to the distribution, storage and dispensing of hydrogen in large volumes and possibly over long distances. Finally, on the demand side, large scale end-use applications need to be further developed, notably in industry and in heavy transport.

Pre-normative research, including the safety dimension, should be tailored to assist deployment plans and enable improved, harmonised standards. Reliable methodologies have to be developed for assessing the environmental impacts of hydrogen technologies and their associated value chains, including their full life-cycle greenhouse gas emissions and sustainability. Coordinated EU research and innovation support is also needed for large-scale high-impact projects across the entire hydrogen value chain.

The Commission aims to address these challenges through its coordinated research and innovation support.

On 11 December 2020, the Council adopted conclusions on steps to be taken towards creating a hydrogen market for Europe.[29] The conclusions gave political guidance to the implementation of the EU Hydrogen Strategy presented by the European Commission on 8 July 2020. In its conclusions, the Council recognised the important role of hydrogen, especially from renewable sources, and the need for the hydrogen market to be significantly scaled up, asking the Commission to further elaborate and implement the EU Hydrogen Strategy. The pathway towards the roadmap's objectives should use joint programmes, be cost-efficient and prioritise energy efficiency and electrification from renewable sources. The Council also sees the need to develop an ambitious hydrogen roadmap and strategy for climate neutrality in the end-use sectors, which makes use of flexible policies.

On 19 May 2021, the European Parliament also adopted a resolution[30] on the European Strategy for Hydrogen. The Member of the Parliament requested for incentives to encourage demand and to create a European hydrogen market and fast deployment of hydrogen infrastructure. They also emphasised the need to phase out fossil-based hydrogen as soon as possible, while certification should be applied to all hydrogen imports, similar to EU-produced hydrogen. Finally, they requested to assess the possibility of repurposing existing gas pipelines for the transport and underground storage of hydrogen.

As the first step in the implementation of the EU Hydrogen Strategy, the 'Fit for 55' package contains a number of measures aiming to promote the production and use of hydrogen and hydrogen based fuels in the different sectors of the economy. The revised Renewable Energy

[29] European Council conclusions, 10-11 December 2020.
[30] European Parliament resolution of 19 May 2021 on a European Strategy for Hydrogen (2020/2242(INI))

Directive[31] proposes the extension of the EU-wide certification system for renewable fuels to include hydrogen, as well as targets for transport and industry that include renewable hydrogen consumption. Additional financial incentives for hydrogen are foreseen by the revision of the EU ETS proposal,[32] which shall extend to maritime, establish emissions trading for transport and buildings; and include electrolytic hydrogen under ETS, thus making low carbon hydrogen eligible for free allowances. Further incentives shall be given through the preferential taxes for the use of low carbon hydrogen, foreseen in the revision of the Energy Taxation Directive.[33] Hydrogen is promoted specifically in the transport sector by three additional targeted proposals: the more stringent CO_2 standards for Cars and Vans;[34] the revision of the Alternative Fuel Infrastructure Regulation[35], requiring one hydrogen refuelling station available every 150 km along the TEN-T core network and in every urban nodes by 2030; and the FuelEU Maritime proposal[36] promoting strongly low carbon hydrogen and hydrogen-based fuels (including methanol and ammonia).

The proposals in the new Gas Markets Decarbonisation package address a number of issues associated with gas markets and networks, most notably ensuring that the necessary hydrogen infrastructure and contestable hydrogen markets are in place to serve the expected rising supply and demand. References to hydrogen have been introduced all over the gas Regulation and Directive, so that provisions for gas markets apply also for the hydrogen market (including the introduction of hydrogen network operators, hydrogen terminals and hydrogen storage facilities). Barriers for blended hydrogen are removed, in order to boost hydrogen's role in the gas market.

The Commission also places a focus on network planning, including a push for gas network operators to include information on infrastructure that can or will be decommissioned and could potentially be repurposed to transport hydrogen. Finally, a certification scheme will be introduced to confirm whether the gas brought on the market is renewable or low-carbon. The European Commission has now added a definition for low carbon gases and fuels under the same certification scheme as renewable gases.

1.2. The R&I support of hydrogen activities of the European Union

The EU has been supporting research and innovation on hydrogen for many years, starting through traditional collaborative projects, and subsequently mainly with the FCH JU established in 2008.

The early EU Framework Programmes (FP) supported research and development in fuel cells and hydrogen technologies with increasing funding levels over time. Nevertheless, these efforts were fragmented and uncoordinated across the different FP sub-programmes. Recognising this issue, the European Commission facilitated the creation of a European Hydrogen and Fuel Cell

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[31] Proposal for a Directive as regards the promotion of energy from renewable sources. COM (2021) 557 final.

[32] Establishing a system for greenhouse gas emission allowance trading with the Union. COM (2021) 551 final.

[33] Restructuring the Union framework for taxation of energy products and electricity, COM (2021) 563 final.

[34] Strengthening the CO2 emission performance standards for new passenger cars and new light commercial vehicles in line with the Union's increased climate ambition. COM (2021) 556 final.

[35] Regulation on the deployment of alternative fuels infrastructure. COM (2021) 559 final.

[36] Regulation on the use of renewable and low-carbon fuels in maritime transport. COM (2021) 562 final.

Technology platform (HFP) (2004-2007), bringing together all interested stakeholders. This process confirmed that a coherent, long-term approach at EU level is essential for achieving critical mass in terms of scale, excellence and potential for innovation.

In May 2008, the Council adopted a Regulation[37] setting up a Joint Undertaking for Fuel Cells and Hydrogen. The aim of FCH JU under FP7 was to accelerate the development and deployment of fuel cell and hydrogen technologies by executing an integrated European programme of Research Technology and Development activities for the period 2007-2013.

The programme entered its second phase, with FCH 2 JU, in Horizon 2020. FCH 2 JU was a public-private partnership with three members: the industry grouping Hydrogen Europe, the research grouping Hydrogen Europe Research and the European Commission. The focus was on accelerating the commercialisation of fuel cells and hydrogen technologies to ensure a world leading, competitive European FCH industry while increasing jobs.

These efforts have enabled several technologies to come close to maturity, alongside the development of high-profile projects in promising applications, and to achieve EU global leadership for future technologies, notably on electrolysers, hydrogen refuelling stations and megawatt-scale fuel cells. EU funded projects also allowed improvement in the understanding of the applicable regulation for boosting the production and utilisation of hydrogen in the EU.

Nevertheless, these developments are far from sufficient to meet the increased ambition reflected in the Hydrogen Strategy. Therefore, the Commission plans to carry out a set of actions targeting research, innovation, and relevant international cooperation, supporting the energy and climate policy objectives.

On one hand, it can provide financial support through the EU ETS Innovation Fund, to facilitate first-of-a-kind demonstration of innovative hydrogen-based technologies, and through targeted support to build the necessary capacity for preparation of financially sound and viable hydrogen projects.

On the other hand, and focusing more on research and innovation rather than deployment, the Council and the Parliament adopted a regulation establishing the Joint Undertakings under Horizon Europe (hereon Single Basic Act or SBA),[38] including the establishment of the Clean Hydrogen Joint Undertaking, the continuation of FCH 2 JU. The Clean Hydrogen JU will have the leading role in research activities related to hydrogen. Since hydrogen can be deployed as a fuel, energy carrier and for storing energy it is essential that the clean hydrogen partnership establishes structured collaboration with many other European partnerships, notably for end-use. However, hydrogen related research will also be supported by other partnerships and EU Funds under direct supervision of the European Commission, as well as collaborative research and innovation actions of Horizon Europe and other EU programmes. Moreover, low technology readiness levels for hydrogen may also be supported through calls for applications of the European Research Council. Finally, intergovernmental coordination of EU Member States and other States under the UN Conference of the Parties (COP) agenda, has led to emergence of a proposal for Mission Innovation 2.0 on hydrogen, where the European Commission is expected to co-lead with Australia, Chile, Germany and the United Kingdom a mission on hydrogen. Mission Innovation 2.0 will also aim at intergovernmental initiatives on research and

[37] Council Regulation (EC) No 521/2008 of 30 May 2008 setting up the Fuel Cells and Hydrogen Joint Undertaking.

[38] Council Regulation (EU) 2021/2085 of 19 November 2021 establishing the Joint Undertakings under Horizon Europe and repealing Regulations (EC) No 219/2007, (EU) No 557/2014, (EU) No 558/2014, (EU) No 559/2014, (EU) No 560/2014, (EU) No 561/2014 and (EU) No 642/2014.

innovation. To this end, a framework of co-operation aiming to benefit from the synergies across the different programmes has been set up, described in more detail in Section 4.1.

The Clean Hydrogen JU is set up in the form of an institutionalised partnership under the Research and Innovation Framework Programme Horizon Europe. Its main focus will be on renewable hydrogen production, as well as hydrogen transmission, distribution and storage, alongside selected fuel cell end-use technologies.

2. Clean Hydrogen Joint Undertaking

2.1. Mission and vision of the Clean Hydrogen Joint Undertaking

Clean Hydrogen JU Vision

Support a sustainable hydrogen economy, contributing to EU's climate goals

Clean Hydrogen JU Mission

Facilitate the transition to a greener EU society through the development of hydrogen technologies.

The Clean Hydrogen JU will contribute to the European climate neutrality goal by producing noticeable, quantifiable results towards the development and scaling up of hydrogen applications. This will help develop a number of hydrogen technologies, which are currently either not competitive or have a low technology readiness level, but are expected to contribute to the 2030 energy and climate targets and most importantly make possible climate neutrality by 2050.

The focus of the research and innovation activities of the Clean Hydrogen JU will have a different scope compared to FCH 2 JU, shifting to areas related primarily to the production of clean hydrogen, as well as the distribution, storage and end use applications of low carbon hydrogen in hard to abate sectors. They will be guided to a large extent by EU's Hydrogen Strategy and the policy developments in this context, contributing to its implementation.

In particular the Clean Hydrogen JU will aim to accelerate the development and deployment of the European value chain for safe and sustainable clean hydrogen technologies, strengthening its competitiveness and with a view to supporting notably SMEs, accelerating the market entry of innovative competitive clean solutions. The final goal is to contribute to a sustainable, decarbonised and fully integrated EU energy system, and to the EU's Hydrogen Strategy, playing an important role in the implementation of its roadmap towards a climate neutrality and circular European Society.

To this end, cross-cutting aspects such as safety, circularity and sustainability may be embedded throughout the entire Clean Hydrogen JU Programme, guiding and underpinning the activities undertaken within. Concerning circularity and sustainability aspects, in particular, it is foreseen that activities should not only address these aspects as part of the "post-development" assessment, but also for orientating and/or looking for solutions and/or taking decisions (e.g. materials selection) to develop a product, technology and/or a value chain in a more sustainable and circular manner. In this sense, "Safety and circularity by design" should become essential aspects across the Clean Hydrogen JU Programme.

2.2. Objectives of the Clean Hydrogen JU for 2021-2027

The Clean Hydrogen JU objectives are defined in articles 4, 5 and 73 of the Single Basic Act[38]. Articles 4 and 5 describe the general, specific and operational objectives common to all partnerships. These objectives were identified in a coordinated impact assessment for all partnerships, aiming to align them with the objectives of Horizon Europe and EU policy in general. Article 73 adds additional general and specific objectives to the Clean Hydrogen JU, more specific to its role and scope.

Overall, the objectives of the Clean Hydrogen JU significantly increase, compared to the ones of FCH 2 JU. In particular, the three general objectives of FCH 2 JU become seven in total, four of which are specific to the Clean Hydrogen JU. Similarly, the specific objectives from five in FCH 2 JU become nine in total, four of which are specific to the Clean Hydrogen JU. To these nine, more operational objectives are added, common to all partnerships. In total, the Single Basic Act identifies twenty-nine objectives for the Clean Hydrogen JU, eleven of which specific to the Clean Hydrogen JU.

The common objectives for all partnerships ensure clear impact for the EU and its people, achieving strategic objectives such as accelerating the transition towards sustainable development goals and a green and digital Europe, while contributing to recovery from the COVID-related crisis. They aim to strengthen and integrate the Union's scientific and technological capacities to support the creation and diffusion of new high-quality knowledge notably with a view to deliver on global challenges, securing Union competitiveness, sustainability and contributing to a reinforced European Research Area.

The objectives specific to the Clean Hydrogen JU reflect the need to strengthen and integrate Union scientific capacity in order to accelerate the development and improvement of advanced clean hydrogen applications ready for market, across energy, transport, building and industrial end-uses. In order for that acceleration to become possible, it needs to be combined with actions strengthening competitiveness of the Union clean hydrogen value chain, and notably SMEs. Particular attention is given to the co-operation with other European partnerships under Horizon Europe.[39] For that purpose, a specific structure – the Stakeholder Representative Group (see Section 6.5) – will be reporting to the Governing Board. The Clean Hydrogen JU would be the only partnership focused on addressing hydrogen production technologies. Collaboration with end-use partnerships should in particular focus on integration and demonstration.

In this context, the Single Basic Act defines the following general objectives specific for the Clean Hydrogen JU, while following the principle of technological neutrality:

a) Contribute to the objectives set out in the 2030 Climate Target Plan and the European Green Deal and the European climate law, by raising the Union's ambition on reducing greenhouse gas emissions to at least 55 % below 1990 levels by 2030, and climate neutrality at the latest by 2050;

b) Contribute to the implementation of the 2020 European Commission's Hydrogen

[39] See also recital 58 of the SBA, where it is explicitly mentioned that "*The clean hydrogen European partnership should interact in particular with the zero emission road and waterborne transport, Europe's railway, clean aviation, processes for the planet and clean steel European partnerships.*".

Strategy for a climate neutral Europe[40];

c) Strengthen the competitiveness of the Union clean hydrogen value chain, with a view to supporting, notably SMEs, accelerating the market entry of innovative competitive clean solutions;

d) Stimulate research and innovation on clean hydrogen production, distribution, storage and end use applications.

These are then translated in the following specific objectives:

1. Improve through research and innovation, including activities related to lower Technology Readiness Levels (TRL), the cost-effectiveness, efficiency, reliability, quantity and quality of clean hydrogen solutions, including production, distribution, storage and end uses developed in the Union;
2. Strengthen the knowledge and capacity of scientific and industrial actors along the Union's hydrogen value chain, while supporting the uptake of industry-related skills;
3. Carry out demonstrations of clean hydrogen solutions with the view to local, regional and Union-wide deployment, aiming at involving stakeholders in all Member States and addressing renewable production, distribution, storage, and use for transport and energy-intensive industries as well as other applications;
4. Increase public and private awareness, acceptance, and uptake of clean hydrogen solutions, in particular through cooperation with other European partnerships under Horizon Europe.

The last specific objective concerning the co-operation with other European partnerships reflects the importance of hydrogen as a fuel, energy carrier and energy storage medium, with application in all end-use sectors. Therefore, it is deemed important that the Clean Hydrogen JU establishes a structured collaboration with many other Horizon Europe partnerships. This aspect is discussed in more detail in Section 4.1.

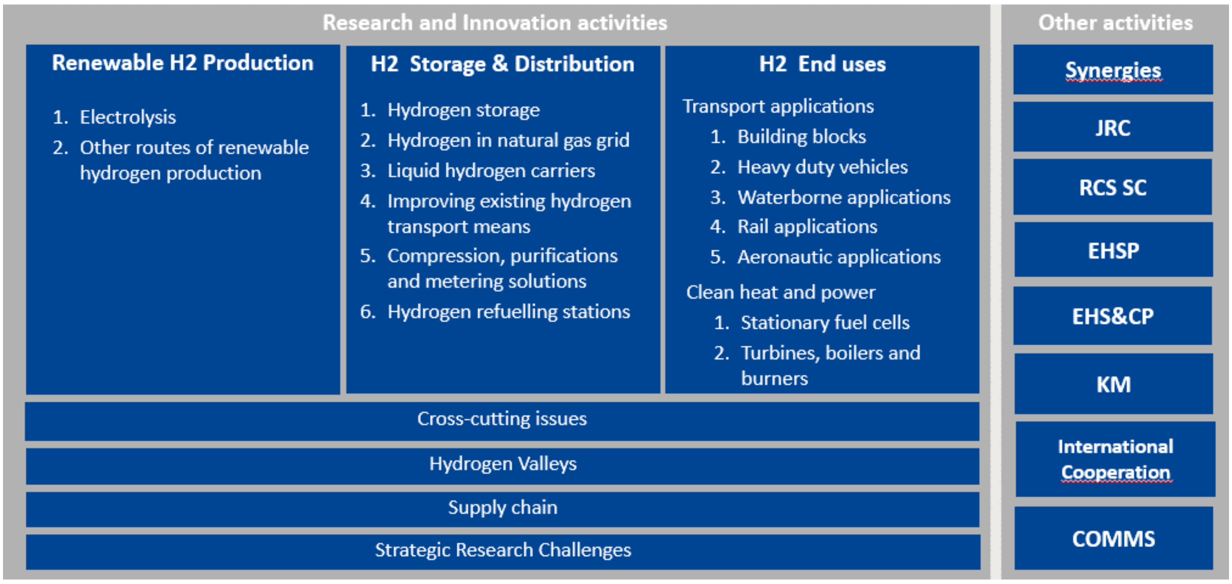
[40] Some objectives by 2030: produce clean hydrogen at around €1.5-3/kg, which will require reaching the 2030 targets in efficiency improvement and lowering CAPEX costs. In addition, this also assumes the availability of renewable electricity at favourable prices, as well as allowing penetration into mass markets, and reducing distribution costs to less than €1/kg of hydrogen at scale.

3. Research and Innovation Activities

3.1. Structure of the Clean Hydrogen JU Programme

The Programme of the Clean Hydrogen Joint Undertaking has been structured so as to cover all aspects of the hydrogen value chain.

Figure 1 Overview of the Clean Hydrogen Joint Undertaking activities



Its main focus will be on research and innovation actions on renewable hydrogen production, but also hydrogen transmission, distribution and storage, alongside stationary and transport end-use technologies, with a strong emphasis on "circularity and safety by design":

Pillar 1: Renewable Hydrogen Production (Section 3.2)

Pillar 2: Hydrogen storage and distribution (Section 3.3)

Pillar 3: Hydrogen end uses

Pillar 3.1: Transport applications (Section 3.4)

Pillar 3.2: Clean heat and power (Section 3.5)

In addition to working within each of these pillars, mass deployment requires support and coordination action, but also flagship actions[41] to be taken at system level. They are thus complemented by four additional horizontal and cross-cutting activities, necessary as follows:

Horizontal Activity 1: Cross-cutting Issues (Section 3.6)

Horizontal Activity 2: Hydrogen Valleys (Section 3.7)

Horizontal Activity 3: Hydrogen Supply Chains (Section 3.8)

Horizontal Activity 4: Strategic Research Challenges (Section 3.9)

For each Pillar and Horizontal Activity, specific objectives are described, accompanied by a

[41] The definition of flagship projects can be found in Section 5.2.

number of actions[42] aiming to contribute towards their achievement. These actions comprise of long-term, breakthrough-oriented research, applied research and technology development, demonstrations and supporting actions, including strategic studies, pre-normative actions and technology assessment. All these elements are described in detail in Section 0. The research and innovation activities are complemented by a number of additional activities described in Section 4.

Types of Actions in the SRIA

Research and Innovation Actions consisting of activities aiming to establish new knowledge (Early Stage Research Actions) and/or to explore the feasibility of a new or improved technology, product, process, service or solution (Development Stage Research Actions). Such actions target in general lower Technology Readiness Level (TRL).

Innovation Actions consisting of activities aimed at producing plans and arrangement or designs for new, altered or improved products, processes or services, and will include prototypes, demonstrations or pilot, and market replication activities. Projects may include limited research & innovation activities and have in general a higher TRL.

Coordination and support actions consisting, inter alia, of measures such as standardisation, dissemination, awareness raising and communication, networking, coordination or support services, and studies.

3.2. Renewable Hydrogen production

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. For that to happen, renewable hydrogen needs to become cost-competitive and its technologies need to be scaled up in a fashion similar to renewable technologies during the last decade. For renewable hydrogen to be competitive with conventional fuels in transport applications, a cost around 5 €/kg at the pump must be achieved for cost parity with diesel fuel[43], which can be further lowered though through the aid of the recently proposed ETS-2 and some of the new measures included in the revision of the Effort Sharing Decision. For Industry, renewable hydrogen costs must reach levels between 2-3 €/kg as a feedstock[44], in order to achieve parity with fossil-based inputs, once the cost of carbon is included in the feedstock cost.

To reach this objective, further improvements are required especially in cost reduction and efficiency increase for a variety of renewable hydrogen production routes, the main workhorse being electrolysis, supported by other routes exploiting direct sunlight such as thermal dissociation of water using concentrated solar energy or through photocatalysis, biomass/biogas or other biological routes. Through electrolysis, higher and more efficient

[42] The actions proposed for all the pillars are based on the final draft of the SRIA-HE/HER (October 2020). These should be considered indicative, especially considering the dynamic and fast growing field of research and development in hydrogen technologies, which may very likely shift the priorities over the next few years.
[43] See Figure 15 in Strategic Research and Innovation Agenda, final draft October 2020, Hydrogen Europe and Hydrogen Europe Research
[44] Green Hydrogen Cost Reduction: Scaling up electrolysers to meet the 1.5°C climate Goal, IRENA 2020

integration of renewables within the overall energy system can be also achieved.

Water electrolysis will be the main technology supported, covering high TRL types - Alkaline Electrolysis (AEL), Proton Exchange Membrane Electrolysis (PEMEL), Solid Oxide Electrolysis (SOEL) - and less mature types - Anion Exchange Membrane Electrolysis (AEMEL) and Proton Conducting Ceramic Electrolysis (PCCEL).

As presented in Annex 2, state of the art electrical consumption at stack level is 50 kWh/kg for AEL and 55 kWh/kg of hydrogen for PEMEL while the target for 2030 is for these figures to be reduced to 48 kWh/kg for AEL and 50 kWh/kg for PEMEL (69% efficiency, LHV). For SOEL current 40 kWh_e/kg for SOEL and 10 kWh_{th}/kg is to be reduced to 37 kWh_e/kg and 8 kWh_{th}/kg by 2030. Similarly, the current cost of MW-size AEL electrolysers is 600 €/kW, for PEM 900 €/kW and 2,130 €/kW for SOEL. These costs are to be reduced to 400 €/kW, 500 €/kW and 520 €/kW for AEL, PEM and SOEL respectively by 2030. Further reduction could be achieved through streamlined manufacturing processes. In regions where renewable electricity is cheap, electrolysers are expected to be able to compete with fossil-based hydrogen in 2030.

Cheap renewable electricity can be produced onshore, but also offshore. The EU Strategy on Offshore Renewable Energy proposes to increase Europe's offshore wind capacity from its current level of 12 GW to at least 60 GW by 2030 and to 300 GW by 2050. Particular attention therefore will be paid to offshore renewable Hydrogen production.

Clean Hydrogen JU's support to hydrogen production demonstration will be limited to renewable hydrogen, while support to low-carbon hydrogen production could be provided by other EU funding programmes, such as the Innovation Fund, or by other partnerships within Horizon Europe. Low-carbon hydrogen, however, is not excluded from the hydrogen storage, distribution and end-use activities of this SRIA.

3.2.1. Electrolysis

Rationale for Support

Water electrolysis has been used to produce hydrogen in industry for nearly a century. Electrolysis has the potential to be a zero-emission form of hydrogen production, if powered by renewables[45]. Electrolysis is a key means for enabling renewable energy penetration into all sectors, with electrolytic hydrogen being produced at, or transported to, the points of use. Renewable hydrogen produced through electrolysis enables the increased penetration of variable renewable energy into hard to decarbonise sectors like industry, transport, building & heating. However, considerable development of electrolyser technology, cost, performance and durability, connectivity to renewables, water management and the scale of deployment is still needed to achieve this vision. Other technologies such as reversible electrolysis and co-electrolysis will contribute to technology progress, widening the impact to the energy and industrial sectors.

Approximately 8 Mt/year of hydrogen[46] is currently used in Europe in a wide range of industrial processes (mainly refining & ammonia production). These quantities are largely fossil-based hydrogen produced by Steam Methane Reforming (SMR) from fossil natural gas and can be replaced by renewable hydrogen. Furthermore, renewable hydrogen can replace fossil fuels as a feedstock in other industrial processes (e.g. coke as a reducing agent in the steel

[45] Following the methodology of the RED and FQD used for balancing GHG emissions.
[46] Based on the capacity reported in the Fuel Cell and Hydrogen Observatory and the 84% average capacity utilisation reported in the European Clean Hydrogen Monitor 2020.

manufacturing process, particularly in Direct Reduced Iron – DRI - furnaces) and can be used in combination with CO_2 (preferably sustainable), producing liquid fuels, synthetic natural gas and important petrochemicals as well as an energy source for heat and power generation. The scale and particularities of industrial forecourts dictate particular developments for electrolysers for their successful integration.

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. R&I will be key to maintain this leadership in time.

Deployment of competitive renewable hydrogen implies the need of tackling electrolysis cost and performance in parallel to renewable power cost (including the electrical grid), since the cost of renewable power is the main driver of the cost of renewable hydrogen. Reaching a competitive renewable hydrogen will request the development of dedicated renewable assets (i.e. wind turbines, associated orchestration systems, hydro, batteries, converters, transformers, other grid assets…). The variable nature of renewable have a direct impact on the design of the electrolysis and respective costs (i.e. CAPEX, OPEX…). A system thinking approach between renewable asset, electrical grid, controls and electrolysis is essential to know which research path are the most viable to reach parity with fossil fuel-based hydrogen production while optimising EU funding availability.

State of the Art

Water and Steam electrolysis demonstration projects for AEL, PEMEL and SOEL technologies up to few MW scale are already operational. Projects ranging from 20 MW to more than 100 MW are under development with current hydrogen costs in the range of 5-8 €/kg. In the context of the Green Deal Call under H2020, the European Commission launched a call for a 100 MW electrolyser. Electrolyser OEMs are scaling up manufacturing facilities to multi-GW per annum, some announcing targets of 1.5 $/kg of renewable hydrogen for 2025[47] provided low-cost renewable power can be secured.

Alkaline systems of more than 100 MW have been deployed worldwide in industry, typically in aluminium production, although historically they were deployed in ammonia plants which pre-date cheap natural gas and for chlorine production in chlor-alkali electrolysis.

The largest electrolyser demonstration projects of FCH 2 JU include:

1. DJEWELS[48] (2019), a 20 MW pressurised AE to be installed at Nobian's Delfzijl site in the Netherlands, to produce green methanol;
2. REFHYNE[49] (2018), a 10 MW pressurised PEME to be installed at Shell's Cologne refinery;
3. H2FUTURE[50] (2016), a 6 MW atmospheric PEME installed and operating since late 2019 in a steel plant in Linz;
4. MULTIPLHY[51] (2019), a 2.6 MW SOEL to be installed at NESTE's Rotterdam biorefinery;

[47] https://nelhydrogen.com/press-release/nel-cmd-2021-launches-1-5-usd-kg-target-for-green-renewable-hydrogen-to-outcompete-fossil-alternatives/
[48] https://cordis.europa.eu/project/id/826089
[49] https://cordis.europa.eu/project/id/779579
[50] https://cordis.europa.eu/project/rcn/207465/en.html
[51] https://cordis.europa.eu/project/id/875123

5. DEMO4GRID[52] (2016), a 3 MW AE for hydrogen provision to a food industry where hydrogen will be combusted displacing natural gas in an oil boiler;
6. HYBALANCE[53] (2014), a 1.25 MW PEME (operating) providing hydrogen to a light metal industry, including electricity grid balancing.

Objectives

Hydrogen production via electrolysis is currently more expensive than via other methods due to the high capital costs of the electrolysers and dependence on electricity costs. The key objectives for realising the 2030 vision are:

1. Reducing electrolyser CAPEX and OPEX;
2. Improving dynamic operation and efficiency, with high durability and reliability, especially when operating dynamically;
3. Increasing current density and decreasing footprint;
4. Demonstrate the value of electrolysers for the power system through their ability to provide flexibility and allow higher integration of renewables;
5. Ensure circularity by design for materials and for production processes, minimising the life-cycle environmental footprint of electrolysers;
6. Increasing the scale of deployment;
7. Improved manufacturing for both water and steam electrolysis.

In terms of industrial scale applications of electrolysers, the goal is to replace fossil-based hydrogen with renewable hydrogen in existing industrial uses such as NH_3 production and refineries, saving 60 $MtCO_2$ per year and to successfully introduce and demonstrate the use of renewable hydrogen in steel, cement and petrochemical industries that need to be converted to use hydrogen. The Clean Hydrogen JU will not be able to provide alone the necessary support/funding for this. Synergies will be sought with the Clean Steel and Processes4Planet (P4P) partnerships for large scale demonstrations in the steel, cement and petrochemical industries, as well as with Member State specific funding programmes such as the National Recovery and Resiliency Plans (NRRP), Important Projects of Common European Interest (IPCEI). Using the example of the steel industry, technological developments or innovations dealing with hydrogen production, distribution and storage will be within the scope of the Clean Hydrogen JU, while developments in new steel production plants or processes will be within the scope of the Clean Steel and P4P partnerships[54].

To ensure a cost-competitive renewable hydrogen supply chain to serve the European economy, further research and innovation efforts are required on the hydrogen production side. This will entail more efficient and cost-effective electrolysers, as well as upscaling to larger size, developing electrolyser modules of tens of megawatts, which would lead to electrolyser plants in the range of gigawatts. Together with mass-manufacturing capabilities and new materials, they would supply renewable hydrogen to large consumers. By the end of 2030, the aim of the EU Hydrogen Strategy is for at least 40 GW of electrolysers to be installed in Europe. Together with improvements in efficiency, the resulting cost reductions should make it possible for electrolysis to be capable of producing renewable hydrogen at a levelised cost of hydrogen

[52] http://cordis.europa.eu/project/rcn/207243_en.html
[53] http://cordis.europa.eu/project/rcn/199464_en.html
[54] See Annex 7

below 3 €/kg assuming 40 €/MWh and 4,000 full load hours operation[55].

In order to contribute towards achieving these objectives, the following areas of research and development appear as good candidates for the support by the Clean Hydrogen JU.

R&D Priorities - Early Stage Research Actions

Future cost reductions and increased lifetime in the different electrolysis technologies may be realised through new materials/manufacturing processes/concepts as per the priorities below.

- Generic for all electrolysis: Develop new electrodes and membranes, reducing / free of critical raw materials (CRMs) and reducing / without per- and polyfluoroalkyl substances in order to avoid in the medium-long term their use in different materials or components such as electrocatalysts, MEAs, etc, as well as novel and breakthrough cell design, to increase the current density, while improving their lifetime and efficiency, develop low-cost metallic materials coatings and seals, develop and validate integrated mounting concepts, thermal management and innovative manufacturing processes;
- Development of novel catalysts (low PGM, non-PGM, bioinspired) for water electrolysis);
- Minimisation of environmental impact / aim for circularity (energy, resources/material, recyclability);
- AEL: develop more compact stack design, reach high current density without noble metals, 3D electrodes, pulsed voltage;
- PEMEL: Reduce precious metals content in catalysts and consider recycling, develop PGM-free catalysts, develop new/advanced membranes, reduce gas crossover while increasing current densities and operating pressures;
- SOEL: pressurised stack, improved hydrogen purity at exit of stack; new stack designs and use of advanced manufacturing techniques;
- AEMEL: improved materials, new membranes, reduction of KOH concentration, increase scale/capacity, aiming for waste minimisation / circularity;
- PCCEL: planar or tubular cells of improved materials and optimised design and performances in view of scaling up to hundreds of kilowatts size;
- Others: investigate the possibility of non-pure water electrolysis.

R&D Priorities - Development Research Actions

Several concepts for reducing electrolyser costs and improving technical Key Performance Indicators (KPI) 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;

[55] The Future of Hydrogen, IEA, 2019

- 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), when relevant in optimised electrical integration with renewables;
- 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;
- Develop new stack and balance of plant (BoP) designs adapted to several end uses, e.g. onshore and offshore windmill direct connection, coupling with renewables in remote areas and related constraints.

R&D Priorities - Demonstration Actions

- Projects are needed to demonstrate that electrolysis technology, when deployed at scale, has the potential to meet cost and performance KPIs, thus demonstrating novel integration concepts, use cases or business models validated in demo activities;
- Develop automation and quality control processes for continuous production of large volumes of cell/stacks components;
- Demonstrate at the MW range the alternative electrolysis technologies – AEMEL and PCCEL;
- 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 energy;
- MW scale direct coupling to renewable generation (both on- and off-grid) including offshore hydrogen production, aiming at identifying the best system configuration to reach competitiveness;
- Integrating large scale electrolysers (50-200 MW) into industrial production plants, demonstrating dynamic operation;
- Renewable hydrogen (both on and off-grid) for refining crude oil into complex fuels (e.g. kerosene/jet fuel);
- Ammonia and methanol production with renewable hydrogen (both on and off-grid) to decrease GHG emissions and managing energy loads;
- Production of synthetic petrochemicals (e.g. olefins, BTX and syngas) using renewable hydrogen (both on and off-grid);
- Demonstrate the ability of renewable hydrogen (both on and off-grid) as a reducing agent in iron and steel production (replacing fossil fuels such as coke and natural gas);
- Consider industrial applications where oxygen and electrolysis waste heat could also be exploited besides renewable hydrogen (both on and off-grid).

Flagship Actions

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 integration of large-scale electrolysers in particular in industrial / building environments could lead to changes to their specifications in order to obtain installation and operation permits, the process providing valuable feedback to the electrolysis industry. In terms of capacity, such flagship projects should aim to develop and demonstrate single modules of large capacity (few tens of megawatts) which when repeated in commercial projects could achieve hundreds of megawatts capacity, on-grid or off-grid, onshore or offshore.

Synergies

Potential synergies will be explored with P4P and Clean Steel partnerships in successfully demonstrating the use of renewable hydrogen in industry. Possible synergies may also be explored with the CETP partnership. See Section 4.1 and Annex 7 for more details on the synergies.

3.2.2. Other routes of renewable hydrogen production

Rationale for Support

Traditionally, hydrogen has been produced from fossil sources by steam methane reforming of natural gas. However, hydrogen can also be produced from a broad range of renewable energy sources, the technology of first choice being water electrolysis using renewable electricity. Solutions at lower Technology Readiness Level need also to be incentivised and developed, such as hydrogen production from biological origin (e.g. algae, microbes) through several processes (e.g. dark fermentation), from direct solar water splitting using solar thermal heat or direct sunlight (photonic energy), or from pyrolysis/gasification processes for hydrogen production from biomass/biogas with solid carbon as a by-product. At the same time, attention needs to be paid to sustainability requirements – these routes could potentially be environmentally positive. The topic of pyrolysis and carbon black production is outside the scope of the current SRIA and will be covered through the synergies with P4P.

State of the Art

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. Gas Goes Green Programme[56] in the UK), yet there are no MW scale plants operating. The FCH 2 JU has supported renewable hydrogen production from dry biomass through gasification or the reforming of raw biogas in novel reactors but efficiencies reached were around 40% (project BIONICO).

Similarly, the FCH 2 JU has supported projects related to the thermal dissociation of water using concentrated light culminating to the construction of a demonstration plant of 750 kW_{th} (Hydrosol-Plant[57]) concluding that there is considerable room for further improvement in materials and processes as there is a significant gap between the theoretical and measured efficiency (25 and less than 1% respectively). There is a range of technologies being explored at the laboratory scale for using solar energy to split water by photochemical and photoelectrochemical means. Solar to renewable hydrogen efficiencies higher than 20% have

[56] https://www.energynetworks.org/creating-tomorrows-networks/gas-goes-green
[57] https://cordis.europa.eu/project/rcn/219835/factsheet/en

been reached on small specimens in the lab, dropping to 10% for cells of a few m² operating with sunlight (project PECSYS).

In terms of biological processes, the FCH JU has supported only one project (HYTIME) and there is a need to move beyond the pilot-plant to demonstration scale. In the case of bio-electrochemical processes, there are several pilot-plant systems throughout the world using different types of feedstocks, producing hydrogen and other by-products from different wastewaters. Currently, higher volume reactors range from 120 litres to 1 m³, with a maximum hydrogen purity between 94% and around 100%. The EU has supported under FP7 some low TRL projects for the treatment of wastewater, or other wastes, and the simultaneous production of hydrogen (Waste2bioHy[58]).

Objectives

The objective of the research and innovation support to be provided by the Clean Hydrogen JU will aim to make a range of technologies available by 2030 which can produce renewable, low cost (around 3 €/kg including feedstock cost) hydrogen operating either at distributed or central facilities with capacities approaching MW of hydrogen production, with reduced land use.

The objectives can be summarised below:

1. Reducing CAPEX and OPEX
2. Improving the efficiency of processes
3. Increasing carbon yield for processes based on biomass/raw biogas (kg hydrogen / kg carbon)
4. Scaling up

The alternative renewable hydrogen production routes on which the current Programme will be focusing are:

1. Biomass & bio-waste gasification for distributed hydrogen production, potentially associated with carbon, capture & storage (CCS), the latter being outside the scope of the Clean Hydrogen JU;
2. Raw biogas reforming for distributed hydrogen production, potentially associated with CCUS (possible negative CO_2 emissions) the latter being outside the scope of the Clean Hydrogen JU;
3. Thermochemical water splitting;
4. Photo electrochemical and photocatalytic water splitting;
5. Biological and bioelectrochemical hydrogen production (e.g. dark and photo-fermentation, algae and electrohydrogenesis).

In order to contribute towards achieving the above objectives, the following areas of research and development appear as good candidates for the support by the Clean Hydrogen JU.

R&D Priorities - Early Stage Research Actions

- Biomass & bio-waste gasification: novel reactor design, materials and processes improving feedstock flexibility and hydrogen yields, novel solutions and methods for syngas cleaning and upgrade. Supercritical water gasification; investigation of CO_2

[58] https://cordis.europa.eu/project/id/326974/reporting

emitted emissions and of potential for integration with efficient CO_2 capture processes, the latter being outside the scope of the Clean Hydrogen JU;

- Biological production: new concepts of bio-reactors with a high rate of production for middle and large size plants; technical solutions to achieve high and stable hydrogen production e.g. inoculum conditioning, feedstock pre-treatment;
- Electrohydrogenesis: new reactors designs; low-cost, stable and efficient electrode and membrane materials; stable improvement of hydrogen production efficiencies and rates; as well as biomass and wastewater flexibility;
- Direct solar: 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.

R&D Priorities - Development Research Actions

- Biogas: development of new, compact and energy efficient reactor concepts for raw biogas reforming;
- Biomass & bio-waste gasification: scaling up of most promising technologies (including e.g. hybrid systems, solar gasification);
- Biological production: development of medium-scale bio-reactors;
- Electrohydrogenesis: improving the volumetric treatment rate, hydrogen production and reactors sizes. Increasing the pilot-plant systems efficiency and long-term operation. Standardisation of reactor designs. Combination with renewables energies;
- Direct solar: scaling up of most promising technologies.

R&D Priorities - Demonstration Actions

Demonstration projects of most promising technologies may include:

- Demonstration-scale plant for waste & biomass gasification;
- Demonstration-scale plant with renewable hydrogen production from biogas;
- Full sized biological reactor demonstration project;
- Medium-sized (100s of kWth) pilots of most promising direct sunlight technologies.

Flagship Actions

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

Synergies

Potential synergies will be explored with P4P especially in the field of pyrolysis of biomass/biogas. See Section 4.1 and Annex 7 for more details on the synergies.

3.3. Hydrogen storage and distribution

As explicitly mentioned in the EU Hydrogen Strategy, it is essential that hydrogen becomes an intrinsic part of an integrated energy system. In order for this to happen, hydrogen will have to be used for daily and/or seasonal storage providing buffering functions thereby enhancing security of supply in the medium term. The strategy also calls for an EU-wide logistical infrastructure that needs to be developed in order to transport hydrogen from areas with large renewable potential to demand centres across Europe. Consequently, a pan-European grid will have to be established[59] along with a far-reaching network of Hydrogen Refuelling Stations[60]. A policy brief[61] by the Joint Research Centre assessing hydrogen delivery options concludes that there is no single optimal hydrogen delivery solution across every transport scenario. The most cost effective way to deliver renewable hydrogen depends on a number of parameters, notably distance, amount of hydrogen, final use and whether there is infrastructure already available. The calculation becomes even more complex when the whole coupled energy system and its congestion management costs and capabilities to integrate renewables are considered, taking into due account electricity, molecules and heat (as a single whole).

In general, the development of infrastructure requires significant investments and should therefore be planned in a sound manner across the whole energy system, not only at vehicle or hydrogen production and delivery level, to avoid costly stranded assets and duplications (for instance between gaseous and liquid hydrogen infrastructure).

For distances compatible with the European territory, compressed and liquefied hydrogen solutions, and especially compressed hydrogen pipelines, offer lower costs than chemical carriers do. The repurposing of existing natural gas pipelines for hydrogen use is expected to significantly lower the delivery cost, making the pipeline option even more competitive in the future. By contrast, chemical carriers become more competitive the longer the delivery distance (due to their lower transport costs) and thus can more easily be traded in the global hydrogen markets.

In line with the above, a pluralistic approach with respect to the technologies that will be investigated and supported is envisaged, in order to have a complete set of technologies that can serve as building blocks of the EU-wide logistical infrastructure.

3.3.1. Hydrogen Storage

Rationale for Support

For hydrogen to become a key solution in the energy transition and to enable the integration of intermittent renewable energy sources in the grid there needs to be an available and low-cost form of bulk storage that can act as a buffer but also in order to support the industrial use of hydrogen. Large-scale seasonal energy storage can be achieved by storing hydrogen in underground salt caverns and gas fields, 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

[59] The Commission is expected to propose specific policy measures in this direction in the upcoming Hydrogen and Gas markets Decarbonisation Package.

[60] The revised Directive on deployment of alternative fuels infrastructure (AFIR) requires Member States to ensure a minimum number of accessible hydrogen refuelling stations by 2030: (a) one HRS with a minimum 2 tonnes/day capacity and at least a 700 bar dispenser per 150 km along the TEN-T core, (b) at least HRS in each urban node, and (c) at least one liquid hydrogen HRS per 450 km. The JU will examine ways to support its implementation.

[61] Science for Policy Briefs: Assessment of Hydrogen Delivery Options, 2021, JRC

hydrogen. However, as underground storage sites are not so common, there will also be a need to store large quantities of hydrogen above ground in large pressurised cylinders, in liquid form or in solid-state to reduce footprint and improve safety to support the hydrogen clusters of the future.

State of the Art

Hydrogen has been successfully stored at a large scale for industrial applications for many years. For example, underground gas storage sites in salt caverns were used to store hydrogen in the Teesside chemical complex in the UK for many years.

The industrial and chemicals sector is very experienced in handling and storing large quantities of hydrogen in salt caverns (Gulf coast). Europe’s industrial actors have tremendous experience in storing large quantities of natural gas in porous or natural caverns. Further work will be necessary to enrich this expertise for the storage of hydrogen in this media.

Large-scale hydrogen industrial storage sites are linked with the pipeline networks in the Benelux region and in Teesside, UK. The storage of hydrogen through blending is also being tested in Europe in aquifer and depleted gas reservoirs.[62]

Regarding cryogenic options, it should be stressed that over the past decade Europe has developed a unique industrial expertise in cryogenic storage for Liquefied Natural Gas (LNG). It therefore has the industrial and academic competences to support the development of liquid cryogenic hydrogen storage.

Objectives

1. To undertake research aimed at improving cost and efficiency of aboveground storage solutions.
2. To demonstrate distributed aboveground storage solutions available at a capital cost lower than 300 €/kg by 2030
3. To undertake research activities on underground storage to validate the performance in different geologies, to identify better and more cost effective materials and to encourage improved designs.
4. Demonstrate the large-scale underground storage across various media at a capital cost lower than 30 €/kg by 2030

In order to contribute towards achieving the above objectives, the following areas of research and development appear as good candidates for the support by the Clean Hydrogen JU.

R&D Priorities - Early Stage Research Actions

Develop novel concepts that 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 (higher than 90% of original storage capacity over at least 1,000 cycles) using lower targets for weight density than needed for other applications.

R&D Priorities - Development Research Actions

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

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modelling. Examples of areas for development are:

- Sustainable and safe designs for underground storage and the associated aboveground infrastructure more suited to energy system applications. This should include improving discharge rates and increasing pressure ranges within the underground storage, while also addressing the purity aspects for the recovery of hydrogen from the storage media;
- Studies on materials to enable long-lasting wells in hydrogen underground storage. Consequently, address costs reduction of these materials, if possible;
- Studies on lined mined caverns for storing hydrogen when neither salt nor porous media are available. Cryogenic and pressurised solutions to be considered;
- Studies on microbial activity and effects depending on the underground media;
- Developing low-cost materials and system architectures for aboveground storage tanks, targeting optimised pressures;
- Storage using solid nanostructured absorbers (microporous materials, metal-organic framework materials - MOFs);
- Low cost metal hydride and adsorbent hydrogen storage materials;
- Novel designs and hybrid solutions for storage containers;
- Techno-economic analysis on the optimisation of the logistics and operation for hydrogen underground storage (iteration with the power market -including ancillaries congestion management and network physics basics-, and renewable energy production, transport strategies, electrolysis operation mode, sizing, etc);
- Feasibility studies are further proposed to study the consequences of hydrogen over main natural gas underground storage infrastructures (e.g. reservoir, wells and treatments plants). In particular:
    - Effects on cap rock and reservoir integrity due to diffusion issues and acidification of reservoir fluids;
    - Changes on the storage efficiency due to diffusion issues, geochemical & microbiological reactions that could impact on the gas quality, effective porosity & permeability, losses in pressure & energy;
    - Wells integrity (cement, tubular couplings & elastomers);
    - Changes on surface facilities efficiency (fluids & treatment process) and integrity.

R&D Priorities - Demonstration Actions

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:

- Medium-scale projects to both prove and optimise aboveground hydrogen storage solutions. Examples here could be:
    - Bulk hydrogen storage for residential quarters running on hydrogen energy;
    - Bulk hydrogen storage for local hydrogen distribution centres;

- Bulk hydrogen storage for Hydrogen Refuelling Stations (HRS) in densely populated regions;
    - Bulk hydrogen storage for isolated systems in remote territories such as islands with high penetration of intermittent Renewable Energy Sources (RES)
- A large-scale demonstration project for underground hydrogen storage that is progressing in terms of state of the art. (e.g. in terms of capacity, or volumetric density).

Flagship Action

- Flagship action for a bulk underground storage of hydrogen of at least 250,000 m³. 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 hydrogen storage for energy or for other industrial applications. This should be done in order to make the case for policy and regulatory support for market activation.

Synergies

Potential synergies can be explored with P4P in successfully demonstrating underground storage of hydrogen in depleted gas fields. Other potential synergies can be identified with the Innovation Fund, which foresees the funding of large-scale energy storage projects. See Section 4.1 and Annex 7 for more details on the synergies.

3.3.2. Hydrogen in the Natural Gas Grid

Rationale for Support

According to the recent Hydrogen and Decarbonised Gas Package proposed by the European Commission[63], low carbon hydrogen and other low carbon or carbon neutral gaseous fuels are expected to gradually replace the use of fossil gas. In terms of transportation of hydrogen via pipelines, developing a dedicated hydrogen infrastructure in the long-term is necessary to release the full potential of this energy carrier is specific end-use applications. In the short and medium term, other forms of low-carbon gases in particular low-carbon hydrogen can play a role, primarily to rapidly reduce emissions from existing hydrogen production and support the parallel and future uptake of renewable hydrogen.

Therefore, the deployment of various renewable and low carbon types of gases is likely to happen in parallel and is expected to develop at a different pace across the EU, requiring:

- a hydrogen-based infrastructure to progressively complement the natural gas grid;
- a gas infrastructure where natural gas will progressively be replaced by clean gases.

Beyond the importance of the natural gas grid for transporting the hydrogen molecule across long distances, it also offers an enormous storage potential, which can play a critical role in a climate neutral future. There is therefore a significant energy system benefit in using existing gas assets, as they can provide large seasonal storage potential and help manage large swings in daily demand.

The pathways that will be explored for the decarbonisation of the natural gas grid and for the

[63] Proposal for Regulation “Internal markets for renewable and natural gases and for hydrogen (recast)”. COM(2021) 804 final, December 2021.

distribution of hydrogen are the following:

- Blending hydrogen with natural gas;
- Repurposing natural gas pipelines for transmission and distribution of 100% hydrogen;
- Building new pipelines for 100% hydrogen transmission and distribution.

ACER conducted a study on “Transporting Pure Hydrogen by Repurposing Existing Gas Infrastructure: Overview of existing studies and reflections on the conditions for repurposing”.[64] The study concludes that all the following conditions should be met in order to consider repurposing for hydrogen as a serious option:

- Presence of loop (parallel) lines of NG pipeline systems, of which at least one string could be repurposed for pure hydrogen.
- Ensuring security of NG supply to consumers, during and after the conversion of a line (or loop) to pure hydrogen. This means that there should be free available capacity for NG transport in that segment of the network, or alternative routes of supply.
- Hydrogen market uptake in the location or regions serving that pure hydrogen corridor. There should be supply developments of low carbon hydrogen production from RES or CSS, synchronously with demand developments. This hydrogen demand could stem from switching from “grey” to “green” or “blue” hydrogen for existing hydrogen industrial consumers, and switching from fossil fuels (coal, gas) to hydrogen for new hydrogen industrial consumers for high-grade heat applications.

The study notes that it is unclear when and where these conditions would be met (if at all). Timing for repurposing NG pipelines would be highly dependent on hydrogen market developments and therefore relative investment decisions should follow a prudent and no-regrets approach.

State of the Art

Injecting hydrogen into the natural gas distribution networks is technically feasible today. Depending on the specific network and / or region, as pipeline networks vary significantly between Member States, blends of hydrogen up to 20% by volume may be possible without requiring pipeline or appliance conversion. High-pressure transmission pipelines have more uncertainties, regarding the impact of hydrogen depending on the materials that are utilised and the pressure ranges of operation. Projects like HyDeploy[65] (UK) and Hyblend[66] (US) aim to understand how higher concentrations of hydrogen could work on different parts of the gas grid and what could be their effects on piping and pipeline materials. In all cases, safety must also be assessed.

For deeper decarbonisation, conversion to 100% hydrogen is possible. Conversion of parts of the gas T&D infrastructure to 100% hydrogen is under consideration in the UK (H21[67], H100[68], HYNET[69]) and plans are developing in countries such as the Netherlands, Germany, Belgium, France and Slovakia. In these cases, existing transmission and distribution infrastructure could

64 Link to ACER study.
65 https://hydeploy.co.uk/faqs/hydrogen-level-set-maximum-20/
66 https://www.nrel.gov/news/program/2020/hyblend-project-to-accelerate-potential-for-blending-hydrogen-in-natural-gas-pipelines.html
67 https://www.h21.green/
68 https://sgn.co.uk/about-us/future-of-gas/hydrogen/hydrogen-100
69 https://hynet.co.uk/

be repurposed for hydrogen. Existing pipelines, as a whole or certain of their critical components, need to be adapted to tolerate hydrogen content. Similarly, other system components, including compression and drivetrain solutions, may need to be replaced. For these purposes, international research and innovation actions across Europe will be important.

There are several demonstration projects injecting hydrogen into natural gas distribution grids, generally up to 20% in terms of volume[70,71]. Limited demonstrations of conversions of steel pipes to 100% hydrogen are commencing. An example is a 12 km pipeline formerly used for transporting natural gas that has been transformed for transportation of 100% hydrogen in the south west of the Netherlands[72] in 2018.Another example is the launch of the "NorthH2" in Groningen that is expected to produce and distribute around 800,000 tonnes of hydrogen through Gasunie's natural gas infrastructure.[73]

The formation European Hydrogen Backbone (EHB) initiative is another indication for the increasing momentum on the repurposing of natural gas pipelines in Europe. The EHB group vision currently involves 23 gas infrastructure companies from 21 countries. In their most recent report it presents a vision for a 39,700km hydrogen pipeline infrastructure expanding in 21 countries. Two-thirds of the network is based on repurposing of natural gas pipelines.[74]

Objectives

1. Development of technologies and materials to explore and support the transportation of H2 via the natural gas grid.
2. Enable through research and demonstration activities the transportation of hydrogen through the natural gas grid either by blending or via repurposing to 100% hydrogen.

In order to contribute towards achieving the above objectives, the following areas of research and development appear as good candidates for the support by the Clean Hydrogen JU.

R&D Priorities - Early Stage Research Actions

- Develop testing techniques in order to precisely map the influence of hydrogen on different pipeline materials
- Qualify the effects of hydrogen on the following types of materials and components:
    - Grades of steel in pipes and their welded joints and induced phenomena (embrittlement, crack propagation, etc);
    - Metallic materials existing in the distribution network (cast iron, copper, brass, lead, aluminium) and induced phenomena (embrittlement, propagation of cracks, fatigue, etc);
    - Materials of elastomer types present mainly in equipment in the distribution network (regulator membranes, meters, etc).
- Precisely model the influence of hydrogen including blends on identified safety and risk

[70] https://www.engie.com/en/businesses/gas/hydrogen/power-to-gas/the-grhyd-demonstration-project
[71] http://www.grtgaz.com/en/press/press-releases/news-details/article/hydrogene-lancement-du-projet-mosahyc.html
[72] https://www.gasunie.nl/en/news/gasunie-hydrogen-pipeline-from-dow-to-yara-brought-into-operation
[73] https://www.gasunie.nl/en/news/europes-largest-green-hydrogen-project-starts-in-groningen
[74] https://gasforclimate2050.eu/news-item/european-hydrogen-backbone-grows-to-40000-km/

areas in order to update design and operating methods, and ensure safe operation;

- Develop insight in the effects of contamination in existing networks on the purity of the hydrogen at the exit point.

R&D Priorities - Development Research Actions

- Develop technologies to limit the impact of hydrogen on the existing network using an internal coating and in situ robotic application or other solutions (e.g. pipe in pipe);
- Identification and development of new materials (steels, joints, components, coatings) optimised for hydrogen transport;
- Develop time energy content tracking for energy billing that are able to cope with admixtures;
- Specify, develop and adapt leak detection/tracking 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 compressor stations and its components, as well as components regularly found in metering and regulating stations such as filters, heat exchangers, pressure regulators and develop new compatible components;
- Since a major cost component for hydrogen transport through pipelines is the construction cost of new infrastructure, actions aimed at understanding the techno-economic potential for repurposing natural gas pipelines should be supported.

R&D Priorities - Demonstration Actions

- Develop methods for connecting current off-grid projects to the gas market;
- Construct local demonstration projects both for hydrogen blending and pure hydrogen pipelines with cross border participation, aiming to a gradual shift to pure hydrogen pipelines.

Flagship Actions

Flagship cluster projects could be foreseen demonstrating cross border transmission. Additionally, possible projects could focus on blending, and a mix industrial, mobility and residential uses. A current example of the latter is the HyNet / H100 project in the UK.

Synergies

Synergies with the Connecting Europe Facility (CEF) could be investigated for the Flagship Actions. See Section 4.1 and Annex 7 for more details on the synergies.

3.3.3. Liquid Hydrogen Carriers

Rationale for Support

Hydrogen is one of the most dense energy carriers by mass, but it is extremely light and so the volumetric energy density in standard conditions is very low. Moreover, liquid hydrogen carriers are currently the only mean of importing mass quantities of renewables (TWh to PWh-order) from long distances (Australia, South America). There is therefore a huge advantage in developing cost effective and efficient ways of transporting hydrogen in liquid form. This can be done by liquefying hydrogen or by bonding it with other molecules forming hydrogen carriers such as liquid organic hydrogen carriers (LOHCs), ammonia and other CO_2 neutral carriers. In order to be able to transport significant amounts of hydrogen in the coming years, all types of hydrogen carriers will be considered.

State of the Art

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 carriers 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 solutions 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:

- Hydrogen 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 the transfer of liquid hydrogen, some is evaporated due to boil-off, which leads to certain losses of hydrogen. The same phenomenon happens during storage but at a far lower level.
- LOHCs: LOHCs are typically hydrogen-rich aromatic and alicyclic molecules that can be easily transported using existing infrastructure. 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, catalysts, operating conditions and number of cycles. Work has been done on this topic already within FCH 2 JU project HYSTOC that aims to demonstrate the feasibility of the LOHC technology for the distribution and storage of hydrogen to supply Hydrogen Refuelling Stations (HRS).[75]
- Ammonia: Ammonia production via renewable hydrogen is receiving increasing interest as costs of renewable energy drop. Conventional ammonia production via the Haber-Bosch process must be adapted for proper integration with renewable hydrogen. Ammonia cracking is done in the presence of a catalyst and generates hydrogen which is followed by a purification step. Development of novel catalysts for the cracking/reforming process could be foreseen. However, it should be noted that actions under the topic of ammonia synthesis are outside the scope of the Clean Hydrogen Joint Undertaking.

Objectives

1. To increase the efficiency and reduce the costs of hydrogen liquefaction technologies.
2. To contribute to the roll-out of next generation liquefaction technology to new bulk hydrogen production plants.

[75] https://cordis.europa.eu/project/rcn/213080_en.html

3. To continue the research on carrier cycling performance, chemistries, catalysis and reactors which show potential for improved roundtrip efficiency and life cycle assessment.
4. Develop a range of hydrogen carriers that will be used commercially to transport and store hydrogen while improving their roundtrip efficiency and lowering their cost.

In order to contribute towards achieving the above objectives, the following areas of research and development appear as good candidates for the support by the Clean Hydrogen JU.

R&D Priorities - Early Stage Research Actions

- Hydrogen liquefaction:
    - Energy efficiency improvements and cost reductions could come from next generation materials and technology for liquefaction such as new cooling materials and devices for 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
    - Develop novel catalysts and reactor technologies;
    - Reduce the amount of expensive raw materials needed in hydrogenation / dehydrogenation reactions;
    - Reduce the CO_2 equivalent footprint (including carrier supply chain and potential degradation);
    - Electrochemical reforming or synthesis of hydrogen carriers
    - Research on the potential hazards (e.g. toxicity, flammability) associated with hydrogen packaging solutions is needed due to their presence in new settings. This research should lead to the development of adequate technological solutions and the elaboration of safety regulations.[76]

R&D Priorities - Development Research Actions

- Hydrogen Liquefaction:
    - Development of new, more energy efficient and lower cost small-scale LH_2-production processes.
    - Design of new processes able to follow fluctuations in hydrogen demand and variable renewable power inputs.
- Hydrogen carriers:
    - Development of most promising concepts from early stage work into working prototype systems, with a focus on new technologies with improved safety, cost and performance. In addition, the possibility of flexible operation of plants in order to profit from favourable low electricity prices should be investigated, in order to bring down costs.[77]

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- Upscale from the prototype to large-scale plants.
- Studies on designing and optimising large capacity hydrogenation and dehydrogenation plants.

R&D Priorities - Demonstration Actions

- Hydrogen Liquefaction and micro-liquefaction: One demonstration project may 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.

Flagship Actions

Flagship actions may be required once the technology readiness has improved and the costs have been lowered. The different hydrogen transportation options are expected to compete for the different end-uses.

Synergies

Potential synergies can be explored with P4P, which is also envisaging work to be done for Ammonia, methanol and LOHCs as hydrogen carriers. See Section 4.1 and Annex 7 for more details on the synergies.

3.3.4. Improving Existing Hydrogen Transport means

Rationale for Support

Hydrogen presents unique challenges for transportation and distribution due to its low volumetric density. If hydrogen is to become a widespread energy carrier, distributed from centralised production facilities in high volumes across large geographic areas, the scale–up of existing transport means as well as the development of novel transportation methods optimised for large-scale hydrogen delivery is necessary.

There are a number of transportation options that can be envisaged:

- Transportation via new-built pure hydrogen pipelines;
- Road transportation of gaseous hydrogen;
- Road transportation of liquid hydrogen;
- Shipping of bulk liquid hydrogen.

State of the Art

Pipelines are the leading option for delivering large volumes of hydrogen over land. In Europe there are already more than 1,000 km dedicated hydrogen pipelines serving the industry, albeit in a very concentrated geographical region. This network should be expanded by new build pure hydrogen pipelines. Development of new high strength materials resistant to hydrogen cracking can increase the pressure and capacity of hydrogen pipelines, decreasing the cost of transportation. Dedicated hydrogen networks remain necessary where hydrogen applications require different pressures and purities, particularly where high purity hydrogen is required. Hydrogen as chemical feedstock requires different purities than hydrogen for combustion, or hydrogen for fuel cell use.

The main limitation for road transport of gaseous hydrogen is that most tube trailers in operation today deliver small quantities of compressed hydrogen gas (up to 300kg of hydrogen per delivery) at a low pressure (up to 200bar). The development of a tube trailers at increased pressure and capacity will reduce costs per kg hydrogen delivered. The ambition is the development of a 700 bar tube trailer (capacity 1,500kg) in the coming years.

Hydrogen in liquid form is the most conventional means of transporting bulk hydrogen on the road. Hydrogen is stored at -253°C in super-insulated 'cryogenic' tankers. However, liquefaction is energy intensive and the storage and transport of the liquid hydrogen results in heat ingress and hydrogen 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 vaporisation inside storage tanks.

Overseas 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. Kawasaki Heavy Industry has built the first LH_2 vessel[78] as a demonstration project. Further technology development is required for the scale-up of LH_2 containment, systems integration and overall ship design.

Objectives

1. To increase the pressure and capacity for new builds of 100% hydrogen pipelines while reducing their cost.
2. To reduce road transport costs of compressed hydrogen by increasing the capacity of tube trailers.
3. To improve the efficiency of road transport of liquid hydrogen while reducing costs.
4. To enable scale-up of solutions for shipping of bulk liquid hydrogen and support its commercialisation.

In order to contribute towards achieving the above objectives, the following areas of research and development appear as good candidates for the support by the Clean Hydrogen JU.

R&D Priorities - Early Stage Research Actions

- Early phase development of new high strength and lightweight materials (both steel and fibre reinforced polymers) resistant to pure hydrogen;
- Welding processes consistent with 100% hydrogen content;
- Research into hydrogen embrittlement / permeation;
- Odorisation of hydrogen in dedicated pipelines, i.e. chemical additives acting as odorants that minimise the negative effects for the use in fuel cells.

R&D Priorities - Development Research Actions

- Development of very high capacity pressurised tube trailer concepts (e.g. at 700 bar);
- Optimisation of transport and storage of liquid hydrogen in road transport, minimising / eliminating hydrogen losses by evaporation. Potential areas for development are improved insulation concepts and the implementation of an integrated refrigeration and

[78] https://global.kawasaki.com/en/corp/newsroom/news/detail/?f=20191211_3487

storage system;

- Development of new thermal insulation concepts and their integration with the containment tank for the scale-up and cost reduction of shipping of bulk LH_2;
- Development of dedicated hydrogen terminals and/or the co-existence of LNG and hydrogen terminals, including investigating and developing methods for the adaptation of LNG terminals towards H_2.

R&D Priorities - Demonstration Actions

A study that considers multiple hydrogen transportation methods may be required before any actions. The key objective of the study would be the techno-economic comparison between the different transportation methods, integration and the optimisation of the hydrogen logistics as a whole.

Flagship Actions

Growing markets for hydrogen and hydrogen applications should provide the pull needed to reach volumes for distribution methods.

No funding from the Programme is considered for these actions.

Synergies

No synergies have been identified.

3.3.5. Compression, Purification and Metering Solutions

Rationale for support

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

- Compression – There is wide range of applications within the Hydrogen Economy that are requiring purpose built hydrogen compressors. As an example, for the transport sector hydrogen needs to be pressurised above 700 bar to enable refuelling of high-pressure storage tanks and in the range of 100 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 compressors designed for purpose with better reliability, lower cost and higher efficiency than today.
- 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, sensors with an accuracy sufficient for weights, measure standards and suitable piping, valves, spare parts compatible with hydrogen or mixture blend, as well as safety aspects and communication protocols.
- Purification and separation – hydrogen for use in low temperature PEM 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, particularly when hydrogen is present at low concentrations). 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. One of the priorities is the separation of hydrogen from hydrogen and natural gas blends with low hydrogen content (up to 20%).

State of the Art

Currently, hydrogen compressors may be available, but are the main source of failure in hydrogen stations. Novel techniques are only available at lab scale (metal hydride, electrochemical). Several options are under development including liquid piston compressor, metal hydride-based compression and electrochemical compression. Innovative compression technologies have been supported already with projects such as H2REF, COSMHYC and COSMHYC XL that have focused on developing solutions tailored towards Hydrogen Refuelling Stations[79]. Large scale turbo compressors and their respective drivetrains are still in early phase evaluations, but will be required for the future gas grid, when hydrogen will need to be distributed.

European manufacturers have now developed systems with the required accuracy but work is still required to produce cheaper systems and monitoring protocols. On the topic of metering the FCH 2 JU has already conducted some work through the procurement of a study for the development of a Metering Protocol for HRS.[80] Still at this point however, current metering accuracy prevents approved custody transfer for hydrogen in filling stations.

Purification is based at the moment on energy intensive pressure swing absorption (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. Some work has been done already through FCH 2 JU projects HyGrid and MEMPHYS that have been developing proof-of-concepts for membrane and electrochemical separation and purification systems.[81,82] It should be noted that AFCs and SOFCs do not require purification of hydrogen from ammonia source.

Objectives

Key technologies for compression, purification and metering of hydrogen are the building blocks of the distribution of hydrogen at large scale. Development of these technologies is therefore critical. The overall objective will be to make sure that by the end of 2030, we have a range of compression, purification technologies available and cost competitive enough to enable further decrease of hydrogen distribution costs.

More specifically the main objectives will be:

1. To develop more efficient compressor and purification technologies
2. To reduce the total cost of ownership of compression and purification technologies
3. To reduce the energy and consumption and increase the recovery factor of purification technologies
4. To increase the reliability and lifetime of compression and purification technologies
5. To improve metering technologies and standards, especially in terms of accuracy and

[79] http://cordis.europa.eu/project/rcn/198235_en.html
[80] Development of a Metering Protocol for Hydrogen Refuelling Stations, FCH 2 JU, 2018
[81] http://cordis.europa.eu/project/rcn/204284_en.html
[82] http://cordis.europa.eu/project/rcn/207240_en.html

protocols.

In order to contribute towards achieving the above objectives, the following areas of research and development appear as good candidates for the support by the Clean Hydrogen JU.

R&D Priorities - Early Stage Research Actions

- Hydrogen Compression:
  - Development of novel and hybrid technologies for compression, including chemical and electrochemical compression;
  - Testing of electrochemical, thermal and hydride compression at low, medium and high temperatures and pressure;
  - Novel cryogenic compression approaches.
  - Development of turbo compressors and their drivetrains to meet future pipeline demands
  - Upscaling of existing HRS compression technologies to meet higher demands (high-flow) while improving their availability
- Hydrogen purification and separation:
  - Development of low or free content PGM solutions;
  - Concepts to increase hydrogen purity levels to 99.999% with a reduction in energy consumption;
  - The purification of hydrogen with medium and high temperature electrochemical processes;
  - Development of new purification/separation technologies (i.e. membranes, electrochemical and thermochemical processes).
  - Purity management to control the ratio between hydrogen & impurities in the natural gas pipeline
- Material compatibility / resistance in contact with hydrogen and blends requires the testing of the materials involved in the key technologies (compression and purification).

R&D Priorities - Development Research Actions

Validation projects are necessary 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, lifetime, capacity) and in-field testing;
- Development of large compression technologies and their drivetrains for injection of hydrogen into gas pipelines (from 5 bar to 100-200 bar);
- Development of a greater accuracy within hydrogen sensors and flow meters;
- Projects which could reduce the cost of hydrogen separation and increase poisoning resistance;
- Methodologies for separating hydrogen from blended natural gas at relevant separation flow rates;

- 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.

R&D Priorities - Demonstration Actions

- Demonstration of novel and hybrid concepts for compression (pure hydrogen or blended hydrogen / natural gas mixture) at a real-world scale (i.e. higher than 200kg/day for hydrogen stations, tens of tons/day for pipeline injection);
- Demonstration of novel concepts for hydrogen purification and separation (i.e. hydrogen purification, hydrogen separation from blended hydrogen / natural gas mixture) at a real-world scale.
- Integration of innovative metering, piping and instrumentation technologies into the overall hydrogen innovation actions.

Flagship Actions

No flagship actions are foreseen.

Synergies

Potential synergies with the European partnership on Metrology[83] could be identified and pursued for the topic of metering. Additionally synergies with the P4P can be foreseen that will be also undertaking work on the topic of hydrogen purification and separation from natural gas streams. See Section 4.1 and Annex 7 for more details on the synergies.

3.3.6. Hydrogen Refuelling Stations (HRS)

Rationale for Support

Deploying hydrogen vehicles and in particular heavy-duty vehicles, is an important part of EU's Hydrogen Strategy. The study procured by the FCH 2 JU on Fuel Cell Hydrogen Trucks,[84] which conducted a comparison of alternative powertrain technologies, showed that FCH applications present a very promising zero-emission alternative. Due to their high operational flexibility and relatively short refuelling time compared to electricity charging, FC heavy-duty vehicles are particularly suited for long-haul operations.

However, in order to have a viable case for the widespread use of FC Heavy-Duty Vehicles (HDV), it will be essential that there is an EU-wide network of publicly accessible HRS. 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. To address this, the revision of the Alternative Fuel Infrastructure Regulation[85], requires one hydrogen refuelling station available every 150 km along the TEN-T core network and in every urban nodes by 2030.

State of the Art

In line with the growing number of trial and demonstration projects, there is an increasing number of HRS in Europe. There have been so far 20 projects funded by FCH JUs that have demonstrated HRS for both cars and buses with the most prominent in terms of deployment

[83] https://ec.europa.eu/info/files/european-partnership-metrology_en
[84] Study on fuel cells hydrogen trucks, FCH 2 JU, 2020
[85] Regulation on the deployment of alternative fuels infrastructure. COM (2021) 559 final.

being H2ME and H2ME2. In total the projects have already contributed to the commissioning of 74 stations.[86] To date, most existing HRS are dedicated to the use of passenger vehicles and cannot be used by heavy-duty trucks due to different technological requirements for filling up the much larger truck tanks. However, the increasing number of stations is promising, and the existing foundation of HRS in Europe could partly be upgraded for truck-specific refuelling soon. As refuelling infrastructure is adjusted to meet the needs of heavy-duty trucks, more demonstration projects become feasible, providing a foundation for larger scale commercial deployment.

European manufacturers dominate the global supply of hydrogen stations. Furthermore, Europe has a larger deployment of hydrogen stations compared to any other region,[87] 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.

Based on the experience from the HRS deployment so far, there are significant issues with publicly accessible stations, which can all be resolved over the coming years:

- The costs of the refuelling stations are high (both CAPEX and OPEX) which creates a challenge in creating a competitive refuelling station business model, particularly in the early years when utilisation is low;
- The station availability is currently too low. This creates issues for customers who cannot rely on their hydrogen supply and can be particularly problematic for HDV users. This situation will be partly resolved through increased throughput at the stations but will also benefit from improved components (particularly compressors and dispensers);
- 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 Vehicles (LDV) will be in place more readily, while for heavy-duty vehicles there is an urgent need for their quick development in order to enable the massive deployment of HDV foreseen by 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 renewable 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.

Objectives

1. To tackle the technical challenges associated with heavy-duty hydrogen refuelling stations in order to develop a commercial solution that conforms to the heavy-duty requirements;

[86] http://cordis.europa.eu/project/rcn/198091_en.html
[87] See Chapter 1 – Technology & Market Report 2021, FCHO.

2. To reduce the energy consumption of Hydrogen Refuelling Stations;
3. To increase the reliability and availability of Hydrogen Refuelling Stations;
4. To support the creation of a network of Heavy-duty HRS across Europe;
5. To decrease the total cost of ownership of Hydrogen Refuelling Stations.

In order to contribute towards achieving the above objectives, the following areas of research and development appear as good candidates for the support by the Clean Hydrogen JU.

Moreover, this work will be facilitating the progress towards the AFIR objectives by investigating technology building blocks on hydrogen infrastructure equipment and processes such as electrolysers, safety and leak detection, transport and storage, novel compression technologies, hydrogen quality and protocols.

R&D Priorities - Early Stage Research Actions

- 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 renewable hydrogen produced on-site;
- Specific components are currently missing and need to be developed to contribute in the HRS schedule e.g.: heavy-duty nozzles and flexibles, chillers for heavy-duty purposes, multipurpose refuelling protocols.

R&D Priorities - Development Research Actions

- 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 higher than 1,000 kg/day capacity and individual fills in excess of 200 kg (in less than 20 minutes);
- Reduction in the CAPEX and OPEX of high capacity HRS through integrating innovative technological components – development work here would focus on how to integrate those components;
- Facilitate the use of locally produced renewable hydrogen, e.g. by enabling low inlet pressure and flexible operation for variable RES.

R&D Priorities - Demonstration Actions

- Standardise and industrialise heavy-duty HRS equipment and components;
- Increase the reliability, safety and availability of heavy-duty HRS equipment and infrastructure for all road vehicles;
- 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 minimisation of boil off during hydrogen transfer and distribution at a HRS based on liquid hydrogen;
- Explore novel business models, for example, on-demand hydrogen refuelling and compact hydrogen mobile stations.

Flagship Actions

Funding through flagship actions will help encourage HRS operators to invest in hydrogen technology by lowering the initial capital cost of HRS and hence helping to create the initial networks required to deploy hydrogen vehicle technologies.

Synergies

Synergies with CEF must support the roll-out of road HRS. European support is envisaged alongside Member State support for a large HRS deployment in Europe. See Section 4.1 and Annex 7 for more details on the synergies.

3.4. Hydrogen end uses: Transport applications

Transport is a key area of economic growth in our society, responsible for around 30% of EU total CO_2 emissions. Most importantly, global transport CO_2 emissions are expected to increase in the future in a business as usual scenario, as the technical improvements in the conventional thermal engines do not seem sufficient to abate emissions from the ever-increasing fleets of newly registered vehicles, heavy-duty trucks, aircrafts, trains and ships. The European Green Deal has set the ambition for at least 90% reduction in transport emissions by 2050 to be consistent with climate neutrality. Hence, there is a need to urgently take measures to decarbonise the transport sector.

Regulatory aspects will define the speed of adoption of new zero emissions transport means. The ‘Fit for 55’ package proposes a number of policy measures that promote the use of hydrogen as a low carbon fuel in the transport sector. Significant focus falls on the road transport sector, by requiring the reduction in CO2 emissions from cars and light vehicles via measures such as the introduction of emissions trading in transport (ETS-2), more stringent CO2 standards, facilitating the development of the necessary hydrogen infrastructure and promoting higher shares of renewable fuels. There is also considerable focus in maritime transport, including regulating access of the most polluting ships to EU ports, obliging docked ships to use shore-side electricity and incentivising the increased uptake of sustainable alternative fuels, as well as specific targets for shore side electricity supply in TEN-T maritime and inland ports. Railway and aviation will need to contribute to the CO_2 reduction of transport as well, but especially for aviation the ReFuelEU aviation proposal[88] specifies that more research, effort and time will be needed to make these promising technologies more mature for wider deployment after 2030.

Regarding transport, there are already some hydrogen applications that have proven to be on the verge of being ready for market deployment. FC material handling vehicles (HyLIFT EUROPE and FCLIFT), FC buses (3EMOTION, JIVE and JIVE2) and - to a lesser degree - FCEV passenger cars (H2ME, H2ME2 and ZEFER), have been successfully developed, demonstrated and, within the scope of activities of the FCH JUs, have are already been deployed with limited further subsidies needed.

Nevertheless, these developments are not sufficient to meet the ambitious emission reductions in transport. We still need to further examine and prove solutions in many sectors such as heavy-duty vehicles, off-road and industrial vehicles, trains, shipping and aviation. Such solutions can be based on the transfer of technical knowledge already gained in FC LDV and FC buses, while cost reductions and higher efficiencies can be achieved by scaling and by

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[88] Ensuring a level playing field for sustainable air transport. COM(2021) 561 final.

process integration, improving the competitiveness of these technologies with a roll down effect, e.g. by platform approaches of FC modules across sectors.

A number of technology routes still need further improvements, especially in the context of reducing costs and increasing durability, in order to make them competitive with incumbent technologies. These include:

- Improvement of main technology building blocks that can be applied across a range of different transport applications, amongst which fuel cell stacks and hydrogen tanks;
- Adapting fuel cell systems from other vehicles (urban buses / cars) for long distance coaches and HDV;
- Producing components for rail freight and shunting locomotive applications;
- Adapting FC components to waterborne transport, and developing next generations based on learnings from first demonstrations;
- Developing tanks and FC technologies specifically adapted for aviation.

It should be also stressed that, especially in the case of hydrogen-based transportation, the competitiveness of hydrogen technologies is dependent on research and innovation breakthroughs, on production volumes of vehicles and components and on the price and availability of hydrogen as a fuel . Therefore, actions aimed at stimulating a broad rollout of FC vehicles around Europe are equally important to research and innovation actions, in particular for hard to abate sectors, in order to drive the Total Cost of Ownership (TCO) of the FC vehicles down. This is particularly true, for example, for the road heavy-duty transport segment where the. TCO is extremely relevant for final users and ultimately for the market uptake. . Monitoring of the FC trucks TCO and comparison with battery-powered trucks electrified trucks and others decarbonisation technologies will be needed. Addressing all of these aspects simultaneously is necessary to allow for hydrogen transport applications to enter mass market.

3.4.1. Building Blocks

Rationale for Support

In order to fully unlock the potential of hydrogen technologies and introduce them as a mainstream means of decarbonisation in all transport modes, vehicle prices will need to evolve 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 BoP, 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. Embedding the concept of modularity in the development of components and BoP will also be important in order to reach mass production efficiently. Modular systems will be adapted to the specific needs of each transport modes, while avoiding the re-engineering of components and systems hence allowing the attainment of mass production dynamics despite the low number of units deployed in different transport modes at early stage.

The strategy for the development of the transport fuel cell system components will continue to pursue three overarching goals: cost reduction, increased performance and lifetime. Advancements in this domain will be beneficial to all transport applications regardless of their current state of the art. Sustainability, recycling and eco-design are also important driving principles that will guide the development of components (these aspects are addressed in more detail in their dedicated chapter).

These efforts will need to be complemented by an adaptation of these “building blocks” to meet the specific technical needs of transport modes where FC applications have more recently become a viable option (i.e. marinisation of fuel cells, on-board storage solutions for aviation etc.).

Within road transport applications, such adaptations will be required for HDV. Due to the fact that research and innovation activities so far have been mainly dedicated to the development of components for road applications (passenger’s cars, urban buses, forklifts etc.), the state of the art of the transport “building blocks” and components for road applications by and large coincide.

Therefore, even though adaptations of the fuel cell system BoP components for road heavy-duty applications will require special attention, these will be fewer in number and less pronounced than the ones required for other transport modes.

Consequently, the strategy for the development of the building blocks and road heavy-duty applications will be similar in many respects and will be addressed jointly.

At the same time, the building block research area will encompass R&D priorities of interest to all transport modes. Low TRL priorities such as reduction platinum loading or increased power density will be pursued with the intention of bringing benefits across all fuel cells applications in all transport modes.

- Fuel Cell systems

It is clear that increasing production volumes will have a significant impact on cost. According to the study on Fuel Cell Hydrogen Trucks study, it is expected that an increased annual production volume of heavy-duty trucks (75.000 units per year in 2030) can lead to a reduction of the Fuel Cell Module[89] cost by around 76%. This cost reduction will be reached more efficiently if the different building block technologies become modular hence reaching faster production rates consistent with mass production for different types of vehicles and associated performance and durability requirements. At the same times Fuel Cell systems may prove to be effective on operative conditions of other transport modalities, such us maritime, that are demanding in terms of power and operational conditions.

- Compressed and liquid hydrogen tanks

Volume production and technology developments will also play a similar role for hydrogen tanks, both gaseous and liquid. The importance of volume is that to develop the components to a competitive cost level, market deployment programmes to stimulate the market and allow the technology to mature along the cost curve are crucial. In parallel, technology development programmes are required to ensure the core technology progresses towards the lower bound of the cost targets.

State of the Art

These components have been developed to the point where they have the operational reliability to allow them to be deployed in small series production to mainstream vehicle customers

[89] The module includes Fuel cell stack, hydrogen supply of the FC system (e.g. inlet valve), air compressor, cooling system, power electronics, control unit.

(thousands of units in the US and Asia[90]); 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 involved in the projects CHIC[91] and 3EMOTION[92] since 2010 have lasted for over 35,000 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 and 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). Spill-overs in terms of technology and upscaling will be considered regarding LDV systems and are expected for other fields of HDV applications such as rail, marine or aviation (where power ranges are comparable to HDVs).

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

Objectives

Low TRL research activities will drive the development of next generation components, which is the necessary step in order to further progress towards the full competitiveness of fuel cells for road applications both in terms of cost and performance.

The main objectives of this technology area will be the following:

1. Improving overall system performance for fuel cell stack technology in terms of power density, reliability and durability;
2. Reduction or replacement of PGM loadings and development of new materials advancing the performance of on-board storage technology;
3. Improvements in design, health monitoring and manufacturability of core components for fuel cell stacks and on-board storage technology;
4. Extending the EU leadership on FC production from automotive to maritime and aviation, given the high pressure for decarbonisation of these sectors.

In order to contribute towards achieving the above objectives, the following areas of research and development appear as good candidates for the support by the Clean Hydrogen JU.

R&D Priorities - Early Stage Research Actions

- Fuel cell stack technology:
    - Development of new disruptive technologies towards improved areal and volumetric power density, increased reliability, extended lifetime (validation at single cell and short stack level) and increased overall system performance;
    - Research at material level for PEMFC to reduce or replace PGM loading and improve the performance of all main stack and fuel cell components (development of high performance membrane, BPP, GDL etc).

[90] IEA "Global EV Outlook 2021" https://www.iea.org/reports/global-ev-outlook-2021, global FCEV stock 34.800 units.
[91] https://cordis.europa.eu/project/id/256848
[92] http://cordis.europa.eu/project/rcn/197067_en.html

- On board storage technology:
    - Development of new materials for high-pressure tanks and fast refuelling enhancing the properties of the liner and targeting cost reduction of the reinforcement;
    - Development of novel storage concepts to improve storage density (conformability), including solid carrier, pressurised tank and liquid cryogenic hydrogen.

R&D Priorities - Development Research Actions

- Fuel cell stack technology (covering both low and high temperature PEMFC):
    - Optimisation of stacks for higher performance, durability and reliability incl. game changing concepts on core components and new methods for stack and system state-of-health monitoring;
    - Developing low cost concepts and improving manufacturability and recyclability (processes, automation, quality control tools, in-line and end-of-line diagnostics).
- Fuel cell system technology:
    - Simplification of the FC system design (in particular for heavy-duty applications) in order to reduce the number of parts and foster the emergence of standard components, interfaces and system configurations hence improving their manufacturability.
- On board storage technology:
    - Development and validation of integrated mounting concepts, safety by design and innovative manufacturing and quality control techniques;
    - Integration of low cost and reliable safety sensors for structural health monitoring and fire detection.

R&D Priorities - Demonstration Actions

No demonstration actions are foreseen.

Flagship Actions

No flagship actions are foreseen.

Synergies

No synergies have been identified.

3.4.2. Heavy-duty vehicles

Rationale for Support

Over 75% of the freight transport in the EU is done via road[93] and heavy-duty trucks are responsible for over 25% of the transport CO_2 emissions[94]. If transport is to contribute to the EU decarbonisation efforts, all transport modes, including heavy-duty, will need to undergo a

[93] Energy, transport and environment statistics, Eurostat, 2019
[94] Carbon dioxide emissions from Europe's heavy-duty vehicles, European Environment Agency, 2020

deep transformation in the coming decade. The rapid uptake of zero emission vehicles is bound to play a key role. Battery-powered heavy-duty trucks are already on the market, and thanks to the rapidly developing scale in batteries, coverage of long-haul mission is soon expected. 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 or liquid hydrogen. In much the same way as fuel cell buses provide a 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 minimal impact on the payload.

The heavy-duty vehicles sector is composed of a wide range of segments, with the most promising for FCs being long-haul heavy-duty trucks for logistics applications (with potential spill overs to other HDV classes) and 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.

A strong collaboration is envisaged between Clean Hydrogen JU and 2ZERO as both partnerships will deal with the development and deployment of hydrogen and fuel cells trucks. An overview of the envisioned distribution of responsibilities between these partnerships is provided in Annex 7.

State of the Art

Despite a growing number of small-scale FC truck development and demonstration projects underway in Europe, US, Canada, Korea and China, vehicles have only recently started being tested and validated in real world operations. A little over 23 projects worldwide led to the deployment of tens of units[95]. Among them H2HAUL[96], which will develop and demonstrate a total of 16 new heavy-duty (26–44t) hydrogen fuel cell trucks in real-world commercial operations, and REVIVE[97] tackling the vocational trucks sector. Even though the situation is rapidly evolving and several announcements[98] indicate that a significant ramp up is to be expected in the near term, the commercialisation of FCH HDV is still at the very early stage; today there is no FCH HDV original equipment manufacturer (OEM) available on the market with a commercial offer on a regular basis.

In order to facilitate the commercialisation step, a number of other items, such as the standardisation and modularity of components, interfaces and development of protocols allowing faster refuelling operations will need to be developed. Projects such as STASHH[99] and PRHYDE[100] are tackling these issues.

Key hurdles to overcome before FC Heavy-Duty Transport (HDT) can become a mainstream decarbonisation solution include relatively high prices of the vehicles and hydrogen as well as the deployment of an appropriate refuelling infrastructure. Following the recent adoption of the EU regulation on the CO_2 standards of Heavy-Duty Vehicles[101], an increasing number of European OEMs started investing in FCH HDV solutions and the variety of products on the

95 Study on fuel cells hydrogen trucks, FCH 2 JU, 2020
96 https://cordis.europa.eu/project/id/826236
97 https://cordis.europa.eu/project/rcn/213073/factsheet/en
98 https://www.reuters.com/article/hyundai-switzerland-hydrogen-trucks-idUSKBN26S1FM
99 https://cordis.europa.eu/project/id/101005934
100 https://cordis.europa.eu/project/id/874997
101 Council Regulation (EC) No 1232/2019 of 20 June 2019 setting CO2 emission performance standards for new heavy-duty vehicles.

market is set to rapidly increase in the coming years.

Objectives

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 in addition to the adaptation of the building blocks for HD purposes. By 2030 FC suppliers, OEMs, truck operators and infrastructure and hydrogen providers intend to put on the EU roads up to 100.000 FCH HDV[102].

Overall, R&D actions in this area have the following objectives:

1. Reducing the cost of core components such as modules and stacks in order to foster the competitiveness of FC heavy-duty applications;
2. Improving overall system performance of FC systems in order to improve the availability and durability and meet the needs of FCH HDV end users;
3. Improvements in design and monitoring procedures of FC systems;
4. Supporting and accelerating the wide roll out of FC HDVs.

In order to contribute towards achieving the above objectives, the following areas of research and development appear as good candidates for the support by the Clean Hydrogen JU.

R&D Priorities - Early Stage Research Actions

- 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 power and energy density and increased durability of HDV systems;
- Improved and lower cost hydrogen on-board storage (gaseous and liquid) solutions.

R&D Priorities - Development Research Actions

- 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 taking into account a hybridisation with a battery pack, 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;
- Stack improvements in terms of performance, durability and reliability (incl. game changing concepts on core components) specifically aimed at meeting HDV needs;

[102] Coalition Statement On the deployment of fuel cell and hydrogen heavy-duty trucks in Europe (https://www.fch.europa.eu/publications/study-fuel-cells-hydrogen-trucks)

- 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);
- Further development of Auxiliary Power Unit (APU) concepts capable of meeting high power demand of vocational heavy-duty applications (e.g. construction trucks, off-road vehicles).

R&D Priorities - Demonstration Actions

Demonstrations should focus on:

- Validating the performance of the technology in a range of real-world operations, specifically KPIs such as availability, lifetime, efficiency and total cost of ownership;
- Preparing the market for wider roll-out, e.g. by training technicians to maintain hydrogen components of 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 most promising range of truck types are tested; (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 pressurised hydrogen.

Flagship Actions

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.

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 meeting customer expectations in terms of FC system reliability and driving range.

Synergies

Potential synergies have been identified with the Towards Zero Emission Road Transport partnership (2ZERO) on various areas. See Section 4.1 and Annex 7 for more details on the synergies. Furthermore the deployment of FC HDV will need to be developed in parallel to the deployment of an increasing number of HRS that will need to support such fleet.

3.4.3. Waterborne applications

Rationale for Support

To put the fight against global climate change at the forefront, the International Maritime Organisation (IMO) adopted an initial GHG reduction strategy in 2018.[103] The strategy envisages that a revised strategy will be adopted in 2023. With projected growth of the shipping

[103] https://www.imo.org/en/MediaCentre/PressBriefings/Pages/06GHGinitialstrategy.aspx

industry, the IMO estimated that the overall GHG contribution from shipping could double in a business-as-usual scenario by 2050. The IMO set a target to reduce CO_2 emissions by at least 50% in 2050. As ships are generally in service for 15 years or more (sea-going ship and 40 years for some inland vessels), the maritime industry faces an enormous task to achieve this goal.

At European scale, achieving the EU objective of climate neutrality by 2050 will also require unparalleled innovations in shipping, including the supply and use of sustainable climate neutral marine fuels as well as the associated port, storage and bunkering infrastructures. Already today, Europe's long-standing leadership in the maritime sector is coming under pressure. The EU's share of worldwide shipbuilding production is in decline. By 2017, over 90% of shipbuilding activity occurred in China, the Republic of Korea and Japan[104]. Much of this activity relates to lower-end maritime technologies, leaving European shipbuilders 'free' to focus on more sophisticated, higher added value, vessels and maritime equipment, where Europe remains a global leader for the time being.

Hydrogen and its derivatives fuels, such as ammonia, together with fuel cells are an important piece of the puzzle. Assuming an adequate supply, hydrogen and its derivative fuels can provide potential zero GHG emissions and the possibility of a rapid decrease of the average GHG emissions for shipping.

Commercial cargo shipping, in particular intercontinental services account for the vast majority of the sector's GHG emissions, consequently it will be important that solutions are scalable to these applications. For example short sea shipping typically carries several hundred tons of fuel oil and the fuel requirements for intercontinental services are around ten times larger.

One of the most important factors to decarbonise shipping is the availability of climate neutral fuels in ports. The Clean Hydrogen JU will support actions on the provision of zero-carbon fuels (hydrogen and its derivatives), shore based infrastructures in addition to adequately sized technology modules such as high power multi MW fuel cells and storage technologies applications for ships.

State of the Art

- Fuel Cells for ships

Fuel cells and hydrogen have been demonstrated in e.g. submarines, small inland and coastal vessels and auxiliary power for supply vessels, proving the viability of the technology at small scale. In addition, several demonstration projects on small ferries are under execution. A few larger cargo ship projects have recently been funded, but commercial scale vessels are generally at the design study stage and a range of fuels and fuel cell types are currently being tested. Multi fuel combustion engines which are capable of operating with a variety of gaseous and liquid fuels are already on or are close to the market. The European hydrogen and fuel cell supply chain is scaling up its interest in waterborne transport, with formal co-operations and joint ventures between FC manufacturers and some maritime power train providers and system integrators.

Demonstration projects are underway to highlight the viability of hydrogen to power ships using FCs and modified combustion engines. For certain use types (inland and small near coastal) and possibly cruise ships, there is recognition that FCs, using hydrogen are a promising zero-

[104] In terms of gross tons delivered, see the Review of Maritime Transport, UNCTAD, 2018.

emission option. Several demonstration projects have already been launched in Europe:

1. "Hydra" LH_2 ferry[105] at Hjelmeland, Norway. A RoPax LH_2 PEMFC ferry now being built (operational September 2021) and operated by NORLED;
2. LH_2 Pilot-E.[106] Very large-scale grant, delivered in tranches, with the aim to build LH_2 infrastructure for maritime transport in Norway. This includes production of LH_2;
3. HySeasIII (H2020).[107] HySeas III's aim is to deliver a sea-going vehicle and passenger ferry fuelled with hydrogen produced from renewable energy;
4. HySHIP (FCH JU), development and validation of a 3 MW fuel cell liquid hydrogen ship, used in a hydrogen bunkering and supply chain;
5. ShipFC (FCH JU),[108] "Scaling up and demonstration of a multi-MW Fuel Cell system for shipping". It plans to retrofit and operate a ship with a 2 MW SOFC ammonia power system;
6. Flagships (FCH JU).[109] In Flagships there are two demonstrators, where one passenger ferry is operated by Norled (Norway) and the other a fluvial barge operated by CFT (France);
7. e-SHyIPS (FCH JU), on pre-normative research on hydrogen-based fuels solutions for passenger ships.

Whilst to date, the scale of demonstrations remains significantly below to what is required for a fuel cell to become the primary power source within an intercontinental ship or cruise ship, several design projects are ongoing to test the applicability of integrating FCs within this type of vessels. However, due to the diversity of waterborne transport, e.g., magnitude of energy storage and power required for various user cases, the implications for ship design, integration, fuel storage and regulation, no consensus on the optimal strategy for fuel and propulsion technology has been reached.

- Hydrogen in ports

Fuel availability and corresponding port facilities are essential in the operations of vessels. Dedicated bunker vessels may supply new fuel to ships in ports, at anchor or in ship-to-ship modes. With the transition to alternative fuels, new bunker vessels have to be developed, and new bunkering infrastructure is needed alongside the European rivers and coasts. The bunkering technology has to be adapted to hydrogen both in gaseous and liquid forms as well as hydrogen derivatives and requires specialised technologies and safety procedures. In addition, with the electrification of vessels, the need arises for high-power charging facilities in areas with grid limitations, including stationary FC may be well suited for cold ironing, using hydrogen FC to supply electricity for operating the vessel while at quay.

Studies and pilot projects have already been launched in Europe and some companies have announced prototypes:

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[105] https://fuelcellsworks.com/news/norse-group-announces-launch-of-mf-hydra-worlds-first-lh2-driven-ferry-boat/
[106] https://www.norled.no/en/news/partners-receive-pilot-e-support-to-develop-liquid-hydrogen-supply-chain-for-maritime-applications-in-norway/
[107] https://www.hyseas3.eu/
[108] https://cordis.europa.eu/project/id/875156
[109] https://cordis.europa.eu/project/rcn/219834/factsheet/en

1. H2Ports (FCH JU), will deploy a mobile HRS, a reach stacker and a yard tractor in the container terminals of the port of Valencia (ES);
1. EVERYWH2ERE (FCH JU), at the Port of Santa Cruz de Tenerife (ES), a hydrogen fuel cell system of 100 kW will be trialled as offshore power system (OPS) for electricity production of passengers ships while at quay.
2. Companies Gaussin, Kalmar, Hyster-Yale, and Terberg have announced working on port machinery of various types for the logistics of containers in port terminals;
3. Study on hydrogen ports and industrial coastal areas (FCH JU), 2021, the study will cover amongst other hydrogen market potential, supply chain and economic forecasts.

Objectives

Development work will focus on improving access to the market for hydrogen, its derivatives and FCs, initially on smaller vessels. It will develop the necessary safety standards, components and fuelling systems required for smaller and subsequently for larger ship types. This will strengthen and consolidate the European maritime hydrogen value chain and set the foundation for large scale deployment.

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

1. For inland waterways and short-sea shipping, hydrogen and its derivatives can become an alternative low emission GHG neutral fuel; For short sea ships, fuel requirements would be equivalent to several hundred tons of fuel oil and the developed safety standards, IMO rules and ship integration would also be largely applicable to much larger ships. In the 5 to 10 MW range, fuel cell power needs would provide a stepping stone towards deep sea shipping services;
2. Intercontinental deep-sea shipping accounts for more than two thirds of waterborne GHG emissions. Compared to short sea shipping, powers are 2 to 3 times larger, fuel capacity 10 times greater with autonomy of around one month. Considering this and the implications for global fuel supply, solutions will build upon those developed for short sea shipping as well as ensuring the feasibility of providing adequate fuel, storage and bunkering infrastructure;
3. For ports, the building of infrastructure to refuel hydrogen and its derivatives, together with development of the necessary safety and standards for hydrogen bunkering at a scale relevant for commercial shipping, and the supply of electricity at shore with stationary FC.

FC and hydrogen technologies can provide a commercially viable option for zero-emission waterborne transport in certain use cases. For small ships, hydrogen, its derivatives 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, including its derivatives, scaling up the power, efficiency and operational performance of FC designs towards commercially relevant applications, initially for smaller vessels and advancing the components and fuelling systems required so that they are relevant for all short sea vessels and other ship types.

Establishment of a distribution and bunkering network in ports and along inland waterways across Europe is key for a large-scale roll-out of hydrogen to provide a feasible service to both maritime shipping and inland navigation.

Safe, flexible bunkering solutions for hydrogen for different waterborne transport segments, will therefore have to be realised to facilitate its increased use.

The definition and development of proper and consistent rules, regulations and procedures will support the introduction of hydrogen as a maritime fuel in ports in the safest way possible for the infrastructure, the environment and the surrounding population. Furthermore, technical standards will be developed for transferring to ship, or recharging ships and the directly related facilities (i.e., nozzles and hoses) to ensure that ships can be serviced throughout Europe.

In summary, R&D actions in this area have the following objectives:

1. Scaling up the power, efficiency and operational performance of FC designs towards commercially relevant applications;
2. Reducing the CAPEX and OPEX of PEMFC or SOFC systems for maritime applications;
3. Improving overall system performance for FC and stacks, especially in terms of power density, bunkering rate and operational flexibility;
4. Improvements in ship design and safety procedures, both for ships and ports bunker terminals;
5. Supporting the wide roll out of FC ships, by providing adequate fuel, storage and bunkering infrastructure and developing new solutions for ships based on hydrogen and its derivative fuels.

In order to contribute towards achieving the above objectives, the following areas of research and development appear as good candidates for the support by the Clean Hydrogen JU.

R&D Priorities - Early Stage Research Actions

- New low cost, scalable technologies with increased power density of FC stacks and BoP. This will involve LT and HT PEM fuel cells, as well as SOFC systems capable of using a range of fuels and achieving a high overall (well-to-wake) efficiency;
- Improvement of on-board storage solution for hydrogen, integrated below the vessel deck and also swappable fuel tank containers on deck;
- Improvement of on-board reforming of hydrogen carriers, if needed.
- Enabling deployment in shipping of hydrogen and ammonia by ensuring safety underpinned by the necessary onshore norms and regulations (protocols and standards).

R&D Priorities - Development Research Actions

- Integration and design activities for using different combinations of fuel cells for short sea ships (or modified internal combustion engines), a novel BoP configurations and different hydrogen carriers and possible reforming options to increase operational flexibility and FC durability;
- Enabling the safe, efficient on-board storage and integration within short sea ships of large quantities of hydrogen and its derivatives fuels;

- Enabling the full integration of fuel cells in short sea ship designs;
- Develop novel storage and bunkering solutions for very large volumes of energy in ports, either as pure hydrogen (Compressed hydrogen gas - CGH_2 - or LH_2) or as hydrogen carriers;
- Supply/bunkering of large quantities of hydrogen both liquid and gaseous, and other hydrogen carriers in ports environment.

R&D Priorities - Demonstration Actions

Further demonstrations in the post-2020 period should focus on:

- Strengthening and consolidating the European maritime value chain by developing and deploying fuel cells and hydrogen-based fuel storage solutions into new and existing vessels and installing the associated high capacity refuelling infrastructure into ports;
- Validation of the technical readiness of novel fuel cells and to determine the preferred fuel option for large vessels;

Integration of fuel cells for large sea-going ships and applicable hydrogen carriers will be developed in the Zero Emission Waterborne Transport partnership (ZEWT) and synergies should be explored accordingly.

Flagship Actions

Ports are coastal hubs where industries and transports coexist. The local demand for hydrogen is thus the sum of the needs for the port operations, the heavy industries and the heavy-duty transport in the vicinity. For the largest ports, it represents quantities of hydrogen currently not available at a single location.

The development and demonstration activities outlined above will lay the foundations for a larger scale FC shipping in the early 2020's, creating the scale required for this sector.

Key priorities in the market activation phase include developing and implementing innovative commercial models to manage risk appropriately and hydrogen supply chain development to ensure that the ships are fully supported throughout their operational lives. Due to their trading and economic importance, ports are at the heart of future hydrogen valleys. Such valleys are ecosystems / clusters with dense concentration of users of hydrogen for energy, transport and industrial purposes. These valleys are the ideal set-ups to initiate a renewable hydrogen transition. Indeed, stakeholders of the valleys can more easily under a common goal, set clear milestones, reach economies of scale, share investment risks and ultimately accelerate the deployment of a hydrogen infrastructure, supply and use.

Synergies

Potential synergies have been identified with ZEWT and P4P (as regards industrial hubs near ports area). See Section 4.1 and Annex 7 for more details on the synergies, as well as a potential distribution of responsibilities between the JU and ZEWT.

3.4.4. Rail applications

Rationale for Support

The majority of trains operating today are either diesel powered or electrified via overhead lines. Whilst electrification will deliver emissions equal to the average electricity mix at the point of use (unless otherwise certified), overhead lines of traditional electric locomotives are expensive and logistically complex (so limited to higher capacity lines). Battery electric propulsion may find applications for passenger trains operating over shorter distances, but hydrogen offers longer range and several advantages over electric pantograph locomotives utilising overhead lines , e.g., freedom of the locomotives to roam, relatively little infrastructure required and the option to secure a zero-carbon fuel supply.

Hydrogen is a key enabling technology for 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, FC trains could provide viable zero emission options for freight trains and shunting locomotives. The technology requires further development, adaptation, optimisation and integration of flexible FC components and systems into trains, 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.

A study of Shif2Rail and FCH 2 JUs[110] 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 TCO for fuel cells, while in others this technology is recognised as the most adequate zero-emission alternative.

State of the Art

Europe has adopted a leading position on the integration and assembly of FC 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):

1. The Alstom iLint FC train[111] has a 400 kW FC, and a max range of 1,000 km (350 bar hydrogen, 260 kg stored on board) and can accommodate up to 300 passengers. Capital costs are around €5.5 million (excluding hydrogen infrastructure). It has been approved for commercial operations in Germany, and 2 prototype trains have been in operation since 2018 with passenger service. In Germany, 41 trains have been ordered for delivery in 2021/2022, and letters of intent for a total of 60 trains have been signed; 14 trains have been ordered in France for delivery from 2023.

2. Siemens are also working on a fuel cell version of their Mireo train[112], 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);

3. The hydrogen-powered FLIRT H2 train[113] from Stadler is planned to be introduced in

[110] Study on the use of fuel cells and hydrogen in the railway environment, FCH 2 JU, 2019
[111] https://www.alstom.com/solutions/rolling-stock/coradia-ilint-worlds-1st-hydrogen-powered-train
[112] https://www.mobility.siemens.com/global/en/portfolio/rail/rolling-stock/commuter-and-regional-trains/mireo.html
[113] https://www.stadlerrail.com/en/media/article/green-tech-for-the-us-stadler-signs-first-ever-contractfor-hydrogen-powered-train/649/

2024. The train is expected to have seating space for 108 passengers and in addition standing room, with a maximum 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.

4. The project FCH2RAIL (FCH JU),[114] "Extending the use cases for FC trains through innovative designs and streamlined administrative framework", is going a step further by addressing: (a) bi-mode solutions for efficient operation on partially electrified lines; (b) transformation and retrofitting of existing trains to hydrogen clean propulsion and; (c) cross-border certification of hydrogen trains. An on-track demonstrator on a CAF/Renfe Train with Toyota Motor Europe fuel cells will be available by 2023.

Objectives

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 or partially electrified routes, with 1 in 5 trains sold for non-electrified railways are powered by hydrogen[110].

Overall, R&D actions in this area have the following objectives:

1. Reducing the cost of stacks;
2. Improving reliability and durability at stack and FC system;
3. Improving power output while reducing weight and dimension of the module;
4. Improvements in train design and safety procedures;
5. Supporting the roll out of FC trains, by providing the viability of the FCH solution in the train transport segment.

In order to contribute towards achieving the above objectives, the following areas of research and development appear as good candidates for the support by the Clean Hydrogen JU.

R&D Priorities - Early Stage Research Actions

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

R&D Priorities - Development Research Actions

- Designing new concepts for on board bulk hydrogen storage e.g., cryo-compressed hydrogen or liquid storage;
- 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;
- Developing new optimised bi-mode system architectures integrating FC systems with new generation power electronics and battery technology to achieve balanced solutions suitable for efficient partially electrified operation.
- Ensuring performance of very high capacity HRS (i.e. hydrogen infrastructure) can meet railway technical, operational and safety specific constraints, in order to optimise production & distribution costs.

[114] https://cordis.europa.eu/project/id/101006633

R&D Priorities - Demonstration Actions

- Ensure early demonstration 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 adapted to the specificities of rail applications.
- Projects could also help to develop maintenance and support strategies for the vehicles and provide a basis to develop regulations to enable FC trains and hydrogen use across Europe.

Flagship Actions

Early deployment of around 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.

Synergies

Possible synergies should be examined with the Europe's Rail partnership, as well as other funding sources – most notably CEF transport and CEF transport blending facilities for mass deployment of FC trains above and the required hydrogen refuelling infrastructure. See Section 4.1 and Annex 7 for more details on the synergies.

3.4.5. Aeronautic applications

Rationale for Support

By 2030, FCs are expected to be increasingly used for auxiliary power units & ground power units but also propulsion in civil aircraft. A selection of FC aviation models will achieve full certification and will be in real-world operation, including small passenger planes (up to 50 seats). The first demonstration (ground, in-flight) of a LH_2 propulsion aircraft (fuel cell / turbine) is expected by 2024[115].

The target of net zero carbon of aviation in 2050 will be reached only by a combination of all available levers, such as technology, air traffic management, but also sustainable alternative fuels. Hydrogen presents a strong potential used in fuel cells or in dedicated turbines. However, key technologies remain to be developed and demonstrated within the framework of the Clean Hydrogen and Clean Aviation partnerships.

High power FCs (1.5 MW) are yet to be developed in order to address the propulsion of small, Regional and Short-Medium Range (RSMR) commercial aircrafts, as well as key technologies such as tailored liquid hydrogen tanks and fuel systems. Low NO_x emitting hydrogen combustion turbines are also needed for larger aircrafts.

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 unmanned aerial vehicle (UAV) market alone, the EU could have a market share

[115] https://heaven-fch-project.eu/

of approximately €1.2 billion per annum by 2025. In the civil aviation, the global market is estimated to exceed 38 000 airplanes by 2034.

State of the Art

- Propulsive application

The use of FC 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 (SUAV, HYPPER) and passenger airplanes (up to 5 passengers). For example, the Hy4[116] platform of DLR involved, among others in the FCH JU project HEAVEN is the world's first four-seat passenger aircraft powered by FC technology, while ZeroAvia[117] performed their first test flight of a six-sitter plane in September 2020. Demonstration projects are progressively targeting larger applications, yet very few demonstrations of hydrogen for propulsion (FC and turbine) have been performed.

In September 2020, AIRBUS announced[118] three game-changing concepts for future commercial passenger aircraft using hydrogen as the primary energy supply:

1. Turboprop - a Regional aircraft concept with 1000 nautic miles mission range and around 100 passengers capacity;
2. Turbofan - a RSMR aircraft concept with 2000 nautic miles mission range and around 200 passengers capacity;
3. Blended-Wing Body - a more scalable concept allowing more space for hydrogen and passengers;

AIRBUS' ambition is to develop these three concepts and deliver the first hydrogen-powered commercial aircraft with entry-into-service by 2035.

In September 2020, Universal Hydrogen Co. and Plug Power Inc. announced[119] working together to retrofit a regional airplane with hydrogen fuel cells to power its two propellers. Together these companies aim to have a plane ready and government-certified to fly by 2024.

- Non-propulsive application

Hydrogen technology has been developed for non-propulsive aviation applications. For example, APUs have been tested through the HYCARUS[120] project (2013-2018). Supported by the FCH JU, this project aimed to develop a Generic Fuel Cell System for use as auxiliary power on larger commercial aircrafts and business jets. 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.

Objectives

Hydrogen is seen as a potential key enabler in the aeronautical scope climate-neutrality

[116] https://h2fly.de/
[117] https://www.zeroavia.com/
[118] https://www.airbus.com/newsroom/press-releases/en/2020/09/airbus-reveals-new-zeroemission-concept-aircraft.html
[119] https://www.ir.plugpower.com/Press-Releases/Press-Release-Details/2020/Plug-Power-Partners-with-Universal-Hydrogen-on-Hydrogen-Fuel-Cell-Propulsion-System-for-Regional-Turboprop-Aircraft/default.aspx
[120] http://cordis.europa.eu/project/rcn/108542_en.html

roadmap.[121] Hydrogen use is foreseen through:

- Fuel cell with liquid / gaseous storage for RSMR aircraft;
- High power fuel cell (1.5 MW+) using liquid hydrogen for the propulsion of RSMR aircraft;
- Low NO_x emitting turbine using liquid hydrogen;
- Non-propulsive energy through fuel cell or turbo-electric architecture;
- Decarbonisation of ground operations.

However, significant developments and academic and vocational trainings are needed and thus will be supported in the following fields:

1. On-board storage of liquid hydrogen;
2. Liquid hydrogen distribution components and system;
3. Fuel cell technology;
4. Low NO_x emitting hydrogen turbines;
5. Low TRL hydrogen combustion research (synergy with stationary turbine developments);
6. Airport infrastructure (of both liquid and compressed hydrogen) and refuelling tech / procedures;
7. Safety and regulation.

Overall, R&D actions in this area have the following objectives:

1. Improving overall system and stack performance for scalable FC in terms of power density, durability and availability;
2. Reducing NO_x emissions of turbines;
3. Addressing Airport infrastructure (of both liquid and compressed hydrogen) and refuelling tech / procedures;
4. Developing aviation dedicated technological bricks, focusing in particular on on-board storage and distribution components and system of liquid hydrogen.
5. Addressing safety and regulation, specific to hydrogen for aviation applications

In order to contribute towards achieving the above objectives, the following areas of research and development appear as good candidates for the support by the Clean Hydrogen JU.

R&D Priorities - Early Stage Research Actions

- Special FC membrane electrode assembly (MEA) components for aircraft applications;
- Aviation dedicated technological bricks: evaporation unit LH_2 tank, gaseous hydrogen compressors, LH_2 pumps, valves and sensors (gauging).

R&D Priorities - Development Research Actions

- Development of 250 kW FC stack and scalability of FC system and components for an

[121] Hydrogen-powered aviation, FCH 2 JU, 2020

at least 1.5 MW module, to be further scaled up first to 5-6 MW and then to a 10 MW system;

- High gravimetric density BoP R&D;
- LH_2 tanks with a capacity of 5t and gravimetric index of 35%;
- Fuel handling LH_2 (including aircraft refuelling);
- New development of components and system controls;
- Development of a low NO_x / high efficiency hydrogen combustion chamber for aviation, in synergy with stationary applications;
- Studies to assess / quantify non-CO_2 effects of hydrogen powered aircraft.

R&D Priorities - Demonstration Actions

- 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:
    - Trials demonstrating the feasibility of aircraft refuelling;
    - GH_2 infrastructure increasingly available at airports;
    - First demo of LH_2 infrastructure.

Flagship Actions

No flagship actions will be supported by the Programme.

Synergies

A strong collaboration is envisaged between Clean Hydrogen JU and Clean Aviation partnership. See Section 4.1 and Annex 7 for more details on the synergies.

3.5. Hydrogen end uses: Clean heat and power

Hydrogen offers a unique chance to decarbonise the power generation and heating sectors reliably and independently from weather or seasonal conditions. In its quality as a dispatchable energy carrier, it can easily cope with high peak demands, and is available any time during the year and day to support grid balancing actions based on hydrogen storage/use strategies in local and regional networks. It is also complementary to, and offering a diversification option, from the direct electrification of the heating sector. Energy conversion in combined heat and power generators do not only cover the thermal needs whenever required, but also reduces the load on the electrical side when demand is usually highest, avoiding grid congestion at the distribution level and allowing to optimise overall costs of the energy system.

The overall goal of this pillar is to support European supply chain actors to develop a portfolio of solutions providing clean, renewable and flexible heat and power generation for all end users' needs and across all system sizes; from domestic systems all the way to large-scale power generation plants. Preferential support will be for solutions running on 100% hydrogen. However, there is still room to support solutions running on a hydrogen mixture in the gas grid (up to 20% within the context of the activities included in this support area) during the transition phase[122]. For gas turbines, in order to enable a smooth transition and assure backward compatibility with conventional fuels during the transition, support for actions running with different hydrogen admixtures are likely to be required to facilitate the development process and to achieve the final goal of 100% hydrogen turbines.

To reach the overall goal of this pillar, support will be provided for the following activity areas:

1. Stationary fuel cells;
2. Gas turbines, boilers and burners.

Fuel cells generate power and heat efficiently and in a silent and clean manner. If hydrogen is generated from renewable energy sources, then the fuel cells proposition is unique, as they are the only technology able to silently generate clean energy with zero emissions. Going up to the MWe scale, fuel cells generate power with the highest efficiencies offering a clean and silent alternative to conventional solutions such as combustion engines.

As power systems start to be dominated by variable renewable energy sources, notably wind and solar, meeting fluctuating demand requires the availability of additional and responsive capacity. Gas turbines fed with low-carbon hydrogen can offer a decarbonised solution for the provision of a stable energy supply at the transmission level. Adaptation of existing gas turbines to hydrogen will reduce the overall costs of the energy transition, as investments in new dedicated assets can be postponed. This would also allow to extend the use of the 180 GWe gas turbine power generation[123,124] currently available in Europe[125].

For the provision of high temperature heat for industry, the use of low-carbon hydrogen in burners and boilers appears to be better placed than other low carbon and renewable solutions.

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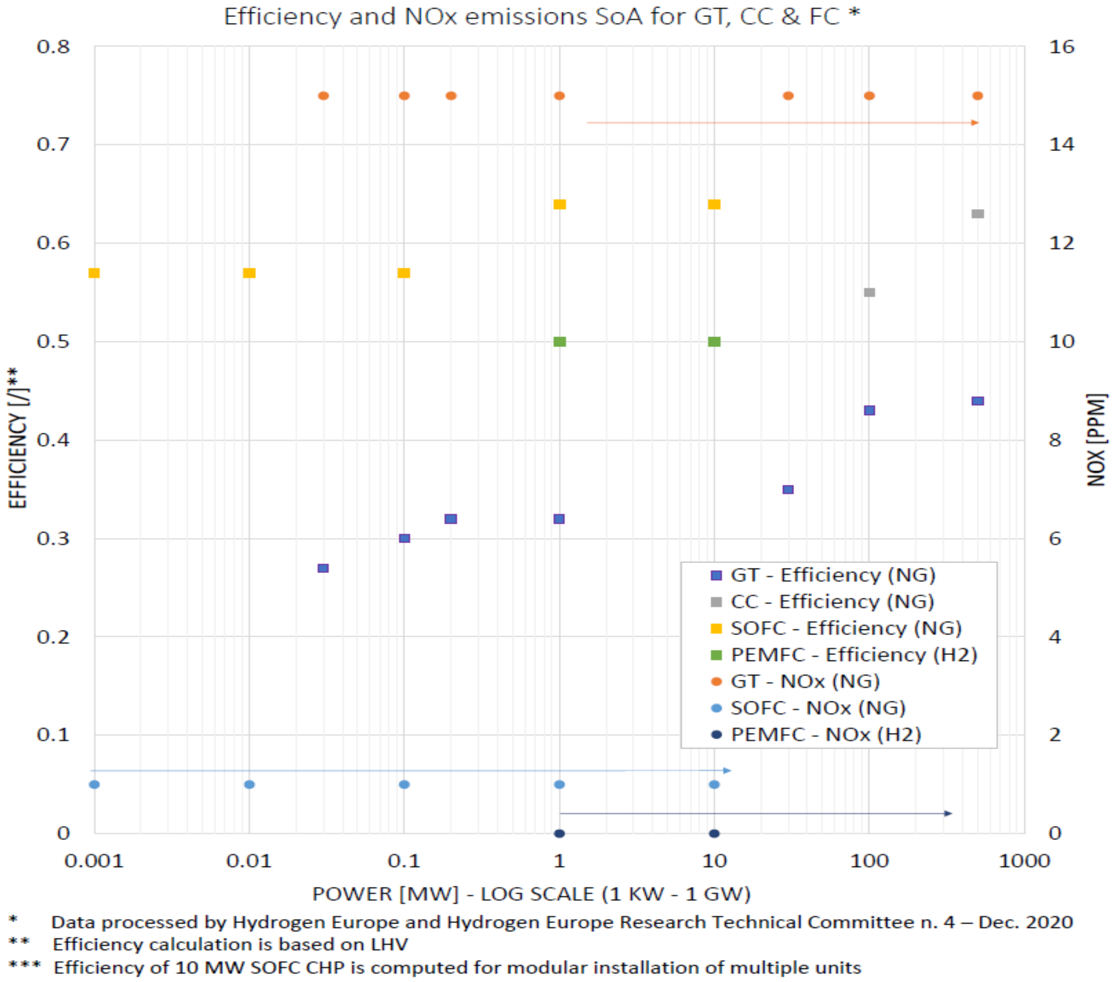
[122] According to the "Hydrogen strategy for a climate-neutral Europe", the blending of hydrogen in the natural gas network at a limited percentage may enable decentralised renewable hydrogen production in local networks in a transitional phase.
[123] World Energy Outlook, IEA, 2020.
[124] Including gas turbines for open and combined cycles

Figure 1 State of the Art net efficiency[126] and NO_x emissions for fuel cells and Gas Turbines



For gas turbines and SOFCs values provided are for natural gas. For PEMFC values provided are for hydrogen.

Support in this pillar will focus on fuel cell solutions up to the 10 MWe scale and gas turbines only for larger systems, possibly for applications above 50 MWe. This range is only indicative, though support in the range of tens of MWe and up to the 50 MWe scale could be provided following a technology neutral approach, where either 100% hydrogen fuel cells or turbines or a combination of both could be favoured. For indicative purposes and to support the narrative included in this section the figure above includes State of the Art (SoA) efficiencies and NO_x emissions for fuel cell and gas turbines with or without combined cycles for a range of power capacities.

3.5.1. Stationary Fuel Cells

Rationale for support

Fuel cells unique proposition, relative to other technologies, resides in that they are the only technology driven by hydrogen that is able to silently generate clean energy with zero emissions. This positions fuel cells as a key technology to decarbonise a number of end user demands across a large range of sizes. Power production is common to all applications. Depending on the specific application, additional value is provided in different forms.

[126] The net efficiency is the ratio between the net electrical power generated and the chemical energy flow rate.

- Fuel cells (hydrogen admixtures in natural gas or 100% hydrogen driven) for Combined Heat and Power (CHP) applications – fuel cells can provide heat for buildings[127] (directly or via district heating networks) as well as electricity at high efficiency. They can also provide heat and power to the service and industrial sectors; when coupled to thermal storage they can offer additional flexibility to the system.
- Back-up power, gen-sets and off-grid power production (typically hydrogen, but also methanol and ammonia fuelled for longer term back-up) – because of fast response times and low maintenance needs compared to diesel systems, fuel cells are an ideal component of back-up and temporary (portable) power systems. Fuel cells can also be used as main power sources for off-grid locations.
- Prime power (hydrogen admixtures in natural gas or 100% hydrogen driven) – fuel cells can also be used as prime power or primary 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.

More advanced reversible fuel cell concepts can provide flexibility to the energy system and provide a means to link different energy sectors, e.g. gas and electricity grid but also heating networks, if by-product heat from the electrochemical conversion can be recovered and put to use.

The focus of the Clean Hydrogen JU will be on hydrogen driven fuel cells. Large-scale deployment projects for residential micro-CHP applications are not foreseen as they were already covered in the FCH 2 JU.

State of the Art

Stationary applications of fuel cells range from a few hundred Watts all the way to multi-MW systems. In Europe, the most mature application is micro combined heat and power, micro-CHP (from 0.5 kWe to 5 kWe), which is typically used to provide heat and power for domestic applications and small businesses. In Europe, most installed units are between 0.7 kWe and 2 kWe. Both PEMFC and SOFC are used, though SOFC units are a more common offering in Europe, and increasingly so globally.

Deployment volumes in Europe are still low compared to other regions of the world. The European domestic market is developing, helped by support programmes such as the FCH 2 JU's Ene.field[128] and PACE[129] projects, and the German KFW433 grant scheme (for systems 0.25-5 kWe). To date Europe has seen systems installed in the order of tens of thousands, in contrast to installations of more than 300,000 in Japan alone. There are no other substantial markets for micro-CHP systems anywhere else in the world.

Support under the FCH 2 JU managed to create a track record of micro-CHP installations, demonstrating the performance and market readiness of these technologies. Power efficiencies as high as 60% and total efficiencies exceeding 90% have been achieved. Availability of 99% over sustained periods have been shown and some manufacturers claim stack durability of 10 years and system lifetimes of 15 years. In addition, the CAPEX of European systems has been reduced (below 10,000 €/kWe) thanks to a combination of research and first industrial

[127] Buildings in Europe are responsible for 40% of our energy consumption and 36% of greenhouse gas emissions. Source: DG ENER, 2020.
[128] http://cordis.europa.eu/project/rcn/104765_en.html
[129] http://cordis.europa.eu/project/rcn/204315_en.html

deployment. There is room to decrease costs further and incremental additional work is needed to allow operation under 0-100% hydrogen admixtures.

Fuel cells for cogeneration can also be used to supply the needs of commercial buildings and the service sector, also in combination with thermal storage, and to be the heat source for district heating networks. These applications typically range between 5 - 500 kWe system capacity. Such a market is considered small, both globally and for Europe. Still a number of actors in Europe have started to demonstrate solutions in real installations, like FCH JU projects DEMOSOFC[130] and ComSos[131]. Costs of Europe's fuel cell systems for these applications still remain high.

In recent years, Europe has developed and trialled reversible fuel cell systems using solid oxide cells. The fuel cell uses natural gas to generate heat and power (and hydrogen if operated in poly-generation mode) and in reversible operation they can generate hydrogen via electrolysis. These concepts are now being tested in the sub 100 kWe scale with promising results, although sustained efforts are required on the way to commercialisation.

Larger size cogeneration applications with fuel cells are possible (500 kWe and over). This market in Europe is still underdeveloped although several European actors offer MWe scale fuel cells. To date, only a few demonstrations have taken place, including FCH JU projects DEMCOPEM2MW[132] and CLEARGENDMEMO[133] using the first generation of MWe scale systems, mainly in overseas markets with more favourable market conditions. The next generation systems, are currently being developed for reduced costs and dynamic operation.

Conventional back-up, portable and off-grid power solutions use fossil fuel based engine generators and are sometimes combined with batteries to provide the required reliability of service. Fuel cells offer a clean and higher efficiency alternative, require less maintenance, provide extended runtimes relative to batteries and are better placed to operate under harsh outdoor environments. Nevertheless, Europe's market in these sectors needs further development. This situation differs largely from the rest of the world where, for instance in the US, most fuel cells for stationary application are used as back-up power supply to reinforce the unreliable power grid.

Fuel cells can also be used as prime power solutions for continuous on-site power generation instead of grid electricity. These applications in Europe have seen limited activity, though in the US and Asia, an increasing number of fuel cells serve as the primary power source for data centres and large corporate campuses, where the provision of reliable power supply is critical.

Objectives

Europe's has an objective for climate neutrality in 2050. This means that a large penetration of variable renewable power generation as well as an increased presence of renewable gases in the years to come and until 2050. Support in this area should therefore be oriented to develop solutions that are compatible with, and come in support of, this scenario.

In terms of ambition, the Strategic Research and Innovation Agenda of the Industry and Research (SRIA-HE/HER) set the vision to deploy over 2.5 GWe of stationary fuel cells by 2030. In addition, the expectations are for numerous European manufacturers producing 500

[130] http://cordis.europa.eu/project/rcn/197931_en.html
[131] https://cordis.europa.eu/project/rcn/213064/factsheet/en
[132] http://cordis.europa.eu/project/rcn/192597_en.html
[133] http://cordis.europa.eu/project/rcn/106349_en.html

MW sales/year by the end of 2030. In order to facilitate such large uptake of stationary fuel cells the objectives of the Clean Hydrogen JU it will be important to improve the techno-economic performance of fuel cells for stationary applications in order to increase the penetration in the market of such solutions. To achieve this the objectives of this pillar are set as follows:

1. Reducing CAPEX and TCO of stationary fuel cells of all sizes and end use applications;
2. Prepare and demonstrate the next generation of fuel cells for stationary applications able to run under 100% H_2 and other H_2-rich fuels whilst keeping high performance;
3. Improve flexibility of systems in operation in particular with reversible fuel cells and integration with thermal storage;
4. Reducing use of critical raw materials and recycling them for further usage;
5. Support development of processes suitable for mass manufacturing.

In order to achieve the above objectives and building on the current SoA, the focus of the support under this activity area is detailed below.

Support to micro-CHP systems shall focus on research activities aiming to prepare the next generation of fuel cell micro-CHP systems. The ultimately objective is to reduce CAPEX and TCO to competitive levels and to validate the performance of units running on 100% hydrogen. Reversible fuel cell concepts at this small scale could be considered if sufficient demand and a positive business case can be identified, empowering end-users.

For commercial buildings and service sector applications, cost reduction through new stack designs and improved components in order to improve the flexibility in operation should be prioritised. Support is foreseen for the demonstration of small and medium reversible fuel cell concepts. Those pave the way to deploy distributed commercial systems capable of linking electricity and gas grids at medium and low voltage levels, and potentially district heating networks using the by-product heat produced. Systems running on 0-20% hydrogen volume in the gas grid or using pure hydrogen are the focus of this support area. Larger reversible systems (above 1 MW in electrolyser mode) fall under the hydrogen production activity area.

For larger FC applications the focus is on systems running on 100% hydrogen, e.g. waste hydrogen from industrial processes or hydrogen grids. Synergies with the district heating sector are to be explored with the view to provide heat using fuel cells fed with 100% hydrogen. Research is needed to decrease the costs of systems further and to demonstrate the next generation for these large-scale applications. Selected demonstrations in real installations to prove the technology in actual long-term operation and to showcase new business models are likely to be needed.

Fuel cells operating in cogeneration mode should be given priority. However, power-only solutions operating as prime power can make sense, especially when using high temperature fuel cells with power efficiencies comparable to, or better then, the most efficient large-scale power generation plants (e.g. Combined Cycle Gas Turbines – CCGT); in particular, at the local grid level and in applications where it is not possible to put the by-product heat to use. This is increasingly the case with more abundant hydrogen availability providing high reliability versus RES for critical infrastructure such as data centres.

Support is also envisaged for back-up, portable and off-grid power fuel cell solutions, especially in remote and isolated locations and where there is a premium on reliable and clean power, and/or where pollutants and noise in urban and low emission zones are critical. Actions in this area could support units running directly on hydrogen or using other hydrogen rich fuels of the likes of ammonia or liquid organic hydrogen carriers, and is open to all type of fuel cells. Whilst the focus is likely to be on research, there is room in the Clean Hydrogen JU to support selected demos for proving adequate uptime and availabilities.

In order to contribute towards achieving the above objectives, the following areas of research and development appear as good candidates for the support by the Clean Hydrogen JU.

R&D Priorities – Early Stage Research Actions

- 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 ceramic proton conductors.

R&D Priorities – Development Research Actions

- 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 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 and/or prime power units from European suppliers (100 kWe – 1 Mwe) to demonstrate this;
- For industrial heat and power development work on prototypes for the smart cogeneration of industrial heat and electricity by FC CHP at 1, 10 and 100 MW scales;
- Integration work on reversible cell concepts, to improve the round-trip efficiency to above 50% and to develop concepts at a range of scales.

R&D Priorities – Demonstration Actions

- Hydrogen ready and cost effective micro-CHP systems;
- Demonstrate the deployment of the next generation of commercial/industrial scale fuel cell CHP and/or prime power units from European suppliers (50 kW to several Mwe);
- For industrial heat and power: demonstration projects on cogeneration of industrial heat and electricity with fuel cells selected industrial environment, e.g. food, biotech;
- 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.

Flagship Actions

Flagship support would be needed to roll-out hydrogen-based fuel cell CHP for power & low/medium grade heat requirements in industry and other large scale applications.

Synergies

Synergies between the Clean Hydrogen JU and P4P will be explored, focusing on industrial applications. Other potential synergies could be with the Built4People (B4P) European partnership and Horizon's Europe Cluster 5[134]. See Section 4.1 and Annex 7 for more details on the synergies.

3.5.2. Turbines, boilers and burners

Rationale for support

- Turbines

Gas Turbines (GTs) use natural, bio or syngas 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, together with thermal storage, 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, GTs 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 ~63% in CCGT configurations. In cogeneration CHP mode, the fuel conversion rate reached is above 90%. There is also a decentralisation possibility with micro CHP in sites with a significant heat demand.

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 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 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 wet low emission (WLE) 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% hydrogen firing by dry low emission (DLE) combustion, still complying with NO_x emissions targets (up to 25 ppm) without the use of diluents and with minimal thermal efficiency penalty.

- Boilers and 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 the share of hydrogen in the gas grid increases and conversion programmes for 100% hydrogen in the grid appear, there will be a need for hydrogen-fired industrial boilers and burners to provide high temperature heat. Gas burners and entire boiler units must be 100%

[134] Cluster 5 Climate, Energy and Mobility, Destination 4 on Buildings and Industrial Facilities in Energy Transition

hydrogen ready and fulfil the same NO_x 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 tolerate traces of other species, enabling therefore the adoption of cost- and energy-effective production and offering hydrogen conversion technologies at large scale.

All in all, the vision for 2030 is to have 100% hydrogen ready European gas turbines & burners fulfilling emissions standards, for zero-carbon sustainable dispatchable power and high temperature heat.

State of the art

- Turbines

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

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

- Heavy-Duty GTs ~44%/63% (100-500 Mwe)
- Industrial GTs ~43%/55% (30-100 Mwe)
- Aeroderivative GTs ~35% (1-30 Mwe)
- Micro GTs ~32% (0.1-1 Mwe)

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

- CHP
- Back-up and peak demand power
- Prime power
- Energy system coupling and flexibility
- Energy supply chain

Europe has a strong turbine industry and a large gas turbine asset.

- Boilers and burners

Today there are no hydrogen burners available on the market for industrial applications. Only a prototype was developed for industrial applications around 1MW. The next generation of boilers will be hydrogen ready to be later retrofitted with hydrogen burners. No hydrogen surface burners are available today. The UK's project Hy4Heat[135] represents an important milestone

[135] https://www.hy4heat.info/

and potential synergy with the Clean Hydrogen JU activity in this context, providing a precious source of data useful in the development of domestic and hydrogen-fired industrial gas appliances.

Objectives

- Turbines

In the long-term climate neutral perspective, the installed electrical capacity of variable renewable energy sources is projected to increase significantly. From a share of around 31% gross electricity generation in 2015 this is projected to reach between 61-69% in 2030 and more than 80% in 2050. The integration of these variable electricity generation sources will require deployment of resources providing flexibility to the energy system. Together with energy storage solutions, gas turbines will also remain key assets for balancing the electricity system (as the current technology derating factors of system adequacy mechanisms for electricity, some recently launched, clearly indicate). The climate neutrality goal for 2050 requires though that the electricity sector is decarbonised already by 2040, which highlights the need that these gas turbines are fuelled by low carbon gases.

The objective of this activity area is to prepare gas turbines to run on 100% hydrogen, whilst keep conversion efficiencies and NO_x emission to acceptable levels. To achieve the objective the focus of the support should be on research to better understand the implications of using hydrogen in combustors including NO_x and flashback control whilst keeping acceptable power efficiencies. Actions such as materials research to cope with the higher temperatures required to use hydrogen would fall out of the Clean Hydrogen JU.

In order to facilitate the development process and facilitate backward compatibility with conventional fuels during the transition period, it is likely that support for actions running with different hydrogen admixtures maybe required in order to achieve the final goal of having 100% hydrogen turbines. Building on this, support could be expected to demonstrate the retrofitting of existing gas turbines to run on 100% hydrogen.

- Boilers and burners

Significant progress has been made recently in the area of domestic hydrogen boilers, especially in the UK, but also in Germany. As hydrogen becomes more available the challenge remains to have industrial 100% hydrogen ready boilers and burners to provide high temperature heat and to comply with the NO_x emissions standards as for conventional gas boilers by 2030. With this in mind support in the Clean Hydrogen JU should be on better understanding the hydrogen combustion mechanism and in developing or retrofitting boilers with combustors and burners respectively able to run on 100% hydrogen whilst respecting the NO_x emissions standards.

Specific actions supporting this area will appear as integral parts of broader projects supporting, for instance, the direct use/storage of hydrogen from electrolysis at low pressure from combustion and include also the flexibility of burners towards various fuels (hydrogen, natural gas, ammonia – normally dedicated to ambient pressure). Those actions should also benefit from the fundamental low TRL activities on gas turbines and result into activities targeting applications in a context of full applications beyond mere combustion.

In summary these are the following objectives in this pillar:

1. Allow turbines to run on higher admixtures of H_2, up to 100% whilst keeping low NO_x emissions, high efficiencies and flexible operation.

2. Develop concepts on safety and plant integration and demonstrate the retrofitting of turbines, boilers and burners so that they are able to run up to 100% H_2.

In order to contribute towards achieving the above objectives, the following areas of research and development appear as good candidates for the support by the Clean Hydrogen JU.

R&D Priorities – Early Stage Research Actions

- Combustion physics, flame stability and combustion dynamics in gas turbine operation with pure hydrogen, focussing on development of new DLE combustion models for hydrogen content of 100%.

R&D Priorities – Development Research Actions

- Development of plant integration concepts, business models and value chains, incl. retrofitting;
- Safety concepts, Standards and Norms (linked to cross-cutting activities);
- Development of pure hydrogen burner for boilers compliant NO_x emissions (industrial scales). Research areas should focus on flame monitoring, optimal mixture formation, impact of buoyancy effects, flame stability & flashback, reduction of emissions. Aspects looking at materials research, such as life-time analysis of thermally high stressed materials, would fall out of the remit of this partnership;
- Investigation of the influence of hydrogen and higher gas supply pressures on component tightness and thermal aging behaviour.

R&D Priorities – Demonstration Actions

Demonstration 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. This should include upgrade existing plants to safely utilise hydrogen.

Flagship Actions

Not foreseen as dedicated actions but they could be part of flagship actions supported under other areas.

Synergies

Synergies between the Clean Hydrogen JU, P4P and Clean Steel will be explored, focusing on industrial applications. Other potential synergies could be with Horizon's Europe Cluster 5. See Section 4.1 and Annex 7 for more details on the synergies.

3.6. Cross-cutting issues

In order to meet the targets set out in the Hydrogen Strategy, Europe needs to ensure safe and frictionless deployment of low-carbon hydrogen technologies. Nevertheless, mass-market commercialisation of hydrogen-based technologies presents a number of systemic (or horizontal) challenges that need to be addressed to effectively kick-start a hydrogen ecosystem of significant scale throughout the EU in the coming decade.

Whilst cross-cutting issues such as knowledge management or communication activities are embedded throughout the entire Programme, a number of specific supporting activities of horizontal nature are still required in view of reinforcing Europe's leadership position and to accelerate mass-market adoption. These supporting activities are encompassed in a cross-cutting activity area.

Cross-cutting activity area is a horizontal area aiming at paving the way for the safe and frictionless roll-out of hydrogen-based technologies at scale by means of the implementation of a comprehensive set of supporting activities. Building on the experiences and successes of the FCH 2 JU Programme, the implementation of cross-cutting activities will support and complement the activities undertaken in other areas of the Programme while facilitating the roll-out and the commercialisation of hydrogen-based technologies in Europe (and beyond).

Cross-cutting activity area is structured around three focus areas: (i) Sustainability; (ii) Education and public awareness; and (iii) Safety, pre-normative research and regulations, codes and standards.

As hydrogen-based technologies become a market value proposition, strengthening the focus on environmental and sustainability aspects (such as water resources for electrolysis, critical raw materials use along hydrogen value chains and pollutant emissions) is required in the framework of the transition to a circular economy, as mentioned in Section 2.1. Furthermore, continuous education and training are fundamental to safeguard existing expertise and to prepare a well-educated workforce needed for a competitive hydrogen market, while underpinning the jobs and value creation in a knowledge-based society in Europe. Public awareness activities are essential for increasing social acceptance and trust in hydrogen-based technologies throughout Europe but in particular, for bridging the potential lack of knowledge or mistrust of key stakeholders directly involved in the first phases of mass deployment in Europe. Moreover, for a safe deployment of hydrogen technologies in Europe, safety-related aspects are of paramount relevance. As the technologies will shift from the industrial domain to the public domain, strengthening hydrogen safety will become one of the priorities of the Clean Hydrogen JU Programme. Besides, a suitable regulatory framework for hydrogen-based technologies is necessary for an EU-wide deployment of hydrogen technologies. To this end, both pre-normative research activities and desk research activities are fundamental for supporting regulations, codes and standards (RCS) development.

There is also the need that cost benefit analysis among technologies is done on a level playing field for all carriers and that whole system analyses are performed (with congestion management costs for all carriers and sector coupling incorporated). All the models used to plan infrastructure and policy should incorporate as a minimum a simplified version of the physical constraints of the carrier networks they represent. Today this is the case for some carriers but not for all, introducing a lack of level playing field in the comparisons and benchmarks run amongst them. The development of more complete multi-carrier hybrid models (including infrastructure physics and correctly reflecting network constraints) is a R&D activity that will have impacts on benchmarks and perceptions.

The following sections provide further details of the research framework envisaged in each of the above-mentioned focus areas.

3.6.1. Sustainability, LCSA, recycling and eco-design

Rationale for support

Hydrogen-based technologies are ready to start their deployment in different applications and levels but it is necessary to develop circular and sustainable approaches in the technology developments and along the hydrogen chain to comply with environmental and social principles and goals. To this end, further efforts in minimising the impacts of products from its design;

ensuring its recovery, reuse and recycling with emphasis on the Platinum Group Metals – PGMs, Critical (Raw) Materials – CRMs and other materials with sustainability or environmental concerns such as those deriving from per- and polyfluoroalkyl substances; and supplying the necessary assessment tools for decision making are still required in the framework of the transition to a circular economy.

State of the Art

Circular economy is about creating value for the economy, society and business while minimising resource use and environmental and social impacts via system thinking. To this end, life cycle thinking tools have been developed to assess the environmental, social and economic impact of a product or activity. Life cycle thinking tools include but not limited to Life Cycle Assessment (LCA), Life Cycle Costing (LCC), Social Life Cycle Analysis (SLCA) and Life Cycle Sustainability Assessment (LCSA). In the hydrogen sector, FCH JU projects such as FC-HYGUIDE[136] or SH2E[137] account for this. Furthermore, projects like HYTECHCYCLING[138] and BEST4HY[139] projects, and eGHOST[140] project have started to propose strategies for recycling as well as for the adaptation of the design of some hydrogen-based products. Nevertheless, still, further research is needed to consider the hydrogen sector a sustainable and circular sector.

Objectives

The overarching goal of this focus area is to contribute that the hydrogen sector becomes a sustainable and circular sector supporting the EU strategy on energy system integration and contributing towards the achievement of the Sustainable Development Goals and the objectives of the Paris Agreement. To improve sustainability and circularity, key focus areas for development are complete and integrated LCSA tools, enhanced recovery of PGMs/CRMs including per- and polyfluoroalkyl substances (PFAS) based ionomers and membranes, development of recycling integrated processes, and development of eco-design guidelines and eco-efficient processes. Thus, the specific objectives in this area are:

1. Develop life cycle thinking tools addressing the three dimensions of sustainable development: economic, social, and environmental.
2. Develop eco-design guidelines and eco-efficient processes.
3. Develop enhanced recovery processes in particular for PGMs/CRMs and per- and polyfluoroalkyl substances.

To this end, further research is needed to develop reliable methodologies for assessing the environmental, economic and social impacts of hydrogen-based technologies and their associated value chains, including their full life-cycle environmental impacts (including “water balance” impacts), circularity and sustainability. Furthermore, securing the supply of critical raw materials in parallel to material reduction, substitution, reuse, and recycling needs to become a core part of the value chain to foster a more circular economy. Critical (raw) materials present in hydrogen-based technologies need be looked at framed in the context of the Critical Raw

136 https://cordis.europa.eu/project/id/256328
137 https://cordis.europa.eu/project/id/101007163
138 https://cordis.europa.eu/project/id/700190
139 https://cordis.europa.eu/project/id/101007216
140 https://cordis.europa.eu/project/id/101007166

Materials Action Plan[141], the implementation of the new Circular Economy Action Plan[142] and EU's trade policy approach with due account being paid to ensuring the security of supply and high levels of sustainability in Europe. As part of the holistic approach on sustainability-related aspects, eco-design and eco-efficiency are effective tools for improving the sustainability of products and processes, contributing to eliminating the least performing products (and/or processes) from the market, and significantly contributing to the industrial competitiveness and innovation by promoting the better environmental performance of products and processes.

Sustainability, LCSA, recycling and eco-design activities will be strategically important by 2030. Indeed, "sustainability and circularity by design" will be addressed in the Clean Hydrogen JU Programme, supporting the activities undertaken within. To contribute to address these issues, a number of actions targeting research and innovation, and coordination and support will be carried out within this focus area. The following list some of the potential actions envisaged:

R&D Priorities - Early Stage Research Actions

Further research to optimise the recycling technology for PEMFC and SOFC, and electrolysis processes, such as for noble metals and critical materials including perfluorosulfonic acid membranes and ionomers from components used in these processes. Learnings from this work should be able to be scaled-up towards market deployment.

R&D Priorities – Demonstration Actions

PEM and Alkaline Electrolysis (PEMEL, AEMEL, and AEL), Polymeric Fuel Cells (PEMFC), and Storage materials recycling processes will be developed by transferring current industrial processes already in place for other different value chains than hydrogen. In this regards, the recycling of the different components of the hydrogen value chain will need to be addressed to optimise systems components and increase sustainability and circularity.

Coordination and Support Actions

Building on the previous projects' activities and results, coordination and support actions will be made throughout the following areas:

- Eco-design/sustainable design guidelines;
- Eco-efficiency integrated in fuel cells and hydrogen-based technologies manufacturing, complementing the activities undertaken in the supply chain area.
- Development of Product Environmental Footprint Category Rules (PEFCRs);
- Regionalised LCSA;
- SLCA-LCC on supply chains;
- Database for LCSA indicators;

3.6.2. Education and public Awareness

Rationale for support

Over the past few years, the European hydrogen industry has made great strides and currently, it is poised to take the next step and achieve significant levels of commercialisation. This will

[141] Critical Raw Materials Resilience: Charting a Path towards greater Security and Sustainability. COM(2020) 474 final.
[142] A new Circular Economy Action Plan. COM(2020) 98 final.

enable significant economic growth to take place primarily within Europe, keeping high value-added jobs, and creating a supply chain of EU companies around a new suite of products based on hydrogen and fuel cell technologies. Combined with EU's leadership in renewables technologies, the emergence of a European hydrogen value chain serving a multitude of industrial sectors and other end uses will employ millions of people, directly or indirectly.

In 2017, the Hydrogen Council[143] indicated the hydrogen sector could provide sustainable employment for more than 30 million people around the world by 2050. Furthermore, the Hydrogen Roadmap Europe analysis[144] pointed a total of 5.4 million direct jobs created by the European industry in 2050 ('ambitious' scenario).

In the EU, the Commission is placing skills at the heart of the EU policy agenda, steering investment in people and their skills for a sustainable recovery after the coronavirus pandemic, and in July 2020 presented the European Skills Agenda[145] for sustainable competitiveness, social fairness, and resilience. As first of the flagship actions under the European Skills Agenda, in November 2020, the Commission launched the Pact for Skills[146] to support a fair and resilient recovery and deliver on the ambitions of the green and digital transitions and of the EU Industrial and SME Strategies.

Therefore, to unlock opportunities for more and better jobs, as well as growth and competitiveness, the training of skilled educated manpower as the upskill or reskill of current workforce in declining industries are crucial to succeeding in the needed scaling–up of this emerging European industry.

On the other hand, mass deployment requires strong knowledge management and effective dissemination of this knowledge. In this context, further efforts are also required to promote the social awareness and public trust in hydrogen technology and hydrogen-based products to raise the levels of knowledge about them and to achieve widespread use while fostering sustainable growth and jobs alongside their deployment.

In this context, there is a need for a generalised market-wise cross-functional expertise across energy carriers, whereby synergies can be detected and exploited amongst all the carriers. Sector coupling will eventually require cross-carrier operational optimisations (and trades with certificates) that will require of this knowledge. Green hydrogen and RFNBOs in general require an understanding of both electricity issues and gaseous molecules potential and about the operation of both markets (and also of heat as an addition). Lack of this knowledge may lead to mono-carrier approaches while one-carrier solutions will be less efficient, cost more to the public and lead to higher emissions and lesser penetration and integration of renewables.

State of the art

Technical knowledge about hydrogen and its technology leads to greater acceptability through increased levels of confidence in the technology. Over the last years, educational and training material and programs on hydrogen technologies have been developed. Projects such as TRAINHY-PROF[147], and more recently KNOWHY[148], NET-TOOLS[149], TEACHY[150] and

[143] Hydrogen: Scaling up, Hydrogen Council, 2017.
[144] Hydrogen Roadmap Europe, FCH 2 JU, 2019.
[145] https://ec.europa.eu/social/main.jsp?langId=en&catId=89&furtherNews=yes&newsId=9723
[146] https://ec.europa.eu/social/main.jsp?catId=1517&langId=en
[147] https://cordis.europa.eu/project/id/256703
[148] https://cordis.europa.eu/project/id/621222
[149] https://cordis.europa.eu/project/id/736648
[150] https://cordis.europa.eu/project/id/779730

FCHGO[151] project to name but a few have developed educational programs and training initiatives related to hydrogen technologies and fuel cells in Europe. Altogether, these projects have addressed different types of and levels of education (formal, vocational, etc.), different target groups (under/post/graduates, policy makers, technicians, responders), different technologies and applications (PEM, SO, fuel cells, electrolysers, hydrogen production by different means, purification) along the hydrogen chain, including horizontal aspects such as safety or life cycle assessment. They have covered different pedagogical approaches ("traditional" transmissive approach, collaborative learning, hands-on), different features (serious games, virtual reality, e-learning) and different levels of accreditations and/or certifications (diploma, certificate, official, private), in line with the European Skills Agenda and the Pact for Skills launched by the European Commission in 2020.

Concerning public acceptance, several studies have been conducted on the social recognition and acceptance of hydrogen energy. Projects like HYACINTH[152] project have provided the base information about the awareness and social trust in the hydrogen technologies in Europe, showing a general higher level of confidence in the technology and acceptability of its use, but lower levels of knowledge about hydrogen technology. Moreover, projects have gathered relevant information on administrative, legal and economic barriers to the implementation of hydrogen technologies, but these findings need to be further transferred to relevant stakeholders, such as local, regional or national authorities, which are ultimately responsible for integration.

Objectives

The goal of this focus area is twofold: to prepare a well-educated and high-skilled workforce needed for a competitive hydrogen market, safeguarding existing expertise and know-how, while raising public awareness and social acceptance about hydrogen technologies. To this end, the specific objectives in this area are:

1. Develop educational and training material and building training programs for professionals and students on hydrogen and fuel cells.
2. Raise public awareness and trust towards hydrogen technologies and their system benefits.

On education, the underlying strategy focus is two-fold. On one hand, activities will focus on updating the educational and training material already in place for the target groups already addressed. On the other hand, to develop new educational and training materials for new targets groups not covered so far. Training programs, in particular, will need to be designed and capacity building planned, incorporating new aspects such as systems modelling. Furthermore, the programs need to be further extended and should be rolled out in more languages to further strengthen the access of the public to such material. To this end, all the educational and training material developed in the Programme will be provided publicly available and accessible free of charge, in particular on the Fuel Cell and Hydrogen Observatory (FCHO) platform[153]. This will grant widespread access to the knowledge while contributing to developing the necessary talent to support a growing hydrogen industry.

Concerning public awareness, the activities will target not only awareness but also raising trust. Activities will focus on hydrogen technology as a whole and will target specific groups of

[151] https://cordis.europa.eu/project/id/826246
[152] https://cordis.europa.eu/project/id/621228
[153] https://fchobservatory.eu/

stakeholders (from technicians to chief executive officers in public and /or private entities) from sectors and territories for which development and deployment of low-carbon hydrogen technologies can play an important role. Communication activities targeting the public will not be disregarded but will be carefully addressed on a case-by-case basis, as the deployment evolves and mainly at the programme level.

To address these issues, the Programme will carry out a number of actions targeting research and innovation, and coordination and support. The following list some of the potential actions envisaged.

R&D Priorities – Early Stage Research Actions

- Further development of innovative education using latest IT technologies and implementation in training processes of stakeholders from children through students to teachers (e.g. digital models, twins, living laboratories, short-term courses).

R&D Priorities – Demonstration Actions

- Integration aspects with social sciences and develop educational and public understanding and trust, including contributions from humanities when relevant.
- Development and installation of a virtual European university on hydrogen and fuel cells educational targets including service and specific events e.g. summer and winter schools.

Coordination and Support Actions

- Preparation and dissemination material for education and training at all levels in different languages.
- Building training programmes for young professionals in the hydrogen and fuel cell field, including events for training and education to different stakeholders.

3.6.3. Safety, Pre-Normative Research and Regulations, Codes and Standards

Rationale for support

The hydrogen industry has accumulated several decades of experience and know-how, built up in an industrial setting, in handling large amounts of hydrogen safely. Nevertheless, the relative lack of general experience with introducing hydrogen-based technologies in settings where it was not traditionally located (in people's cars, buses, homes, fuelling ships, in refuelling stations alongside conventional fuels, etc.) increases the risks of incidents or accidents and delays the time necessary for commercial product deployment. A high-level degree of hydrogen safety is essential to build the confidence needed for widespread take-up and safe commercialisation of hydrogen technologies. Consistent safety approaches along the hydrogen chain should be built on best practices for the implementation of safety principles and procedures facilitating the safe design, operation and management of hydrogen-based technologies in Europe and beyond. Hydrogen safety culture needs to be embedded at all levels and will become a priority in the Programme.

Furthermore, driving hydrogen development past the tipping point needs an enabling policy and regulatory framework. Beyond policies, which are out of the scope of the objectives of the Programme, there is still a need to develop even further comprehensive regulatory and enabling frameworks for hydrogen technologies in Europe. In many instances, the lack of clear rules, technical regulations and standards is a core reason why "projects" do not evolve into mass-market “products”. For example, regarding hydrogen injection in natural gas networks, Regulations, Codes and Standards for hydrogen technology will need to be developed at the EU level to ensure these applications are not restricted in their roll-out.

State of the art

Safety is paramount for frictionless development, perception, acceptance of and trust in new technologies in modern society. Over the last decades, hydrogen safety-related activities have advanced the state of the art and fundamental aspects related to hydrogen behaviour in the event of accidental (unwanted) releases and their consequences. The activities scope has also encompassed progress in the understanding of both, passive and active safety measures to reduce and/or de-risk the use of hydrogen in confined, semi-confined and open-air sites and locations. Recent projects such as HYSEA[154], PRESLHY[155], HYTUNNEL-CS[156] or H2SENSE[157] to name but a few account for this. Furthermore, education and training programs have also tackled safety aspects, the HYRESPONSE[158] project being a good example. Nevertheless, recent safety-related events have shown that more efforts are required to embed such a culture within this fast-growing sector.

EU funded projects also allowed improvement in the understanding of the applicable regulation for boosting the production and utilisation of hydrogen in Europe, while strengthening the European leadership in international fora for technical standards, regulations and definitions on hydrogen. The majority of the projects have encompassed Pre-Normative Research (PNR) activities aiming at providing sound scientifically and technological facts to either filling the existing gaps in RCS or progressing beyond the knowledge available at that point in time. Projects such as HYCORA[159], FIRECOMP[160], HYTUNNEL-CS[161], STACKTEST[162] or SOCTESTQA[163] account for this. Moreover, recent projects like HYLAW[164] have undertaken desk research to understand the legal and administrative barriers blocking the widespread commercialisation of hydrogen technologies in Europe, while proposing solutions to overcome the challenges. Another relevant initiative has been conducted by the CERTIFHY[165] project and follow up initiatives which have assessed the necessary market and regulatory conditions to develop the complete design and initiate a unique European framework for renewable and low-carbon hydrogen guarantees of origin.

Objectives

The goal of this focus area is twofold: safety is understood and treated as a holistic, integrated and value-adding approach at each stage of the implementation, and to ensure that hydrogen and fuel cell specific harmonised RCS are in place and support the safe and efficient deployment of hydrogen technologies in Europe and beyond. To this end, the specific objectives in this area are:

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154 https://cordis.europa.eu/project/id/671461
155 https://cordis.europa.eu/project/id/779613
156 https://cordis.europa.eu/project/id/826193
157 https://cordis.europa.eu/project/id/325326
158 https://cordis.europa.eu/project/id/325348
159 https://cordis.europa.eu/project/id/621223
160 https://cordis.europa.eu/project/id/325329
161 https://cordis.europa.eu/project/id/826193
162 https://cordis.europa.eu/project/id/303445
163 https://cordis.europa.eu/project/id/621245
164 https://cordis.europa.eu/project/id/735977
165 https://www.certifhy.eu/

1. Increase the level of safety of hydrogen technologies and applications
2. Support the development of RCS for hydrogen technologies and applications, with the focus on standards

Further research is needed to ensure hydrogen technologies are as safe as competing technologies and to demonstrate that the risks associated with hydrogen technologies are at least equivalent to, if not lower, than for established energy technologies.

Moreover, further research is needed to support policymaking, in particular, to enable improved and harmonised RCS. To this end, the role of PNR activities in supporting technical regulations and standards will become fundamental. PNR activities will encompass research activities and strengthen desk research activities in view of supporting RCS developments.

Furthermore, following up on the activities started in the CERTIFHY project and subsequent FCH 2 JU initiatives, supporting activities are also envisaged to contribute to the EU effort to introduce a common low-carbon threshold/standard for the promotion of hydrogen production installations based on their full life-cycle GHG performance. Activities would introduce a comprehensive terminology and European-wide criteria (or support the European Commission work on the international-wide criteria within collaborations with International Partnership for Hydrogen and fuel cells in the Economy – IPHE - and Clean Energy Ministerial - CEM) for guarantees of origins and the certification of renewable and low-carbon hydrogen.

Altogether, in light of the 2030 targets recently published by the European Commission, support could contribute to the update of energy and climate framework, in particular:

- EU ETS directive and Effort Sharing Regulation;
- Renewable Energy Directive;
- Energy Efficiency Directive;
- Energy Taxation Directive;
- Sustainable Alternative Fuels initiatives;
- TEN-E / TEN-T Regulation and Alternative Fuels Directive;
- CO_2 performance standards.

To address these issues, the Programme will carry out a number of actions targeting research and innovation, and coordination and support.

The following list some of the potential actions envisaged.

R&D Priorities – Early Stage Research Actions

- Improved understanding of the hydrogen behaviour on both gaseous and liquid form in the event of accidental (unwanted) releases and their consequences to support the development of RCS in heat, maritime, railways, heavy-duty and aerospace application;
- Improved understanding of hydrogen embrittlement, thermal attacks and effects also in non-metallic materials;
- Safe refuelling, 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 standardisation, including recognition of FCEV and health state of on-board storage by responders (road, rail, maritime), development of

protocols for non-destructive testing of composite overwrapped pressure vessels (COPVs);

- Review of refuelling processes and quantification of over-conservatism in refuelling and on-board storage;
- PNR and benchmarking for hydrogen sensor selection, integration, installation and operation;
- Improved understanding of effects of increased hydrogen content on combustion and performance of end-use gas appliances;
- PNR to support performance testing standardisation (hydrogen production, distribution, storage and usage);
- Valorisation and possible development research for metering of hydrogen and hydrogen/methane blends;
- Support for development of standards associated with introduction of hydrogen in residential and commercial buildings (incl. measurement systems, information for first respondents, etc.).

Coordination and support actions

- Support the development of fact-based legal and permitting regulations across Europe;
- 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;
- Continuous monitoring of the regulatory barriers.

3.7. Hydrogen valleys

Rationale for support

Since 2014, FCH JU has pursued the concept of hydrogen territories, which have evolved into the most recent concept of Hydrogen Valleys. A Hydrogen Valley is a defined geographical area, city, region or industrial area where several hydrogen applications are combined together and integrated within an FCH ecosystem. The idea is to demonstrate how all the different parts of the use of hydrogen as an energy vector fit together in an integrated system approach. This concept has gained momentum 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. Hydrogen Valleys have started to form the first regional "hydrogen economies", as bottom-up steppingstones in the development of the New Hydrogen Economy overall. Now, hydrogen valleys are going global, with new projects emerging worldwide[166] and Mission

[166] In straight cooperation with the European Commission (on behalf of the European Union) in its role of co-leader of the Innovation Challenge 8 (Renewable and Clean Hydrogen) of Mission Innovation, the FCH 2 JU developed the Hydrogen Valley Platform (www.h2v.eu), a global information sharing platform providing valuable data. Already more than 30 hydrogen valleys are presented in this platform. An analysis of these valleys has been performed and findings are presented in the report 'Hydrogen valleys – insights into the emerging hydrogen economies around the world' – Fuel Cells And Hydrogen

Innovation members having committed to facilitate the delivery of at least 100 large-scale clean hydrogen valleys worldwide by 2030[167].

The aim of supporting the creation of Hydrogen Valleys is to demonstrate the role of hydrogen in energy system integration and synergies between the three pillars (production, storage & distribution and end use applications), to identify the best business-cases and showcase the value proposition of hydrogen with emphasis on sectoral-integration, while applying existing regulations.

The emphasis is not on the technology development of an application, but on system integration of hydrogen production, its distribution and storage, and its subsequent valorisation as an energy vector in transport, as industrial feedstock for the production/upgrading of chemicals/fuels and/or in the electricity/gas grid.

A Hydrogen Valley should not only demonstrate how hydrogen technologies work in synergy, but it should also work complementary 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.

Although for the sake of these demonstrations it can be foreseen that in the early stages low carbon hydrogen could be used, the objective is to move to renewable hydrogen as an ultimate objective. CCS, SMR or coal gasification investments are excluded from partnership funding.

State of the art

Currently, the FCH 2 JU supports three hydrogen territories,[168] in the norther Scottish islands of Orkney, the northern regions of the Netherlands and the island of Majorca (Spain). Although they vary significantly in size, they all have in common integrating hydrogen production from renewable electricity. In some cases, this electricity would have been curtailed and the integration of hydrogen into the energy system is avoiding this, defying the common metrics for energy efficiency. Also common to all of them is the search for various storage and distribution solutions that are really specific to each territory, the amount of hydrogen produced, the type of end use and the distance to the end uses. And finally, in the three supported cases, different end uses from various sectors are represented. The main difference between the projects lays in the size/amount of hydrogen used. But it is clear that in all cases, there are synergies between the different applications and the holistic virtues of the overall system.

Additionally the Mission Innovation Hydrogen Valley Platform, developed by the Fuel Cells and Hydrogen Joint Undertaking, aims to create a global collaboration and go-to-platform for all information on large-scale hydrogen flagship projects around the world. By promoting the emergence and implementation of value chain integrating hydrogen projects, as well as raising awareness among policy makers, it aims to facilitate the clean energy transition. Dedicated to all current and future hydrogen project developers, it will help them to gather meaningful

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2 Joint Undertaking, 'Hydrogen valleys – insights into the emerging hydrogen economies around the world', 2021 https://www.fch.europa.eu/sites/default/files/documents/20210527_Hydrogen_Valleys_final_ONLINE.pdf.

[167] http://www.mission-innovation.net/missions/hydrogen/

[168] http://h2territory.eu/

information from experienced peers and will promote collaboration among them.

Objectives

In terms of innovation the projects to be developed should seek:

1. System integration: what is expected is not innovation in developing one technology but in integrating several elements together to improve overall synergies and facilitate sector coupling;
2. System efficiency: what is expected is the improvement of overall energy and economic efficiency of the integrated system;
3. Improved security and resilience of the energy system, e.g. via hydrogen production using locally available renewable energy sources;
4. Market creation: demonstration of new market for hydrogen, especially when applications are used in synergies;
5. Complementarity of hydrogen with RES, integration with other technologies, existing infrastructure, etc;
6. Assessment of the availability and affordability of clean (pollution free) energy provision for industry and cities uses; whilst also considering environmental impacts like water utilisation;
7. Mutualisation of production or distribution and storage, assuming decentralisation as key parameter;
8. Help set or test regulation requirements at the relevant governance level;
9. Increase the knowledge management with assessment of the socio-economic and environmental impacts, including the concept of digital twin assuring an effective monitor and optimisation strategy for the operation and further development of the valley;
10. Development of public awareness of hydrogen technologies including contributions from Social Science and Humanities when relevant.
11. Support development of Hydrogen Valleys in areas of Europe with no or limited presence of Hydrogen Valleys;

R&D Priorities

When defining the scope of a valley, these should combine production, hydrogen logistics or distribution and its use in several sectors, such as in transport and/or stationary/industrial applications. Systems modelling and simulation can generate different integration scenarios to support decision-making, including the integration with renewables, existing infrastructures, etc. Some of the larger projects are expected to be reaching the €100 million or more total costs. However, the financial contribution requested from the Clean Hydrogen JU should be limited to 20-30%, with the additional expenditure coming from the project promoters or from other sources. An important element of these hydrogen valleys would be the regional and national political support.

A very important aspect to be expected of the valleys is their replicability and continuity/future expansion. Already in the previous FCH 2 JU Programme, this aspect has been key in the selection of the appropriate projects and they have been requested to show initiatives and activities to facilitate the replication of their concept in other territories. The availability of modelling tools and the different scenarios developed in previous project will ease the replicability assessment. In the current Programme, the valleys should be defined such that it is technically and economically feasible to reproduce them across Europe (spill-over effect). As for their continuity and expansion, these projects should be defined such that they will not be dismantled once the funding ends, but rather that they will be just the seed for further developments.

Some examples of hydrogen valleys could be:

- Ports with combined production, transport and use of hydrogen for various applications such as ship fuel, port operation (material handling/power use at berth, etc), transport (possibly import/export) and storage, the port industrial hinterland and/or logistical hub (truck or trains);
- Airports with combined production, transport, liquefaction, storage, distribution and use of hydrogen:
    - for aviation fuel (hydrogen as a fuel; hydrogen made fuels; hydrogen fuel cells),
    - for mobility uses: (a) airport operation (ground support equipment/ground power units at airport), (b) intramodality hub (buses, cars, and/or trains), and (c) logistical hub (trucks, heavy handling equipment),
    - for stationary uses (energy and heat for airport and surrounding territory buildings),
    - and for industrial uses in the airport vicinity.
- Industrial hubs with mutualised hydrogen production and transport and/or storage with multiple hydrogen uses (steel, refineries, chemicals, glass, industrial heat and power, etc);
- Logistical hubs with combined production and use of hydrogen for mutualised and decentralised production, mobility uses (trains, HDVs, last mile, forklifts, etc.) and uses in buildings and industrial heat and power;
- A Hydrogen island (or area) combining production, distribution and different end uses in buildings, transport, industry and agriculture.

3.8. Supply chain

Rationale for support

A typical supply chain comprises a series of steps, from the manufacture of materials and components to production of assemblies and systems for various end-uses. These steps are similar to those involved in the value chain concept. While the supply chain focuses on integrating suppliers and manufacturing, the value chain approach takes into account additional aspects such as increasing value to the customer, the socio-economic aspects or creating competitive advantage against other players.

This section proposes a set of actions for the next decade aiming at strengthening the overall supply chain of hydrogen technologies, from processing the raw materials into specialised materials (e.g. electro-catalysts), production of components and sub-system to system integration. The supply chain is complemented by the wider view of the value chain approach vis-à-vis creation of jobs, added value to economy and industry competitiveness.

Hydrogen technologies and systems have been recently identified by the European Commission as an emerging and strategic value chain for Europe.[169] A strong and sustainable European supply chain of hydrogen technologies will avoid that the manufacturing capacity becomes a limiting factor to technology uptake, improve the competitiveness and innovation of industries, support the decarbonisation of the economy and reduce dependence on fossil fuels, CRMs and components imports.

To ensure a sustainable, innovative and competitive industry in the future, a greater number of qualified companies is required along the whole hydrogen supply chain (materials, machines, systems, etc). Otherwise, the long-term value will go elsewhere as other countries will develop more mature capabilities and supply chain clusters.

Moreover, Europe will have to increase its production capacity for hydrogen technologies and raise private investments from EU organisations, including creation of partnerships between small and large companies, in line with the European Hydrogen Strategy goals.

State of the art

In the recent years, the FCH 2 JU concluded several studies to map the EU supply/value chain for hydrogen and fuel cell technologies to identify weaknesses and find appropriate solutions.[170] A list of suppliers of fuel cell systems and components and service providers is currently available through the FCHO.

The supply chain of hydrogen-based technologies is still under development and consists mainly of relatively small organisations. European companies and research organisations are frontrunners in many segments along the hydrogen supply chain. This should give an advantage to the EU countries in the upcoming race for market capture and competitive advantage with other key players such as Japan, South Korea, USA and more recently China.

About 300 European companies contribute to the development of hydrogen technologies and many more are involved in various steps of the hydrogen supply chain. These providers are sustained by over 250 knowledge-based European universities and research institutes across different domains of expertise.

The European suppliers consist mainly of SMEs that are eager to increase their manufacturing capacities to enable cost reductions of their products. These organisations must focus for instance on R&I platforms, development of new machines and more efficient manufacturing processes, which should also facilitate the implementation of the circular economy principles. All these will allow them to reach a greater market penetration and expand their businesses also to overseas markets.

As regards hydrogen production, Europe is a global leader of various electrolyser technologies covering the entire hydrogen supply chain. For many years, European manufacturers have developed innovative electrolyser technologies and now they are ready to scale up their products. About 20 European companies offer various electrolysis systems to the market. Further development of the electrolyser technologies, the integration with renewable sources and increasing mass production will significantly reduce the total hydrogen production cost in the next 10 years and beyond. It is essential to ensure Europe will have enough electrolyser manufacturing capacity to meet its local hydrogen production targets.

Europe has further strengths in hydrogen storage and distribution infrastructure, with

[169] Strengthening Strategic Value Chains for a future-ready EU Industry, EC, 2019.
[170] Value added of the hydrogen and fuel cell sector in Europe, FCH 2 JU, 2019.

indigenous developers and suppliers in relevant areas, though some weaknesses exist in the supply chain. For example, high-pressure hydrogen storage is one of the existing solutions for on-board transport applications. However, Europe lacks production of high-quality carbon fibre, an important material used in the manufacture of compressed hydrogen tanks, which is mainly imported from Asia. In addition, Europe should increase its efforts to develop other cost competitive solutions (e.g. LOHCs, metal hydrides, ammonia, etc.), optimise the roundtrip efficiency of the hydrogenation-dehydrogenation cycle and support their industrial deployment. In the long-term, large-scale storage facilities need also to be created close to the MW scale electrolysers, including underground hydrogen storage in reconverted salt caverns and depleted gas fields.

In the medium and long-term an integrated transportation system and infrastructure must be created to allow clean hydrogen to reach various industrial sectors, thus helping to establish a global hydrogen market.

Regarding the end-use of hydrogen, Europe is well positioned for competitive fuel cell materials, components and stacks for both transport and small-scale stationary applications. This includes quality control and manufacturing techniques as well as a well-established knowledge transfer between academia/research centres and industry.

Objectives

European manufacturers must cover the main segments of the supply chain, including the production of very specialised materials, components and equipment, and should consider the recovery and recycling of by-products and wastes. The components manufacture and their scale-up based on a circular approach will be the central part of the hydrogen supply chain. The Clean Hydrogen JU activities will contribute to reinforce the EU leadership on advanced materials and components used in hydrogen technologies by optimisation of the manufacturing processes, using abundant natural resources, improving the products quality (targeting zero defect products), developing new architecture, reducing the time to market through technological/research platforms, etc. Alongside the manufacture of components for FCH products, it will also be worth looking at the production of machines/robotics needed for the automation of manufacture processes. All these activities will allow the cost reduction and scaling up of components and product equipment for hydrogen and fuel cell technologies.

A particular attention will be paid to continuously monitor the hydrogen supply chain, including mapping the EU suppliers in each step of production as well as the refuelling infrastructure in Europe. This monitoring exercise will be complemented by a gap analysis aiming at identifying potential vulnerabilities in the domestic supply and define R&I actions to mitigate such weaknesses. While the study will focus primarily on the market supply side, the economic aspects should be also captured through a value chain analysis.

Another key objective is to bring relevant hydrogen technologies close to commercialisation and support, from a technological point of view, the increase of production capacity in Europe. Cross-border cooperation, pan European research and technology infrastructures with leveraged R&I investments, skills for cross-cutting activities and synergies with other EU initiatives and funding programmes will promote further the industrialisation and commercialisation of hydrogen-based technologies. In addition, a greater participation of major European manufacturers is needed in the whole supply chain, which can be stimulated by raising public and industry awareness.

A common understanding of the impact of materials in contact with hydrogen is needed not only for structural and safety reasons, but also on the quality of hydrogen for various applications. As an example while fuel cells are reacting quite sensitive to minor outgassing of sulphur containing species, such traces are irrelevant in combustion engines, turbines of steel production.

Reducing the use of CRMs in hydrogen electrolysers and fuel cells, sustaining the recovery and recycling of by-products and wastes, and circularity of end-of-life products will reinforce the upstream part of the supply chain.

Overall, the main objectives of this pillar can be summarised to:

1. Identification of potential vulnerabilities in EUs hydrogen supply chain;
2. Development of new and improved manufacturing technologies and production processes that facilitate the safe and sustainable use of non-critical (raw) materials as well as facilitate the adoption of the circular economy principles;
3. Reducing the use of critical (raw) materials. with sustainability or environmental concerns, such as for instance those deriving from poly/perfluoroalkyls.

In order to contribute towards achieving the above objectives, the following areas of research and development appear as good candidates for the support by the Clean Hydrogen JU.

R&D Priorities – Early Stage Research Actions

- Development of new manufacturing technologies and production processes, including innovative sensors and actuators for semi-automation and automation of equipment production and real-time quality control;
- Improve production speed, circularity, process capabilities and production yield through fast detection of defects, technical cleanliness, etc;

R&D Priorities – Development Research Actions

- Continuous mapping, gap analysis and monitoring of the critical components and sub-systems supply, weaknesses and bottlenecks along the hydrogen supply chain through joint, well-coordinated actions;
- Identifying changes in manufacturing approach that will improve production speed, labour costs and circularity.
- Identification of materials in contact with hydrogen for different use cases.
- Training and skills on manufacturing (qualified people, technicians, maintenance and after-sales, etc.), linked with cross-cutting activities;
- Integration of new manufacturing technologies and improve the production speed, circularity, process capabilities and yield in parallel with real-time quality control in the manufacturing process;
- Identification of synergies between EU suppliers of machines with multiple uses that can contribute to increasing the manufacturing capacity of hydrogen technologies;
- Exploring the possibility of using artificial intelligence 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 stabilisation,

system optimisation, 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.

R&D Priorities – Demonstration Actions

- Supply chain innovation approach and implementation of quality measures within medium and large manufacturing capacity;
- Development of pan European technology (testing) platforms based on the gap analysis of the study of the supply and value chains.

3.9. Strategic Research Challenges

To ensure a continuous generation of early stage research knowledge, the above actions will be supplemented by multidisciplinary investigations, gathering expertise at different technology scale (materials, component, cell, stack and system). All the generated knowledge needs also to be combined in such a way to allow further 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 considers gathering, with a long-term vision and covering the whole Clean Hydrogen JU activities, the needed capabilities and expertise from European Research and Technology Organisations (RTO).

Potential synergies in the field of basic research linked to breakthrough hydrogen technologies and innovation are emphasised with the European Innovation Council (EIC), for example on the other routes of renewable hydrogen production through the EIC Pathfinder Challenge and the research areas on hydrogen proposed by the European Energy Research Alliance (EERA).

The alignment of European RTOs' efforts in critical research areas enables to complement the strengths of each organisation by streamlining access to unique research tools, developing missing strategic capabilities, and developing a public database of information. The result will lead to a generally comprehensive strategy investigating new design, characterisation and testing, thus accelerating the developments in basic low-TRL research and innovation actions. Based on the early stage research actions mentioned in the different previous roadmaps, the following strategic research challenges appear the most relevant:

- Low or free PGM catalysts (including bioinspired catalysts), reducing critical (raw) materials use in electrolysers and fuel cells, and safe and sustainable use of all material, including developing of per- and polyfluoroalkyl substances (PFAS)-free ionomers and membranes.
- Advanced materials and processes for hydrogen storage (e.g. carbon fibres, H_2 carriers, additive manufacturing)
- Advanced understanding of the performance / durability mechanisms of electrolysers and fuel cells.

For these early stage research actions, providing testing facilities to SMEs could facilitate them to test their innovative technologies and bring them up in TRL to potential products. The implementation of Open Innovation Test Beds (OITB) in the Hydrogen Sector will be further explored.

4. Additional activities

4.1. Interface with EU policies and other programmes (Synergies)

4.1.1. Need to reinforce synergies

An important element supporting the implementation of the European hydrogen strategy is the reinforcement of synergies among European funding instruments and actions to close the innovation gap in Europe. Synergies are needed pull together resources, align priorities and ultimately maximise the impact of clean hydrogen R&I investments.

The Single Basic Act establishing the Horizon Europe Joint Undertakings underlines the impact-driven approach to European partnerships. This Regulation aims at a more effective use of institutionalised European partnerships notably by focusing on clear objectives, outcomes and impact that can be achieved by 2030, and by ensuring a clear contribution to the related Union policy priorities and policies. For this endeavour, close collaboration and synergies between JUs and other relevant initiatives at Union, national and regional level are key in achieving greater scientific, socio-economic and environmental impact and ensuring uptake of results.[171]

Furthermore, the SBA considers it is essential that the clean hydrogen partnership establishes structured collaboration with many other European partnerships, notably for end-use. Structured cooperation will facilitate the creation of collaboration and synergies between European partnerships, allowing to identify areas in which complementary or joint activities would address the challenges more effectively and efficiently, avoid overlaps, align timing of its activities and ensure access to results and other relevant means of knowledge exchange.[172,173] The Clean Hydrogen JU should interact in particular with the zero emission road and waterborne transport, Europe's railway, clean aviation, processes for the planet and clean steel European partnerships.[174] In line with the Single Basic Act, a structure will be set up reporting to the Governing Board in order to ensure the co-operation and synergies between these partnerships in the domain of hydrogen.[175]

Likewise, beyond the Governing Board[176] and the Executive Director[177], other bodies of the Joint Undertaking also share responsibilities regarding synergies, namely in what concerns reporting about the national or regional policies relevant to the scope of the JU and identifying specific ways of cooperation (policies and support schemes) with the actions funded by the JU in view facilitating the acceleration of market uptake of innovative clean hydrogen solutions. The State Representatives Group[178] and the Stakeholders Group[179], shall be consulted on links to Horizon Europe and other Union, national and, where relevant, regional initiatives, including

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[171] As per *Recital 14* of the SBA.
[172] *Recital 11* of the SBA
[173] *Recital 51* of the SBA
[174] *Recital 51* of the SBA
[175] *Recital 51* of the SBA
[176] Relevant articles in the SBA developing on the Governing Board responsibilities regarding synergies are *Art. 16* and *Art. 80*
[177] Relevant articles in the SBA developing on the Executive Director responsibilities regarding synergies are *Art. 18*, *Art. 24(2.e)* and Art. 81
[178] *Article 18a* of the SBA, paragraphs (7), (9) and (11).
[179] *Articles 21(5) and 82* (1-2) of the SBA.

cohesion policy funds in line with smart specialisation strategies.

To deliver the magnitude of synergies envisaged in the SBA it is necessary to resort to the whole toolbox made available under the Horizon Europe framework and establish the proper cooperation mechanisms that will put these tools to work, as described below.

4.1.2. Toolbox to generate funding synergies

In view of generating funding synergies, the Single Basic Act enables JUs to make use of all the tools made available under the Regulation (EU) 2021/695 establishing Horizon Europe, namely.[180] Horizon Europe provisions to enable different types of synergies include alternative, cumulative and combined funding and transfer of resources.[181]

These tools materialise into the following categories:

- *Alternative funding* following the awarding of a *Seal of Excellence* foreseen for calls for proposals in the work programme. Actions which were awarded a *Seal of Excellence* may be eligible for support by other Union programmes provided that they comply with all of the following conditions:
  - they have been assessed in a call for proposals under the Programme;
  - they comply with the minimum quality requirements of that call for proposals;
  - they have not been financed under that call for proposals only due to budgetary constraints.
- *Co-funded actions* between different Programmes. These actions allow cumulative funding between different Union programmes, provided that the contributions do not cover the same costs. The rules of the relevant Union programme shall apply to the corresponding contribution to the action. The cumulative financing shall not exceed the total eligible costs of the action.
- *Transfer of Resources* from Member States to the Programme. Those resources shall be used for the benefit of the Member State concerned only.

The overall principle is that the JU activities shall be implemented in synergy with other Union programmes while aiming for maximal administrative simplification. A non-exhaustive list of synergies with other Union programmes is included in *Annex IV - Synergies with other Union programmes* of the Regulation (EU) 2021/695. It makes explicit reference to synergies between Horizon Europe and EAFDR, ERDF, ESF+, CEF, Life, InvestEU, Innovation Fund, Just Transition Mechanism, Euratom, European Defence Fund, Recovery and Resilience Facility, etc.

Building on the successful experiences from the previous programming period, specific areas for synergies between different funding instruments and the JU could be flagship projects related to Hydrogen Valleys and the implementation of AFIR.

Figure 2 provides a non-comprehensive overview of the EU programmes supporting research, innovation and deployment activities on clean hydrogen.

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[180] *Recital 14* of the SBA.
[181] See *Article 7(7)* abd *Article 15 – Alternative, combined and cumulative funding and transfers of resources*; and *Annex IV – Synergies with other Union programmes* of the Regulation (EU) 2021/695 establishing Horizon Europe.

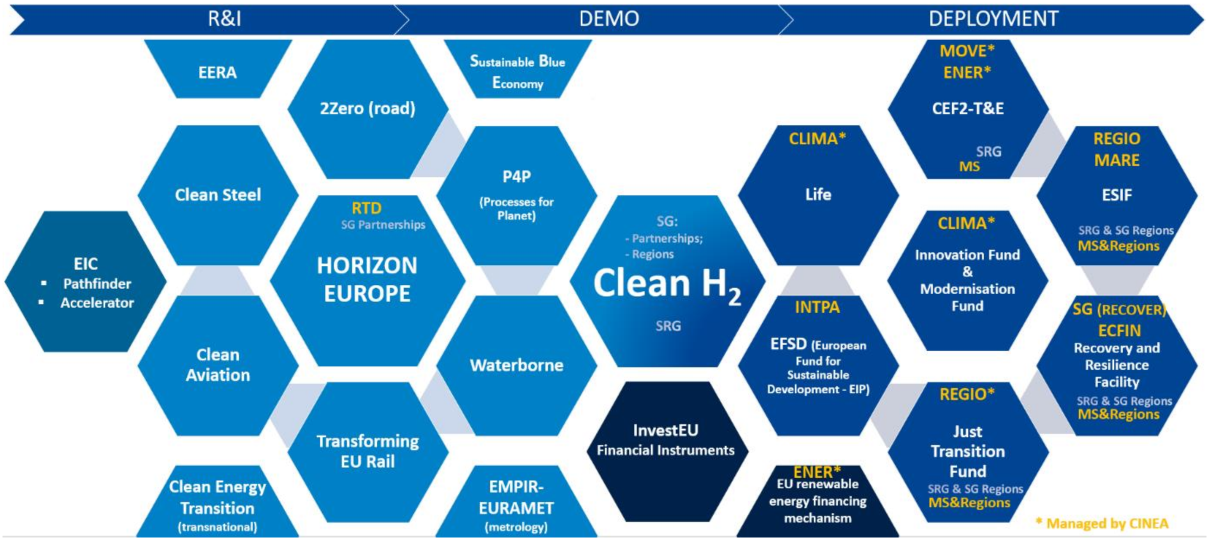

Figure 2 Mapping of EU Programmes & Funds supporting research and deployment activities for hydrogen.

4.1.3. Cooperation mechanisms to deliver synergies

Given the multitude of actors in the different bodies of the JU and to cover the full spectrum of synergies the JU may contribute to (and benefit from) to achieve its 2030 targets, the following areas have been identified in view of establishing effective cooperation mechanisms:

- *Synergies with other European partnerships and EU Funds*

Hydrogen is a cross-cutting technology with applications in numerous sectors having specific needs in terms of research, innovation and market development and deployment. The Clean Hydrogen JU will be at the core of research and innovation activities related to hydrogen production, distribution and end uses for energy, transport and industry. The integration, deployment and scale-up of hydrogen technologies in all related sectors will require additional, complementary and coordinated research and innovation efforts which will be carried out in synergy with the end-use partnerships covering hydrogen in their programme[182].

The Clean Hydrogen JU is called upon to set up a structured cooperation with the hydrogen end-use European partnerships, seeking opportunities to involve them in discussions during the drafting of their work programmes, in order to identify the areas in which complementary or joint activities would address the challenges more effectively and efficiently, avoid overlaps and align timings of the activities to ensure access to results and other relevant means of knowledge exchange.

In addition, the European Commission has an important role to play in enhancing synergies, collaboration and bridging the gaps between different partnerships and beyond. It is also important that the Horizon Europe governance arrangements bridge these gaps and deliver on the expectations for enhanced cross-fertilisation between initiatives[183].

By strengthening linkages with other Horizon Europe initiatives as well as other EU funded programmes, the Clean Hydrogen JU together with the other European partnerships have better chances to deliver on the ambitious 2030 targets and contribute to EU priorities and policies.

[182] *Recitals 11, 12 and 51* of the SBA.
[183] Coherence and Synergies of candidate European Partnerships under Horizon Europe, EC, October 2020 DG R&I, A4 Partnership Sector

- *Synergies with Member States*

The JU *"(…) should ensure that Member States are sufficiently informed of the joint undertakings' activities, can provide timely information on activities undertaken in the Member States and have the opportunity to contribute to the preparatory and decision-making processes. Such dialogue with Member States is particularly important in the context of synergies and the need to ensure the alignment of efforts and activities at national, regional, Union and European level to create more impact.*" Given that Member States are not directly or indirectly involvement as members or constituent entities of the JU, a State Representatives Group shall be established with the aim of aligning the JU's activities with the policies and actions taken at national and regional level.[184]

- *Synergies with other Stakeholders*

In addition, with the view to ensuring that the JU is aware of the positions and views of stakeholders from the entire hydrogen value chain, it should set up an advisory Stakeholders Group (SG), to be consulted on horizontal issues or specific questions, as per its needs.[185] For the Clean Hydrogen JU, the SG shall consist of representatives of sectors which generate, distribute, store, need or use clean hydrogen across the Union, including the representatives of the of other relevant European partnerships, as well as representatives of the European Hydrogen Valleys Interregional Partnership and of the scientific community.[186] The Stakeholder Group shall provide suggestions to enable concrete synergies to take place between the JU and the adjacent sectors or any sector with which synergies are deemed of added value.[187]

4.2. Cooperation with JRC

For the Horizon 2020 period, a Framework Contract between FCH 2 JU and JRC had been approved by the Governing Board in 2015. The scope of the Framework Contract covers the activities provided by JRC at the level of the FCH 2 JU programme. In line with the JRC mission, these support activities contribute primarily to the formulation and implementation of the FCH 2 JU strategy and activities in the areas of pre-normative research, RCS, safety, technology monitoring and assessment, including, more recently, the sustainability aspects.

The JRC support activities to the FCH 2 JU programme covered by the Framework Contract are prepared and agreed on an annual basis between the JRC and the Program Office, with involvement of a representative of Hydrogen Europe Industry and of Hydrogen Europe Research, and become integral part of the FCH 2 JU Annual Work Plan of the FCH 2 JU.

The present Framework Contract is valid until end of 2022. The two parts have already expressed the intention to continue the collaboration on the same way. In 2022, the Clean Hydrogen JU and the JRC will prepare a new Framework Contract covering the Horizon Europe period. Its scope will cover similar activities with the previous (abovementioned) Framework Contract, building on JRC's experience on topics like RCS, technology monitoring, safety and sustainability.

[184] As per *Recital 27* of the SBA.
[185] As per *Recital 28* of the SBA.
[186] As per *Article 82 (#1)* of the SBA.
[187] As per Article 82 (#2) of the SBA.

4.3. Regulations, Codes and Standards (RCS) Strategy Coordination[188]

The implementation of suitable and hydrogen-specific regulatory and enabling frameworks is crucial for the EU-wide deployment of hydrogen, fuel cells and hydrogen-based technologies in order to meet the goals set out in the EU Hydrogen Strategy. Indeed, setting up these frameworks is one of the major priorities in the first phase of the Strategy (2020-2024).

The term "Regulations, Codes and Standards" (RCS) is widely used in Europe and other regions of the world to somehow refer to regulatory aspects in general, but it is important to underline some few remarks on each of them, particularly within the European context.

The European Union is based on the rule of law and relies on law to ensure that its policies and priorities are realised in the Member States.[189] Regulations, directives, decisions, recommendations, etc. are types of EU legal acts[190] putting EU policies into practice.

Regulations in the EU apply automatically and uniformly to all EU countries as soon as they enter into force, without needing to be transposed into national law. Regulations are binding in their entirety on all EU countries and are distinguished from directives in which the latter must be incorporated by EU countries into their national legislation. In general terms, regulations and directives can refer to codes or standards, or be created completely on their own and, unlike a code or a standard, a regulation does not necessarily require an industry consensus to put it in effect. It serves to the general interest.

In the EU, the European Commission is responsible for planning, preparing and proposing new EU laws and policies. In addition, the effective application, implementation and enforcement of the law is a responsibility entrusted to the Commission. With regards to international regulatory cooperation, the Commission cooperates closely with international partners, both in multilateral dialogues, for instance with the United Nations, the Organisation for Economic Co-operation and Development or the World Bank, as well as in bilateral dialogues.

Nevertheless, sometimes, the term "regulation" in the expression "regulation, codes and standards" does not refer to a regulation in the sense of EU law (a directly applicable EU rule) but to a rather technical, low-level rule, adopted by the government or a simple administration.

On the other hand, in an industrial context, a code, in general, is a set of rules or norms that serve as generally accepted guidelines recommended for the industry to follow. They exist for the purpose of safety, quality or another benefit. On its own, a code is not a law that must be followed, but compliance is often a best practice. Industry codes can be voluntary or mandatory and can be developed by the industry on its own or by public institutions. The intent of a code is for it to apply widely across the industry within the economic sector at the scope, but can be adopted into law, or included in a business contract.

Standards are part of the knowledge economy that underpins industry and society.[191] Standards are, in essence, an agreed way of achieving a set objective. In simple terms, a regulation or a code sets out "what" is required, and a standard sets out "how" to do it. Standards can be used to improve safety and performance, protect consumers, workers and

[188] This section does not provide detailed information on the European standardisation framework, including the recent developments in relation to the EU Strategy on standardisation. These will be properly reflected in a future amendment of the SRIA.

[189] Article 2, Treaty on the Functioning of the European Union (TFEU).

[190] https://ec.europa.eu/info/law/law-making-process/types-eu-law_en

[191] https://www.cencenelec.eu/standards/Pages/default.aspx

the environment, etc. Overall, the majority of standards are initiated by business and developed in partnership with other stakeholders either in sectoral associations, or in Standardisation Developing Organisations (SDOs), such as the International Standardisation Organisation (ISO)[192] and International Electrotechnical Commission (IEC)[193] at international level, or the European Committee for Standardisation (CEN), the European Committee for Electrotechnical Standardisation (CENELEC)[194] at the European level, to name but a few. The use of standards by market players can in addition support the implementation of public authorities' policy and legislation and help stakeholders to comply with legislation. For example, about 30 % of European Standards are mandated by the European Commission in the framework of EU legislation and perform this supplementary function[195]. Among the different manners to classify standards, standards can fall into two general categories:

- Non-statutory standards: this type of standards, also named as voluntary, is generally established by a private sector and made available to persons or organisations, whether private or public, to use. Also considered voluntary standards are those known as "industry standards" or "consensus standards".
- Statutory standards. this type of standards, also named as mandatory, requires compliance because of a European regulation or national statue, an organisation internal policy or contractual requirement. Failure to comply with a mandatory standard's requirements can cause legal repercussions.

The implementation of suitable and hydrogen-specific regulatory and enabling frameworks requires a strategic approach, which focuses, especially during the timeframe referred in the first phase of the hydrogen strategy, on aspects where enforcement action can make a real difference to streamline the rollout of hydrogen technologies in Europe. In this sense, the term 'regulation' means both legislation and other policy actions at EU and Member State level. To this end, this approach necessitates a structured, systematic and effective coordination and assessment of the existing gaps and barriers in the current (and upcoming) regulatory framework in order to identify the needs and prioritise actions.

The Clean Hydrogen JU will contribute to supporting the implementation of hydrogen-specific regulatory and enabling frameworks by a strategic and coordinated approach to RCS issues within the Programme, which will mostly be implemented through Pre-Normative Research activities. To this end, PNR activities will encompass research activities and desk research activities in view of supporting RCS developments.

Whilst the Regulations, Codes and Standards Strategy Coordination (RCS SC) group[196] set up by the FCH 2 JU have certainly contributed for better coordination in the last years, in the light of experience, these activities need an even more strategic approach in the Clean Hydrogen JU's Programme. To this end, a RCS SC Task Force composed of the Commission, Hydrogen Europe and Hydrogen Europe Research, and the Clean Hydrogen JU Programme Office (PO) will be set up.

[192] https://www.iso.org
[193] https://www.iec.ch
[194] https://www.cencenelec.eu/
[195] https://www.cencenelec.eu/STANDARDS/Pages/default.aspx
[196] https://www.fch.europa.eu/page/rcs-strategy-coordination-group

The main goal of the RCs SC Task Force will be the definition, coordination and monitoring of the strategy related to RCS within the Programme with the ultimate goal of increasing the EU impact in RCS development in Europe and beyond, with the main focus but not limited to Standards. The RCS SC Task Force will support the Commission and the Member State organisations in its activities on international regulatory cooperation when required, will ensure the Clean Hydrogen JU will speak with one single voice and will support the synergies related to RCS with other partnerships.

Regulatory policy is a responsibility entrusted to the Commission and Member States organisations while the Clean Hydrogen JU can contribute to its development, the main contribution and impact of the Programme is envisaged on supporting the development of technical regulations. In this respect, it is important to remark that the European Union can only act in those areas where its member countries have authorised it to do so, which makes unrealistic the adoption of EU unified, harmonised documents valid everywhere. For example, aspects regarding the permitting and/or licensing processes for HRS in the EU depend on local authorities, which apply Member States rules, codes, and/or regulations.

On standards, the Programme activities will mostly focus on supporting the development as well as the actual use of harmonised performance-based standards for hydrogen and hydrogen-based technologies at European and international level. The goal is to provide rigorous, fact-based and scientifically sound evidence to establish and/or further develop standards that can be referred to in regulatory documents while facilitating the hydrogen market deployment.

To this end, it is envisaged that RCS SC Task Force prioritises the coordination of the following activities:

1. Follow up of RCS development related to hydrogen, fuel cells and hydrogen technologies through a continuous global watch function with the main focus but not limited to standards. To this end, at the request of the European Commission, the RCS SC Task Force may explore the possibilities to support the Commission and the Member States in the international regulatory bodies cooperation, such as with the United Nations (e.g. with the United Nations Economic Commission for Europe), international organisations like IPHE, or bilaterally with the US, Japan, etc., and with standardisation developing organisations at both, international and European level. With respect to the latter, if required, the possibilities of formal liaisons could also be explored, for instance, through participating in the Technical Advisory Boards.
2. Assessment of RCS development needs of strategic importance in Europe. Building on the monitoring activities mentioned previously and in consultation with relevant stakeholders, the RCS SC Task Force will assess what RCS developments could contribute the most to foster a regulatory friction-less EU-wide hydrogen market, while meeting the EU Hydrogen Strategy goals and the interests of the European industry and research organisations. This will facilitate to lay down the RCS strategy in the Programme.
3. Identification and prioritisation of the requirements and needs for research and innovation, and coordination actions to support the RCS development identified as strategic for Europe and that standardisation and regulatory aspects are appropriately addressed in the Programme. The majority of the targeted actions in the Programme will be conducted through PNR activities and will encompass but not be limited to research activities and desk research activities in view of supporting RCS

developments. This will contribute to the development of the Annual Work Plans of the Clean Hydrogen JU, and will support the Annual Union Work Programme for European standardisation when necessary.

4. Follow up and support the research and innovation, and coordination actions undertaken in the Programme contributing to ensure to the best possible actual use of PNR results in RCS developments. This support can encompass the establishment of a systematic and structured approach to supporting formal liaison between SDOs and projects, financial support to entities for participation in SDOs, etc.
5. Dissemination of results. This could include the collection and effective transfer of RCS-relevant results in regulatory and standardisation bodies; targeted communication actions, awareness workshops, development of training content, etc.

Altogether, the RCS SC Task Force will contribute to coordinating and establishing an approach to enhance European participation and contribution in international and European RCS bodies while contributing to lay down a regulatory friction-less hydrogen market in Europe and beyond if possible.

4.4. European Hydrogen Safety Panel (EHSP)

Hydrogen is nowadays recognised as a key clean energy vector and hydrogen-based technologies are undergoing rapid expansion across multiple applications. This is a result of the credibility it has built up as a flexible, versatile, reliable and safe, technology.

A high degree of safety to date has been achieved through an evolving "state-of-the-art", identifying, understanding and solving scientific and engineering challenges in this early phase. Nevertheless, based on the progress and expected further rapid development of hydrogen and hydrogen-based technologies, some few key observations that will influence development in this field moving forward and will directly impact safety need to be considered:

- Quantitative growth across "established" applications, such as private FCEVs, electrolysers, stationary fuel cell (FC) applications, FC buses, etc., will increase the use and demand for hydrogen, and for example increase the number and size of refuelling stations. While there is no direct impact on each individual refuelling and/or delivery activity, this will increase the demands on the delivery infrastructure. For the example of FCEV refuelling, implications are increased bulk deliveries to refuelling stations, greater utilisation of refuelling station storage, and possible requirements to build new refuelling stations urban areas.
- Qualitative change, i.e. innovation in applications, building on the success of established applications and recognising the inherent advantages offered by fuel cells and hydrogen-based technologies is foreseen as an important development in the coming years. Key elements of the new hydrogen systems, such as electrolysis or pressure vessels, are validated and established technologies. However, the new operational conditions and their integration into new applications with direct contact to consumers will generate safety challenges. In the area of transport, key aspects include the development of rail, truck and marine applications, which will have greater on-board storage: 50-100 kg for trucks, 200-500 kg for rail, and potentially tons of hydrogen for marine. This implies new fuelling requirements and risk profiles for these sectors.
- The inevitable consequence of this increase in consumption will be the requirement for an increasingly large and competent workforce to enable the development to take place

effectively and safely. Providing such service to facilitate the development is going to put a significant number of technicians, engineers, manufacturers, regulatory authorities etc. on a steep hydrogen learning curve.

Moreover, in the recent times there have been some "warning signs", with hydrogen incidents involving a hydrogen tube trailer in the USA, a hydrogen refuelling station in Norway and an incident leading to some fatalities and several injuries involving power to gas facility in Korea. Further accidents in more concerning scenarios, notably tunnel accidents, could become temporary "show-stoppers" that could seriously impact short-term deployment and support for these technologies, causing significant delays.

In this context, there is clearly a need to provide independent safety expertise, objective information, education and training in different forms for various groups of stakeholders; and support the anticipated upscaling of hydrogen energy applications. Besides, there is also the need for broad information and awareness raising for society to increase the acceptance of hydrogen.

The FCH 2 JU launched the European Hydrogen Safety Panel (EHSP) initiative[197] in 2017 to support the development and deployment of inherently safer hydrogen systems and infrastructure, contributing to achieving the following vision: "hydrogen and fuel cell technologies shall be safely developed, safely introduced, and safety used in projects as well as in the wider society".

To achieve this vision, the EHSP activities started in the FCH 2 JU will continue and will be reinforced in the Clean Hydrogen JU. The EHSP is initially envisaged as a multidisciplinary pool of experts grouped in ad-hoc working groups (task forces) according to the tasks to be performed and to expertise. Collectively, the members of the EHSP will have the necessary scientific competencies and expertise covering the technical domain needed to make science-based recommendations to the Clean Hydrogen JU. In any case, different working arrangements will be explored in order to assess how the EHSP activities could be best suited to maximise its contribution to the Programme and in the last instance, its impact.

The mission of the EHSP in the Programme will be twofold:

- To assist the Clean Hydrogen JU at both programme and project levels, in assuring that hydrogen safety is adequately addressed and managed, and
- To promote and disseminate hydrogen safety knowledge and culture within and outside of the Programme.

Sharing information, coordinating and contributing to addressing the above-mentioned challenges will be the critical role for the EHSP as a focal point or "safety advisor" to the Programme. To this end, it is envisaged that EHSP prioritises the following themes for its activities:

1. Awareness: Increased awareness of the hazards associated with hydrogen energy systems, and the measures required to reduce the inherent risk of such systems to a tolerable level. This includes increased understanding of concepts such as hazards and risk, and the importance of assessing the knowledge available for risk assessments, as well as quantifying the inherent uncertainty in risk assessments, especially for emerging

[197] https://www.fch.europa.eu/page/european-hydrogen-safety-panel

technologies.

2. Foresight: Understanding developing and future technologies in terms of innovation, implementation, operation and safety. Evidence suggests progress will be rapid and it is essential that safety does not become a barrier nor undermine the future of hydrogen technologies. By working closely with the Clean Hydrogen JU's full spectrum of stakeholders, the EHSP will be able to maximise the effectiveness and impact of the state of the art to anticipate safety challenges and solutions.
3. Collaboration: As already illustrated for the state-of-the-art to date, collaboration is essential. To maximise safety and development of the future state-of-the-art this collaboration must continue. Strategies to reinforce the impact of collaboration with European and international stakeholders will be deployed.
4. Public outreach: Sharing lessons learnt and formulating recommendations, knowledge and best practice for safety is clearly an important part of improving the state-of-the-art in hydrogen safety and accidents. However, in light of the recent incidents mentioned above, an argument can be made that with the rapid expansion of hydrogen systems and infrastructure, this activity needs even greater attention. It is fundamental to ensure that such incidents are prevented, or at least that the consequences are reduced as far as possible through inherently safe or robust design and appropriate mitigating measures. Lessons learnt from accidents should be properly analysed and made available for all relevant stakeholders. With the widespread use of hydrogen in society, a growing fraction of the general population will be exposed to potential hazards. As such, the risk picture is about to change dramatically, as the technology is transferred from highly trained and knowledgeable experts in controlled industrial environments to the general public. The EHSP can play an important role in this transition.
5. Exploitation: Funding from the EU and other sources internationally have resulted in achievements in a number of areas related to hydrogen safety. It is important to analyse the progress and identify knowledge that can inform quantitative risk analysis and industrial practice. The EHSP could contribute to guide and direct the international community to the exploitable outcome from previous achievements.

Altogether, the EHSP will contribute to coordinating and establishing approaches to address hydrogen safety-related matters in Europe, while contributing to promoting a hydrogen safety culture and a safe hydrogen market in Europe and beyond if possible.

4.5. European Hydrogen Sustainability and Circularity Panel (EHS&CP)

One of the key aspects for the development of our society is sustainability, ensuring the protection of the environment, the economic feasibility looking at creating new job opportunities, and the social responsibility taking into account Social and Intergenerational Equity. In 2015, the United Nations adopted 17 SDGs, aiming at "transforming our world" by ending poverty, protecting the planet, and ensuring that all people enjoy peace and prosperity by 2030. One of them, Goal 12 – Responsible Consumption and Production – calls for efficient management of natural resources, reducing waste and promoting recycling. As part of the sustainable development agenda, the "2030 Agenda"[198], all countries are committed to developing strategies to build economic growth and address a range of social needs while tackling climate

198 https://sdgs.un.org/2030agenda

change and environmental sustainability.

In the EU, sustainable development is a core principle of the Treaty on European Union and a key objective for the Union's internal and external policies[199]. Indeed, the EU is firmly committed to delivering on the UN's SDGs through several policies and initiatives[200]. In the area of climate and energy, sustainable development is at the heart of the European Green Deal[201], which along with other policies[202] has set the EU on a course to become a sustainable climate-neutral and circular economy by 2050.

Building a circular economy means reducing its carbon and material footprint, stimulating sustainable consumption and production patterns while bringing significant new jobs and growth potential. Circular economy is about doing more and better with less. It also aims at reducing the environmental impact by minimising waste and excessive resource use throughout value chains and production processes, for example by turning goods at the end of their lifespan into resources for others through re-use, re-manufacture and recycle, trying to reflect natural ecosystems.

Circularity is an essential part of a wider transformation of the European industry towards climate neutrality and long-term competitiveness, representing one of the key building blocks of the New Industrial Strategy for Europe[203] and the Recovery Plan for Europe[204]. The first Circular Economy Action Plan (CEAP) was adopted by the Commission in 2015[205], establishing concrete actions covering the whole products life cycle: from extraction and transformation of raw materials to advanced materials and components, to waste management and the production of secondary raw materials. Building on the CEAP, in 2018 the Commission adopted the circular economy package, which included among others the development of a monitoring framework for the circular economy[206] and a report on critical raw materials and the circular economy[207]. In 2020, the Commission has adopted the new CEAP[208], which represents Europe's new agenda for future sustainable growth. The new action plan includes initiatives along the entire life cycle of products aiming to reduce the pressure on natural resources, promote circular economy processes and encourage sustainable consumption.

The linear economy is based on linear processes that rely on the abundant and infinite availability of raw materials at a relatively low cost, and endless waste sinks. The typical linear system consists of a series of steps – resource extraction, manufacturing, consuming, and disposing of products at the end of their life cycle- almost without any interaction among them. However, the Earth's resources are limited and the depletion of raw materials is inevitable without sustainable development. On the other side, demand for raw materials is projected to double by 2050[203], making sustainable sourcing essential to increase Europe's security of supply. Indeed, among the main environmental reasons towards a circular economy are resource scarcity, particularly for strategic resources, the volatility of (and rising) commodity

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199 https://ec.europa.eu/info/strategy/international-strategies/sustainable-development-goals_en
200 https://knowsdgs.jrc.ec.europa.eu/policies-sdgs
201 COM(2019) 640 final.
202 https://ec.europa.eu/info/strategy/international-strategies/sustainable-development-goals/eu-holistic-approach-sustainable-development_en
203 New Industrial Strategy for Europe. COM(2020) 102 final.
204 Europe's moment: Repair and Prepare for the Next Generation. COM(2020) 456 final.
205 COM/2016/0739 final
206 COM/2018/029 final
207 COM/2016/0739 final
208 COM/2016/0739 final

prices, and negative environmental impacts of unsustainable production and consumption.

Reliable and unhindered access to certain raw materials is a growing concern within the EU. The strategic importance of securing the supply of raw materials was also recognised by the EU Green Deal to fulfil its ambition to become climate-neutral by 2050 based on the use of several raw materials in strategic areas such as batteries, renewable energies, hydrogen, digital applications, etc.[209]

The EU is addressing this challenge through the Raw Materials Initiative[210], which defines the strategic policy framework to secure a sustainable supply of raw materials for Europe. As part of this initiative, the Commission is monitoring the EU's resilience in relation to raw materials and reviews the list of critical raw materials (CRMs) for the EU every three years based on their importance to the EU economy and of the high risk associated with their supply. The most recent assessment published in 2020 identified 30 CRMs[211], more than double compared to the CRMs list from 2011.

Hydrogen and fuel cell technologies will play an essential role in the sustainable transition and future energy system. Nevertheless, the hydrogen technologies value chains are under development and need further development to become an environmentally sustainable, socially responsible and circular market value proposition. Overall, the European hydrogen sector is based on a linear economy approach and further efforts are still required to minimise the impacts of these technologies from their design, manufacturing and deployment, to ensuring their recovery, reuse, and recycling or disposal.

With regard to the upstream supply chain, around 30 raw materials are needed for producing and storage of hydrogen and fuel cell technologies[212]. Of these materials, 13 materials namely cobalt, magnesium, REEs, platinum, palladium, borates, silicon metal, rhodium, ruthenium, graphite, lithium, titanium, and vanadium are deemed critical for the EU economy according to the 2020 CRM list. China is the major supplier of these raw materials with more than 20% share, followed by South Africa and Russia.

The fuel cell industry relies heavily on platinum-based catalysts, with platinum making up about half of the cost of a fuel cell stack. Apart from the platinum group metals (PGM), major growth in demand is expected also for copper for use in fuel cell electric vehicles. Platinum is produced mainly in South Africa (71% of global production), followed by Russia (16%) and Zimbabwe (6%). Boosting recycling and the use of secondary raw materials will help reduce this dependency.

The rapid growth of clean hydrogen produced by water electrolysis using renewable energy will lead to high demand for nickel, zirconium, rare earth elements (i.e. lanthanum and yttrium) and PGM (i.e. platinum, palladium and iridium) used in various types of electrolysers.[213] Scarce raw materials such as iridium and platinum can represent a barrier to industrial scale up of PEM electrolysers and reducing their cost (e.g. the current production of iridium and platinum will only support an estimated 3-7.5 GW annual manufacturing capacity of PEM electrolysers, compared to an estimated annual manufacturing requirement of around 100 GW by 2030).[214]

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[209] COM/2021/ 350 final
[210] https://ec.europa.eu/growth/sectors/raw-materials_en
[211] COM(2020) 474
[212] EC, Critical materials for strategic technologies and sectors in the EU – a foresight study, 2020
[213] IEA, The role of critical minerals in clean energy transition, May 2021
[214] IRENA, Green hydrogen cost reduction; scaling up electrolysers to meet the 1.5 C climate goal, 2020

Diversifying supply chains, fostering technology innovation, and improve resource efficiency and circularity are potential solutions to increase the EU's resilience in relation to raw materials used in hydrogen technologies (notably on electrolysers and fuel cells). The EU can lead the way towards a sustainable and circular hydrogen economy. Innovation and technological progress are key to finding lasting solutions to both economic and environmental challenges, including access to resources and sustainability. Indeed, in line with the European Green Deal objectives, research and innovation activities should not make significant harm to any of the six environmental objectives (EU Taxonomy regulation[215]), and should follow the "Do No Significant Harm" principle.

The Clean Hydrogen JU is committed to contributing to putting the EU hydrogen sector at the forefront of the sustainable and circular transition of hydrogen technologies and their associated value chains. To this end, the research and innovation actions included in particular within the sections "Sustainability, LCSA, recycling and eco-design" and "Supply Chain" will play a key role in providing the methodological foundation to strengthen the sustainability and circularity of these technologies and their industrial value chains in Europe. Nevertheless, the transition towards a fully-fledged sustainable and circular hydrogen economy requires an integrated approach beyond these activities. To this end, the Clean Hydrogen JU will set up a European Hydrogen Sustainability and Circularity Panel (EHS&CP) at the Programme level.

The Sustainability and Circularity Panel will support the Clean Hydrogen JU Programme in the transition towards a sustainable and circular hydrogen economy. The EHS&CP is envisaged as a multidisciplinary pool of experts (10-15 experts approx.) with knowledge and experience in the relevant areas, covering the technical domain needed to make science-based recommendations to the Clean Hydrogen JU. They will act as a focal point or "advisor" to the Programme in these matters in an independent, coordinated and consolidated way.

The mission of the EHS&CP in the Programme will be two-fold:

- To assist the Clean Hydrogen JU in assuring that sustainability and circularity aspects are adequately addressed and managed at both programme and project levels, encompassing environmental, social and economic aspects as a whole, and
- To promote and disseminate knowledge and a more sustainable and circular culture within and beyond the Programme.

To this end, the scope of the activities of the EHS&CP is preliminary envisaged around three main areas.

Support at programme and project levels

The EHS&CP will provide advice for developing an overarching and comprehensive strategy on sustainability and circularity at the Programme level. To this end, the EHS&CP will define and coordinate a package of measures to raise the sustainability and circularity of the projects by integrating learnings, expertise and planning with respect to sustainability and circularity so that the DNSH principle is taken into consideration in the Programme as a whole. This could include the provision of specific guidelines on sustainability and circularity measures in projects, strengthening the impacts and influence of the R&I actions undertaken in the cross-cutting issues and supply chain areas across the Programme, and proposing new methodologies and tools to ensure actual sustainable and circular systems.

[215] Regulation (EU) 2020/852

Data collection and assessment

In this regard, the EHS&CP tasks may include the coordination and development of a systematic data collection approach to extract valuable information from projects to provide further guidance to both projects and the Clean Hydrogen JU based on a regular monitoring activity. This could include the development of sustainability and circularity indicators to monitor progress and a better understanding of environmental and social impacts of products and services, identifying “hot spots” within the value chains where interventions have the greatest potential to improve the sustainability and circularity, providing data and knowledge to make informed decisions, etc.

Public outreach

Framed within the context of the intended broad information, activities in this category may include the development of newsletters, set up events and a regularly updated webpage, containing for example lessons learned and links to other important hydrogen-sustainable and circular-related information.

Altogether, the EHS&CP will provide the Clean Hydrogen JU a unique, practical and direct support to reach the following objective: ensure that the sustainability and circularity considerations are taken into account in the development and implementation of research and innovation actions and are embedded in the Programme as a whole, integrating and balancing the three dimensions of sustainable development: the economic, social and environmental.

4.6. Knowledge management

4.6.1. (Current) Knowledge activities in previous JUs

Knowledge management refers to a range of practices and techniques used by organisations to create, share and exploit knowledge to achieve organisational goals. The predecessor FCH 2 JU, being at the centre of creation of knowledge for fuel cell and hydrogen technologies, has been implementing knowledge management activities since its beginning.

The initial focus of these activities was to improve technology monitoring. Initially based on the TEMONAS tool developed under FCH JU[216], technologies began to be monitored in a more structured way, assisting in measuring the progress of the research & innovation and innovation activities of FCH 2 JU Key Performance Indicators (KPI). TEMONAS was subsequently replaced by the platform TRUST[217], developed in 2017, which was at the heart of a more elaborate annual data collection exercise from the FCH 2 JU projects. The findings of the data collection exercise were presented in the annual Programme Review Report, focusing mainly on the added value, effectiveness and techno-economic efficiency of FCH 2 JU projects.

Parallel to the development of TRUST, the knowledge management activities expanded beyond technology monitoring. The FCH 2 JU website has provided already detailed information on projects, while an internal database following the deployment of fuel cell and hydrogen deployment was developed and maintained. The collaboration with JRC on knowledge management activities, dating back to FCH JU, was strengthened further, both via the development of the Tools for Innovation Monitoring (TIM) database[218], the preparation and

216 https://www.fch.europa.eu/project/technology-monitoring-and-assessment
217 TRUST data collection methodology, FCH
218 https://www.fch.europa.eu/page/tools-innovation-monitoring-tim

publication of reports on the developments in specific technological areas and by supporting the Programme Office on mapping the international state-of-the-art for the various technologies and benchmarking FCH JU activities against it. Moreover, on 15 September 2020, there was the launch of the Fuel Cell Hydrogen Observatory, providing data and up to date information about the entire hydrogen sector. It focuses on technology and market statistics, socio-economic indicators, policy and regulation, as well as financial support.

4.6.2. Clean Hydrogen as the Knowledge Hub for Hydrogen in Europe

The Clean Hydrogen JU will build on the wide range of activities and experience acquired so far by the predecessors JUs, further developing them in order for the Clean Hydrogen JU to better accomplish its objectives and improve its operations. In particular, the main goals of the Clean Hydrogen JU knowledge activities and in close co-operation with the European Commission and the Industry will be:

1. Support the collection and diffusion of high quality new knowledge;
2. Contribute to the implementation of the European Clean Hydrogen Strategy;
3. Strengthen the knowledge capacity of hydrogen value chain actors through data collection and knowledge collection;
4. Support evidence-based implementation of Union policies;
5. Monitor progress towards the achievement of the objectives of the Clean Hydrogen JU objectives and its technology KPI;
6. Improve Clean Hydrogen JU's operational and planning capacity;

The ultimate goal of this Strategy is to gradually turn the Clean Hydrogen Joint Undertaking into the Knowledge Hub for Hydrogen in Europe, and the Programme Office into a knowledge intensive organisation.

The strategy for turning the Clean Hydrogen JU into a hydrogen Knowledge Hub will be based on the following pillars:

Annual Data Collection Exercise and Programme Review Report

The annual data collection exercise, monitoring the progress towards the technology KPI targets, and the Programme Review report, presenting the findings of the exercise, have proven to be very successful and will be continued as a main source of knowledge for the successor of FCH 2 JU. An effort will be made to reduce the duration of the exercise, starting from 2021, bringing the reporting period forward and enriching the report with more information valuable to its readers.

Monitoring hydrogen technologies across EU programmes and partnerships

The Clean Hydrogen JU is mandated to keep the key competence knowledge for hydrogen and fuel cell technology. Hydrogen topics (and related projects) are addressed in various EU programmes and partnerships under Horizon Europe. The Clean Hydrogen JU will examine ways to monitor and assess technology progress and deployment for all these projects, integrating this information in one EU hydrogen database. The ultimate goal would be that all projects relevant to hydrogen participate in the Clean Hydrogen JU's annual data collection exercise, thus providing an up to date and complete database of the output from all European funded projects.

Knowledge Management Tools

The Programme Office will continue to use and further develop the tools used in FCH 2 JU to collect and monitor information, most notably the data collection platform TRUST and the TIM tool developed by JRC. These will be complemented by the tools provided by DG RTD (CORDA, COMPASS, CORTEX, etc), as well as the databases and tools developed internally to better manage information for supporting the operations of the Programme Office.

As all the above-mentioned tools are independent and accessed separately, it is envisaged that a new knowledge management tool should be introduced, either replacing or integrating the existing tools and further enhancing their capacity. Such a tool would include, in the same platform, a data collection tool (which could also be TRUST), an extended database fed by many different sources, analysis capabilities and strong reporting and visualisation capabilities.

Fuel Cell and Hydrogen Observatory (FCHO)

The FCHO shall remain as the main portal for European hydrogen data. Considering the development of similar observatories and knowledge hubs by other international organisations, there will be initiatives to collaborate with them.

At the same time FCHO will be further populated with data, aiming to fill in current knowledge gaps. Data quality controls shall be further enhanced, to ensure FCHO provides a robust set of data, allowing it to become the reference point for European hydrogen data.

Clean Hydrogen JU website

The Clean Hydrogen JU website will be enriched with more information concerning the Clean Hydrogen JU's projects, technology developments, etc. Combined with FCHO, the two websites should become a one stop shop for all information related to clean hydrogen in Europe.

Feedback to Policy

The JU will identify and report, in line with the common policy feedback framework and with strategies and actions to support the European Green Deal objectives, the relevant knowledge acquired from the management of research and innovation projects and their results to the Commission to serve as input for monitoring, evaluating and rectifying, where necessary, existing policy measures or shaping new policy initiatives and decisions.

Moreover, it will provide the Commission with the necessary technical, scientific and administrative support to carry out its tasks for the purposes of ensuring the proper functioning and development in the Union of the hydrogen sector.

Support from JRC

JRC will continue being an important partner to the Clean Hydrogen JU, supporting all knowledge activities, as described in Section 4.1.1.

Co-operation in terms of knowledge management with Member States and Hydrogen Valleys

Co-operation with Member States and Hydrogen Valleys will be vital in ensuring the Knowledge Hub goal of the Clean Hydrogen JU. There will be significant mutual benefits by exchanging information on hydrogen activities and technology developments. Moreover, the Clean Hydrogen JU will provide the opportunity to the Member States and Hydrogen Valleys to present more widely their activities, mainly through the State Representative Group (SRG) and the European Research Area (ERA). To achieve this, it will also be useful to develop links with the associated organisations, in charge of implementing national hydrogen strategies. The Hydrogen Valley Platform,[219] co-funded by FCH 2 JU and Mission Innovation, will be further developed to foster exchange of know-how and best practices at the European and international level.

Targeted studies/roadmaps

The knowledge spectrum shall be complemented with studies, focusing on the areas where gaps are identified. One particular area where studies will be required, mandated by the SBA[220], concern the assessment and monitoring of technological, economic and societal barriers to market entry, including in emerging hydrogen markets.

Sharing public data, while guarding confidential data

The Clean Hydrogen JU is accumulating significant knowledge from its projects and activities, sharing of which could benefit the whole hydrogen community. Considering the increasing interest in hydrogen related technology data, the Clean Hydrogen JU will investigate ways to make non-confidential technology and deployment data from hydrogen projects increasingly available to the stakeholders and public, complementing the ones available via FCHO. At the same time it will continue guarding all confidential data, as declared by the beneficiaries of its funding, protecting the trust relationship built between the partnership and its beneficiaries.

4.6.3. Dissemination & Exploitation of the project results

Hydrogen is currently gaining more and more attention, its visibility increased significantly since 2019. The Clean Hydrogen JU will play a key role in strengthening and closely monitoring the dissemination of the results/outcomes of hydrogen projects, as well as the exploitation of their results.

Efficient and pro-active dissemination activities are of great importance for the success of the Clean Hydrogen JU, with objectives to:

- Ensure that the Clean Hydrogen JU is perceived as the key European strategic initiative for focused, coordinated and competitive innovation activities in the field of clean hydrogen;
- Raise awareness of the role of clean hydrogen in creating a sustainable, secure and affordable energy system, while at the same time increasing EU competitiveness and contributing to job creation;
- Ensure internal interaction and coordination with members and stakeholders managing their expectations and promoting continued interest in the Clean Hydrogen JU activities speaking with one voice;
- Engage external stakeholders to encourage increased innovation investment in clean hydrogen technologies.

Dissemination & Exploitation (D&E) Tools/Services

All dissemination and communication activities will be in line with the European Commission's strategies for dissemination and exploitation of the projects results in Horizon Europe. According to the governance of D&E Strategy for the post-H2020 period and the Horizon

[219] https://www.h2v.eu/hydrogen-valleys
[220] See Article 74 (a) of the SBA.

Europe, the governance structure for implementation will consist of the following coordination groups (which will replace the former D&E Network configuration and its six Working Groups):

- The Horizon Dissemination & Exploitation Group, and
- The Horizon Feedback to Policy Group.

Also the D&E Action Plan 2021 – 2022 aims to create a D&E ecosystem for R&I results, in which all main actors (e.g. beneficiaries, EU policy makers, investors, social entrepreneurs, national and regional administrations, etc.) will be contributing to and benefiting from a dynamic circulation of knowledge stemming from R&I projects. A non-exhaustive list of already existing services and tools, parts of the EC D&E ecosystem follows:

1. Horizon Results Platform[221]: A result-oriented platform for project beneficiaries to upload their results, to valorise and promote them to the targeted groups (e.g. business partners, angel investors, venture capitals, policy makers, business development assistance etc);
2. Innovation Radar[222]: A European Commission initiative to identify high potential innovations and innovators in EU-funded research and innovation projects, based on a data driven method;
3. Horizon Results Booster[223]: A package of tailor-made specialised services to maximise the impact of R&I public investment and further amplify the added value of the Programme, by building the capacity of projects for disseminating research results, increasing their potential for exploitation and improving access to markets;
4. Dealflow.eu[224]: Mainly addressed to innovations analysed by the Innovation Radar, this package of services aims to support EU-funded start-ups in commercialising their innovations and connect them with investors and corporates (fundraising, venture building and networking).
5. IP Booster[225]: Specialised professional Intellectual Property service for public research organisations looking to realise value from their research results;
6. Open Research Europe[226]: The new EC scientific publishing service for fast publication and open peer review for research scientific articles stemming from H2020 projects.

Also, 1000 Solutions[227], an initiative of the Solar Impulse foundation to grant a Solar Impulse Efficient Solution Label to 1000 products, processes or services that meet high standards of both sustainability and profitability, can be an additional platform for the Clean Hydrogen JU to disseminate the projects results.

These tools and services are expected to improve the dissemination of information within and beyond the hydrogen community, and to enable further exploitation of the project results and a larger impact of the Clean Hydrogen JU on European society.

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[221] https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/opportunities/horizon-results-platform
[222] https://ec.europa.eu/digital-single-market/en/innovation-radar
[223] https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/opportunities/d-e-booster
[224] https://dealflow.eu/
[225] https://ipbooster.meta-group.com/
[226] https://open-research-europe.ec.europa.eu/
[227] https://solarimpulse.com/

Programme Review Days

The Clean Hydrogen JU will organise annually the Program Review Days as part of the Hydrogen Week event, a major opportunity to raise visibility on Clean Hydrogen JU activities and to assess projects and innovation pillars, as well as ultimately its Programme development, especially in relation to international developments. Support material produced and provided parallel to the event for D&E purposes consists of:

1. The publishable version of the Programme Review Report, presenting briefly the major developments in each panel and the non-confidential major outcomes of the active projects, and
2. The Success Stories, a portfolio of narratives that highlight the most prominent achievements of a single project or a cluster of projects and the progress they make.

Additionally, the Clean Hydrogen JU will also upgrade existing tools already used in the previous period to support D&E activities in program level, mainly through the new upgraded website in which the project results will continue to be published. These type of tools/activities are presented in Section 4.6.2 of this document.

4.7. The role of small and medium-sized enterprises

Small and medium-sized enterprises are an important source of innovation and represent a large share of companies engaged in early markets, involved in many industrial supply chains. Their role is crucial for future commercialisation and are best placed to take advantage of the opportunities offered by new technologies and grow by creating new jobs requiring advanced skills. This is possible through adapting existing methods as well as through novel methods of production.

The hydrogen 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. This allows them to grow successful businesses and position themselves strongly within the hydrogen supply chain.

The predecessors JUs haves been a key instrument for SMEs, providing a stable regulatory environment as well as the long-term stability that comes with public sector funding. Working alongside larger companies in the same field enables SMEs to tap into the expertise, distribution networks, support and customer pools of those organisations. Through financial and networking support, FCH and FCh 2 JUs have helped many SMEs in the fuel cell and hydrogen sectors to achieve their business goals, from obtaining private investment to the marketing of new products and services. There are plenty of successful SME beneficiaries in the areas of electrolysis, gasification of biomass and biowaste and the development of hydrogen carriers.

The Clean Hydrogen JU will continue to rely on the innovativeness of SMEs. To do this, it will need to deal with two of the largest obstacles that SMEs must overcome, the need to raise financing, especially in the early stages of growth, and to kick-start sales and thereby gain valuable field experience. In order to address the specific limitations and risks of SMEs, the Clean Hydrogen JU will continue to explore ways to open access to the necessary manufacturing and process capabilities through partnership schemes and education initiatives. It will help raise awareness of projects' results within the finance community, while at the same time trying to address the private sector funding and financing challenge that acts as a market barrier for deployment of hydrogen technologies and wider hydrogen integrated solutions.

In parallel, the JU will promote the involvement of SMEs and start-ups in its activities and ensure the provision of timely information to them, in line with the objectives of Horizon Europe and the SBA, by implementing measures for attracting newcomers (see also Section 5.2).

4.8. International cooperation strategy

The recent Communication of the European Commission on the global approach to research and innovation[228] presents the EU's new strategy on international cooperation on research and innovation. The EU aims to take a leading role in supporting international research and innovation partnerships and to deliver innovative solutions for making our societies green, digital and healthy.

The strategy builds on two principal objectives: preserving openness in international research and innovation cooperation, while promoting a level playing field and reciprocity underpinned by fundamental values. To achieve its goals, the EU will embark on several actions, implemented through EU bilateral cooperation and pooling global efforts to tackle global challenges. It will modulate cooperation with priority countries and region, by:

- Strengthening cooperation with industrialised non-EU countries and emerging economies;
- Giving particular priority to partners in its immediate vicinity, including through association to Horizon Europe;
- Deepening EU partnerships with Africa, Latin America and other regions and countries.

Examples of such cooperation include the support of researchers and their organisations to help accelerate sustainable and inclusive development in low and middle-income countries[229], as well as leading international efforts in climate and environmental science towards a just green transition.

The Clean Hydrogen JU will support the Commission in the endeavour, in accordance with its objectives under Articles 4, 5 and 73 of the SBA, as well as the additional tasks described under Article 74. In particular, the SBA calls for the Clean Hydrogen JU to:

1. Contribute to the objectives set out in the 2030 Climate Target Plan, which foresee actions on the international dimension. In particular, the European Commission will seek mutually beneficial alliances around new sustainable technologies, such as renewable hydrogen, and using EU's cooperation platforms[230] for the deployment of international environmental standards and promotion of clean technologies through trade. Following the Commission's request, the Clean Hydrogen JU could potentially support the Commission in these actions;
2. Support the Commission, including through technical expertise, in its international initiatives on the hydrogen strategy, such as the International Partnership for Hydrogen Economy (IPHE) and fuel cells in the Economy, Mission Innovation (and notably the

[228] Europe's strategy for international cooperation in a changing world, COM(2021) 252 final.
[229] Including through an ambitious 'Africa initiative' under Horizon Europe, to strengthen cooperation with African countries.
[230] Notably the 'Hydrogen Mission' with Australia, Chile, Germany and the UK, launched at the Mission Innovation 2.0 conference in June 2021.

Clean Hydrogen Mission) and the Clean Energy Ministerial (CEM) Hydrogen Initiative;

3. Notwithstanding the Commission's policy prerogatives, under the Commission's policy guidance and supervision, contribute to the development of regulations and standards with the view to eliminating barriers to market entry and to supporting interchangeability, inter-operability, and trade across the internal market and globally;
4. Strengthen international cooperation in support of Union policy objectives and international commitments.

In order to meet these objectives, the Clean Hydrogen JU will support the European Commission in the implementation of its international cooperation agenda in research and innovation.

It will support the Commission on possible links with major deployment programmes globally of hydrogen technologies, continue to support the Commission in the work on standards and regulations harmonisation, as well as to accelerate the market uptake of these technologies. Under the Commission's policy guidance and supervision, the Regulations, Codes and Standards Strategy Coordination group and the Sustainability and Circularity Panel, described in more detail in Sections 4.3 and 4.5, will support the Commission in its activities on international cooperation when required. The European Hydrogen Safety Panel, presented in Section 4.4, will continue and expand its collaboration with European and international stakeholders in order to maximise safety and development of the future state-of-the-art.

The Clean Hydrogen JU will continue to provide technical support to the European Commission on its international activities in relation to hydrogen research and innovation, as well as promote its Calls for Proposals intended for international cooperation. The main envisaged support to the Commission relate to the IPHE, the Clean Energy Ministerial Hydrogen Initiative, Mission Innovation 2.0 and Hydrogen Energy Ministerial.

For the purpose of the IPHE, the Clean Hydrogen JU can support the European Commission in the current and forthcoming working groups, such as Standards, Education and Certification, as well as support with technical expertise the European Commission in the Steering Group. In addition, the Clean Hydrogen JU will continue to support the European Commission in providing periodical updates on hydrogen activities at EU level to the IPHE.

In the context of the Clean Energy Ministerial Hydrogen Initiative, the Clean Hydrogen JU will support the European Commission with technical expertise in the different tasks the Commission either co-leads or participates, such as enabling deployment of hydrogen technologies in transport (e.g. ports) and identification of national targets and definition of Global Aspirational goals for hydrogen.

Following the successful and close collaboration of the FCH 2 JU with EC representatives on the Mission Innovation – IC8 and the setting up of the Hydrogen Valley Platform, a platform for exchanges between worldwide initiatives on hydrogen valleys, the Clean Hydrogen JU will continue to contribute in this direction. It will maintain and further improve the Hydrogen Valleys platform, while the Clean Hydrogen JU will support the European Commission in its co-lead activities.

Similarly, the Clean Hydrogen JU PO will continue to support JRC by contributing to the Commission activities for the International Energy Agency (IEA) Hydrogen Technology Collaboration Programme (HTCP) executive committee. More specifically, it was agreed for the Clean Hydrogen JU to follow the newly created tasks on Renewable H2 production, Underground Hydrogen Storage and Hydrogen Export Value Chains, in addition to ongoing IEA HIA Task 41 on Analysis and Modelling of Hydrogen Technologies. Moreover, the Clean Hydrogen JU PO may provide expertise upon request to the IEA Advanced Fuel Cells TCP.

In terms of knowledge management activities, the Clean Hydrogen JU will will seek to sign mutually beneficially cooperation agreements on the sharing of knowledge and the exchange of data with international energy organisations active in the area of hydrogen, such as the International Renewable Energy Agency (IRENA), the World Energy Council and IEA, while keeping the EC and the JRC fully informed.

In view of assisting in the implementation of the International Cooperation Strategy of the Commission, the Clean Hydrogen JU may be involved at the Commission's request in different actions. In terms of strengthening EUs cooperation with Africa, it can provide technical assistance in terms of future hydrogen usage, production and export potentials, that could enable their green energy transition.

At the same time, the co-operation with our industrialised partners, especially the ones sharing a similar vision with EU for hydrogen, is essential. In these cases one could envisage more formal co-operation with bodies similar to the Clean Hydrogen JU, promoting research and innovation in hydrogen, as well as activities such as education and training, public awareness and RCS, through e.g. joint events, webinars, roadshows, exchange of expertise. In particular, the Clean Hydrogen JU, through its PO upon GB validation, intends to build on the long-term cooperation of the FCH JU with US DOE / EERE, METI / NEDO (Japan) and NRCan (Canada), but also develop relations, as necessary, with other countries and regions according to EU's international cooperation agreements. On an annual basis, the JU will take stock of these activities, summarising them in a report submitted to the Governing Board.

4.9. Communication

Communication has become increasingly important and ambitious, in an environment that is keen to absorb increasing amounts of information about the hydrogen technologies. It forms a key element of the partnership activities; moreover, it is included as one of the specific objectives of the partnership.

The communication policy of the Clean Hydrogen JU will focus on the following objectives:

- Position the partnership as an important factor in the development of the hydrogen technologies sector and a key partner to achieve the targets of the EU Green Deal.

Communication will raise the profile of the Clean Hydrogen JU as being the key European strategic initiative for focused, coordinated and competitive research activities in the field of hydrogen technologies.

- Build public awareness and acceptance of the hydrogen technologies

Communication and dissemination activities will contribute towards building a strong societal and political support for the development and uptake of the hydrogen technologies.

- Ensure communication towards and between key stakeholders

Cooperation with other European partnerships under Horizon Europe will be key for building the public awareness and political support for the technology. Communication will benefit from building synergies and establishing strong links with the projects, the members of the partnerships , and other initiatives and networks – at European and global level, such as the

Horizon Europe NCP network.

- Inform about the funding opportunities facilitated by the partnership and about the results of the projects and initiatives

Present and promote the results of the projects funded by the partnership. Attract relevant and varied types of beneficiaries for developing innovative, successful projects.

The details of JU's Comunciation Policy can be found separately in the relevant document.[231]

[231] The Communication Policy will be adopted separately by the GB.

5. Programme implementation

5.1. Budget

The budget of the Clean Hydrogen JU shall be formed of contributions from the Union and its members other than the Union – namely Hydrogen Europe and Hydrogen Europe Research.

The contributions to the joint undertaking shall cover administrative and operational costs up to the maximum amounts specified in Part III of the SBA under Articles 76 and 77. The Union contribution may be increased with contributions from third countries associated with Horizon Europe provided that the total amount by which the Union contribution is increased is at least matched by the contribution of members other than the Union, or their constituent or affiliated entities.[232] Additionally the budget may be complemented through additional Union funds, corresponding to additional tasks entrusted to a joint undertaking, which shall not be accounted for in the calculation of the Union maximum financial contribution.[233]

The administrative costs shall not exceed EUR 60 386 000; it shall be covered by financial contributions on an annual basis, divided equally between the Union and the private Members. If part of the contribution for administrative costs is not used, it may be made available for the operational activities of the Clean Hydrogen JU. Administrative costs will cover administrative expenditures such as staff costs, rental of building, equipment, IT equipment and maintenance, evaluation costs, meetings, etc.

The operational costs of the Clean Hydrogen JU will be covered through the financial contribution from the Union (EUR 969 807 000, not including contributions from third countries), and through in kind contributions (consisting of the eligible costs incurred in implementing indirect actions less the EU contribution) by Members other than the Union. The EU contribution is approximately 30% less than the requested budget by the private members to achieve the objectives of SRIA-HE/HER. Nevertheless, the SRIA retains the ambitiousness of the SRIA-HE/HER in term of activities and related objectives, under the understanding that certain prioritising may need to be implemented over the seven years. Therefore, not all activities described in this document may be performed by the Clean Hydrogen JU without the additional required contributions to the Clean Hydrogen JU budget.

For the implementation of the budget, in accordance with the Legislative Financial Statement accompanying the SBA, the Clean Hydrogen JU will conclude a Delegation Agreement, as well as annual Transfer of Funds agreements with the European Commission[234]. Financing Agreements with its private Members will be concluded for their contribution to administrative budget.

In order to achieve its objectives, the Clean Hydrogen JU shall provide financial support mainly in the form of grants to participants following open and competitive Calls for proposals. At least 10% of budget should be implemented through activities at low TRL.

[232] Article 10(2) of SBA.
[233] Article 10 paragraphs (4)-(6) of SBA.
[234] In accordance with the latest instructions from the Commission, the Delegation Agreement referred to in the Legislative Financial Statement will take the form of a Financial Framework Partnership Agreement (FFPA) and the Transfer of Funds agreements will take the form of Contribution Agreements.

5.2. Conditions for participation and eligibility for funding

Any legal entity, regardless of its place of establishment, or international organisation may participate in indirect actions funded under the Clean Hydrogen JU Programme, provided that the conditions laid down in the Horizon Europe Regulation have been met together with any specific conditions laid down in the work programme or call.

In line with the Horizon Europe Regulation[235], one of the Clean Hydrogen JU objectives is to increase commitments and contributions in a qualitative and quantitative manner in order to demonstrate the added value and directionality of the partnership, while keeping transparency and openness as regards the identification of priorities and objectives, and the involvement of partners and stakeholders from different sectors. Private members should, therefore, make a substantial share of their contributions at the level of indirect actions funded by the Clean Hydrogen JU. In order for the private partners to deliver their in-kind contributions to operational activities and to additional activities, and considering that both contributions can only be made by the constituent entities of the private members[236], the Clean Hydrogen JU should encourage such membership.

The establishment of a Joint Undertaking ensures a mutually beneficial public-private partnership for the members involved, including the promotion of certainty on budget allocations for the relevant industries over a period of seven years. Becoming a member or being affiliated to a member of the Joint Undertaking allows involvement in the preparation and implementation of the Joint Undertaking's work programme, either directly or through the private members' representatives, via the Governing Board of the Joint Undertaking, and through participation to the private members' associations own related Technical Committees (TCs), where input to the definition of the Joint Undertaking research and innovation priorities is prepared. The Governing Board is the decision-making body of the Joint Undertaking that decides on the long-term strategic orientation of the partnership, as well as its annual priorities. Members should therefore be able to contribute to the Joint Undertaking's agenda and priority setting through the adoption and possible amendment of the SRIA (based on the Strategic Research and Innovation Agenda of the industry), as well as the adoption of the annual work-plans. This may include the specific conditions of the calls for proposals and the applicable funding per call topic.

Without doubt, a reinforced community of industrial and research organisations brought together around a common long-term strategic research agenda as proposed by the Clean Hydrogen for Europe Joint Undertaking is of added value. A wider and strengthened community will also work towards achieving the Horizon Europe and institutionalised partnership's general objectives[237] to improve through research and innovation the cost-effectiveness, reliability, quantity and quality of clean hydrogen solutions, including production, distribution, storage and end uses developed in the Union. By continuously increasing its membership, the founding members will strengthen their efforts to drive towards a more strategic and impact-based approach to research and innovation, strengthening the knowledge and capacity of the scientific and industrial actors along the Union's hydrogen value chain. This will enable the realisation of demonstrations of clean hydrogen solutions with the view to local, regional and Union-wide deployment, addressing renewable production, distribution, storage, and use for transport and energy-intensive industries as well as other applications. At the same time, the

[235] See Annex III of the Horizon Europe Regulation on Partnerships selection/objectives
[236] Article 2 of the SBA
[237] Article 4 of the SBA

EU's industry, through the pooling of resources under each association, will increase its active role in working together with the Union for delivering the objectives of the European Green Deal and of the EU Hydrogen Strategy.

In this respect, all legal entities participating in the Clean Hydrogen JU programme should be continuously encouraged (e.g. through Call Info-Days, Coordinators-Days etc) in becoming members of the Clean Hydrogen JU through affiliation with the private founding members.

Members other than the Union / private founding members (the Associations), will do their utmost to encourage membership of Hydrogen Europe Industry and Hydrogen Europe Research. They will especially adopt measures for attracting newcomers, in particularly SMEs, higher education institutions and research organisations.[238] In addition, both associations are strongly committed to deliver their financial contributions for the entire duration or the JU programme (as has been the case for the FCH JU and FCH 2 JU) as well as promote and enforce openness throughout the programme. However, since IKOP and IKAA financial contributions may only be reported for Associations' member companies or organisations, in duly justified cases additional conditions requiring the participation of members of the joint undertaking or their constituent or affiliated entities may be specified in the work programme.

Indeed, in line with the SBA[239] in justified cases, it should be possible to introduce additional conditions in a call topic that require the participation of a member of the Clean Hydrogen JU or their constituent or affiliated entities, targeting activities where the industrial and research partners of the Clean Hydrogen JU can play a key role, such as large-scale demonstrations, flagship projects and strategic research projects. It is also possible[240] to limit in exceptional cases the participation in specific actions in the work programme in accordance with Article 22(5) of the Horizon Europe Regulation and in accordance with the position agreed on a case-by-case basis between the Commission and the Member States in SRG. The limitations to participation shall respect the provisions of Article 23 of the SBA,[241] ensuring coherence with the approach taken for actions funded under the Horizon Europe work programme adopted in accordance with Article 13(2), point (b), of the Specific Programme implementing Horizon Europe regarding the application of Article 22(5) of the Horizon Europe Regulation, as well as Union legislation and guidance relevant for its application in similar topics in the work programme of the JU. The level of participation of private members should be monitored by the Executive Director in order to empower the Governing Board to take appropriate actions, ensuring a balance between commitment from partners and openness.

Therefore, the annual work-plans of the Clean Hydrogen JU can include, at the level of call topics for key Innovation Actions of strategic importance[242], the additional condition[243] that requires the participation of a member of the Clean Hydrogen JU or their affiliate entities.

Such strategic topics may target activities where the industrial partners of the Clean Hydrogen JU can play a key role in accelerating the commercialisation of hydrogen technologies by being closely linked to the Clean Hydrogen JU constituency which could further ensure full alignment with the Strategic Research and Innovation Agenda of Hydrogen Europe and Hydrogen Europe Research and the SRIA. This would also ensure the continuity of the work performed within

[238] Article 17 (2) (m) of the SBA.
[239] Recital 16 and Article 15(2)(a) of the SBA.
[240] Article 17(2)(l) of the SBA.
[241] See also recitals 16 to 18 of the SBA.
[242] Key Innovation Actions of strategic importance are considered as justified cases.
[243] Recital 21 of the SBA.

projects funded through the H2020 and FP7, by building up on their experience and consolidating the EU value-chain.

It is crucial to secure that relevant project results are exploited fully in line with the commercialisation needs of the EU hydrogen industry with maximised cross-fertilisation of knowledge within the whole sector, which can be greatly facilitated by the presence of members or their affiliates of the Clean Hydrogen JU in the projects' consortia. Moreover, strengthened exchange of information between the sector players (through presence of members) will help avoid duplication of effort with other activities performed outside the Clean Hydrogen JU and contribute to a maximum coherence of the overall European technology investment and a maximum impact of the EU funding, in reaching the EU hydrogen Strategy final objectives.

As stated above for certain key innovation topics of strategic importance selected as described above such as flagship projects, there could be additional eligibility conditions for the consortium).

5.3. Types of action: specific provisions and funding rates

The call for proposals will distinguish between different levels of technology readiness and may consider decreasing funding rates or capping the funding from the EU/JU to be complemented by higher industry and/or research investment.

In consideration of the specific objective of the Clean Hydrogen JU to increase commitments and contributions in a qualitative and quantitative manner (see above), it is expected that private members should make a substantial share of their contributions at the level of indirect actions ('projects') funded by the Clean Hydrogen JU.

A key element of the Clean Hydrogen JU is therefore to leverage EU funding with contributions of private members. This will be achieved by a lower funding intensity of projects and a higher co-investment/co-funding of project participants/beneficiaries. For example, the Clean Hydrogen JU's programme may limit the funding for a flagship project, corresponding to higher industry (and research) investment or co-funding.

A flagship project is a project that is expected to have significant impact in accelerating the transition to a hydrogen economy. A limited number of flagship projects could be selected to become "Green Deal accelerator projects" to contribute to the European Green Deal objectives and that has identified on EU, national or regional level concrete synergies with other programmes and instruments such as partnerships (large impact is the main goal while the magnitude of investment is variable).

A number of flagship projects, without limitation in numbers, can be identified with the specific objective to demonstrate the viability of clean hydrogen solutions at scale, are actions (mostly Innovation Actions, but may also be strategic Research Actions) that constitute a first-of-a-kind demonstration at scale, in real operational environment of the different generations of hydrogen applications (including sectoral integration such as Hydrogen Valleys). Geographical balance should be ensured in the case of these flagship projects to ensure pan-European impact.

It is expected that after completion of such flagship project the hydrogen application(s) is/are fully demonstrated (including its business model) and if successful, can further enter the market deployment stage and be replicated at scale (or on a commercial basis). These projects will be implemented through Innovation Actions (or Research and Innovation Actions exceptionally) and may include some special characteristics i.e. a high total budget to achieve volume and scale, therefore limited funding and demanding a large co-funding from participants/beneficiaries such as industry (and consequently related strong involvement of most of the industrial players supporting the concerned hydrogen applications).

The exact limit of funding will be defined at the level of each annual work-plan for the relevant call topics, and should be based on the specific strategic agenda of the Clean Hydrogen JU and the related commitment of industry[244], and approved annually by its Governing Board.

For these flagship projects, where a reduction of funding will be applied, and where it is expected that important involvement from industrial stakeholders and/or end-users (such as public authorities) and corresponding contributions shall be made, synergies with other sources of funding and financing shall be sought[245]. In that respect, consortia will be encouraged to identify and secure additional funding and financing sources. The flagship topics may consequently require that proposals include a financing scheme describing the business model, including envisaged sources of co-funding/co-financing in line with state-aid rules.

In line with the SBA[246] in duly justified cases, the capital expenditure for, e.g. large scale demonstrators or flagship projects, may be considered as an eligible cost in line with the applicable legal framework and synergies with other partnerships apply.

Therefore, it is considered that in the flagship projects[247] where the activities may receive limited funding under the Clean Hydrogen JU, the full capital expenditure of equipment to be demonstrated should be considered as eligible costs. To this end, option 2 of section C2 of Article 6.2 "Specific eligibility conditions for each budget category" of the Horizon Europe Model Grant Agreement[248] would be enabled, at topic level, in the annual work-plan, in order to allow for the purchase of equipment, infrastructure and other assets specifically for the action to be declared as full capitalised costs.

5.4. Rules for participation

The Horizon Europe Regulation shall apply to the actions funded by the joint undertaking under Horizon Europe[249].

Each joint undertaking shall be considered as a funding body and shall provide financial support to indirect actions pursuant to Article 6 of that Regulation. In addition, actions funded by the JU under Horizon Europe may also be subject to any specific provisions set out in Part Two of the SBA, as well as in section 5 of the present document.

In accordance with article 3 of the SBA, in order to take into account the duration of Horizon Europe, calls for proposals under the joint undertakings shall be launched at the latest by 31 December 2027. In duly justified cases, calls for proposals may be launched by 31 December 2028, at the latest.

[244] As set out in the SRIA-HE/HER
[245] See articles on synergies in the SBA and Horizon Europe Regulations and section 4.1.
[246] Recital 18 of the SBA
[247] Flagship projects considered as dully justified cases.
[248] HE model grant agreement is followed mutatis mutandis by the Clean Hydrogen JU.
[249] Article 22 of the Horizon Europe Regulation.

6. Governance

6.1. Main actors: roles and representation

Under Horizon Europe the Clean Hydrogen JU will continue to be an industry led private-public partnership. The private sector will be represented by the Hydrogen Europe AISBL (the 'Industry Grouping') and the Hydrogen Europe Research AISBL (the 'Research Grouping'). The European Union will be represented by the Commission. Each of the Members will appoint its representatives at the Governing Board of the Clean Hydrogen JU.

The bodies of the Clean Hydrogen JU shall be:

(a) the Governing Board (GB);

(b) the Executive Director (ED);

(c) the States' Representatives Group (SRG); and

(d) the Stakeholders Group (SG).

The States Representatives Group and the Stakeholders group are advisory bodies[250].

6.2. Governing Board[251]

The GB is the decision-making body of the JU that decides on the long-term strategic orientation of the partnership, as well as its annual priorities. It has overall responsibility for the strategic orientation and the operations of the JU and supervises the implementation of its activities.

The GB is chaired by a representative of the private members with a representative of the European Commission as Vice Chairperson and constituted by representatives of the EC on behalf of the Union (50% of voting rights which are indivisible), six representatives of Hydrogen Europe (43% of the voting rights which are indivisible) and one representative of Hydrogen Europe Research (7% of the voting rights).

6.3. Executive Director [252]

The ED shall be the chief executive responsible for the day-to-day management of the joint undertaking in accordance with the decisions of the GB. The executive director shall be the legal representative of the JU. He or she shall be accountable to the GB of the JU.

He or she shall provide the GB with all information necessary for the performance of its functions. This includes in particular, the preparation and submission of the annual work programmes and the corresponding expenditure estimates for the joint undertaking to implement the SRIA and regular reporting on the progress of private members in achieving the targets on in-kind contributions to operational activities. The ED shall also establish a formal and regular collaboration with the European partnerships identified in the Strategic Research and Innovation Agenda, with priority on those mentioned in the SBA, and in accordance with the strategic orientation provided by the GB. The ED proposes activities that favour synergies with relevant activities and programmes at Union, national, and regional level and support and

[250] Section 3 Part One of the SBA
[251] Articles 17 and 82 of the SBA
[252] Articles 19 and 83 of the SBA

contribute to other Union initiatives related to hydrogen. He or she shall convene an annual European Clean Hydrogen JU forum. This may be organised jointly and/or in parallel with the European Hydrogen Forum of the Clean Hydrogen Alliance.

6.3.1. Programme Office[253]

The Programme Office set up by and operating under the responsibility of the ED will execute all the necessary tasks for the implementation of the mandate of the Clean Hydrogen JU. It shall in particular ensure the establishment and management of an appropriate accounting system in accordance with the financial rules for the JU;[254] manage the implementation of the work programme of the JU throughout the implementation cycle; provide to the members and the bodies of the JU all relevant information and support necessary for them to perform their duties; act as the secretariat of the bodies of the JU and provide support to advisory groups set up by the GB. In this regard, digital working methods including collaborative tools will be used to facilitate the work of the bodies in particular the GB and the SRG.

6.4. States Representatives Group[255]

The SRG of the Clean Hydrogen JU shall consist of up to two representatives and up to two alternate from each member state and of each associated country. The SRG shall be consulted and, in particular, it shall review information and provide opinions on the programme progress and achievement of the Clean Hydrogen JU's targets as part of Horizon Europe, including the information on calls for proposals results and the proposals evaluation process; on the updating of strategic orientation in line with the Horizon Europe strategic planning and with other Union and member states funding instruments; on the links to Horizon Europe and other Union, national and, where relevant, regional initiatives, including cohesion policy funds in line with smart specialisation strategies; on the work programmes and on the involvement of SMEs.

The SRG shall also regularly report to the governing board, and act as an interface with the Clean Hydrogen JU on relevant national or regional research and innovation programmes and identification of potential areas of cooperation, including the ERA pilot on Hydrogen,[256] specific measures taken at national level or regional level with regard to dissemination events, dedicated technical workshops and communication activities and deployment activities as well as national or regional policies and initiatives with the view to ensuring complementarities with regard to the Clean Hydrogen JU SRIA and annual work programmes.

The SRG shall submit, at the end of each calendar year, a report describing the national or regional policies in the scope of the JU and identifying specific ways of cooperation with the actions funded by the JU.

6.5. Stakeholders' Group[257]

The SG of the Clean Hydrogen JU shall be open to all public and private stakeholders, including organised groups, active in the field of the JU, international interest groups from member states, associated countries as well as from other countries. It shall consist of representatives of

[253] Article 19.6 of the SBA
[254] Link to the financial rules of the JU.
[255] Article 20
[256] https://www.bmbf.de/bmbf/shareddocs/kurzmeldungen/en/green-hydrogen-for-a-sustainable-future.html
[257] Articles 22 and 84 of the SBA

sectors which generate, distribute, store, need or use clean hydrogen across the Union, including the representatives of other relevant European partnerships, as well as representatives of the European Hydrogen Valleys Interregional Partnership and of the scientific community. The GB shall establish the specific criteria and selection process for the composition of the SG and shall aim to balance representation in terms of geographical distribution, gender, sector and stakeholders' expertise.

The SG shall also provide input on the strategic and the technological priorities to be addressed by the JU as laid down in the SRIA; provide suggestions to enable concrete synergies to take place between the JU and the adjacent sectors or any sector with which synergies are deemed of added value and provide input to the European Clean Hydrogen partnership forum and to the European Hydrogen Forum of the Clean Hydrogen Alliance.

It shall be regularly informed of the activities of the JU and shall be invited to provide comments on the JU's planned initiatives. The meetings of the SG shall be convened by the ED.

The ED may advise the GB to consult the SG on specific questions. Where such consultation takes place, a report shall be submitted to the GB after the relevant discussion in the SG.

7. Programme monitoring and reporting

The European Commission monitors the EU research and innovation framework through a systematic process of data collection, addressing in particular how the Horizon Europe programme is implemented. The activities of the joint undertakings are subject to continuous monitoring and periodic reviews in accordance with their financial rules, to ensure the highest impact, scientific excellence and the most efficient use of resources. The outcomes of monitoring and periodic reviews feed into the monitoring of European partnerships and evaluations of the Joint Undertakings as part of Horizon Europe evaluations. This provides the necessary evidence base to guide the effective and efficient implementation of partnerships throughout their lifecycle and inform the strategic discussions on the partnership policies.

To achieve that, all European partnerships need to establish a monitoring system that can track progress towards their objectives as set out in the SBA and the Horizon Europe Regulation, as well as the priorities of the Union and the SRIA.[258]

As part of this effort, the Clean Hydrogen JU will continuously monitor its management activities and perform periodic reviews of the outputs, results and impacts of its projects, implemented in accordance with the Horizon Europe Regulation. The monitoring shall be performed (a) via reporting on indicators towards the achievements of its objectives, and (b) by reporting information on a number of social, technologic and administrative indicators, including on its financial performance.[259]

A. Horizon Europe KIPs (Key Impact Pathways)

At the level of the Horizon Europe Programme, the monitoring will be simplified and standardised as much as possible. These indicators will be determined by the European Commission, which will also collect the necessary information on projects, their results and expected impact through its IT systems. This will allow to trace the contributions of the Clean Hydrogen JU to the Key Impact Pathways, set out in the Annexes of the Horizon Europe Regulation, through their projects automatically and in a consistent manner with the rest of the programme.

B. Partnership KPIs

At the level of partnerships, an Expert Group has been set up to support the Strategic Coordination Process, the new governance framework for EU R&I partnerships. In its first interim report,[260] the Expert Group focused on developing a framework for reporting and monitoring on the progress made by all forms of European partnerships – individually ('partnership-specific indicators') and as a whole ('common indicators'), while making sure it is aligned with the Horizon Europe monitoring system and its Key Impact Pathways.[261]

In particular, the Expert Group has proposed a set of common indicators for all the partnerships, including recommendations to make them operational, such as methodologies and identification of required data to monitor these indicators. The aim of these indicators is to

[258] Articles 5.2(h), 17.2(a), 19.4(f)/(g)/(o), 36, 74(a) and 171 of the SBA.
[259] Article 171 of the SBA.
[260] A robust and harmonised framework for reporting and monitoring European Partnerships in Horizon Europe, 2021, RTD, https://europa.eu/!b3TBfW.
[261] As stated in the executive summary of the interim report, the "proposed common indicators represent the best understanding of the Expert Group at the time this report is written, the Expert Group will continue its work until summer 2022… the Expert Group or the Commission may decide it is necessary to revise the proposal for the common indicators at a later stage".

monitor quantitative and qualitative information and aspects, which should be able to capture the full value the partnerships, an aspect not well developed in the past. The monitoring system and indicators defined are expected to be closely related to the data reporting system of the European Commission, although not all data will become available directly through its IT systems. In those cases, the JU will need to setup the appropriate processes for the collection and reporting of the data.

C. Clean Hydrogen JU Strategy Map and JU specific KPIs

The Expert Group also supported the partnerships in preparing their set of specific indicators intended to monitor the progress towards the achievement of its partnership specific objectives. To this end, the Expert Group prepared a set of guidelines with recommendations for the partnerships on how to establish and design the monitoring framework, as well as define the appropriate indicators. In particular, the Expert Group stated the view in its interim report that despite the usefulness of the generic monitoring frameworks reflecting the objectives set in the regulations, a more simplified and easier to communicate approach is required to simplify the multiple layers of objectives and monitoring frameworks. Moreover, these objectives tend to be policy objectives, often overlapping with each other and missing interlinks between the different levels, than the clearly defined, distinct, well-structured and measurable objectives that are needed for a monitoring framework.

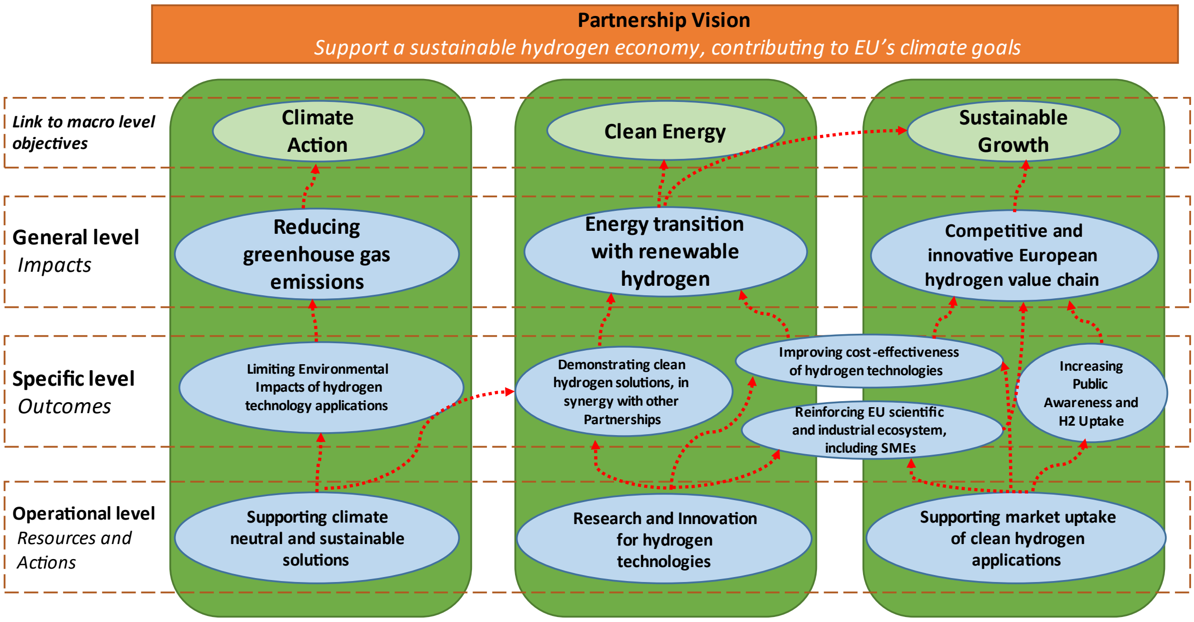
In practice, each partnership needs to meet a number of high level objectives: from the two sets of general objectives in the SBA (one for all partnerships and one for each specific partnership), to the objectives of the Horizon Europe Regulation and the policy objectives and priorities of the Union. The latter can be reflected to a large extent in the Key Strategic Orientations for research and innovation of the Horizon Europe Programme[262] and the relevant impact areas, and on an even higher level to the "2030 Agenda" and the associated SDGs. Each partnership can have an impact by contributing through its Programme to certain aspects of these high level objectives. The monitoring framework should thus be able to capture these efforts/actions, their outcomes and their subsequent impact.

The Clean Hydrogen JU, following these recommendations and in communication with the European Commission and the Expert Group, prepared a comprehensive set of indicators fitting the proposed framework. Following the proposed “Strategy Map logic” of the Expert Group, the proposed indicators aim to link the resources of the partnership and the actions taken (operational objectives / indicators) towards concrete outcomes (specific objectives / indicators) and directly to one (or more) of the general objectives and intended impacts of the Clean Hydrogen JU, which would contribute in turn to one or more high-level objectives of the Union.

Figure 3 below presents the JU’s strategy map, linking actions with expected outcomes and intended impacts. Annex I provides a detailed description of the KPIs that will be used to monitor them, as well as the link of the different items of the strategy map with the various JU objectives (the links are mentioned in the second column of the table in Annex I).

[262] https://op.europa.eu/en/web/eu-law-and-publications/publication-detail/-/publication/3c6ffd74-8ac3-11eb-b85c-01aa75ed71a1

Figure 3 Strategy Map of the Clean Hydrogen Joint Undertaking



It needs to be emphasised that the strategy map does not aim to replace the legal objectives of the JU, as reflected in the SBA and the Horizon Europe Regulation, but to restructure and further specify them, in order to be able to better define the relevant indicators for the monitoring framework, avoid overlaps and make more obvious the interlinkages between them.

More specifically, on the different levels of the strategy map:

(macro level objectives) Three high-level policy objectives, relating to major societal challenges, were identified as most relevant to the JU: Climate Action, Clean Energy and Sustainable Growth. These high-level objectives are linked with a number of SDGs, but one Key Strategic Orientation of the Horizon Europe Strategic Plan: making Europe the first digitally enabled circular climate neutral and sustainable economy, through the transformation of its mobility, energy, construction and production systems.

(general level impacts) The general level objectives of the JU should aim to have an impact towards the achievement of the above macro level objectives. The Clean Hydrogen JU has two sets of general objectives, as defined in the SBA:

a. On one hand, the general objectives applicable for all partnerships, which contribute in the key impact pathway categories (Scientific, Societal and Economic/Technological). These are made more specific in the context of Horizon's Europe Cluster 5 and its Strategic Plan, by linking them with impact areas (or "Destinations") and the expected impacts the JU could contribute in these areas. The relevant impact areas for the JU[262] are (22), (23) and (24), related to the clean energy transition and climate neutrality, as well as (15) concerning global leadership in clean and climate neutral value chains;

b. On the other hand, the general objectives of the JU are to contribute towards the Green Deal and the Hydrogen Strategy, to strengthen the Union clean hydrogen value chain, notable supporting SMEs, and to stimulate research and innovation in clean hydrogen technologies.

Combining the two sets of objectives above and placing them in the context of the macro level objectives leads to the three areas where the JU would be able to contribute the most:

1. Action against climate change by drastically reducing greenhouse gas emissions;
2. Transition to a clean energy system with renewable hydrogen as one of its main pillars;
3. Emergence of a competitive and innovative European hydrogen value chain.

Therefore the above form the general level impacts of the JU in its strategy map.

(specific level outcomes) The specific level objectives of the JU identify what should be the main direct outcomes and results from the activities of the JU. These should be contributing to the general level impacts of the JU. As in the case of the general objectives, the Clean Hydrogen JU has two sets of specific objectives, as defined in the SBA. They both focus on the acceleration of the transition towards the goals set by the Green Deal, the enhancement of the research and innovation ecosystem, including SMEs and involving stakeholders in all MS, as well as the delivery of innovative technology solutions and their uptake by the market, with the view to local, regional and Union-wide deployment.

On the basis of these objectives, seen in the specific context of the Clean Hydrogen JU, these were translated in the following specific level outcomes in the context of the strategy map:

1. Limiting the environmental impact of hydrogen technology applications;
2. Improving the cost-effectiveness of clean hydrogen solutions;
3. Demonstrating clean hydrogen solutions, in synergy with other Partnerships;
4. Increasing public awareness and uptake of hydrogen technologies;
5. Reinforcing EU scientific and industrial ecosystem, including SMEs.

The particular value of the above five points is that they turn the more general language of the specific objectives of the JU into more concrete, separated and measurable outcomes, that can be used for its monitoring framework. Moreover, they provide a clear link between the JU impacts and actions, offering the necessary consistency needed for the JU's strategy map as a whole.

(operational objectives and additional tasks) The bottom level of the strategy map describes the necessary actions and activities of the JU that will lead to the aforementioned outcomes. These should be in line with the operational objectives and tasks of the JU, as specified in the SBA, and fall in line with the activities described in the present SRIA:

1. Supporting climate neutral and sustainable solutions;
2. Research and Innovation for hydrogen technologies;
3. Supporting market uptake of clean hydrogen applications.

D. SRIA Technology KPIs

Further to the above monitoring activities, one of the tasks of the Clean Hydrogen JU defined in the SBA is to identify and report the knowledge acquired from the management of research and innovation projects and their results, to serve as input for monitoring, evaluating, and rectifying (if necessary) existing policy measures or shaping new policy initiatives and decisions. The progress of the research and innovation projects will be measured by comparing the results of the projects against the relevant technology KPIs proposed in the Annexes 2 to 6 of this SRIA. This shall help measure how the outcomes of Clean Hydrogen JU's R&D actions contribute towards the achievements of the technological objectives of each pillar. Moreover, the technology monitoring activity of the Clean Hydrogen JU will support EU policy making by providing timely information on the state-of-the-art and the achievements of the Clean Hydrogen JU. Technology monitoring shall be performed via the knowledge management activities described in Section 4.6, supported also by JRC.

The methodology for the selection and definition of the technology KPIs, as well as the identification of the SoA and future targets, was performed by JRC. The KPIs were defined so that they could address specific aspects for improvement of technologies or applications and are aligned with a given objective of the SRIA. They should be measurable, while future target values should be realistic, i.e. achievable related to the Programme objectives within the set timeframe, considering also the available resources.

The process of setting the KPIs was coordinated by the Programme Office and mobilised several working groups composed of experts from industry and research organisations designated by Hydrogen Europe and Hydrogen Europe Research. Each working group corresponding to a specific pillar of the SRIA followed the same methodology to evaluate the SoA in 2020 and set the KPIs targets for the years 2024 and 2030.

The methodology was based on draft forms including a clear definition of the KPIs, the boundary conditions and the sources of the data to ensure full transparency and traceability. The SoA was well-documented, with all associated references, and a justification was provided on how the future targets were agreed during the exercise. The sources included market surveys, literature reviews, expert opinions, data provided by OEMs either through field measurements or model calculation, learning curves, etc. Moreover, FCH technologies are often co-existing or competing with incumbent technologies. Hence, when defining KPIs, establishing SoA values and setting targets, the related performance of other technologies against these KPIs was also considered in order to be relevant and appropriate.

E. Financial Performance monitoring and reporting

The ED will report annually on the actions carried out and the corresponding expenditure, the proposals submitted, including breakdown per participant type, SMEs and country distribution, the actions selected for funding, the additional activities undertaken by its members other than the Union and the collaboration and synergies with other partnerships as well as national and regional initiatives[263].

Furthermore, the Clean Hydrogen JU PO will prepare annually the accounts and the report on budgetary and financial management[264].

The ED will also monitor and report regularly to the GB on the level of in-kind contributions to operational activities and the progress in achieving the targets and will propose measures to remedy if necessary[265].

The private Members of the Clean Hydrogen JU shall report each year by 31st of May to the GB on the estimated value of the in-kind contributions to additional activities incurred during the previous financial year.[266]

In addition, the Clean Hydrogen JU will carry out periodic reviews of its activities in line with Art.171.7 of the SBA.

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[263] Art.25.2 of the SBA
[264] Art. 25.3 and 25.4 of the SBA
[265] Art.19 of the SBA
[266] Article 11 of the SBA

8. Modern Administration

8.1. Objective of human resource management

Clean Hydrogen JU ensures an effective management of human resources aiming to optimise the capacity to deliver on the Clean Hydrogen JU's objectives and core business.

The Clean Hydrogen JU relies on a performance culture in which staff is motivated and can deliver work of a consistently high quality, adding value.

8.2. Main principles of the human resources management of the Clean Hydrogen JU

The Clean Hydrogen JU will ensure its organisational structure and staff allocation is adapted to its needs and priorities, allocating staff efficiently taking into account the talent and potential of staff and workload issues. It will pay special attention to staff development and to implementing new effective ways of working.

The Clean Hydrogen JU will foster modern working methods. The feeling of belonging to the Clean Hydrogen JU and of solidarity among colleagues is also crucial. It will build on the momentum and revive the principles of the FCH culture. It will also prioritise digitalisation in HR processes through further modules of the EC tool SYSPER when available to the Clean Hydrogen JU, adoption of MIPS (EC mission tool), implementation of SYSTAL (recruitment tool contracted and developed jointly with other JUs).

Diversity aiming at ensuring geographical balance where possible and gender balance will be important considerations in selection procedures, without compromising competency-related criteria.

Attention will also be paid to leadership development actions aimed at fostering a strong and inspiring management adapted to the new working environment. Engagement and wellbeing efforts will continue by implementing various actions (workshops, events, coaching, etc) and will be measured by periodic staff surveys.

Internal communication play an important role in staff management and staff engagement. Actions will include modernising and enhancing the intranet and the ways of communicating both through established channels (meetings, information sessions, etc) and through new tools (for example O365 package).

8.3. Staff establishment plan and human resources policy of the Clean Hydrogen JU

The staff establishment plan of the Clean Hydrogen JU comprises temporary agents, contract agents and seconded national experts. Other staff resources may include interim staff, trainees and structural service providers.

The human resources policy of the Clean Hydrogen JU will be implemented in accordance with SBA, the Staff regulations and conditions of employment of other agents of the EU and the related implementing rules adopted by the GB of the Clean Hydrogen JU.

8.4. Sound financial management

<u>Objective</u>: Resources to be used in accordance with the principles of sound financial

management[267]. Cost-effective controls to be in place, which give the necessary guarantees concerning the legality and regularity of underlying transactions.

8.4.1. Assurance and audit

Objective: *Ex-post controls, internal and external audits and reviews will continue to provide the Executive Director and the Governing Board with the elements underpinning the reasonable assurance that the resources assigned to the activities of the Clean Hydrogen JU have been used for their intended purpose and in accordance with the principles of sound financial management, and that the control procedures put in place give the necessary guarantees concerning the legality and regularity of the underlying transactions.*

In this context, the objective is that the Clean Hydrogen JU will apply an agreed-upon control framework, common to all Horizon Europe implementing services, laid down in:

i. 'Comprehensive control strategy for Horizon Europe';

ii. 'Common ex-ante control for Horizon Europe';

iii. 'Horizon Europe Ex-post audit strategy'; and

iv. 'Horizon Europe Antifraud strategy'

The Clean Hydrogen JU, in addition to implementation of the common framework, will apply the following strategies in different types of audits:

Ex-post audits

The aim for Horizon Europe is to exercise the risk-based approach and efficient use of resources in all stages of the Horizon Europe audit campaign. This includes prevention of double-auditing and building on the lessons learnt from the most common mistakes of the H2020 programme.

Internal Audits

The Clean Hydrogen JU will continue to support the Internal Audit Service (IAS) in conducting their audit and consulting engagements, with the aim to add value and to improve the effectiveness and efficiency of the internal controls in order to achieve strategic and operational objectives of the Horizon Europe programme.

Specific aim will be put on addressing the recommendations of the IAS stemming from their reports in a timely manner.

ECA, EPPO, OLAF audits

The Clean Hydrogen JU will provide support and assistance to the Court of Auditors, the European Anti-fraud Office and the European Public Prosecutor's Office in their on-the-spot checks, desk reviews, audits and investigations and will ensure timely follow up and implementation of the action plans stemming from these engagements.

8.4.2. Financial management

To demonstrate its commitment to the best use of financial resources, the Clean Hydrogen JU will aim for an error rate, over the course of the multiannual expenditure period, within a range of 2-5 % on an annual basis, with the ultimate aim to achieve a residual error rate as close as

[267] Art.71 of the Regulation (EU,Euratom) 2018/1046

possible to 2 % at the closure of the SRIA[268]. To meet this target, the JU will ensure sound financial management through the management of transactions. The JU will strive to attain effectiveness through update of its monitoring tools, workflows, procedures, guidelines, templates, check-lists, training sessions and additional guidance for actors in the financial circuits.

Another aspect of sound financial management is the relationship between the costs of controls and its benefits. The JU's control system will reflect the right balance between attaining an acceptable error rate and the control burden required, to avoid compromising on the attractiveness of the JU programme[269].

Furthermore, efficiency and cost effectiveness of financial activities will further improve thanks to the adoption of various corporate tools: eProcurement, SUMMA (accounting system).

The Clean Hydrogen JU will accurately assess the needs for financing the activities described above by assuring a close follow-up of the execution of budget, correcting the budget with transfers with the aim to reach 100% budget execution and subsequently provides detailed periodic reporting on the budget implementation to the management.

8.4.3. Internal control and risk management

Objective: The Clean Hydrogen JU will continue to reinforce processes designed to provide reasonable assurance of achieving the following objectives:

1) Effectiveness and efficiency of operations

2) Reliability of reporting

3) Compliance with applicable laws and regulations.

The Clean Hydrogen JU has set up and will further strengthen processes to ensure the adequate management of the risks relating to the legality and regularity of the underlying transactions, taking into account the multiannual character of its programme as well as the nature of the payments concerned.

Ethical and organisation values are embedded in the JU's internal control framework. Control system includes procedures for selecting the best projects through independent evaluation, ensures a robust project and contract management throughout the lifetime of every project, performs ex-ante checks on 100% of claims and includes ex-post audits on a sample of claims[270]. Specific attention will be placed in mitigating the inherent risk of conflict of interest[271].

8.5. Fraud risk management

Objective: The Clean Hydrogen JU is committed to the protection of the financial interests of the Union and the fight against fraud affecting these interests.

The JU applies 'mutatis mutandis' the common Research Family Anti-Fraud Strategy (RAFS) and the DG R&I AFS and participates to the Fraud And IRregularities (FAIR) meetings organized by DG R&I. The JU uses the EC IT tools for grant management, financial systems and procurement activity that encompass tools to prevent or detect fraud (such as for example

[268] Art. 2.2.3 of the Clean Hydrogen Legislative Financial Statement
[269] Art. 2.2.1 of the Clean Hydrogen Legislative Financial Statement
[270] Art. 2.2.1 of the Clean Hydrogen Legislative Financial Statement
[271] Art. 2.2.2 of the Clean Hydrogen Legislative Financial Statement

plagiarism, double funding, undisclosed conflict of interest). It is also vigilant in the management of external service providers and prioritises resilience against cyber-attacks.

It will continue to take actions including

- Emphasising the anti-fraud strategy and raising fraud awareness (through anti-fraud training and surveys)
- Making proficient use of tools for identifying double funding.
- Applying the preventive measures including the use of IT tools for detecting suspicious circumstances and know-how on how to identify irregularities.
- Including identifying and assessing fraud risk during the risk-assessment exercises

8.6. Document Management, digital transformation and information management

The Joint Undertaking is aligned with the vision of President von der Leyen for each EC organisation to lead by example in digital transformation. The Commission's Digital Strategy[272], adopted in November 2018 and the implementation Plan, approved by the Information Technology Cybersecurity Board (ITCB) in March 2020, is key to a transition to a new digital era and is clustered on the following pillars:

- paperless, streamlined procedures that use technology to remove mechanical tasks.
- improved access to and use of data to work more efficiently and be more transparent.
- staff collaborating efficiently and easily anytime, anywhere and with all stakeholders.

The Clean Hydrogen approach will be fully in line with the above pillars and will support the following objectives:

8.6.1. Information Management

Objective: The Clean Hydrogen JU will use a portfolio of secure, state-of-the-art corporate digital solutions

This portfolio is composed of many digital systems for administrative supports. The Directorates General own these systems and they are crucial for the efficiency and effectiveness of the JU as it automates its processes. It is essential that the Clean Hydrogen JU continues to use or adopt flagship digital solutions developed by DIGIT, such as for example: in the domain of human resources (SYSPER), document management (ARES), procurement (eProcurement), grants (eGrants), web presence (Next-EUROPA), citizens' engagement (EUSurvey), collaboration (AresBridge) and information systems which are:

- either connected to a managed service such EU LOGIN, EU SIGN, EU SEND or EU ACCESS or
- deploying a building block (via an EU Programme) such as eID, eSignature, eDelivery

In that context, the Joint Undertaking will continue to grow on the current IT Landscape, adopting the reusable solutions platform (RSP) as much as possible offered by the Commission and DIGIT to the Joint Undertakings were the costs efficiency on long term are obvious.

Objective: The Clean Hydrogen JU will exploit the potential of data, information, knowledge and content management for running the program, communication to citizens and stakeholders and

[272] https://ec.europa.eu/info/sites/info/files/file_import/digitally-transformed_user-focused_data-driven_commission_en.pdf

best staff engagement

Digital solutions already available to the Joint Undertaking facilitate the interaction with internal actors (collaboration, intranet, My IntraComm) and external stakeholders and citizens (web presence platform (Europa), collaboration, engagement (EU Survey), e-learning).

But we will keep also our autonomy to adopt specific digital solutions necessary to perform our tasks related to the administrative implementation of the program helping to the collecting of data's and reporting on the KPIs, or adopting new platform for sharing and reuse of information's that are not available directly to the Joint Undertakings from existing catalog of services.

8.6.2. Digital Transformation

Objective: The Clean Hydrogen JU will build a performing digital infrastructure and a fit-for-purpose Digital Workplace

Each staff member will benefit from a modern, individualised digital workplace remotely accessible, allowing for more flexibility and work-life balance. The digital ecosystem is supported by standardised and centrally managed IT equipment and support services as well as by cloud services. The adoption of emerging technologies will allow us to easily access data repositories in the cloud, mobile device integration, and the ability to participate in calls, videoconferences, and other collaborative workgroup from anywhere at any time.

Concerning the digital infrastructure, we will continue to consolidate the secure, hybrid infrastructure cloud services of the previous Joint Undertakings hosted in the White Atrium, which combines services running in the community cloud and in the public cloud, and rely on the secure pan-European networks for the Commission, executive agencies and other European institutions. We will further exploit and offer the reusable element to the other Joint Undertakings or interested agencies

Objective: The Clean Hydrogen JU will reinforce its resilience to ever evolving digital security threats

Cybersecurity is essential for modern, secure, and trustworthy IT both for the Joint Undertaking and in its interaction with outside stakeholders. The strategy sets four long-term objectives:

- IT security processes: To ensure that key IT security processes are in place, in line following good practices and recommendations.
- Monitoring and response: To ensure state-of-the-art monitoring and response capabilities, to detect attacks timely and resolve IT security incidents quickly.
- Infrastructure security: To provide a secured infrastructure by design.
- Governance and awareness: To ensure that senior management, IT experts and normal end-users are well informed about threats and risks.

Objective: The Clean Hydrogen JU will deliver modern, trustworthy, efficient, and transparent IT Governance

We will continue to invest in agile, transversal, and empowered IT Governance collaboration, with a bottom-up review platform for approval and delegate the project implementation to key IT services providers. Service level agreements already in place for the common digital infrastructure will be renewed and possibly extended to improve synergies and efficiencies among JUs. The execution of the Governance and the Business Continuity activities will be also supported by studies services such as advice, benchmarking, and high-level consultancy. We will also continue to participate in the representative user groups for corporate solutions, in the network of agencies for ICT Advisory and join any added-value interinstitutional framework contracts or inter-agency joint procurement.

Raising awareness and paying attention to change management related to the digital skills is essential. Our mind-set will evolve:

- Digitally skilled managers should lead by example.
- We will align management and culture with more collaborative, more transparent ways of working.
- The Clean Hydrogen JU will count and build upon digital skills of existing or new staff.
- And establish recommended IT training for all staff, leaving no-one behind.

8.6.3. Document Management

The Clean Hydrogen JU is keeping a close eye on the EC Digital Strategy[273] (ECDS) adopted to steer the digital transformation of the Commission. The Clean Hydrogen JU`s document management is a cornerstone and fully aligned with this transition towards a fully digitisation era.

Objective: *The European Commission electronic archiving and document management policy will apply by analogy in the Clean Hydrogen JU for automated registration, filing and preservation of records in a corporate tool*

The Clean Hydrogen JU applies "mutatis mutandis" the EC`s decision[274] and its implementing rules[275] on records management and archives (known as "e-Domec" policy). Its main implementation IT tool Hermes-ARES-NomCom will continue to interact with all the main operational and daily administrative activities and processes directly or indirectly via integrations in other IT tools

To achieve this objective the JU is planning to:

- embed modern record management in the processes
- ensure access to information and data by making registered records easily retrievable and as widely available as possible by their secure and systematic filing and preservation in Hermes/Ares/NomCom
- treat the pre-"e-domec" paper archives according to the Common Retention List of files, make inventories and apply actions of digitalisation, elimination or transfer to the Commission Historical Archives
- include staff upskilling and reskilling as part of the strategy to increase progressively the collective behavioural and culture change on document management
- raise staff awareness on efficiency gains such as that record management can create synergies

The Clean Hydrogen JU has already a significant digital solutions portfolio, which enables fast, effective and transparent policy implementation and monitoring of its activities within a modern paperless administration and "e-only" document and approval process environment, thanks to the "eSignature" CEF module already used.

Objective: *The Clean Hydrogen JU aim to take further advantages of any secure, interoperable digital solutions*

To achieve this objective:

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[273] https://ec.europa.eu/info/sites/info/files/file_import/digitally-transformed_user-focused_data-driven_commission_en.pdf
[274] https://ec.europa.eu/info/sites/info/files/c_2020_4482_en.pdf
[275] https://myintracomm.ec.europa.eu/sg/edomec/Documents/SEC_2020_800_en.pdf

- The document management and archiving policy of the Clean Hydrogen JU will then use more reusable corporate CEF building blocks and services (eArchiving, eDelivery, eTranslation, eInvoicing) or full electronic case handling (eGrants, eSubmissions, eSignatures and electronic certificates)
- The Clean Hydrogen JU will foster a culture of correct processing of shared information
- The JU will encourage the use of collaborative electronic tools with a more 'open, inclusive, cooperative, co-create, co-innovative and co-deliver way of working'
- The tools adopted will consider the right of access to documents, data protection, sharing information, data management and knowledge management aspects with a view to creating opportunities for efficiency gains, modernisation and improvements

8.7. Sound environmental management

<u>Objective</u>: The Clean Hydrogen JU will strive to improve its environmental impact in all its actions and will actively promote measures to reduce the related day-to-day impact of the administration and its work.

The Covid-19 crisis triggered the need to explore alternative working solutions, as the concept of a ‘new normal’ working landscape emerged. The Clean Hydrogen JU will redesign certain working, business, and organisational processes. We plan to transform the program office into a safe, modern and welcoming place to work, with good quality, sustainable and green solutions. Among others, we will contribute to the delivery and implementation of:

- paperless procedures and enablers (such as electronic signatures or eProcurement, supported by mobile apps enabling staff to work in a smarter, seamless way) that will be further improved and integrated at corporate level.
- remote work as integrated way of working.
- the use of modern technologies (such as “more wireless, less cables”, Wi-Fi everywhere, connected meeting rooms) can make the working place safer and easier.
- improving the ways to identify yourself with a single sign on (EU Login) enhance the security but also facilitate the access to any information.
- the use of web/videoconferencing-based meetings as valid sustainable alternative to staff missions and physical meetings, which represents a significant benefit in terms of environmental footprint, efficiency, and work-life balance.
- more dynamic approaches to the use of office space;
- investigate with the building owner the integration of new technology to make our actual building smart and eco-friendly.
- reducing and managing waste (sorting stations, glass containers, awareness raising campaigns).
- promoting green public procurement by introducing specific office supplies’ catalogues, including only 100% green items.

Annex 1 – Programme Level Key Performance Indicators for the Clean Hydrogen for Europe Joint Undertaking

Table 1 Programme Level Key Performance Indicators

CLEAN HYDROGEN JOINT UNDERTAKING - Monitoring framework							
Objectives		**Key Performance Indicators**	**Data sources and methodology used**	**Baseline and targets[276,277]**			
				Baseline	**2023**	**2025**	**2027**
Operational level resources and actions (Linked to the JU's objectives and additional tasks in the SBA and the strategy map)	Action-1 Supporting climate neutral and sustainable solutions *Link with SBA[278]:* *GO (a)/(b), SO (d)* *Link with Strategy Map:* *Outcome-1, Impact-1*	KPI-1a Share of JU budget supporting hydrogen end-use solutions in hard to abate sectors *Concerns projects with direct application in the industrial and heavy-duty transport sectors.[279]*	Data Source: Project data Methodology: Cumulative JU funding for relevant projects over total JU funding up to the reference year. Measurement Unit: % of JU budget	2.5	15	30	40

[276] Baseline values for KPIs (1a), (1b), (2), (3), (4), (9), (11), (12) and (13) refer to the achievement over the lifetime of the predecessor partnership (FCH 2 JU). Some of the values may go up to 2020, due to data unavailability at the moment of drafting the SRIA.
[277] Target values for KPIs (1a), (1b), (3), (4), (9), (11), (12) and (13) for the JU have been set based on relevant FCH JU data and trends, while considering the increased budget of the Clean Hydrogen JU and its new objectives.
[278] GO: General Objectives, SBA art 73(1); SO: Specific Objectives, SBA art 73(2); AT: Additional Tasks, SBA art 74.
[279] Note that certain projects may fall bother under KPI-1a and KPI-1b.

		KPI-1b Share of JU budget supporting circular and sustainable solutions *Concerns projects which include KPIs or objectives related to sustainability, recycling, circularity.*	Data Source: Project data Methodology: Cumulative JU funding for relevant projects over total JU funding up to the reference year. Measurement Unit: % of JU budget	<1	5	10	15
	Action-2 Research and Innovation for hydrogen technologies *Link with SBA:* *GO (a)/(b)/(d), SO (a)/(b)/(c)* *Link with Strategy Map:* *Outcome-2/3/5, Impact-2/3*	KPI-2 Early research projects *Share of JU budget supporting projects starting at TRL up to level 3.*	Data Source: Project data Methodology: Cumulative JU funding for relevant projects over total JU funding up to the reference year. Measurement Unit: % of JU budget	10	10	10	10
		KPI-3 Demonstration projects *Number of JU projects with a goal to end at least at TRL 7*	Data Source: Project data Methodology: Cumulative number of relevant JU projects. Measurement Unit: Number of Projects	43	20	40	60

	Action-3 Supporting market uptake of clean hydrogen applications *Link with SBA:* *GO (a)/(b)/(c), SO (b)/(c)/(d), AT (a)/(b)/(c)* *Link with Strategy Map:* *Outcome-3/4/5, Impact-3*	KPI-4 Education and training *Number of projects addressing education and training, including skills*	Data Source: Project data Methodology: Cumulative number of relevant JU projects. Measurement Unit: Number of Projects	4	2	4	6
		KPI-5 Monitoring technology progress *Qualitative indicator summarising related actions performed*	Methodology: Description of main actions performed in relation to the assessment and monitoring of technological progress. Measurement Unit: -	N/A	N/A	N/A	N/A
		KPI-6 Supporting European Commission in its activities targeting the market uptake of hydrogen *Qualitative indicator summarising related actions performed*	Methodology: Description of main actions performed in relation to: (a) JU's contribution to the development of regulations and standards, and (b) supporting the European Commission in its international initiatives on the hydrogen strategy. Measurement Unit: -	N/A	N/A	N/A	N/A

Specific level outcomes (Linked to the JU's specific objectives in the SBA and the strategy map)	Outcome-1 Limiting the environmental impact of hydrogen technology applications *Link with SBA:* *GO (a)/(b), SO (d)* *Link with Strategy Map:* *Impact-1*	KPI-7 Environmental impact and sustainability *Indicator which will cover different elements of sustainability such as LCA, CRMs, circularity, recycling, re-use, ecodesign, etc*	Data Source: Project data Methodology: Based on JU project data and deliverables, in combination with the work of the EHS&CP. Measurement Unit: TBD	TBD[280]	TBD	TBD	TBD
	Outcome-2 Improving the cost-effectiveness of clean hydrogen solutions *Link with SBA:* *GO (b)/(c), SO (a)/(d)* *Link with Strategy Map:* *Impact-2, Impact-3*	KPI-8a Capital cost of electrolysers *For selected technologies, based on projects funded by the JU*	Data Source: Project data Methodology: Capital cost for all relevant technologies, based on project results. Measurement Unit: €/kW	TBD[280]	TBD	TBD	TBD
		KPI-8b Capital cost of heavy-duty transport applications *For selected transport applications, based on projects funded by the JU.*	Data Source: Project data Methodology: Capital cost for all relevant applications, based on project results. Measurement Unit: €/kW	TBD[280]	TBD	TBD	TBD

[280] KPIs, including baseline and targets values, will be added as soon as the methodology/definition is determined. The methodology will be published on the website of the Clean Hydrogen Partnership.

	Outcome-3 Demonstrating clean hydrogen solutions, in synergy with other Partnerships and Programmes *Link with SBA:* *GO (b)/(d), SO (c)* *Link with Strategy Map:* *Impact-2*	KPI-9 Research and Innovation Synergies *Number of projects co-funded with other Partnerships, EU Programmes, Regional and National Funds.*	Data Source: Project data Methodology: Cumulative number of relevant JU projects. Measurement Unit: Number of Projects	5	5	10	20
	Outcome-4 Increasing public awareness and uptake of hydrogen technologies *Link with SBA:* *GO (b), SO (c)/(d)* *Link with Strategy Map:* *Impact-3*	KPI-10 Public perception of hydrogen technologies *Qualitative indicator based on a public opinion on hydrogen technologies and associated aspects.*	Data Source: Periodic Public Opinion Survey Methodology: The JU will conduct a periodic survey gaining insights into the public opinion concerning these aspects. Measurement Unit: -	N/A	N/A	N/A	N/A
		KPI-11 Total persons trained *Number of persons trained from projects funded by the JU.*	Data Source: Project data Methodology: Cumulative number of persons. Measurement Unit: Number of persons	4,163	1,000	3,000	6,000

	Outcome-5 Reinforcing EU scientific and industrial ecosystem, including SMEs *Link with SBA:* *GO (b)/(c)/(d), SO (b)/(c)* *Link with Strategy Map:* *Impact-3*	KPI-12 Patents and publications *Cumulative number generated by projects funded by the JU.* *For patents, due to the long time required for their approval, they will also include FCH JU projects.* *For publications they will be reported cumulatively as of 2022, with the initial publications stemming from FCH JU projects.*	Data Source: JRC (TIM), e-CORDA, CORTEX, FCHO, European Patent database, Project data Methodology: There is an inherent difficulty to collect all relevant data and associate them with specific JU projects. Therefore, these indicators will be reporting to the extent possible what can be identified in the sources above as linked to JU projects (which in many cases may not be possible).	12 / 289	17 / 100	20 / 250	25/ 450
		KPI-13 Promoting cross-sectoral solutions *Share of JU budget supporting projects covering more than one area of the hydrogen value chain*	Data Source: Project data Methodology: Cumulative JU funding for relevant projects over total JU funding up to the reference year. Measurement Unit: % of JU budget	15	10	15	25

General Level Impacts (Linked to the general objectives in the SBA specific to the JU, the priorities of the Union[281] and the strategy map of the JU)	Impact-1 Action against climate change by drastically reducing greenhouse gas emissions *Link with SBA: GO (a)* *Link with SDG: (12)/(13)* *Link with KSO:* *Expected Impact (22)* *Link with KIP:* *Societal Impact (4)*	KPI-14 Expected avoided emissions *For 2030 and 2050 based on the expected replacement of fossil fuels or fossil hydrogen feedstock by clean hydrogen in the sectors targeted by the JU.*	Data Source: Fuel Cell and Hydrogen Observatory (FCHO)[282] or study or desk research of existing studies Methodology: Economic analysis of emissions in the specific sectors, comparing prolongation of current technologies and fuels versus scenarios where the technologies developed by the JU projects can be scaled up and achieve their targets, replacing conventional technologies and fuels when it is economic to do so. *Note: The aim will be to assess the development of low carbon solutions and not to compare them versus other competing low carbon solutions.* Measurement Unit: Million tonnes of CO2-eq	TBD[280]	Targets, to be determined, will be set for 2030 and 2050.

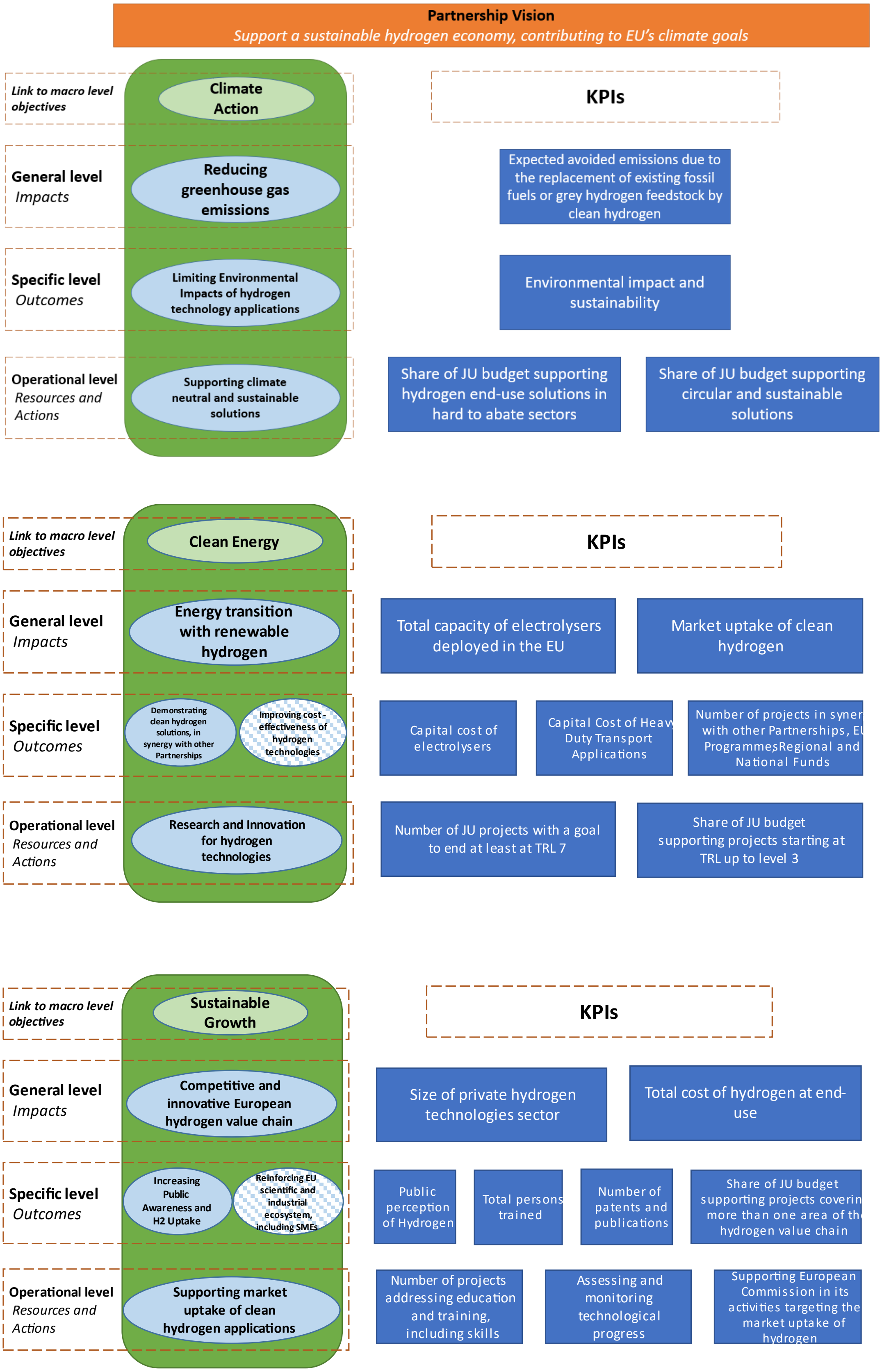
[281] As reflected by the UN's Sustainable Development Goals (SDG), as well as the Key Strategic Orientations KSO of the Horizon Europe Programme – including their impact Areas and destinations -, and the Key Impact Pathways (KIP) which will be used to monitor the implementation of Horizon Europe. In particular, the whole Programme of the JU falls under KSO (C): making Europe the first digitally enabled circular, climate neutral and sustainable economy. The relevant impact areas are (1) climate change mitigation and adaptation, (2) affordable and clean energy, (3) smart and sustainable transport and (4) circular and clean economy, each associated with more specific expected impacts of the Programme.

[282] https://www.fchobservatory.eu/

	Impact-2 Transition to a clean energy system with renewable hydrogen as one of its main pillars *Link with SBA: GO (a)/(b)/(c)/(d)* *Link with SDG: (7)/(11)* *Link with KSO:* *Expected Impact (22)/(23)/(24)* *Link with KIP:* *Societal Impact (4)/(5)* *Technological/Economic (7)*	KPI-15 Deployment of electrolysers *Total capacity of electrolysers deployed in the EU*	Data Source: FCHO, Project data Methodology: Aggregate the capacity of electrolysers deployed in EU, reporting also the ones that were funded by the JU. Depending on data availability, report if possible separately renewable hydrogen production. Measurement Unit: GW	1	4[283]	6	10
		KPI-16 Market uptake of clean hydrogen *Quantity of clean hydrogen consumed in EU.*	Data Source: FCHO Methodology: Total clean hydrogen consumed in the EU in the end-use sectors or used as feedstock. Measurement Unit: Mt of clean hydrogen consumed	0.155	0.7[283]	1	2
	Impact-3 Emergence of a competitive and innovative European hydrogen value chain *Link with SBA:GO (b)/(c)/(d)* *Link with SDG: (9)* *Link with KSO: Expected Impact (15)/(22)/(23)/(24)* *Link with KIP:* *Scientific (1)/(2)* *Societal Impact (6)* *Technological/Economic (7)/(8)*	KPI-17 Total cost of hydrogen at end-use *Final cost at end-use, including production and distribution.*	Data Source: FCHO Methodology: Calculation of final cost at end-use, ideally for different applications, based on a transparent methodology. Measurement Unit: €/kg	8	6.5[283]	5.5	4.5
		KPI-18 Size of hydrogen technologies sector. *Quantitative indicator, describing the situation of private companies active in the hydrogen sector.*	Data Source: FCHO Methodology: Present the developments in the hydrogen technologies sector, in the context of number of companies, size, financial assets (depending on availability)	N/A	N/A	N/A	N/A

[283] Targets based on EU's Hydrogen Strategy, Communication COM(2020) 301 of 8 July 2020, which includes targets for 2024 and 2030. Values for 2023, 2025 and 2027 based on interpolation.

Figure 4 KPIs used for the monitoring of Clean Hydrogen Joint Undertaking



Annex 2 - State-of-the-art and future targets – Renewable Hydrogen production

Table 2: KPIs for Alkaline Electrolysis (AEL)

No	Parameter	Unit	SoA	Targets	
			2020	2024	2030
1	Electricity consumption @ nominal capacity	kWh/kg	50	49	48
2	Capital cost	€/(kg/d)	1,250	1,000	800
		€/kW	600	480	400
3	O&M cost	€/(kg/d)/y	50	43	35
4	Hot idle ramp time	sec	60	30	10
5	Cold start ramp time	sec	3,600	900	300
6	Degradation	%/1,000h	0.12	0.11	0.1
7	Current density	A/cm^2	0.6	0.7	1.0
8	Use of critical raw materials as catalysts	mg/W	0.6	0.3	0.0

Notes:

(General for system): Standard boundary conditions that apply to all electrolytic 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. Correction factors may be applied if actual boundary conditions are different.

All KPIs are interdependent and should be met simultaneously.

KPI-1: Electrical energy demand at nominal hydrogen production rate of the system at standard boundary conditions, including energy required for cooling.

KPI-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.

KPI-3: Operation and maintenance cost averaged over the first 10 years of the system. Potential stack replacements are not included in O&M cost. Electricity costs are not included in O&M cost.

KPI-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).

KPI-5: Time required to reach nominal capacity in terms of hydrogen production rate when starting the device from cold standby mode.

KPI-6: 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.

KPI-7: Mean current density of the electrolysis cell running at operating temperature and pressure and nominal hydrogen production rate of the stack. Measured in Ampere per square centimetre (A/cm^2).

KPI-8: The critical raw material considered here is ruthenium for the cathode (mostly as RuO_2).

Table 3: KPIs for Proton Exchange Membrane Electrolysis (PEMEL)

No	Parameter	Unit	SoA	Targets	
			2020	2024	2030
1	Electricity consumption @ nominal capacity	kWh/kg	55	52	48
2	Capital cost	€/(kg/d) €/kW	2,100 900	1,550 700	1,000 500
3	O&M cost	€/(kg/d)/y	41	30	21
4	Hot idle ramp time	sec	2	1	1
5	Cold start ramp time	sec	30	10	10
6	Degradation	%/1,000h	0.19	0.15	0.12
7	Current density	A/cm^2	2.2	2.4	3
8	Use of critical raw materials as catalysts	mg/W	2.5	1.25	0.25

Notes:

General for system: 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. Correction factors may be applied if actual boundary conditions are different.

All KPIs are interdependent and should be met simultaneously.

(KPI-1) to (KPI-4): Similar conditions as for alkaline technology (Table 2).

KPI-2: CAPEX is based on the assumption of 100 MW manufacturing for a single company, as per current definition.

KPI-5: time required to reach nominal capacity in terms of hydrogen production rate when starting the device from cold start from -20°C.

KPI-6: 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.

Degradation and energy consumption KPIs are interdependent and should to be met simultaneously.

KPI-7: Mean current density of the electrolysis cell running at operating temperature and pressure and nominal hydrogen production rate of the stack.

KPI-8: These are mainly iridium and ruthenium as the anode catalyst (SOA 2.0 mg/cm^2) and platinum as the cathode catalyst (SOA 0.5 mg/cm^2).

Table 4: KPIs for Solid Oxide Electrolysis (SOEL)

No	Parameter	Unit	SoA	Targets	
			2020	2024	2030
1	Electricity consumption @ nominal capacity Heat demand @ nominal capacity	kWh/kg	40 9.9	39 9	37 8
2	Capital cost	€/(kg/d) €/kW	3,550 2,130	2,000 1,250	800 520
3	O&M cost	€/(kg/d)/y	410	130	45
4	Hot idle ramp time	sec	600	300	180

5	Cold start ramp time	h	12	8	4
6	Degradation @ U_{TN}	%/1,000h	1.9	1	0.5
7	Current density	A/cm^2	0.6	0.85	1.5
8	Roundtrip electrical efficiency	%	46	50	57
9	Reversible capacity	%	25	30	40

Notes:

(General for system): 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. Correction factors may be applied if actual boundary conditions are different.

All KPIs are interdependent and should be met simultaneously, except for reversible parameters which concern only reversible systems.

KPI-1: Electrical energy demand similar as for alkaline technology (Table 2). Heat demand is the heat absorption of the system at nominal capacity (mostly provided by steam).

KPI-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.

KPI-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.

KPI-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).

KPI-5: Time required to reach nominal capacity in terms of hydrogen production rate when starting the device from cold standby mode.

KPI-6: Degradation under thermo-neutral conditions (@UTN) 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. Testing time should be a minimum of 2000 h.

KPI-7: Mean current density of the electrolysis cell running at operating temperature and pressure and nominal hydrogen production rate of the stack.

KPI8: 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.

KPI-9: 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 5: KPIs for Anion Exchange Membrane Electrolysis (AEMEL)

No	Parameter	Unit	SoA	Targets	
			2020	2024	2030
1	Electricity consumption @ nominal capacity	kWh/kg	55	53	48
2	Capital cost	€/(kg/d)	2,250	1,200	600
		€/kW	1,000	550	300
3	O&M cost	€/(kg/d)/y	34	27	21
4	Hot idle ramp time	sec	30	15	5
5	Cold start ramp time	sec	1,800	450	150
6	Degradation	%/1,000h	> 1.0	0.9	0.5
7	Current density	A/cm^2	0.5	0.6	1.5
8	Use of critical raw materials as catalyst	mg/W	1.7	0.4	0

Notes:

General for system: 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. Correction factors may be applied if actual boundary conditions are different.

(KPI-1) to (KPI-7): Similar conditions as for alkaline technology (Table 2) and applying ISO 14687-2.

KPI-7: Only data from scientific papers available, target values for KOH based electrolyte < 1.0 %mol.

KPI-8: This is mainly IrOx as the anode catalyst and Pt/C as the cathode catalyst.

Table 6: KPIs for Flexible electrolyser operation

No	Parameter	Unit	SoA	Targets	
			2020	2024	2030
1	Ramp duration	sec	18	18	10
2	Stability	%	2.9	2.5	2.5
3	Ramp precision	%	1.9	0	0
4	Reliability	%	90	99	99

Notes:

KPI-1: Ramp duration (time) to reach full power

KPI-2: Stability in constant power sections,

KPI-3: The ramp precision is the percentage of data points outside of the desired range, linked to KPI 2, both KPIs are closely related because they describe the precision of power control of electrolyser systems

KPI-4: Percentage of operations following the ramping protocols that were successfully completed as described. linked to KPI 1 to 3. It is the success rate of following the protocols / procedures measured using KPIs 1 to 3.

Table 7: KPIs for hydrogen production from raw biogas

No	Parameter	Unit	SoA	Targets	
			2020	2024	2030
1	System energy use	kWh/kg	64	60	57
2	System capital cost	€/(kg/d)	1,250	1,150	1,000
3	System operational cost	€/kg	1.35	1.32	1.28

Notes:

KPI-1: The energy use here considers both heat and electricity. (N.B.: The electricity consumption is reported as an equivalent heat consumption considering a reference thermal-to-electricity conversion efficiency of 45%). The system energy use is based on the efficiency value of 51.7% related to a plant on Anaerobic Digestion (AD) based on steam reforming conversion process. It is considering the LHV as calorific value of the Hydrogen. The best steam reforming case with AD biogas (58% of CH4) and a plant size is 100 kgH_2/day, including Pressure Swing Adsorption (PSA) system.

KPI-2: Capital cost of the production plant per nominal daily production (€/(kg/d)). Capital cost should include all the cost related to all the equipment necessary for the normal operation of the plant. Plant size is 100 kgH_2/day. Output of hydrogen meeting ISO 14687-2 at a pressure of 20 bar and hydrogen purity 5.0. Clean biogas without H2S is assumed.

KPI-3: The value includes the expenditures for biogas and water, electrical and heat consumption, maintenance, spare parts, catalyst, adsorbent material and desulphurisation.

Table 8: KPIs for biological production

No	Parameter	Unit	SoA	Targets	
			2020	2024	2030
1	System carbon yield	kg H_2 / kg COD	0.012	0.015	0.021
2	Reactor production rate	kg $H_2/m^3/d$	7.5	15	>15
3	Reactor scale	m^3	3	10	100
4	System capital cost	€/(kg/d)	450	400	350
5	System operational cost	€/kg	3.2	3	2.5

Notes:

KPI-1: System carbon yield: Kg H_2 obtained from biomass fed to the reactor expressed in Kg COD (Chemical Oxygen Demand). Max theoretically obtainable is 0.041 KgH_2/kg.

KPI-2: kg H_2 produced per day per m^3 of reactor volume

KPI-3: Reactor size measured in m^3 of fermenter

KP-4: Capital cost of plant divided by the nominal hydrogen production. Capital cost includes all the cost related to all the equipment necessary for the normal operation of the plant. Based on an estimated production of 949,200 m^3 H_2 per year, therefore the capacity of the reference plant is 232 kg H_2/d.

KPI-5: Operation and maintenance cost averaged over the first 10 years of the system. Routine maintenance and "wear and tear" (rotating parts, cleaning of equipment...) considering a lifespan of 20 years. Costs such as water use, personnel and chemicals are included. The fermenter size is assumed as 200 m^3, treating 100 tons of food waste per day.

Table 9: KPIs for solar thermal production

No	Parameter	Unit	SoA	Targets	
			2020	2024	2030
1	Hydrogen production rate*	$kg/m^2/d$	1.13	2.16	4.11
2	System capital cost	k€/(kg/d)	29.99	15.19	7.41
3	System operational cost	€/kg	1.17	0.59	0.30

Notes:

* Boundary conditions: location with direct normal irradiation (DNI) of 2500 kWh/m^2/year. Output of hydrogen meeting ISO 14687-2 at a pressure of 15 bar and hydrogen purity 5.0.

KPI-2: System capital cost for a specific hydrogen production rate based on kg of hydrogen generated per day at a given cumulative DNI per year. Capital cost should include all the cost related to all the equipment necessary for the normal operation of the plant.

KPI-3: O&M cost averaged over the first 10 years of the system. Routine maintenance and "wear and tear" (rotating parts, cleaning of equipment, etc). Electricity costs for operation of auxiliary units included. System level losses such as heliostat collector area losses, replacement parts, operation, and maintenance are included in the cost calculations.

Table 10: KPIs for hydrogen production via waste/biomass gasification

No	Parameter	Unit	SoA	Targets	
			2020	2024	2030
1	System carbon yield	kg H_2 / kg C	0.15	0.22	0.32
2	System capital cost	€/(kg/d)	1,806	1,514	1,264
3	System operational cost	€/kg	0.013	0.011	0.009

Notes:

Boundary Conditions: the specific average gas composition considered for a typical product gas is: 40% H2, 24% CO, 23 % CO2, 10% CH4 and 3% C2H4. Output of hydrogen at a purity of 99.97% at 10 bar.

KPI-1: Ratio between the kg of H_2 produced from the gasification process and the kg of C present in the syngas product.

KPI-2: CAPEX considered includes investment costs for the chemical plant of a double bed fluidised gasifier. The value also includes the plant start-up expenses as 10% of the investment cost. Capital cost should include all the cost related to all the equipment necessary for the normal operation of the plant.

KPI-3: Operation and maintenance cost averaged over the first 10 years of the system. Routine maintenance and "wear and tear" (rotating parts, cleaning of equipment...) was estimated considering a plant life of 20 years. Feedstock and electricity costs are not included in O&M cost.

Annex 3 - State-of-the-art and future targets – Hydrogen storage and distribution

Table 11: KPIs for hydrogen storage

No	Parameter	Unit	SoA		Targets
			2020	2024	2030
	Underground storage – Depleted gas fields				
1	Capital cost	€/kg	n/a	10	5
	Underground storage – Salt Caverns				
2	Gas field size	ton (100% H_2)	880	>1000	>3000
3	Capital cost	€/kg	35	32	30
	Aboveground storage				
4	Storage size	ton	1.1	5	20
5	Capital cost	€/kg	750	700	600

Notes:

Depleted gas field: pressure hydrogen storage in a depleted gas field, around 1,000 and 2,000 meters below the ground

Salt cavern: underground hydrogen storage in a located between 1,000 and 2,000 meters below the ground level, pure H_2 considered (100% H_2)

Aboveground storage: hydrogen storage system formed by a vessel or group of vessels, built over a unique structure (rack, container, skeleton trailer, etc.) and shipped individually that is storing and supplying hydrogen as a single unit

KP-1: Capital costs include all necessary components to operate the storage system, including compression (120 bar) and purification. The costs are referred to the mass of hydrogen recovered from the storage.

KPI-3: Based on the working mass of hydrogen stored, pure hydrogen considered.

KPI-4: Storage density of more than 40 kg-H_2 per m^3 storage vessel. KPI applicable to compressed gas H_2, in spheres, tubes, pipes, per-stressed concrete containers, etc.

KP-5: Cost of the storage vessel including all necessary components to operate the storage system, including compression and purification, excluding pumping, liquefaction etc. The costs are reffered to the working mass of hydrogen

(KPI-4) and (KPI-5) should be reached together.

Table 12: KPIs for hydrogen carriers

No	Parameter	Unit	SoA	Targets	
			2020	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	4	2.5	<2

4	Hydrogen carrier specific energy consumption	kWh input/ kg H_2 recovered	20	17	12

Notes

Boundary Conditions: Assumed electricity price of 50€/MWh

KPI-1: Total quantity of energy required to convert normal hydrogen at 20 bar and 25 °C to liquid (para) hydrogen at 20 Kelvin and ambient pressure, expressed per kg of liquid hydrogen produced. This total quantity of energy includes electricity for compression drives, power requirements for (pre)cooling cycles and other pumping duties. Power recovery from expansion work from the LH_2 process may be subtracted from these power requirements.

KPI-2: Cost target for hydrogen liquefaction expressed as total cost attributable to the hydrogen liquefaction system as OPEX, as well as annualised CAPEX, per kg of hydrogen liquefied.

KPI-3: Total cost attributable to a hydrogen carrier system to supply, on average, 1000 tpd of Hydrogen over a round trip distance of 3000 km, expressed on a Per KG hydrogen delivered basis. Hydrogen supply conditions: 20 bar and ambient temperature, Hydrogen delivery pressure: 20 bar and ambient temperature, ISO14687 quality. Total cost includes Opex and Capex elements required, including cost for inventorising the supply chain, as well as operational make up cost due to carrier loss/degradation. The transportation cost includes the loading of the molecule, the cost of the transportation (including ship, fuel, personnel, maintenance...) and the unloading of the molecule to the on shore tank. To make it easy: "from on shore tank to on shore tank all inclusive.

KPI-4: Carrier energy consumption for 3000km distance. Boundaries: from hydrogen conversion into a dispatchable form to the hydrogen recovered, including carrier supply chain/degradation, except hydrogen production. Total quantity of energy required by the hydrogen carrier system (including shipping) to deliver hydrogen from supply point to delivery point under the boundary conditions as specified for KPI 3.

Table 13: KPIs for hydrogen transportation

No	Parameter	Unit	SoA	Targets	
			2020	2024	2030
	Hydrogen Pipelines				
1	Total capital investment	M€ /km	1.1	1	0.9
2	Transmission pressure	bar	90	100	120
3	H_2 leakage	%	na	0	0
	Road transport of compressed hydrogen				
4	Tube trailer payload	kg	850	1,000	1,500
5	Tube trailer CAPEX	€/kg	650	450	350
6	Operating pressure	bar	300	500	700
	Road transport of liquid hydrogen				
7	LH2 tank trailer payload	kg	3500	4000	4000
8	LH_2 tank trailer capex	€/kg	>200	200	100
9	LH_2 tank trailer boil-off	%/d	0.3-0.6 %	0.3	0.1
	Shipping of bulk liquid hydrogen				
10	On shore LH2 tank capacity (ports)	ton	300	700	7,000
11	Onshore LH2 containment tank capex	€/kg	100	70	<20
12	LH2 boil-off	%/d	<0.3	0.1	<0.1
13	LH2 ship tank capacity	ton	80	350	2,800

14	LH2 ship tank Capex	€/kg	na	50	<10
15	LH2 boil-off	%/d	na	0.5	<0.3

Notes:

General for pipelines: 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

KPI-1: For an 8-inch diameter pipeline, excluding right-of-way - 100% hydrogen new construction.

KPI-3: Percentage of hydrogen transported

KPI-4: Payload capacity = quantity of hydrogen contained in the trailer

KPI-5: CAPEX of the Lorry (excluding tractor), including cylinders' racks, chassis and piping interconnexion

KPI-6: Operating cylinder Pressure.

KPI-7: LH2 quantity in kg contained by the trailer. (This is practically equal to the LH2 delivered)

KPI-8: Lorry CAPEX, including chassis and valving system but excluding the tractor cost, Estimate is cost is representing the case where with hundreds of units per year.

KPI-9: Quantity of liquid hydrogen boiled off after a day as a percentage of the total payload. Lorry fully load - trailer in standby, stop in a parking place 2hrs (no motion) - The % loss is based on the nominal capacity.

KPI-10: Quantity in T of Hydrogen stored in one single storage. Concerning the tank capacity, please consider: 125 t = 1,500 m^3, 1,400 t = 20,000 m^3

KPI-11: Full CAPEX incl. installation. Scope includes all equipment and tank installation without civil work (too dependent of the location), without any compression system (pumps or others) and without the pipe connexion from the LH2 unit or to the loading system. Costs assumed for production of a few units per year for 2024 and few tenths per year in 2030.

KPI-12: The boil-off is measured as a percentage of the nominal capacity

KPI-13: Quantity in T of Hydrogen stored in one single storage, real quantity in the tank including "un pumping" inventory

KPI-14: Full CAPEX incl. installation, the scope is the storage only with all equipments (valves, support...) but not the ship

KPI-15: Potential usage of the boil-off is not considered at this point. All data are without this optimisation. % of the total capacity.

Table 14: KPIs for hydrogen distribution

No	Parameter	Unit	SoA	Targets	
			2020	2024	2030
Hydrogen compression					
1	Technical lifetime	year	10	14	20
2	Energy consumption pipeline (30 to 200 bar)	kWh/kg	3	2.5	2
3	Energy consumption HRS (5 to 900 bar)	kWh/kg	6	4	3
4	MTBF	h	25,000	40,000	60,000
5	OPEX pipeline OPEX HRS	€/kg	0.05 0.1	0.03 0.07	0.01 0.03
6	CAPEX for the compressor pipeline CAPEX for the compressor HRS	€/kW	1,300 7,700	1,000 5,600	650 3,500
Hydrogen purification					
7	Lifetime	y	5	10	20

8	Energy consumption - separation	kWh/kg	4	3.5	3
9	Energy consumption - purification	kWh/kg	3.5	3	2.5
10	Hydrogen Recovery factor	%	80	90	95
11	H_2 levelised cost purification	€/kg	1.5	1	0.5

Notes:

KPI-1: Time that a maintained compressor system, with its minor components/parts (no core) being replaced, is able to operate until End-of-Life (EoL) criterium is met. For mature technology (TRL≥6), the main EoL criterium is the optimisation of total cost of system (evaluated as TCO, total cost of ownership as CAPEX + n·OPEX(n), with OPEX dependent by time [year(n)] due to performance degradation). In mathematical terms, assuming a linear time degradation, lifetime is expressed in years as the square root of the ratio between CAPEX and yearly degradation (expressed as the yearly increment of maintenance and consumption cost due to the degradation of performance with respect to Beginning-Of-Life – BoL -, i.e., additional substitution spare parts). For emerging technology (TRL ≤5), EoL criterium assumes compression system (core parts) achieved the 90% of BoL performance (as compressed flow rate or pressure ratio).

KPI-2: Energy consumption to compress a kilogram of H2 from 5 bar(a) to 100 bar (without considering cooling power). Inlet pressure 5 bar(a), outlet pressure 100 bar(a) sufficient for most pipeline streams. This KPI is specifically for Pipeline application, and large-scale compression system (>1000 kg/d). Energy consumption needs only for the compression process, not include the cooling power. For mature tech (TRL≥6), KPI is focused on the system level, while for innovative tech (TRL ≤5), it regards the core part of technology.

KPI-3: Energy consumption to compress a kilogram of H_2 from 30 bar(a) to 900 bar(a). This KPI is specifically for HRS application, and mid-scale compression system (200-1000 kg/d). Energy consumption needs only for the compression process, does not include the cooling power. For mature tech (TRL≥6), KPI is focused on the system level, while for innovative tech (TRL ≤5), KPI regards the core part of technology.

KPI-4: Mean time between failure (or stoppage) of the system that render the system inoperable without maintenance. PI connected to the technology. Reliability should be estimated by sufficient failure events in proper long-term tests. For mature tech (TRL≥6), failure can be associated to rupture, wear, degradation of compressors parts which occurs without correct maintenance while for innovative tech (TRL ≤5), failure focus exclusively on the key element of technology (e.g., membrane, electrochemical cell, or active material)

KPI-5: Ratio of the maintenance costs, both fixed and variable (including overhaul cost, repair cost, replacement cost, maintenance cost) per unit of compressed hydrogen output. Energy cost is not considered. Values is estimated as the ratio of total O&M cost (typical as annual percentage of CAPEX) and the yearly amount of compressed hydrogen, considering compressor availability/operating time about 100% (8760 hrs.). Same boundaries conditions as for KP-2 and KPI-3 for pipeline and HRS.

KPI-6: Capital cost of manufacturing of the compressor device (capital cost of system) normalised to the daily nominal capacity of the system. Fluid is pure hydrogen compliance with ISO 14687:2019. Same boundaries conditions as for KP-2 and KPI-3 for pipeline and HRS.

KPI-7: Concerning purification system.

KPI-8: Energy consumption to separate hydrogen from mixture. This KPI regards separation process, where it is necessary to extract hydrogen from a mixture with low hydrogen content. (e.g. H_2 from gas grid). Energy consumption must take in consideration pressure and temperature requirements of the process. Additional efforts (compression, thermoregulation) should be taken in account to normalise the energy cost with respect to reference case (feed stream pressure 30 bar, temperature 300K). For mature tech (TRL≥6), KPI is focused on the system level, while for innovative tech (TRL ≤5), it regards the core part of technology. The feed/inlet H_2 molar fraction must be between 0.1 to 0.75. KPI should be evaluated with a minimum recovery rate of hydrogen about 80%. Output H_2 molar fraction must be > 99%

KPI-9: Energy consumption to purify hydrogen. This KPI regards purification process, where it is necessary to extract hydrogen from a mixture with high hydrogen content. (e.g. syngas). KPI for high TRL technology should be considered on the overall system, while it should be focused on the key components for low TRL technology. Energy consumption must take into consideration the technology's requirements for pressure or temperature. Additional efforts (compression, thermoregulation) should be taken in account to normalise the cost with respect to reference case (feed stream pressure 30 bar, temperature 300K).

KPI-10: Ratio between output purified hydrogen flow and hydrogen content into the input feed flow. For high technology TRL this regards overall purification/separation system. For low technology TRL, KPI focuses on the key elements of technology as membrane/electrochemical cell/active material. Output feed must be in compliance with ISO 14687:2019. Molar fraction in feed gas H_2 for separation application should be in range between 0.1-0.75 molar fraction in feed gas H_2 for purification application should be in range between 0.75-0.9995.

KPI-11: Levelised cost of separation or purification process, expressed as the cost for the processed mass of H_2 in kg. KPI focus exclusively for high TRL technology. Minimum hydrogen recovery factor is 80%. Output H_2 molar fraction must be > 99% or in compliance with ISO 14687:2019 for purification application, where it needs.

Table 15 KPIs for hydrogen refuelling stations

No	Parameter		Unit	SOA	Targets	
				2020	2024	2030
1	Energy consumption	700 bar 350 bar LH_2	kWh/kg	5 3.5 0.5	4 2.5 0.5	3 2 0.3
2	Availability	700 bar 350 bar LH_2	%	96 97 95	98 98 97	99 99 99
3	Mean time between failures	700 bar 350 bar LH_2	d	48 96 144	72 144 216	168 336 504
4	Annual maintenance cost	700 bar 350 bar LH_2	€/kg	1 0.66 1	0.5 0.35 0.5	0.3 0.15 0.3
5	Labour	700 bar 350 bar LH_2	person h/kh	70 42 70	28 17 28	16 10 16
6	CAPEX for the HRS 700 bar (200-1,000 kg/d)	700 bar 350 bar LH_2	k€ / (kg/day)	2-6 0.8-3.5 2-6	1.5-4 0.65-2.5 1.5-4	1-3 0.5-2 1-3
7	HRS contribution in hydrogen price	700 bar 350 bar LH_2	€/kg	4 2.5 4	3 2 3	2 1.25 2

Notes:

KPI-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 H2 at 700bar in GH_2 from a source of >30 bar hydrogen.

KPI-2: Percent of hours that the hydrogen refuelling station is able to operation versus the 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).

KPI-3: Mean time between failures (MTBF). How long the HRS will run before failing. A filling failure is stated when the fuelling cannot reach 80% of the reservoir capacity.

KPI-4: Parts and labour 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.

KPI-5: Person-hours of labour for the system maintenance per 1,000 h of operations over the station complete lifetime.

KPI-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 200-1,000 kg/d. CAPEX is dependent on the size of the station, the number of dispensers, the profile of consumption required, the need for buffers, the design.

KPI-7: Contribution of the HRS to the final cost of the hydrogen dispensed, amortisation and O&M costs included. Hydrogen production and transport is not considered. Public subsidies are excluded.

Annex 4 - State-of-the-art and future targets – Hydrogen end use: transport applications

Table 16 KPIs for fuel cell technology for Heavy-Duty-Vehicles

No	Parameter	Unit	SOA	Targets	
			2020	2024	2030
Fuel Cell Building Blocks					
1	FC module CAPEX	€/kW	1,500	<480	<100
2	FC module availability	%	85%	95%	98%
3	FC stack durability	h	15,000	20,000	30,000
4	FC stack cost	€/kW	>100	<75	< 50
5	Power density	W/cm^2	1 @ 0.650 V	High TRL 1.0@0.675V Low TRL>1.2@0.650V	High TRL 1.2 @ 0.675V Low TRL >1.5@ 0.650V
6	PGM loading	g/kW	0.4	High TRL 0.35 Low TRL < 0.30	High TRL 0.30 Low TRL < 0.25
Hydrogen on-board storage					
7	Storage tank CAPEX (CG H_2)	€/kg H_2	800	500	300
8	Storage tank CAPEX (LH_2)	€/kg H_2	n/a	320	245
9	Gravimetric capacity (CG H_2)	%	6	6.5	7
10	Conformability LH_2	%	40	45	55
11	Gravimetric Capacity LH_2	%	8	10	12
12	LH_2 tank volumetric Capacity	gH_2/l system	35	38	45

Notes:

KPI-1: FC module is defined as FC stack plus air supply system, cooling system, internal ECU, media manifold and other BOP (recirculation, humidifier, sensors, DCDC, etc). Based on an annual production rate of 2,500 units in 2024 and 25,000 units in 2030.

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

KPI-4: FC stack cost includes all the costs related to all components (materials, manufacturing, assembling) from electrodes to end-plates. Linked to FC stack durability, FC stack Power Density, PGM Loading.

KPI-5: Power density in W/cm^2 (referring to the active geometric area of the electrodes) at a defined cell voltage. Linked to FC stack efficiency, PGM Loading. Low TRL figures are also valid for all types of end-use applications, not only HDV vehicles (as per the Building Blocks, Section 3.4.1).

KPI-6: Ratio of the PGM loading (in mg/cm^2) over the power density (in W/cm^2) at a defined operating point in voltage. Linked to FC stack cost, FC stack Power density, FC stack efficiency. Low TRL figures are also valid for all types of end-use applications, not only HDV vehicles (as per the Building Blocks, Section 3.4.1).

KPI-7: Total cost of the CGH_2 storage tank, including one end-plug, the in-tank valve injector assembly assuming 200,000 units/year in 2030.

KPI-8: Total cost of the LH_2 storage tank, including one end-plug, the in-tank valve injector assembly assuming 200,000 units/year in 2030.

KPI-9: Mass of stored compressed gaseous hydrogen divided by the mass of the system (included mass of hydrogen), at tank system level. KPI-9: % of the available design space. In a given, cuboid space, the internal capacity of the tank uses only around 25% of the available design space. Idea of conformable tanks are being promoted, seeking to use up to 55% of the design space in 2030.

KPI-10: Ratio between the volume where the H2 fluid is stored and the corresponding parallelipedic volume in which the system has to be installed

KPI-11 Mass of stored liquid hydrogen divided by the mass of the system (included mass of hydrogen), at tank system level.

KPI-12: Mass of stored hydrogen (in grams) divided by the outer volume of the system (in litres)

Table 17 KPIs for Maritime

No	Parameter	Unit	SoA	Targets	
			2020	2024	2030
	Fuel Cells for ships				
1	FC power rating	MW	0.5	3	10
2	Hydrogen bunkering rate	ton H_2 /h	0	2	20
3	Maritime FCS lifetime	h	20,000	40,000	80,000
4	Product design reaching type approval	number	0	15	40
5	PEMFC system CAPEX	EUR/kW	2.000	1,500	1.000

Notes:

KPI-1: Power output of fuel cell based power generation (FC system output power)

KPI-2: Bunkering capacity of hydrogen in compressed, liquid form or as part of another hydrogen carrier (shore to ship infrastructure).

KPI-3: Lifetime of integrated fuel cell systems in maritime conditions and associated operation profile, not excluding the replacement of fuel cell stacks and system components at SoA intervals.KPI-4: Type approval on FC and H2 storage solutions. To allow products to be used for maritime propulsion beyond prototype phase, products need to be type approved.

KPI-4: Type approval is a procedure for the approval of the product design for compliance with classification or flag administration requirements. The type approval is a mandatory requirement for critical apparatus installed on any classified vessel.

KPI-5: CAPEX of PEMFC for shipping per kW of power at certain (low) production volume. FC module is defined as FC stack plus air supply system, cooling system, internal engine control unit, media manifold and other BoP (recirculation, humidifier, sensors, DC-DC converter, etc).

Table 18 KPIs for Trains

No	Parameter	Unit	SoA	Targets	
			2020	2024	2030
	Fuel Cells for Trains				
1	FC stack durability	h	15,000	20,000	30,000
2	FC stack cost	€/kW	n/a	n/a	<50
3	Areal power density	W/cm^2 @ V	n/a	1.0@ 0.675	1.2@ 0.675
4	PGM loading	g/kW	0.4	High TRL 0.35	High TRL 0.30 Low TRL < 0.25

				Low TRL < 0.30	
5	Number of starts	-	5,000	12,000	30,000
6	FC system availability (Uptime)	%	94	97	>99
7	Hydrogen consumption	kg/100km/ton	0.12	0.11	0.08
8	FC module volumetric density	kW/m³	n/a	53	>60
9	FC module gravimetric density	kW/ton	n/a	135	>160

Notes:

KPI-1: The durability target account for less than 10% performance loss at nominal voltage.

KPI-5: If we consider 16 h/day of operating hours at FC level and 5 start/stops during the day => 4,687 for 15,000 h.

KPI-6: Percent of time vehicle is in operation against planned operation and related to FC system

KPI-7: Hydrogen consumption for 100 km driven under operations using exclusively hydrogen feed. Based on standard cycle EN50591, unit => [kg/100km/ton]. Standard cycle is a flat profile (low demanding power, no heating, ventilation, and air conditioning)

KPI-8 and KPI- 9: FC system is defined as FC plus BoP (including cooling system). It excludes tanks and DC-DC converter

Table 19 KPIs for Aviation

No	Parameter	Unit	SoA	Targets	
			2020	2024	2030
	Fuel Cells for planes				
1	FC module durability	h	15,000	20,000	30,000
2	FC system efficiency	%	43.5	45	50
3	FC system availability	%	85	95	98
4	FC system gravimetric index	kW/kg	0.75	1	2
5	Tank gravimetric efficiency	%weight	12	16	35
6	Continuous fuel flow for FC aircraft	kg/s	na	50	180 for peak power 100 for cruise

Notes:

KPI-1: Durability target account for less than 10% performance loss at nominal voltage between beginning of life and end of life

KPI-2: Fuel cell efficiency at system level shall include stack and balance of plant (cathodic ancillaries incl. compressor, anodic ancillaries excl. H_2 storage, thermal management incl. heat exchanger, controls, excl. power converters). KPI target depend on application and will vary between a propulsive FC system for light aviation and SMR APU or hybridised power unit.

KPI-3: FC system availability is defined, in the case of aviation, by the ratio of successful system start. Global reliability of the system (i.e. in service failure rate/hour) will have to comply with conventional aviation certification KPI (10^{-9} failure/hour). Nevertheless, the efficiency as defined above (ratio of successful system start) is key for economic viabilityKPI-4: gravimetric density at system level shall include stack and balance of plant (cathodic ancillaries incl. compressor, anodic ancillaries excl. H_2 storage, thermal management incl. heat exchanger, controls, excl. power converters).

KPI-5: Gravimetric efficiency of storage tank, mass of stored hydrogen divided by the mass of the system (included mass of hydrogen). The system is based on a vacuum double layers tank technology. The tank volume target is more than 1 ton of LH_2, with minor boil-off after 2 days.

KPI-6: Continuous fuel flow supplied to the system during peak power / climb (15 minutes) and conventional operation of the aircraft (cruise- few hours), defined in kg/hr. A similar KPI may be set for turbine aircraft, as soon as the exact configuration is defined within Clean Aviation

Annex 5 - State-of-the-art and future targets – Hydrogen end use: stationary applications

Table 20: KPIs for SO stationary fuel cells (SOFC)

No	Parameter		Unit	SoA	Targets	
				2020	2024	2030
System						
1	CAPEX	<5 kWe 5-50 kWe 51-500 kWe	€/kW	10,000 10,000 10,000	6,000 5,000 5,000	3,500 2,500 2,000
2	O&M cost	<5 kWe 5-50 kWe 51-500 kWe	€ct/kWh	10 12 10	8 7 5	2,5 2.0 1,5
3.1	Electrical Efficiency η_{el}	<5 kWe 5-50 kWe 51-500 kWe	% LHV CH_4	35-55 (90) 55 (85) 55 (85)	55 (90) 58 (85) 60 (85)	55 (90) 62 (85) 65 (85)
3.2	Electrical Efficiency η_{el}	<5 kWe 5-50 kWe 51-500 kWe	% LHV H_2	47 (85)	52 (90)	57 (95)
4	Availability	5-50 kWe	%	99 98 98	99 99 99	99 99 99
5	Warm start time		min	15	10	2
Stack						
6	Degradation @ CI & FU=75%		%/1,000h	0.6	0.4	0.2
7	Stack production cost		€/kWe	4,000	2,000	≤800
Technology Related						
8	System roundtrip electrical efficiency in reversible operation		%	32	38	50

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. For KPI – 3.2 Input of hydrogen from pipeline (above 99%), tap water (if necessary) and ambient air; output of electrical power and heat. The selected power range exclude larger fuel cells at MW scale. Multi-MW scale fuels cells will consist of FC system modules of max 500 kWe. For reversible fuel cells running in electrolyser mode the KPIs defined under the hydrogen pillar for high temperature electrolysers can be used.

KPI-1: Capital cost are based on 100 MW/annum 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 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.

KPI-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.

KPI-3: Electrical efficiency 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.

KPI-4: The time a system was expected to operate minus the downtime, divided by the time a unit was expected to operate, expressed as a percentage. For micro-CHP demonstration, a minimum of ten units should be considered. For mid-scale or large-scale single units should be reported. Linked to O&M Cost (KPI-2): if maintenance interval is increased, then the availability of in base load running units will be also increased (i.e. 1 week in two years for maintenance).

KPI-5: Warm Start Time is equal to hot idling condition, when system is electrically disconnected and the connection will be restored again. This condition should cover grid disconnection events.

KPI-6: 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 intensity (CI) and fuel utilisation (FU) of 75%. For example, 0.125%/1,000h results in 10% power loss over a 10-year lifespan with 8,000 operating hours per annum. Values are for steady state operation. Minimum test time = 3,000 hours.

KPI-7: Stack production cost are based on 100 MW/annum production volume for a single company. Stack production costs doesn't include margins, distribution and marketing costs.

KPI-8: 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 21: KPIs for low temperature PEM stationary fuel cells (PEMFC)

No	Parameter		Unit	SoA	Targets	
				2020	2024	2030
System						
1	CAPEX	<5 kWe 5-50 kWe 51-500 kWe	€/kW	6,000 2,500 1,900	5,000 1,800 1,200	4,000 1,200 900
2	O&M cost	<5 kWe 5-50 kWe 51-500 kWe	€ct/kWh	10 10 5	8 7 3	4 3 2
3	Electrical Efficiency η_{el}	<5 kWe 5-50 kWe 51-500 kWe	% LHV	50 45 50	50 50 52	56 56 58
4	Availability	<5 kWe 5-50 kWe 51-500 kWe	%	97 97 98	97 97 98	98 98 98
5	Warm start time		sec	60	15	10
Stack						
6	Degradation @ CI		%/1,000h	0.4	0.2	0.2
7	Stack Production cost		€/kWe	400	240	150
8	Non-recoverable CRM as catalyst		mg/W_{el}	0.1	0.07	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.

KPI-1: Capital cost are based on 100 MW/annum production volume for a single company and on a 10-year system lifetime running in steady state operation, whereby 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.

KPI-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.

KPI-3: Electrical efficiency at beginning of life (η_{el}) 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.

KPI-4: (The time a system was expected to operate minus the downtime) divided by (the time a unit was expected to operate) expressed as a percentage.

KPI-5: Time required to reach the nominal rated power output when starting the device from warm standby mode (system already at operating temperature).

KPI-6: Stack degradation defined as percentage power loss compared to nominal rated power at BoL for fuel composition and utilisation specified by stack manufacturer at constant current (density). Minimum testing time of 3,000 hrs (4 months)

KPI-7: Stack production cost are based on 100 MW/annum production volume for a single company. Stack production costs doesn't include margins, distribution and marketing costs.

KPI-8: The critical raw material considered here is Platinum.

Table 22: KPIs for Turbines (DLE combustion)

No	Parameter	Unit	SoA 2020	Target 2024	Target 2030
1	H_2 range in gas turbine fuel	% mass	0 – 5	0 – 23	0 - 100
		% vol.	0 - 30	0 - 70	0 - 100
2	NO_x emissions		(30% vol H2)	(70% vol H_2)	(100% H_2)
		NO_x ppmv@15%O_2/dry	<25	<25	<25
		NO_x mg/MJ fuel	31	29	24
3	Max. H_2 fuel content during start-up	% mass	0.7	3	100
		% vol.	5	20	100
4	Max. efficiency reduction in H_2 operation	% points	10@30% H2	10@70% H2	10@100% H2
5	Minimum ramp rate	% load / min	10@30% H2	10@70% H2	10@100% H2
6	Ability to handle H_2 content fluctuations	% mass / min	±1.4	±2.21	±5.11
		% vol. / min	±10	±15	±30

Notes:

KPI-1: Hydrogen percentage content in gas turbine fuel, by mass (volume).

Boundary Conditions: applicable only to DLE technology. WLE technologies are not in scope. While state-of-the-art gas turbines can already handle 20% hydrogen by vol (blended in natural gas), development of gas turbines (and more specifically combustors) able to handle 0-100% H_2 is a challenging and necessary task. Gas turbines operating in the range 0-100% H_2 are required by users in the power generation market to ensure security of power supply in case of H_2 shortages or lack of availability. Development of such combustors can be reached by gradually increasing the amount of H_2 in gas turbines in the years to come to reduce technical risks.

KPI-2: NO_x (NO + NO2) content in exhausts.

Boundary conditions: A fuel switch to hydrogen aims to retain all present strengths and ensure carbon-free energy conversion. Although the technological development of GT combustors aims to minimise NO_x emissions, an increase in NO_x formation is expected as the hydrogen content in the fuel is increased. This is a consequence of the higher reactivity of hydrogen and the related impact on flame stability, flame temperature etc. Conserving the same low-NO_x emissions level of 25 ppmv@15%O2/dry when advancing from 30% (by volume) to 100% H_2 remains a challenge. The conventional NO_x normalisation method (15%O2/dry) is not designed to be translated across different fuels with different reactivity and exhaust gases. A more appropriate normalisation for NO_x emissions is expressed in mg/MJ of fired-power, and therefore the KPI table also provides this alternative normalisation.

KPI-3: Hydrogen content during gas turbine start-up.

Boundary conditions: during start-up gas turbines are commonly fuelled with natural gas or liquid oil.

KPI-4: Reduction in electric efficiency of power plant when hydrogen-firing of the gas turbine is introduced (overall efficiency of power plant may be unaffected or increased through CHP schemes)

Boundary conditions: Evaluated at Full Speed Full Load condition. It refers to combined cycle gas turbines with bottoming steam cycle (CCGT). For the SoA, the actual maximum efficiency reduction is class-specific and largely depends on the class of the gas turbine.KPI-3: H_2 content during gas turbine start up (during start up gas turbines are commonly fuelled with natural gas or liquid oil)

(KPI-4) and (KPI-2) are interdependent, increasing efficiency may increase NO_x emissions, thus these two parameters require optimisation.

KPI-5: Percentage variation per minute of the gas turbine load with respect to the full load

KPI-6: Gas turbine ability to operate stably when facing unexpected H_2 content in fuel. Evaluated with respect to nominal H_2 content in fuel composition (blend of natural gas and H_2).

Annex 6 - State-of-the-art and future targets – Cross-cutting issues

Table 23: KPIs on recycling processes

No	Parameter	Unit	SoA	Targets	
			2020	2024	2030
1	Minimum CRMs/PGMs (other than Pt) recycled from scraps and wastes	%	n/a	30	50
2	Minimum Pt recycled from scraps and wastes	%	n/a	95	99
3	Minimum ionomer recycled from scraps and wastes	%	n/a	70	80

Notes:

KPI-1: [amount recycled]/[amount present in the whole system (including main equipment and BoP)] in %

KPI-2: amount of Pt recycled from FC/ electrolysers at end-of-life

KPI-3: amount of ionomer recycled from FC/electrolysers at end-of-life

These recycled rate values refer to a TRL 7 (system prototype demonstration in operational environment)

Table 24: KPIs for Education and Public Awareness

No	Parameter	Unit	SoA	Targets 2024			Targets 2030		
			2020	Tier 1	Tier 2	Tier 3	Tier 1	Tier 2	Tier 3
Education									
1	Trained pupils in primary and secondary education	No	1,300	9,000	4,000	3,000	23,000	12,000	11,000
2	Trained professionals	No	1,000	50,000	7,500	5,000	120,000	40,000	20,000
3	Universities/ Institutes offering courses on hydrogen	No	12	300	100	40	550	200	200

Notes:

(General) These KPI's consider different awareness levels in the EU based on the HyLaw analysis, target are set for each of the 3 tiers:

- Tier 1 countries: Germany, Denmark, United Kingdom and France;
- Tier 2 countries: Belgium, Netherlands, Austria, Sweden, Norway, Finland, Latvia, Spain and Italy;
- Tier 3 countries: rest of EU countries and associated countries

KPI-1: Number of trained pupils (primary and secondary education).

KPI-2: Number of trained professionals (qualified workers, technicians and engineers).

KPI-3: Number of educative centres and/or universities offering higher education course modules and/or fully dedicated educational programmes on hydrogen and/or fuel cells (included in existing curricula and not full academic diploma on hydrogen exclusively).

Table 25: KPIs for Safety, PNR & RCS

No	Parameter	Unit	SoA	Targets	
			2020	2024	2030
1	Projects with proactive safety management	%	0	80	100
2	Safety reporting	%	10	80	100
3	Safety, PNR/ RCS Workshops	No/ y	1	2	4
4	Impact on standards at scope	No/ project	0.6	0.9	1

Notes:

KPI-1: Critical projects with pro-active safety management, including a periodically reviewed safety plan, educational measures, monitoring, etc. in percentage. Critical projects will be identified by the European Hydrogen Safety Panel, which will also assess the project safety management.

KPI-2: Projects reporting on safety (no events, near misses, incidents, accidents). Definitions of near-miss, incident, and accident according to EIGA document (INCIDENT/ACCIDENT INVESTIGATION AND ANALYSIS SAC Doc 90/13/E). Off-normal conditions to be reported in HIAD2.0 and/or HELLEN databases.

KPI-3: Number of safety workshops (e.g. on research priorities, risk assessment, end-use safety, etc.) and/or PNR/RCS workshops (e.g. permitting procedures for end-use installations, gaps analyses in specific aspects of the supply chain, etc.) at the programme level.

KPI-4: Number of Standards, Technical Specifications or Technical Reports at the scope of a PNR project. The impact will be measured after the end of the project, because of the different timelines of a PNR project and the SDO activities.

Annex 7 – Common R&I Roadmaps

The Clean Hydrogen JU co-operated closely with other partnerships in an effort to align their work Programmes and identify synergies. When possible, they developed common Roadmaps, aiming to better coordinate the planned activities per partnership in the context of R&I in hydrogen technologies. This common planning should prevent overlaps, enable synergies and lead to a more effective allocation of funds towards hydrogen technologies in the context of the Horizon Europe Programme.

This Annex presents the commonly developed Roadmaps with the following partnerships:

- Processes4Planet (P4P)
- Clean Steel
- 2ZERO
- ZEWT
- Clean Aviation
- EURAMET
- EIC
- EERA

Additionally, and in the same context, the Clean Hydrogen JU had exchanges with Europe's Rail partnership, ERA on Green Hydrogen and BEPA identifying possible synergies in their Programmes. The discussions with Europe's Rail partnership are at an advanced level, but a Common Roadmap has not been established yet (until the adoption of the SRIA). The discussions with BEPA have not identified significant areas of collaboration at first stage, but the two partnerships will inform each other on any developments relevant to both. The exchanges with ERA on Green Hydrogen have identified a large potential for collaboration of the JU with ERA / Member States in many topics, so exchanges will continue to update each other on the topics/results from both programs, and potentially align topics (and complement funding) in future calls for proposals.

Further exploratory meetings will be pursued both with the above partnerships, but also with other partnerships and programmes, such as B4P, to ensure that the actions that are funded by each programme are complementary.

Processes4Planet partnership

A strong collaboration is envisaged across the whole hydrogen value chain between the Clean Hydrogen JU and P4P partnership. The Clean Hydrogen JU focuses on the development of fuel cell and hydrogen related technologies (e.g. electrolysers, fuel cells, H2 storage) whilst P4P focuses on the adaptation of industry processes to accommodate the integration and demonstration of such technologies. Key to this collaboration are the synergies between the Clean Hydrogen JU "H2 Valleys" and the P4P "Hubs for circularity". As some of the R&I areas are common to both a clear allocation of responsibilities in the work programmes to come will be essential to avoid overlaps and maximise the impacts the Clean Hydrogen JU and P4P can bring. An overview of the division of areas between P4P and Clean Hydrogen JU is provided in the table below.

Table 26 Envisioned distribution of responsibilities between Clean Hydrogen JU and P4P partnership

<table>
<tr><th>Research Area</th><th>Clean Hydrogen JU</th><th>P4P</th></tr>
<tr><td>H_2 in industry</td><td>Next generation of electrolysers for industry
Co-electrolysis for synthetic fuel production</td><td>Adaptation of processes to accommodate integration with electrolysers including valorisation of both H_2 and O_2 integrated to large underground H_2 storage
Integration of co-electrolysis plants in industrial processes demanding CO/CO_2</td></tr>
<tr><td>H_2 for heat, industrial boilers</td><td>Actions aiming at filling gaps not addressed by P4P</td><td>Development of H_2 burners for boilers
Oxy-combustion
NH_3 boilers</td></tr>
<tr><td>H_2 turbines</td><td>Combustion physics & dynamics in gas turbine operation with pure hydrogen.
Retrofitting of existing gas turbines to 100% H_2</td><td>Hosting H_2 turbines demonstrations for industrial processes
NH_3 turbines</td></tr>
<tr><td rowspan="2">Alternative hydrogen production routes</td><td colspan="2">Photoelectrocatalysis</td></tr>
<tr><td>Thermo-chemical splitting or Small scale distributed plants operating on biomass or biogas</td><td>Large scale gasifiers and pyrolysis plants operating on biomass or natural gas</td></tr>
<tr><td>Hydrogen storage</td><td>Above and underground H_2 storage</td><td>Hosting on-site buffer storage to ensure uninterrupted production of industrial processes</td></tr>
<tr><td>Alternative Hydrogen Carriers</td><td>LOHC & ammonia as an energy carrier including dehydrogenation
NH_3 fuel cells</td><td>Ammonia, ethanol and methanol production/synthesis.
NH_3 as fuel in combustors or burners, but also in some metallurgical processes.</td></tr>
<tr><td>Separation and Purification of H_2</td><td>Membrane based separation of H_2 from natural gas at downstream level.
Purification leading high purity H_2 for Fuel Cell applications.</td><td>Membrane separation technology development.
H_2 purification technologies</td></tr>
<tr><td>Flagship projects</td><td colspan="2">Joint efforts between the Clean Hydrogen JU and P4P, together with other funding programmes, could lead to the installation of 100MW+ scale electrolysers in industrial environment.
Synergies between the Clean Hydrogen JU “H2 Valleys” and “P4P” Hubs for circularity</td></tr>
</table>

Clean Steel partnership

The steel and hydrogen industries have both a lot to gain in terms of upscaling electrolysers to the GW scale, supplying enough green hydrogen to achieve low-CO_2 direct iron ore reduction through hydrogen. This is evident in the synergistic Work Plans of the two partnerships. Clean Hydrogen will focus on the development of electrolysers, including high temperature electrolysers that can use waste heat from the iron processes and Clean Steel will focus on converting the smelting process to iron ore reduction using hydrogen. Hydrogen and Oxygen produced from electrolysis can also be used in high temperature combustion processes with suitable combustors. Safety and education related aspects of this transition are of importance to both partnerships.

An overview of the task division between the Clean Hydrogen JU and the Clean Steel partnership is provided in the table below.

Table 27 Envisioned distribution of responsibilities between Clean Hydrogen JU and Clean Steel partnership

Research Area	Clean Hydrogen JU	Clean Steel
Direct Iron Ore reduction using hydrogen	Scaling up and further developing PEM and Alkaline electrolysers. Thermal integration of Solid Oxide electrolysers	Modifying the iron production process to use Hydrogen as a reducing agent. Energy management/ Integration of electrolysers in steel plant.
High temperature processes	Hydrogen and Oxygen production.	Development of suitable burners, modification of melting and smelting processes.
Safety	PNR to support performance testing standardisation. European Hydrogen Safety Panel.	Safety issues in electrolysis processes and hydrogen application in general.
Education, training	Education and training at all levels, included training for industries available.	Upskill/support of staff regarding handling new safety issues (e.g. handling of hydrogen).

Synergies with 2ZERO partnership

A strong collaboration is envisaged between Clean Hydrogen JU and 2ZERO as both partnerships will deal with the development and deployment of hydrogen and fuel cells trucks.

The Clean Hydrogen JU will focus on the development of fuel cells system components starting from low TRL research activities to the development of commercial products. Components include stacks, module, BoP, tanks and the overall FC system.

The 2ZERO partnership will focus on the integration of the fuel cell system in heavy-duty vehicles and the demonstration activities of these prototypes. Large demonstration activities fall within the remit of the Clean Hydrogen JU, as well as the development and deployment of hydrogen refuelling stations.

An overview of the task division between 2ZERO and Clean Hydrogen JU is provided in the table below.

Table 28 Envisioned distribution of responsibilities between Clean Hydrogen JU and 2ZERO

Research Area	Clean Hydrogen JU	2ZERO

Fuel Cells	Actions related to FC stacks and FC modules. Leading actions on FC system in collaboration with 2ZERO.	Actions on FC system in collaboration with the Clean Hydrogen JU.
FC Trucks Components & Integration	Strong Collaboration between the two partnerships on onboard storage and powertrain integration. The Clean Hydrogen JU to lead the work on onboard storage, while 2ZERO the work on powertrain integration.	
Demonstrations	Strong Collaboration between the two partnerships, with 2ZERO leading on the work for a Prototype demo, while the Clean Hydrogen JU leading the actions for a large scale demo.	
Other	Actions on H2 infrastructure and End of Life.	

Synergies with Zero Emission Waterborne Transport partnership

A strong collaboration is also envisaged between the Clean Hydrogen JU and ZEWT.

The development of the different technologies (e.g. fuel cells and tanks for hydrogen and zero carbon hydrogen-derivative fuels) will be performed by the Clean Hydrogen JU following the specifications set in coordination with ZEWT.

ZEWT will address technology integration, implementation and validation, for both maritime and inland large scale shipping, while the Clean Hydrogen JU would focus on smaller scale maritime and inland shipping.

The Clean Hydrogen JU will also address technology transfer from land application of H2 technologies (FC, tanks or refuelling infrastructure) as a prospect of rapid deployment, initiating demonstration projects to validate technologies.

Regarding bunkering of alternative fuels at ports, i.e. standards, technical and operational solutions, the Clean Hydrogen JU will focus on carbon-free fuels, and ZEWT would address carbon neutral fuels.

An overview of the task division between the Clean Hydrogen JU and ZEWT is provided in the table below.

Table 29 Envisioned distribution of responsibilities between Clean Hydrogen JU and ZEWT

Research Area	Clean Hydrogen JU	ZEWT
Alternative fuels supply	H2 production, storage and supply to the port	Non-H2 production, storage and supply to the port
Ports and bunkering of alternative fuels	Standards, technical and operational solutions for carbon free fuels (H2, NH3, and LOHC)	Standards, technical and operational solutions for carbon neutral fuels (MeOH, and others)
Alternative fuels on-board storage	Development of dedicated H2 tanks	Development of dedicated non-H2 tanks (e.g. MeOH and NH3)
Fuel Cell (including	Development of dedicated SO and	For large scale fuel cells, integration

dedicated fuel system)	PEM fuel cells for maritime applications Adaptation of the FC stack and components to maritime requirements For small scale fuel cells, integration in the ship and demonstration	in the ship and demonstration
Safety / Regulation	All aspects linked to carbon free fuels (H2, NH3, and LOHC)	All aspects linked to carbon neutral fuels (MeOH, and others)

Synergies with Clean Aviation partnership

A strong collaboration is envisaged between Clean Hydrogen JU and Clean Aviation partnership.

The development of the different technologies (e.g. fuel cells and liquid hydrogen tanks) will be done in Clean Hydrogen JU following the specifications set in conjunction with Clean Aviation partnership.

The integration of these technologies into ground and later on flying demonstrators will be in the scope of Clean Aviation partnership.

All technologies related to the airport hydrogen infrastructure will be developed and tested under Clean Hydrogen JU, although the interface with the airplanes for refuelling will need strong coordination.

An overview of the task division between Clean Aviation partnership and Clean Hydrogen JU is provided in the table below.

Table 30. Envisioned distribution of responsibilities between the Clean Hydrogen JU and Clean Aviation partnership

Research area	Clean Hydrogen JU	Clean Aviation
LH2 logistics	Production Logistics to the airport Logistics in the airport (including synergies between aircraft usage and ground usage)	Refuelling technology
Storage in the aircraft	Development of dedicated LH2 tanks in link with other applications	Definition of fuel line and tank integration
Fuel Cell (including dedicated fuel system)	Development of a dedicated fuel cell for propulsive applications, with a target of 1.5+ MW Adaptation of the FC stack to aviation requirements	Adaptation of the FC-stack to aviation requirements, including heat management, handling fuel on board 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	Development of dedicated turbine (including fuel lines) Integration in the aircraft

	developments)	Ground and in-flight demos
Safety / Regulation	All aspects linked to fuel logistics	All aspects linked to aircraft operations
Environmental aspects	Well-to-Wake GHG balance	Non-CO2 effects

<u>Synergies with EURAMET</u>

On the topic of hydrogen metering two main actions have been foreseen within the Clean Hydrogen JU's multi-annual work plan:

- Development of a greater accuracy within hydrogen sensors and flow meters;
- Integration of innovative metering, piping and instrumentation technologies into the overall hydrogen innovation actions.

It is therefore considered opportune to explore potential synergies and joint actions with EURAMET aiming to accelerate the global lead of Europe in metrology research. Exploratory meetings will be pursued to ensure that the actions that are funded by each programme are complementary and to determine if there are any possibilities for jointly funded actions.

<u>Synergies with the European Innovation Council and the European Energy Research Alliance</u>

A strong collaboration is envisaged with the EIC and the European Energy Research Alliance (EERA) mainly on low-TRL research activities.

The implementation of the Clean Hydrogen JU Programme could benefit from the basic research performed through the EIC programme in the field of hydrogen technologies.

Breakthrough research on other routes of renewable hydrogen production, hydrogen storage, building blocks of hydrogen use in transport applications and reducing the loading of critical raw materials in electrolysers and fuel cell is expected to be done by EIC, complementary to the Clean Hydrogen JU projects. Successful research outcomes will be taken over and further advanced by the Clean Hydrogen JU calls.

Additional synergies are also emphasised with the EERA's Joint Programme on Fuel Cells & Hydrogen related to research areas on electrochemical aspects of water electrolyser and fuel cell and non-electrochemical hydrogen production, handling and storage through the 7 sub-programmes of the Implementation Plan 2018-2030 such as:

- Electrolyte materials for low and high temperature fuel cells and electrolysers;
- Next generation of highly active, low cost and durable catalysts/electrodes;
- Cost effective manufacturing of manufacturing of stack materials and novel design development;
- Development of innovative fuel cell system concepts;
- Better understanding of the physico-chemical processes through modelling, validation and diagnosis;
- Cost effective and efficient hydrogen production and handling, including the development and implementation of new codes and standards

- Different technologies for hydrogen storage.

An overview of the possible areas of collaboration between Clean Hydrogen JU and EIC/EERA is provided in the table below.

Table 31. Potential synergies between Clean Hydrogen JU and EIC/EERA on low-TRL research activities

Research area	Clean Hydrogen JU	EIC	EERA
Electrolysis	Electrodes, membranes and cell designs PGM-free or low-PGM for water electrolysis Environmental impact and circularity Alkaline, PEM, SO, AEM, PCC electrolysers Others possibility of non-pure water electrolysis Understanding performance / durability mechanisms	Thin Film Reversible Solid Oxide Cells for Ultra-compact electrical Energy Storage Spin-polarised Catalysts for Energy-Efficient AEM Water Electrolysis	Electrolytes Catalysts and electrodes Stack Materials and Design Modelling, Validation and Diagnosis
Other routes of renewable hydrogen production	Biomass & bio-waste gasification Pyrolysis Biological production Electro-hydrogenesis Direct solar	Producing hydrogen from low temperature methane (from biogas) decomposition (MD) Novel routes to green hydrogen production	Non-electrochemical hydrogen production: Biomass/Biowaste, Algae, Water Thermolysis, Photocatalyis Safety, Codes and Standards for Other Hydrogen Production Methods
Hydrogen Storage	New concepts of large scale storage Advanced materials for hydrogen storage	Shaping Covalent Organic Frameworks for Industrial Applications Making hydrogen easy to deliver Highly efficient Power Production by green Ammonia total Oxidation in a Membrane Reactor	Different Hydrogen Storage Technologies
Building blocks for hydrogen use in transport applications	FC disruptive technologies Low or free-PGM loading	Novel screening method to find efficient fuel cells that rely on cheap	Electrolytes Catalysts and electrodes Stack Materials and Design Modelling, Validation and Diagnosis

	High-pressure tanks Novel storage concepts Understanding performance / durability mechanisms	materials Light to Store chemical Energy in reduced Graphene Oxide for electricity generation	
Heavy-duty vehicles	New design of HDV systems Disruptive FC concepts for HDV	Converting combustion engines from fossil fuel to hydrogen burners	
Stationary Fuel Cells	New cell materials and stack technologies Advanced reversible cell concepts Understanding performance / durability mechanisms		FC systems, looking at developments on both system and component level, including development of innovative fuel cell system concepts, decreased costs of components, prolonged life-time and availability of components.
Turbines, boilers and burners	Gas turbine operation with pure hydrogen	Modular Plants for Renewable Chemical Products	
Education and public Awareness	Educational and public understanding and acceptance E-learning materials	Active Living Infrastructure	