Hydrogen Europe

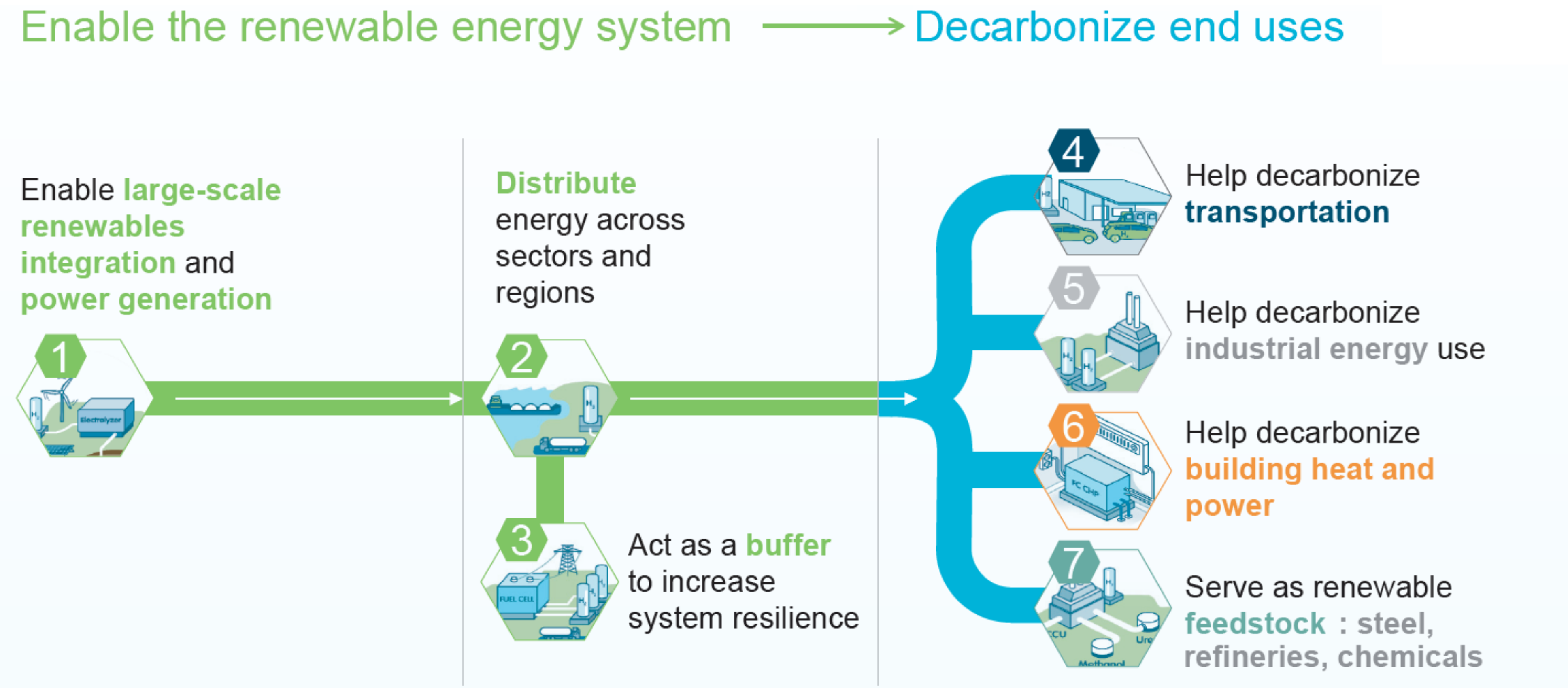
HYDROGEN, ENABLING A ZERO EMISSION EUROPE

TECHNOLOGY ROADMAPS FULL PACK

September 2018

Hydrogen enables the decarbonization of all major sectors in the economy

Hydrogen can enable a full renewable energy system, providing the sector integration needed for the energy system transition and decarbonize energy end uses



SOURCE: Hydrogen Council

Projections for Europe indicate that 5 million vehicles and 13 million households could be using hydrogen by 2030, while a further 600kt of hydrogen could be used to provide high grade heat for industrial uses. In this scenario, **hydrogen would be abating 80Mt CO_2 and account for an accumulated overall investment of $62B (52B€) and 850,000 new jobs**.

To achieve this vision, the sector needs to achieve a range of 2030 targets

1. A diversity of clean hydrogen production routes have matured, *producing hydrogen at a cost of €1.5-3/kg, allowing penetration into mass markets .*

2. Hydrogen production enables increased penetration of 100’s of MWs of renewable electricity.

3. Hydrogen can be moved to target markets at low cost.

Transport costs <€1/kg at scale.

4. An affordable zero carbon fuel can be delivered to fuel cell transport applications, *with total fuel cost below diesel, taking into account taxation.*

5. Fuel cell vehicles (road, rail, ships) are produced at a price equivalent to other vehicle types, *with a compelling user case.*

6. Hydrogen meets demands for heat and power at a meaningful scale, with:

- 25 TWh of hydrogen blended into the natural gas grid
- Fuel cell CHP efficiency contributes to reducing energy usage, with 0.5 million FC CHP units deployed in the EU.

7. Hydrogen is actively displacing fossil fuels as a clean energy input into a wide range of industrial processes:

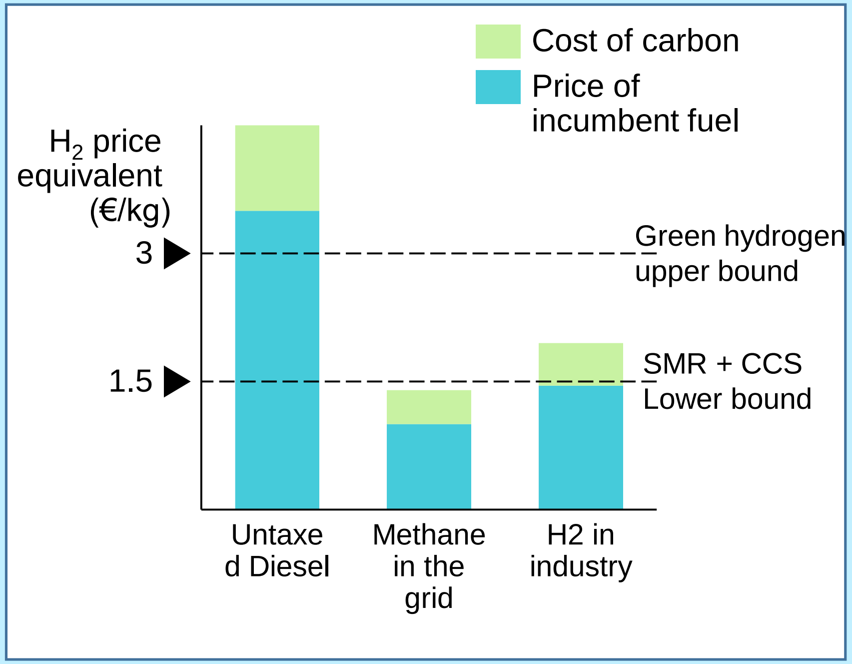
- 8TWh of hydrogen used for industrial heat.
- Clean hydrogen replaces conventional fossil-fuel derived hydrogen.
- Replacing other fossil fuels e.g. coke in the steel making process, methanol production etc.

8. Regulations, standards and training/education programmes are supporting the transition to a hydrogen economy.

By achieving these targets, clean hydrogen can be produced and distributed to markets **at competitive prices…**

Production costs for clean H_2 compete with conventional fuels

Hydrogen produced at a cost between €1.5-3/kg is competitive with conventional fuels for transport applications amongst others once a 2030 carbon price is taken into account[1]. These prices are viable for SMR with CCS[2] and for electrolysis (assumptions as per roadmap targets).



Distribution costs for centralised H_2 production are lower at scale

Some hydrogen will be produced in large centralised production plants for access to low-cost renewable energy. The distribution costs need to be minimised to ensure the fuel remains competitive.

Transport of hydrogen at scale is expected to cost at most €1/kg

On-site hydrogen production offers an alternative

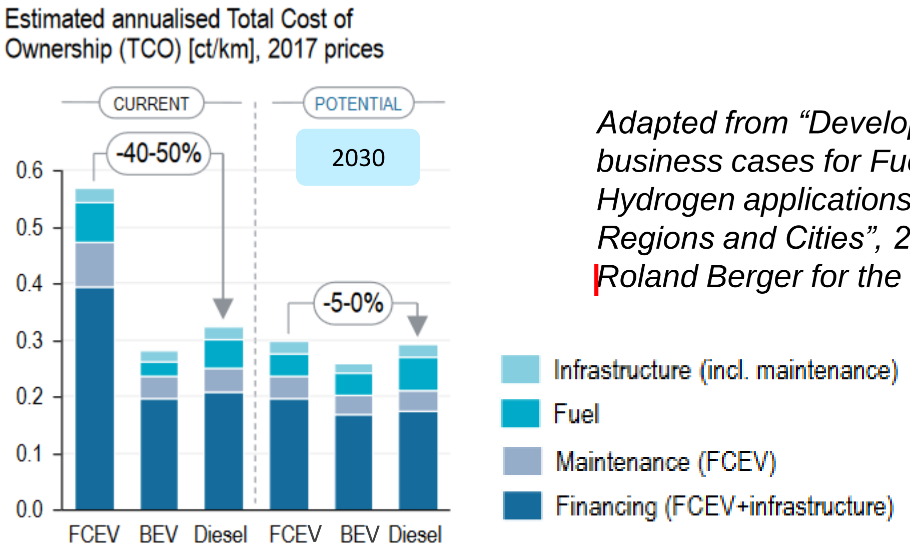
In some locations, decentralised hydrogen production may offer a lower cost route. Distribution costs are avoided, but production costs may be higher at smaller scales. The best solution will be location-specific.

A commercially competitive energy vector

1 – 2030 CO2 price of €55/tonne based on "Closing the gap to a Paris compliant EU-ETS" by Carbon Tracker, 2018
2 - Assuming €40/tonne transport and storage cost for the CO2

…. prices that are competitive in a range of applications that are key to decarbonising Europe's economy

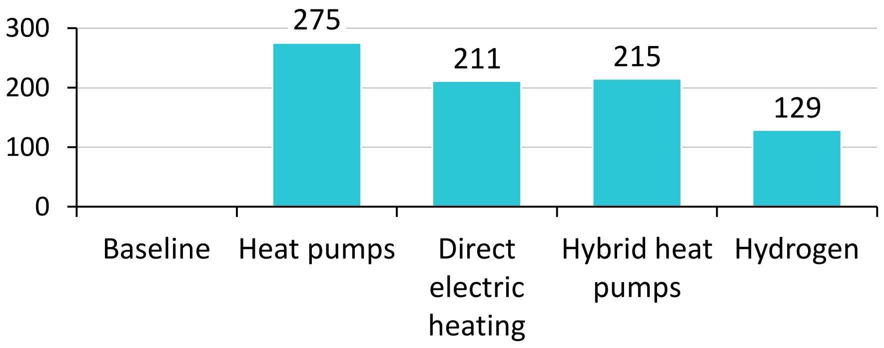
Transport – for example, FC cars are projected to achieve cost parity with diesel at commercial production volumes at a H_2 cost of €5/kg.



Adapted from "Development of business cases for Fuel Cell and Hydrogen applications for Regions and Cities", 2017, Roland Berger for the FCH-JU

Industry and gas – clean H_2 as a feedstock can reach parity with fossil-based inputs once the cost of carbon is included.

Net cost of CO_2 abatement for different options for decarbonising heat
€/tonne CO_2



Adapted from data in "Cost analysis of future heat infrastructure options" Report for the UK National Infrastructure Commission, 2018. Data = whole system costs for 4 options & cumulative carbon emissions from heat, €/£ = 1.14

Buildings – fuel cell CHPs are high efficiency and can reduce energy use and associated CO_2 emissions even in advance of grid decarbonisation. Hydrogen may be the lowest cost way to decarbonise the gas grid.

Developing these technologies is an essential part of meeting many of Europe's policy goals….

We are confident that this vision for hydrogen's role in the 2030 energy system is achievable. With the right support, the hydrogen option can be competitive and mature by 2030, and a vital tool to meet some of Europe's key policy aims:

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

1. Clean Energy for all Europeans is being provided by a diversity of clean hydrogen production routes. *Clean hydrogen provides 8% of required emissions reductions between now and 2030, and 25% by 2050.*

2. Renewable energy targets are being met and energy market design is improved due to the role of hydrogen in supporting the energy system.

Hydrogen production directly results in an additional 20-40 GW of renewables on the grid, equivalent to 5-10% of today's RES-E capacity.

4. & 5. Fuel cell vehicles are improving environmental outcomes in all transport sectors, contributing to the aims of:
- the Clean Vehicle Directive.
- CO_2 emissions standards.
- the Alternative Fuels Directive.
- Roadmap to a Single European Transport Area on maritime & aviation emissions.
Hydrogen is fuelling at least 5 million clean vehicles (1.5% of total EU fleet) by 2030.

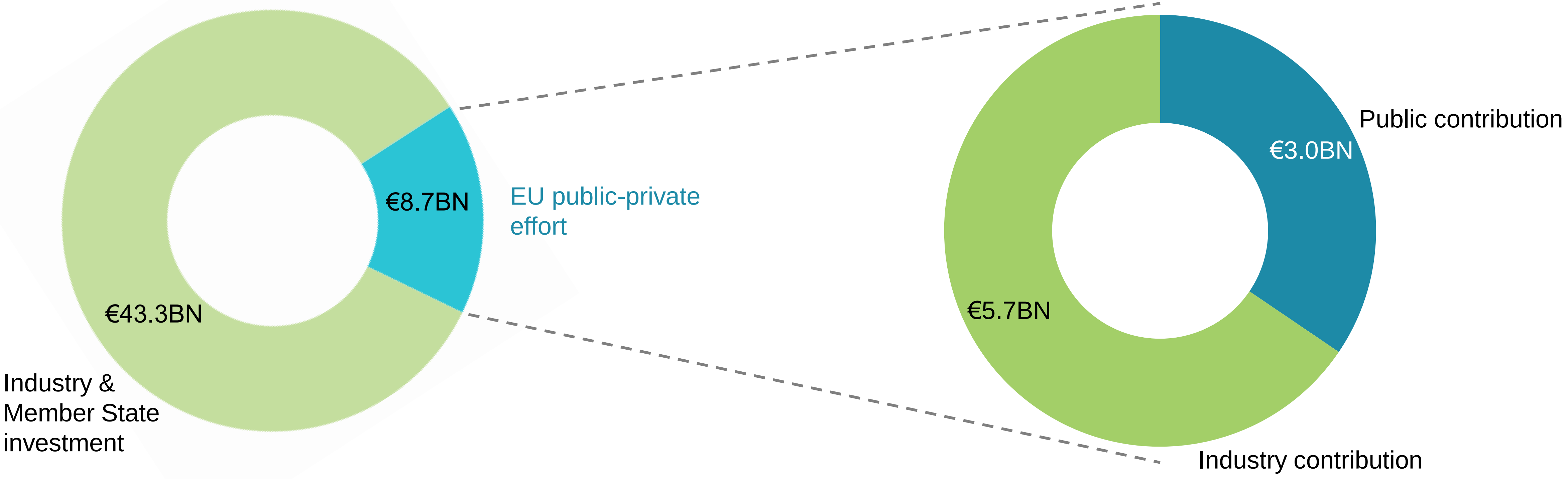
6. Decarbonisation of the gas grid and improving energy usage in buildings targets are being realised by FCH technologies:
*- hydrogen–methane blends in the gas grid save 6 $MtCO_2$ pa contributing to **the forthcoming gas policy package.***
*- FC micro-CHP efficiency reduces energy needs in buildings contributing to the **Energy Efficiency & Energy Performance of Buildings Directives.***
*- clean hydrogen for heat and power reduces emissions in the industrial sector, contributing to the **Emissions Trading Scheme Directive.***

7. Clean hydrogen in industry is essential to achieving deep decarbonisation of industry, *contributing to the aims of the **Emissions Trading Directive** and sectoral agreements on decarbonisation.*

An EU public-private effort of €8.7BN can trigger the €52BN investment needed to realise this vision

Total investment for the 2030 vision is €52BN[1], mostly funded by Industry contributions & Member State investment

Total investment managed by Europe 2021-2027



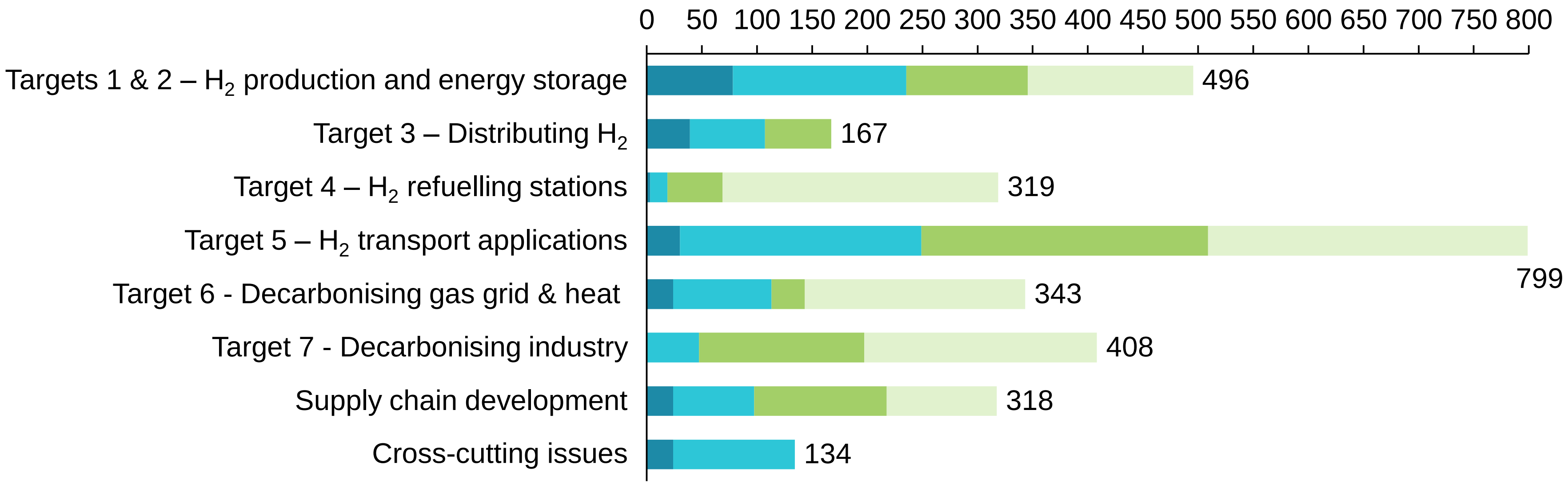
The €8.7BN programme proposed here will be 65% funded by industry and 35% supported by public contributions.

There is a strong case for public funding to support development of hydrogen as an element *sine qua non* the energy transition cannot successfully achieve the deep decarbonisation requirement to meet ambitious decarbonisation targets.

1 – Hydrogen: Scaling Up. Hydrogen Council report 2017

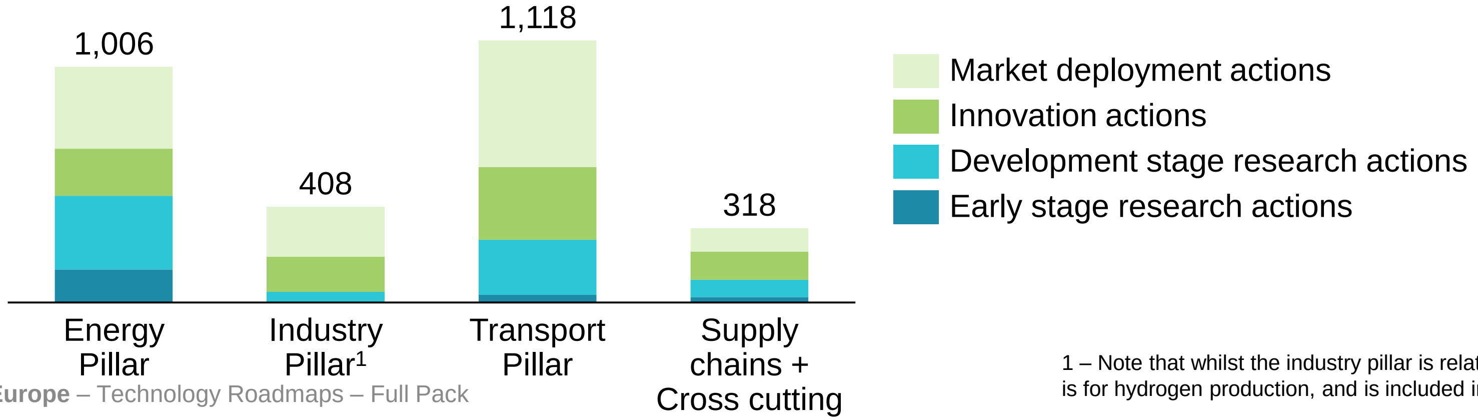
The €8.7BN programme will contribute to all aspects of the 2030 vision: funding breakdown

Total funding proposed to support actions which can meet targets of the vision by the development stage



Development stage	Funding rate
Early stage research actions	100%
Development research actions	75%
Innovation actions	50%
Market deployment actions	<25%

Total funding proposed for each core pillar of the programme



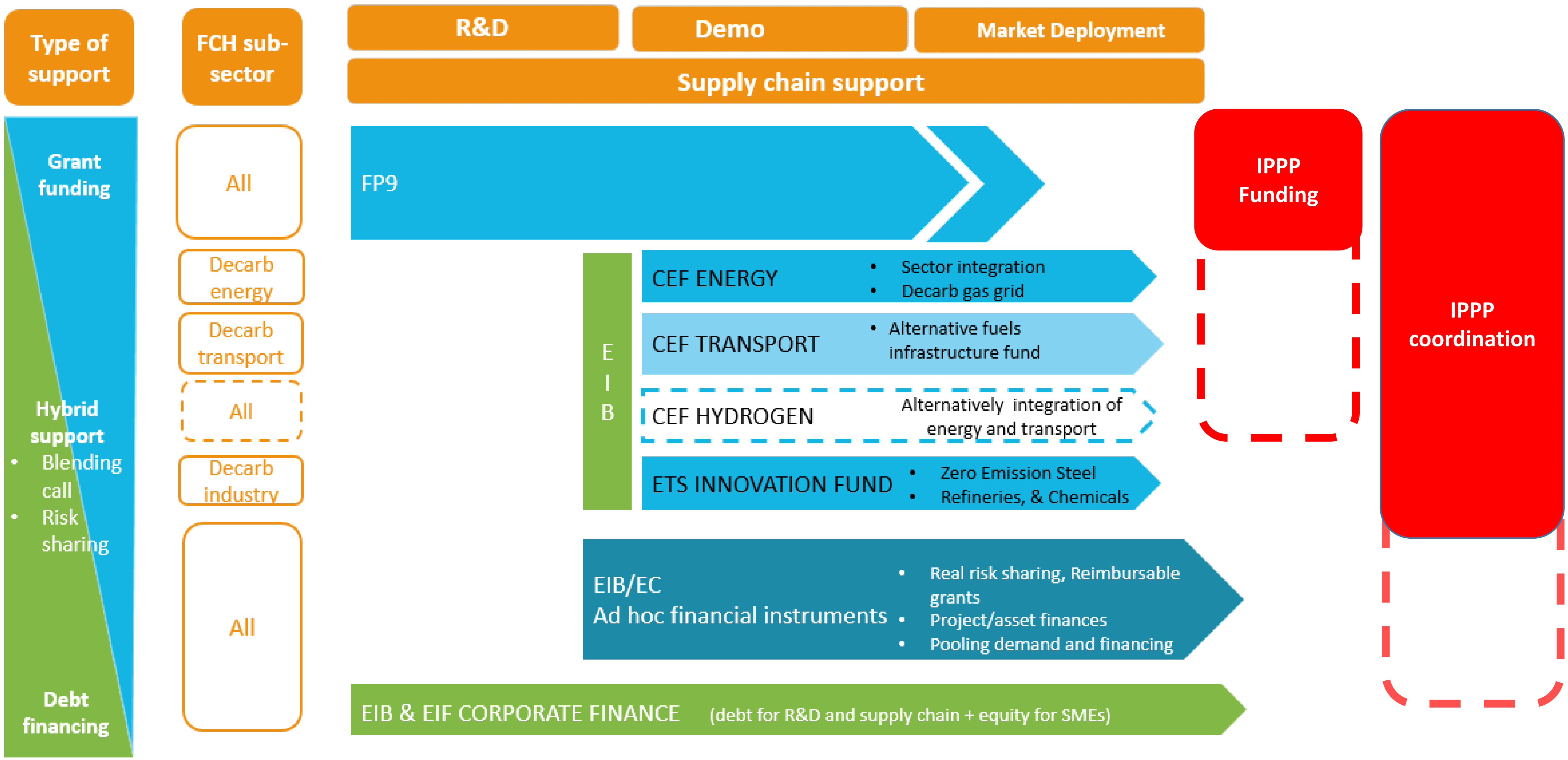
Three core pillars will be supported:

- **energy system** (targets 1, 2, 3 & 6)
- **industrial applications[1]** (target 7)
- **transport applications** (targets 4 & 5)

Supply chain development and cross-cutting issues (pre-normative research, safety, education and monitoring) will underpin actions in each of the three pillars.

1 – Note that whilst the industry pillar is relatively small, the majority of the budget needed for clean hydrogen to decarbonise industry is for hydrogen production, and is included in the energy pillar

The coordination of several funding and financing streams will be vital to maximise the impact of this funding programme



The remainder of this document describes roadmaps for each relevant technology, and the role for EU budget support (1/2)

The remainder of this document describes roadmaps for each relevant technology, and the role for EU budget support (2/2)

5 Fuel cell vehicles (road, rail, ship) are competitively priced

6 Hydrogen meets demands for heat and power

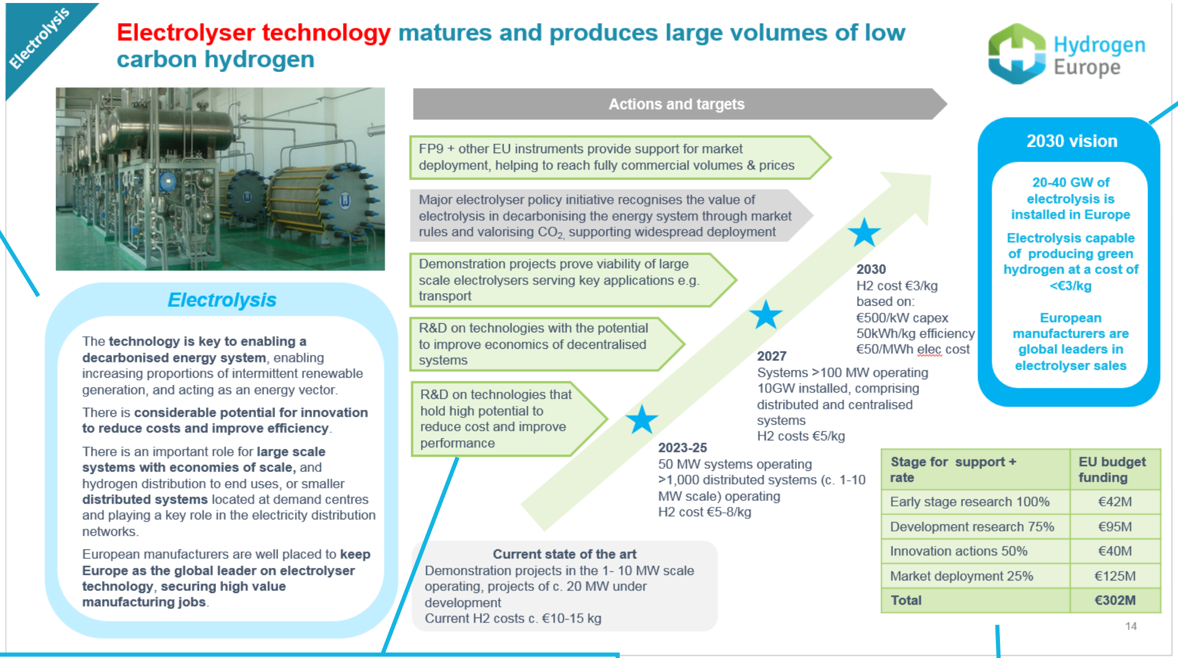
7 Hydrogen decarbonises industry

8 Horizontal activities support the development of hydrogen

The summary technology roadmaps aim to show the key steps to achieve the vision, and the role for EU budget support

At a glance
Overview of the role of the technology, challenges and opportunities for EU companies.

2030 vision
The end point for the roadmaps – a quantitative target for the role of the technology in Europe's energy system.



Actions
Actions which the FCH industry and research community will be undertaking to realise the interim targets ★ and 2030 vision. Actions where an EU public private partnership could play a direct role are marked in green, others in grey. Each action described is expected to be important throughout the 2021-2027 period.

Proposed EU budget funding
Summary of proposed request for EU budget by area, broken down by research actions, innovation actions and market deployment actions.

Data sources:

These roadmaps are based on data and information from:

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

Electrolysis

Electrolyser technology matures and produces large volumes of low carbon hydrogen

Electrolysis

The **technology is key to enabling a decarbonised energy system**, enabling increasing proportions of intermittent renewable generation, and acting as an energy vector.

There is **considerable potential for innovation to reduce costs and improve efficiency**.

There is an important role for **large scale systems with economies of scale,** and hydrogen distribution to end uses, or smaller **distributed systems** located at demand centres and playing a key role in the electricity distribution networks.

European manufacturers are well placed to **keep Europe as the global leader on electrolyser technology**, **securing high value manufacturing jobs**.

Actions and targets

- FP9 + other EU instruments provide support for market deployment, helping to reach fully commercial volumes & prices.
- Major electrolyser policy initiative recognises the value of electrolysis in decarbonising the energy system through market rules and valorising CO_2, supporting widespread deployment.
- Demonstration projects prove viability of large scale electrolysers serving key applications e.g. transport.
- R&D on technologies with the potential to improve economics of decentralised systems.
- R&D on technologies that hold high potential to reduce cost and improve performance.

Current state of the art
Demonstration projects in the 1- 10 MW scale operational.
Projects of c. 20 MW under development.
Current H_2 costs c. €10-15 kg.

2023-25
50 MW systems operational.
>1,000 distributed systems (c. 1-10 MW scale) operational.
H_2 cost €5-8/kg.

2027
Systems >100 MW operational.
10GW installed, comprising distributed and centralised systems.
H_2 costs €5/kg.

2030
H_2 cost €3/kg based on:
€500/kW capex.
50kWh/kg efficiency.
€50/MWh elec.

2030 vision

20-40 GW of electrolysis is installed in Europe.

Electrolysis capable of producing zero emission hydrogen at a cost of <€3/kg.

European manufacturers are global leaders in electrolyser sales.

Stage for support + funding rate	EU budget funding
Early stage research 100%	€42M
Development research 75%	€95M
Innovation actions 50%	€40M
Market deployment 25%	€125M
Total	**€302M**

Overview of electrolysis: vision, current status and supply chain

Electrolysis is the key technology for energy system integration – enabling penetration of intermittent renewable energy, and transfer of that clean energy to other sectors

Introduction

Water electrolysis has been used to produce industrial hydrogen for nearly a century. Electrolysis powered by low carbon electricity has the potential to be an ultra-low CO_2 form of hydrogen production. In addition, electrolysis can be used as a means to enable penetration of renewable electricity into all sectors, with electrolytic hydrogen providing an energy store for clean electrons which can be transported to their point of use. In so doing, electrolysis can be a key enabler for increasing the amounts of intermittent renewable energy connected to electricity grids of the future, and also for capturing renewable energy which is difficult or prohibitively expensive to connect to the grid. However further development of electrolyser technology, cost performance and the scale of deployment is needed to realise this vision.

Current status of the technology and deployments

ENERGIE PARK MAINZ

Hydrogen production via electrolysis is currently more expensive than via other methods – due to the capital costs and dependence on electricity costs. The key steps needed to realise the 2030 vison is reducing cost and improving efficiency of electrolysis, in particular by increasing the scale of deployments for PEM technology, to match the maturity of alkaline technology*, has been deployed at 10-100 MW scale in industry (typically in aluminium production, but historically in ammonia plants which pre-date cheap natural gas. The largest PEM electrolyser currently operating is the 6MW PEM system at EnergiePark Mainz, with a 75% conversion efficiency.

REFHYNE
CLEAN REFINERY HYDROGEN FOR EUROPE

In development are a series of FCH JU funded projects including REFHYNE, where a 10 MW PEM electrolyser will be installed at Shell's Cologne refinery, H2FUTURE where a 6MW PEM electrolyser will be used in the steel making process and Demo4Grid, a 4MW alkaline electrolyser for grid balancing. Many European electrolyser companies are developing designs for 100 MW scale projects.

European supply chain

Europe has a strong presence globally in electrolysis, both in component supply and in final product manufacture. Roughly half of all electrolyser suppliers are located in Europe, with most of the major ones, including Nel, McPhy, Hydrogenics (for one of their two technologies), Siemens, ITM Power, Sunfire and Areva H2Gen all located in Europe. Expertise in EU spans the three main technologies – PEM, alkaline and SOEC

2030 vision
20-40 GW of electrolysis is installed in Europe
Electrolysis capable of producing zero emission hydrogen at a cost of <€3/kg
European manufacturers are global leaders in electrolyser sales

*There are a range of electrolyser chemistries. Alkaline electrolysers are a mature technology but there remains potential for cost reductions if demand increases.. PEM (proton exchange membrane) and SOEC (solid oxide electrolyser cell) technologies are in contrast relatively new.

Electrolysis: detailed technology roadmap

Actions and interim targets

2020 — 2025 — 2030

Current State of the Art

AC system efficiencies: 55-70 kWh/kg

System cost: €1300/kW to €2000/kW

- 6 MW Siemens project operating, 10 MW ITM Power project under construction
- 20 MW project supported by the FCH JU2 (TBC)

Current and planned deployment projects prove technology at 10's MW scale

Current projects achieve lower cost (due to H2020 R&D + deployment at 10 MW scale)

★ 50 MW systems operating, >1000 decentralised (1-10MW) systems operating

★ Installed cost of €720/kW including all BoP
Plant AC efficiency of 50 kWh/kg.
H_2 cost c. €5/kg at scale

Continued research on technologies with major impact potential e.g. on cost reduction, increased efficiency, operation at high pressure

High efficiency concepts are demonstrated in real world applications at scale (e.g. solid oxide electrolysers at 10MW)

EU programme supports R&D on technologies to reduce cost and improve performance

★ Improved technical KPIs achieved:
- Installed cost of €500/kW
- Plant AC efficiency of 48 kWh/kg
- Cell stack lifetime exceeding 60,000 hrs

Large scale projects (10-100 MW scale are developed)
Decentralised projects (1-10 MW) demonstrate wide range of roles electrolyser can play in energy system management

Rapid response technologies for electricity system storage and flexibility continue to be developed and tested at a range of scales

EU programme supports demonstration projects at scale linked to key applications (transport, energy storage, heat & power)

★ 100 MW systems operating, >10GW installed across Europe

Low cost green electricity procurement strategies identified, including grid balancing income. These strategies are enabled by regulation and allow prices <€50/MWh

Projects at range of scales from 1 MW – 100 MW scale are developed on a commercial basis

EU programme provides support for market activation mechanism, helping to reach fully commercial volumes and therefore prices

★ 20-40 GW installed
H_2 cost €3/kg based on:
€500/kW capex
50kWh/kg efficiency
€50/MWh elec. cost

2030 vision

20-40 GW of electrolysis is installed in Europe

Electrolysis capable of producing zero emission hydrogen at a cost of <€3/kg

Background assumptions:
- Policy changes allow electrolysis plants to access cheap electricity (e.g. German regime)
- Resolution to Renewable Energy Directive to allow procurement of green electricity to count towards CO_2 and renewable fuel standards

Legend
- Action
- ★ Interim target
- **Role for EU programme**

* See next page for breakdown of projects

Electrolysis: proposed areas for support

Stage of development and potential areas for support	Proposed budget	Proposed funding source
Early Stage Research Actions (TRL 2-3) – these actions will continue throughout the budget period 2021-2027		
Future cost reductions in electrolyser technology may be realised though new materials and manufacturing processes. Below are examples of areas which could lead to future breakthroughs, enabling cost reduction targets to be achieved: • Development of new catalyst materials with the ability to increase the current density has significant potential to reduce capital costs. • Cell level techniques to enable an increased current density without harming lifetime and efficiency. • Reduced precious metal content in catalysts. • Development and cost reduction of corrosion and high temperature resistant materials and seals (Solid Oxide electrolysis).	• 14 projects • €42M budget • 100% funding rate • €42M funding	FP9
Development Research Actions (TRL 4-6)		
A number of concepts for reducing electrolyser costs and improving technical KPIs have been demonstrated in the laboratory. Support to develop these technologies can ensure that promising options are not left stranded. This area can support promising applications identified through the research programme suggested above as well as: • Larger cell area to reduce the overall costs for high power systems. • Improved balance of plant to reduce parasitic losses and reduce cost (e.g. purpose built rectifiers, integrated cooling systems). • High pressure stacks to avoid the need for downstream compression.	• 18 projects • €126M budget • 75% funding rate • €95M funding	FP9
Innovation Actions (TRL 7-8)		
Projects are needed to demonstrate that electrolysis technology, when deployed at scale, have the potential to: • Meeting cost targets of below €750/kW installed cost and performance targets (including efficiency of 50 kWh/kg and other relevant KPIs.). • Providing a compelling economic and environmental case for key applications such as transport, energy storage, heat and power.	• 4 projects • €80M budget • 50% funding rate • €40M funding	FP9
Market Deployment Actions (TRL 9)		
Market entry support 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). Market entry support could stimulate the deployment of 0.5 GW of electrolysis.	Budget €500M • Deployment of 500 MW of electrolysis • 25% funding rate • €125M funding	FP9 ETS-IF

Other modes of hydrogen production have matured and produce significant volumes of low carbon hydrogen

Other modes of H_2 production

There are a **range of H_2 production options which could be environmentally neutral or even positive.**

New technologies (focus of this programme):
Producing H_2 from biomass or waste guarantees ultra-low carbon hydrogen. Technologies currently at the early stages of development **will provide breakthroughs in terms of cost and environmental impacts –** for example direct solar production from water, or biologically produced hydrogen from algae.

CCS and SMR+CCS
Developments in these technologies will be important for the hydrogen economy and are therefore included here. However it is important to recognise that this technology cannot provide full energy system benefits – technologies that can, should remain the focus of a hydrogen economy (and the proposed FCH programme).

Actions and targets

- Regulatory regime ensures low carbon hydrogen for all production options.
- Support for first commercial trials of new direct solar and direct biological production systems.
- Member States + EU funds support deployment of reformer + CCS systems at scale.
- Deployment of gasification systems at scale.
- R&D on technologies that hold high potential to produce zero emission H_2 at low cost.

Current state of the art
One reformation + CCU unit operating in Europe. Biomass and solar production have trial plants operating or under construction. Waste gasification and biological production concepts are at the laboratory scale.

2023-25

Solar production and waste gasification prove technology concepts.

Successful completion of current planned trial projects on reformer + CCS.

2027

MW scale projects operating for solar production, production from waste, & biological production.

Deployment projects at the 100MW scale for reformer + CCS.

2030

>10MW scale gasification production commonplace Commercial 10MW scale direct solar and direct biological production.

Reformation + CCS is widespread and mandatory for new deployment.

2030 vision

A range of technologies which can produce low carbon, low cost (€3/kg) hydrogen at scale, are operating either at industrial scales or close to industrial scales.

Fossil based routes including CCS achieve below €2/kg.

Stage for support + funding rate	New tech. funding	SMR + CCS funding
Early stage research 100%	€30M	-
Development research 75%	€42M	-
Innovation actions 50%	€40M	€20M
Market deployment 25%	€25M	€100M
Total	**€137M**	**€120M**

Overview of other modes of hydrogen production: vision, current status and supply chain

A broad range of hydrogen production modes can ensures supply and can produce low cost, low CO_2 hydrogen

Introduction

Most hydrogen produced today is made by steam-methane reforming of natural gas (SMR). SMR is a mature technology but produces CO_2 emissions. The relatively pure stream of CO_2 is suitable for carbon capture and storage (CCS) and there is increasing interest in SMR + CCS to produce low carbon hydrogen – the technology combination is at the demo/pilot stage in Europe. Biomass or waste gasification is a method of low carbon hydrogen production currently at the MW demonstration stage. If it can be combined with CCS it has the potential to be a negative emission technology. There is also increasing interest in other novel production methods such as using sunlight to directly split water into hydrogen and oxygen,and biological methods such as H_2 production via algae.

Current status of the technology and deployments

SMR is currently the cheapest method of hydrogen production with production cost at <€2/kg (Shell Hydrogen study 2017). Adding CCS is estimated to increase costs by 50-100% (Innovate UK FCH Roadmaps 2016). In Europe Air Liquide operate an SMR+CCU (carbon capture and utilisation) plant at Port-Jérôme, producing refinery H_2 and CO2 for local industrial markets. The main developments needed in this sector are on transport and storage of CO_2 to facilitate large scale deployment of CCS.

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

The FCH-JU supported HYDROSOL-PLANT project is constructing a demonstration plant for solar thermal hydrogen production in a 750 kWth scale. There are a range of technologies being explored at the laboratory scale for using solar energy to split water.

European supply chain

European companies are well placed to capitalise on hydrogen production technology – key global gas companies such as Air Liquide, Linde and Air Products all have SMR offerings (+CCU for Air Liquide), and other companies e.g. Equinor (formerly Statoil) are developing offerings. Much of the activity on novel methods of production is at the University/Institute level but some European SMEs are developing technologies..

2030 vision
A range of technologies which can produce low carbon, low cost (€3/kg) hydrogen at scale, are operating either at industrial scales or close to industrial scales.
Fossil based routes including CCS achieve below €2/kg

Other modes of hydrogen production: detailed technology roadmap

Actions and interim targets — 2020 / 2025 / 2030

Current State of the Art

Reformation +CCS/U

Current state: 1 SMR + CCU in Europe

SMR + CCS : not proposed as part of the FCH programme

- Action: Development of new reformation +CCS flow schemes to optimise efficiency, cost and CO_2 capture
- Action: Development of European CCS networks
- Interim target: SMR included in 1st CCS deployments
- Action: Continued development of European CCS networks
- Interim target: New centralised reformer plants are only deployed with CCS or CCU producing H_2 <€2/kg and >92% CO_2 capture

Biomass gasification

Current state: 10's of kW scale trial facilities

- Action: Deployments of biomass to H_2 plants prove technology at MW scale
- Action: Commercial projects are developed at 10's MW scale
- Interim target: Large biomass/biowaste to H_2 plants deliver renewable hydrogen at <€3/kg to industrial users

Solar hydrogen

Current state: 0.75 MW H_2 production plant in construction /commissioning

Waste gasification

Current state: Small prototype concepts

Biological production from algae

Current state: Lab-scale concepts

EU programme supports R&D&D on the most promising technologies and concepts

- Action: Continued research on range of most promising technology options within solar hydrogen production, waste gasification and biological production of hydrogen
- Action: Most promising concepts are developed at prototype level
- Solar - Action: Successful operation of existing/planned demonstrations
- Solar - Action: Demonstration projects proving operation of MW scale reactors with high H_2 production rates
- Interim target: First 10 MW scale solar demonstration project in operation HE data producing H_2
- Waste - Action: Successful demonstration of existing prototypes
- Waste - Action: Demonstration projects based on second generation concepts at the 10's of MW scale
- Interim target: Small compact gasifiers are operating in town and cities,
- Bio - Action: Demonstration projects proving operation of commercial scale reactors with high H_2 production rates
- Interim target: Biological production of H_2 from algae proved at scale

2030 vision

A range of technologies which can produce low carbon, low cost (well below €3/kg) hydrogen at scale, are operating either at industrial scales or close to industrial scales

Background assumptions:

- CO_2 transport and storage technology matures and is being deployed across Europe during the 2020's
- Policy support for hydrogen decarbonisation via taxes/mandates

Legend

- Action
- Interim target
- Role for EU programme

Other modes of hydrogen production: proposed areas for support

Technology targeted and funding proposed	Proposed budget	Proposed funding source
Early Stage Research Actions (TRL 2-3)		
Biomass & waste gasification: Novel reactor design for increasing feedstock flexibility; research on new materials for high temperature processes; research on new processes for syngas cleaning at high temperatures. ***Biological production from algae:*** New concepts of bio production reactors with a high rate of production for middle and large size plants. ***Direct solar:*** Range of thermo-chemical cycles developed and tested (simulation and experiment). Novel system designs for integration of a collector/reactor.	• 10 projects • €30M budget • 100% funding rate • €30M funding	FP9
Development Research Actions (TRL 4-6)		
Biomass & waste gasification: Scaling up of most promising technologies. ***Biological production from algae:*** Development of medium-scale bio-reactors. ***Direct solar:*** Scaling up of most promising technologies.	• 8 projects • €56M budget • 75% funding rate: • €42M funding	FP9
Innovation Actions (TRL 7-8)		
Demonstration projects of most promising technologies: • 1 Demonstration-scale plant for **waste gasification.** • 1 Full sized **biological reactor demonstration project.** • 2 Medium-sized pilots of most promising **direct sunlight technologies.**	• 4 projects • €80M budget • 50% funding rate • €40M funding	FP9
Funding not proposed here: SMR+CCS: There is a case for European and Member State support for deploying new reformer concepts with CCU/CCS. European support for prototyping and testing of specific components (TRL7 stage) will be beneficial as a pre-cursor to novel designs. An indicative budget for this would be two projects with a €40M budget and €20M funding. This type of support may be provided by instruments such as the ETS-IF and would not be suitable for management under an FCH support programme.		
Market Deployment Actions (TRL 9)		
Support for decarbonised hydrogen in all deployment schemes are available from policy and regulation. There is a case for supporting one very large scale deployment of the most promising direct sunlight technology, given the potential for this technology to revolutionise the energy system. **Funding not proposed here: SMR+CCS:** Given the scale of the systems that will need to be deployed, it is likely that new reformer concepts with CCS will be deployed under commercial contracts, with the support of Member States + European support (e.g. from ETS-IF and the EIB). An indicative budget for four projects would be €400M which with 25% support means a funding request of €100M. This type of support is not included in these budgets	• 1 project • €100M budget • 22% funding rate • €25M funding	FP9 ETS-IF

Energy Storage

Electrolysers play an essential role in large scale energy storage, supporting increasing amounts of renewable generation on the grid

Electrolysis in the energy system

H_2 production via electrolysis offers unique advantages: it can **store energy for long periods** (e.g. in gas grids or in underground storage), and also **transfer these clean electrons into other sectors.** H_2 offers a locally produced clean energy vector for all applications**, ensuring security of the EU energy supply.**

Increasing levels of renewable electricity generation brings a range of challenges to the electricity grid. **Electrolysis can play a vital role in solving many of these challenges, helping to secure the EU energy system**:

- Increasing renewable generation on the grid without the need for new investments in under-utilised grid assets.
- Increasing renewable generation off-grid by using electricity to create hydrogen, especially in off-shore areas or adjacent to underground storage.
- Providing a range of energy storage and load balancing services to match supply and demand.

Actions and targets

Regulatory changes enacted to allow the value of electrolysis to the energy system to be realised.

Continued and new projects demonstrate the viability of hydrogen production by electrolysis to:

- Increase renewable generation, both on and off-grid.
- Increase grid utilisation.
- Provide load-balancing services.

Modelling proves the value of electrolysis to the energy system in the range of use cases described above.

2023
First renewables project goes ahead due to the role of hydrogen production in supporting the energy system.

2023-25
10's MW scale systems successfully proving technology in a range of roles within the energy system.

2027
Meaningful reduction in the cost of electricity system management due to H_2 production.

2030
GW scale RE deployment enabled by H_2.

Current state of the art
Demonstration projects, both on and off-grid, in the 1-10 MW scale.

2030 vision

An additional 20-40 GW of renewable generation is accommodated as a result of hydrogen production by electrolysis, resulting in the transfer of 70-140 TWh of Europe's renewable electricity to other sectors.

Stage for support	EU budget funding
Of the €40M funding outlined in the roadmap for innovation actions demonstrating electrolysis technology, c. €10M will go towards the target of this roadmap.	

Energy Storage

Electrolysis for large scale energy storage: detailed technology roadmap

Actions and interim targets

2020 | 2025 | 2030

Current State of the Art

BIG HIT (1.5 MW) is using otherwise constrained electricity from a wind farm for H_2 generation

HyBalance (1 MW) is providing grid flexibility services and generating H_2

EnergiePark Mainz project (6 MW) is directly connected to a wind farm and to the grid

Actions

Modelling work to demonstrate potential value in a variety of electricity system roles, e.g.:
- Distribution System level, helping to balance distribution system and enable increased use of local renewables as well as better utilisation of existing electricity grid assets
- Direct coupling to renewable generation (both on and off-grid)
- Providing flexibility services to grid operators

★ Consensus achieved on the roles where hydrogen adds maximum value to the energy system and the price for that value.

Existing and new demonstration projects prove the technology in these roles at a range of scales e.g.:
- Demo4Grid will demonstrate a 4MW system providing grid balancing services
- Project REMOTE will demonstrate electrolysis in 4 micro-grid or off-grid locations

EU programme supports demonstration projects at scale on energy storage (see previous roadmap)

★ Value of electrolysis for electricity systems accepted by all electricity market stakeholders

Policy work to develop options to share the value of electrolysis on electricity systems in a fair way

Regulatory changes to realise the value of hydrogen in the energy system e.g. in DSO markets, as an inter-seasonal energy store etc

★ First renewables project deployed due to hydrogen production

★ Meaningful cut in the costs of flexibility to the energy systems due to hydrogen production

2030 vision

An additional 20-40 GW of renewable generation is accommodated as a result of hydrogen production by electrolysis, resulting in the transfer of 70-140 TWh of Europe's renewable electricity to other sectors

Background assumptions:
- Policy changes allow electrolysis plants to access cheap electricity (e.g. German regime)
- Resolution to Renewable Energy Directive to allow procurement of green electricity to count towards CO_2 and renewable fuel standards

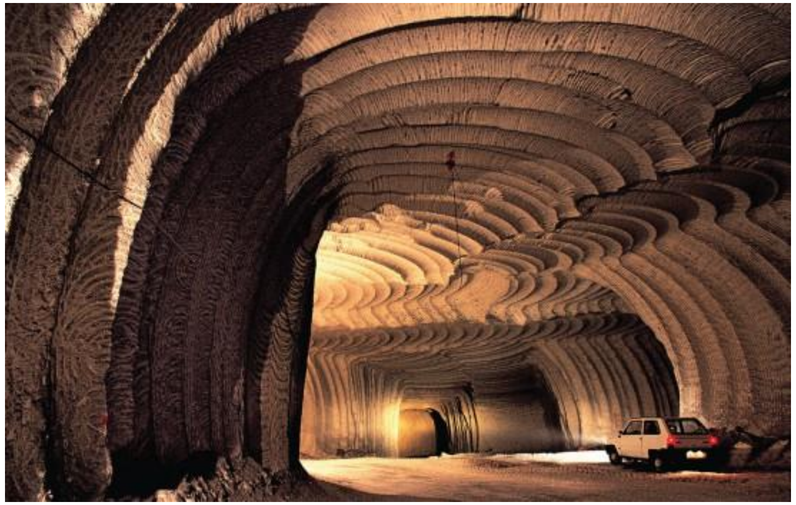
Legend

Action

★ Interim target

Role for EU programme

Bulk hydrogen storage is available at low cost to support long term energy storage and sector coupling



Bulk hydrogen storage

The ability to store very large quantities of hydrogen at low costs is key to realising the vision of hydrogen as a clean energy vector for sector coupling.

Hydrogen offers the lowest cost option for long term energy storage (e.g. inter-seasonal).

For example the underground storage cost target of <€5/kWh (>1,000 tonnes) is almost two orders of magnitude lower than the cost of battery stores.

A number of bulk storage options exist and operate today, including underground storage in large salt caverns and large scale above ground pressurised stores[1].

Actions and targets

- Regulations are adapted so that large scale storage of energy (particularly inter-seasonal) is valued within the energy system.
- Energy system studies demonstrate the importance of hydrogen storage to the future energy system & make the case for early regulation to ensure the option is ready in advance of need.
- Demonstrations explicitly couple large scale stores to long term energy system challenges e.g. storage of renewable electricity or storage to enable 100% hydrogen grids.
- R&D projects are funded which offer meaningful improvements in the cost and efficiency of bulk storage.

Current state of the art
Bulk hydrogen storage options have been deployed for large industrial activities. Cost <€15/kWh of hydrogen stored.

2025
Definitive system models produced which prove the role of hydrogen in all plausible future energy scenarios. Regulators introduce measures to incentives use of hydrogen storage in energy systems.

2027
Proven systems for above ground storage <€10/kWh of hydrogen stored.

2030
Proven systems for underground storage <€5/kWh of hydrogen stored (>1,000 ton).

2030 vision

Hydrogen storage is recognised and incentivised in European and Member State energy policy. Large scale energy stores demonstrated at <€5/kWh of hydrogen. Distributed above ground stores for <€10/kWh.

Stage for support + funding rate-	EU budget funding
Early stage research 100%	€6M
Development research 75%	€21M
Innovation actions 50%	€30M
Market deployment 25%	-
Total	**€57M**

1 - Note that it is also possible to envisage large scale bulk storage in liquid carriers which are covered in the liquid carriers roadmap – this roadmap deals with bulk pressurised systems.

Overview of bulk hydrogen storage: vision, current status and supply chain

Introduction

For hydrogen production to become a significant part of energy storage, there needs to be an available and low cost form of bulk storage. Potential stores include gas grids (see roadmap on pages 89-91), and bulk storage above and below ground. Hydrogen has been successfully stored at a large scale for industrial applications for many years. For example underground gas stores in specially constructed salt caverns were used to store hydrogen in the Teesside chemical complex in the UK for many years.

Hydrogen can also be stored in large pressurised cylinder farms for above ground storage of smaller quantities of hydrogen,

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

All of these solutions are validated in the field, but will need to be adapted to a role in supporting the overall energy system. For example the rate at which salt caverns can be depleted is constrained by geology (to avoid cracking the caverns), which will make them suitable for long term storage, but could constrain their value for short term inter-day storage.

Furthermore, there is potential for improved cost and efficiency, for example by hybridising the pressurised vessels with hydride solid state storage materials

Finally, there is a challenge that these large scale systems are needed for an energy system of the future, but in order to be ready in time, they need to be developed and proven now. This means there is a need to work to define the role of these long term stores in the future energy system to justify policy which accelerates their uptake in real world projects today.

Teesside and East Riding underground gas storage (UK)

Bulk hydrogen storage in industrial applications

European supply chain

Europe’s industrial and chemicals sector is very experienced in handling and storing large quantities of hydrogen, as well as possessing the required geological knowledge to build new salt caverns. Large scale stores are associated with the pipeline networks in the Benelux region and also in Teesside in the UK. These companies are well placed to design, engineer and install the large scale bulk hydrogen storage systems of the future.

2030 vision
Hydrogen storage is recognised and incentivised in European and Member State energy policy.
Large scale energy stores demonstrated at <€5/kWh of hydrogen. Distributed above ground stores for <€10/kWh

Bulk H_2 Storage

Bulk hydrogen storage: detailed technology roadmap

Actions and interim targets

2020 | 2025 | 2030

Current State of the Art

- Bulk gaseous hydrogen storage used widely in industry
- Costs <€15/kWh of hydrogen stored available today for above ground pressurized stores

Actions and interim targets

EU programme supports research and development aimed at reducing cost

- Underlying research supported aimed at improving cost and efficiency of above ground store . For example hybridising pressure vessels with robust hydride materials to improve energy density and decrease cost
- Concept design work for underground storage to validate the performance in different geologies, encourage improved designs and meeting energy system needs
- Concept work on line-pack strategies for storage in gas pipes

EU programme supports demonstration to prove the inter-linking of real energy system needs and bulk energy stores

- Demonstration projects which link bulk energy storage (>10 tonnes for above ground, ideally >1,000 tonne for below ground storage) to energy applications such as storage of intermittent energy for remote locations and islands

EU programme supports definitive techno-economic work to prove the value of hydrogen in future energy systems

- Detailed energy system modelling (working with the leading energy models and modellers) to demonstrate the role of hydrogen energy storage in future energy system scenarios

Regulators and policy makers introduce forward looking policies aimed at encouraging early uptake of hydrogen for energy storage in advance of need

Interim targets:

- First >10 tonne energy storage application working
- First underground stores operating for energy system applications
- Capital cost of underground stores <€5/kWh of hydrogen stored, Strategies enabling OPEX < €0.005/kWh developed
- Capital cost of pressurised stored <€10/kWh of hydrogen stored, strategies enabling OPEX <€0.01/kWh demonstrated

2030 vision

Hydrogen storage is recognised and incentivised in European and Member State energy policy. Large scale energy stores demonstrated at <€5/kWh of hydrogen. Distributed above ground stores for <€10/kWh

Background assumptions:

- Near term energy policy influenced by long terms needs of the energy system
- Continued reliance on high penetration of RE to cut energy sector CO_2 emissions
- Uptake of hydrogen for 100% gas networks will accelerate the need for bulk storage.

Legend

- Action
- Interim target
- Role for EU programme

Bulk hydrogen storage: proposed areas for support

Stage of development and potential areas for support	Proposed budget	Proposed funding source
Early Stage Research Actions (TRL 2-3)		
The bulk of the early stage work on storage techniques is covered by other roadmaps (e.g. novel hydride carriers, improved pressure vessels). There is however merit in researching novel concepts which can reduce the cost and improve the efficiency of hydrogen storage at a bulk level. This includes the use of lower pressure (lower cost) vessels in concert with hydride storage materials, using lower targets for weight density than needed for other applications. Other examples include novel concepts for underground storage and also for line pack strategies for hydrogen gas grids.	• 2 projects • €6M budget • 100% funding rate. • €6M funding	FP9
Development Research Actions (TRL 4-6)		
Development projects are required to develop the maturity of new concepts for on-the-ground and underground storage and their integration into the energy system. Examples of areas for development are: *On-the-ground* • Development of novel materials for above ground storage tanks, targeting optimised pressures. • Novel designs and hybrid solutions for storage containers. *Underground* • Novel designs for both caverns and the associated above ground infrastructure designs more suited to energy system applications, including improving discharge rates and increasing pressure ranges within the caverns.	• 6 projects • €28M budget • 75% funding • €21M funding	FP9
Innovation Actions (TRL 7-8)		
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 over ground and underground operation, aiming to reduce cost and improve efficiency, including: • Two medium scale projects to both prove, and optimise, H_2 storage solutions above ground. • A large scale demonstration project for underground H_2 storage with high capacity and volumetric density.	• 3 projects • €60M budget • 50% funding • €30M funding	FP9 ETS-IF
Market Deployment Actions (TRL 9)		
No market activation for hydrogen storage is proposed. However, 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 for bulk energy storage using hydrogen and hence the case for policy and regulatory support for market activation.	No funding proposed	

Sections 1 & 2 covered hydrogen production options. Sections 3 & 4 will cover the technologies needed for the transport of hydrogen and its distribution to customers

2030 vision

In 2030 most H_2 transport applications are available at competitive prices. This creates a demand for an optimised low cost distribution system taking hydrogen produced at centralised plants to the point of use at hydrogen refuelling stations. A chain of technologies (e.g. compression, purification etc) are readily available to support the distribution system. Several pathways for distribution have been demonstrated to work reliably and efficiently, and the first pathways demonstrated are now commercially competitive with the incumbent infrastructure.

Production locations

- There will be a mix of onsite production e.g. at industrial sites, power-to-gas sites, and small/medium scale HRS, and centralized production sites located for e.g. renewable generation plants, proximity to CCS clusters or underground storage etc.

Hydrogen storage

- Hydrogen is stored in several large underground caverns across Europe, providing a means for large scale energy storage (see bulk gaseous storage roadmap in hydrogen production section).

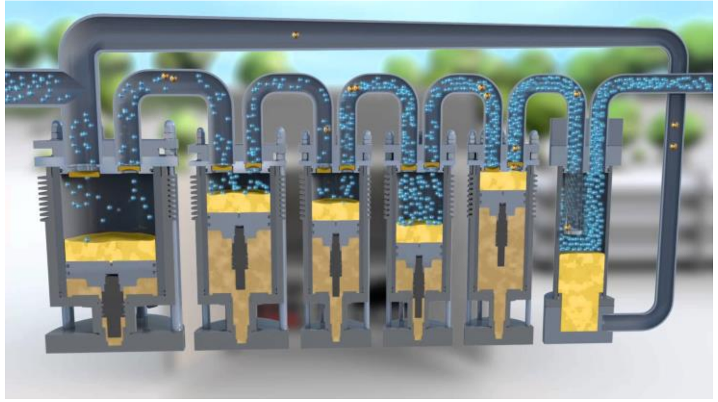
Hydrogen transport

- Existing logistics e.g. road trailers carrying gaseous hydrogen will have reduced in cost. A parallel distribution infrastructure, based on liquid hydrogen or hydrogen carriers will start to appear to transport large quantities of hydrogen across Europe by ship and rail as well as road.
- Hydrogen pipeline systems operating at 70-80 bar will be extended and new small scale networks will be developed.
- Hydrogen will be injected into natural gas grids in large volumes, to decarbonize heat in industry and in buildings.
- A few cities or regions will have converted gas networks to 100% hydrogen

Hydrogen refuelling stations

- New HRS designs with novel components and system architecture will be developed to reduce costs.
- New HRS designs for dispensing very large quantities of hydrogen to e.g. ships, trucks will be operating successfully

Key technologies in the distribution system (compression, metering, purification and separation) are optimised to support low cost hydrogen distribution



Distribution key technologies

There is **considerable scope for optimisation of a number of technical issues along the supply chain.** These include:

- **Compression** – particularly for high pressure hydrogen fuelling stations and also new concepts appropriate for hydrogen injections into large pipelines.
- **Metering** – ensuring sufficient accuracy to allow retail sales of hydrogen.
- **Purification and separation** – novel techniques to reduce the cost and improve the efficiency of hydrogen purification equipment.

European companies are world leaders in these components. Resolving these issues will keep European hydrogen logistics companies at the forefront of the global supply chain.

Actions and targets

R&D program aimed at novel techniques for compression and purification and separation of hydrogen from other gas streams.

Campaign to validate concepts using scale prototypes to prove longevity and efficiency over representative duty cycles.

Field trials for novel compressors. Larger scale deployment of big compressors and purification systems underwritten by industry using results from early stage studies.

2025
Range of novel compressors validated in real-world tests, offering improved efficiency and greater reliability.
Metering issues resolved and accepted by European weights and measures bodies.

2027
Novel membrane based purification technologies are field tested, improving efficiency of hydrogen production from hydrocarbons and intermediate carriers (e.g. ammonia).

2030
Compressors meeting <€1000/t/day target at >99% reliability.
Large compressors delivering 10's tonne/day validated.

2030 vision

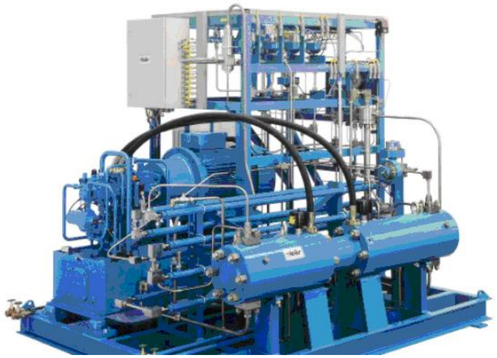
Range of compression and purification techniques develop and compete. European companies supply world leading components which remove the existing technical barriers to the hydrogen distribution.

Current state of the art

Hydrogen compressors are available but are the main source of failure in hydrogen stations. Novel techniques only available at lab scale (hydride, electrochemical). Metering accuracy prevents approved custody transfer for hydrogen in filling stations. Purification based on energy intensive PSA.

Stage for support + funding rate	EU budget funding
Early stage research 100%	€24M
Development research 75%	€47M
Innovation actions 50%	€30M
Market deployment 25%	-
Total	**€101M**

H_2 compression, metering, purification and separation: vision, current status and supply chain



Introduction

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

- **Compression** – for the transport sector hydrogen needs to be pressurised above 700 bar to enable refuelling of high pressure storage tanks. Furthermore hydrogen refuelling stations have intermittent usage which means compressors are subject to stop-start loads. There is a need to create purpose designed compressors with a lower cost than today and with high efficiency. A number of options are under development including improvement on current designs by European companies such as Nel, ionic compressors (Linde), metal hydride based compression (for example Hystorsys) and electrochemical compression (HyET)
- **Metering** – the accuracy of current hydrogen meters has been poor. There is a need for more accurate and cheaper meters with an accuracy sufficient for weights and measures standards. European manufacturers (e.g. KEM Küppers Elektromechanik) have now developed systems with the required accuracy but work is still required to produce cheaper systems and monitoring protocols.
- **Purification and separation** – hydrogen for use in low temperature fuel cells requires a very high purity, as much as 99.999%. Current purification techniques are costly and inefficient, novel methods to purify hydrogen at lower cost would improve the overall supply chain. The separation of hydrogen from other gases will be valuable for a range of future industrial uses (e.g. separation from ammonia, methane or CO_2 streams). A range of new membrane and electrochemical techniques are being developed to improve processes for both purification and separation of hydrogen from different gas streams.

European supply chain

European companies are undoubtedly leading in the field of hydrogen logistics and handling for hydrogen applications. Companies such as Nel, Linde, HyET and Hystorsys (developing novel compressors) are global leaders, two of the main industrial gas companies are based in Europe (Linde and Air Liquide) and there is considerable experience within the European oil and gas and chemicals industries. Europe is well placed to lead on the innovation and exploitation required in this area.

2030 vision
Range of compression and purification techniques develop and compete
European companies supply world leading components which remove the existing technical barriers to the hydrogen distribution

H_2 compression, metering, purification and separation: detailed technology roadmap

Actions and interim targets (2020 – 2025 – 2030)

Current State of the Art

Compression
Issues with reliability in intermittent use (H_2 stations), efficiency (from 20 bar) is >4kWh/kg

Meter accuracy – only one meter capable of delivering ±1% accuracy, challenges with weights and measures legislation

Purification and separation
Separation and purification primarily via pressure swing absorption, new technologies at lab stage

Actions

EU programme supports R&D & field trials on novel compression technologies:
- Research programs to develop early TRL concepts for electrochemical, thermal (via hydride) and cryogenic compression
- Prototype development and testing for novel compressors at different sizes and pressures
- Testing and validation of large compressors at capacities required by industry (i.e. >200kg/day stations) in the field
- Adaptation of existing large compressor concepts and/or new designs for hydrogen energy uses, particularly pipeline injection

Interim target: Novel compressors validated in real-world applications at relevant scale)

- Validation of larger format compressors for injection into pipelines up to 100 bar

Interim target: Low cost hydrogen compressors 10's of t/day deployed in energy applications (pipeline inject)

Interim target (2030): Mix of compressor options validated in the field and competing for market share. Achieving target costs of <€1,000/t/day (for demands >1 t/day). Energy consumption <3.5kWh/kg (20 bar suction pressure). Reliability >99%

- Competition for novel meters for supply to existing station increases breadth of European supply (and reduces cost)
- Standardisation of rules affecting "custody transfer" for hydrogen, including metering accuracy and protocols

Interim target: Accuracy of H_2 metering within 1% range for > 3 years. Range of European suppliers

EU programme supports R&D & testing of novel purification technologies:
- Novel membrane and electrochemical technologies developed at lab scale to facilitate separation of hydrogen for a range of gases, including CO_2, CO, CH_4 and ammonia
- Testing of prototype systems at sufficient scale to validate novel purification techniques prior to field deployment

Interim target: Field deployment of novel purification at a large scale CAPEX <€1,500/kg/day

- Field deployment of novel purification techniques in large scale hydrogen production (and separation) plants

2030 vision

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

Background assumptions:
- Continued policy support and industry momentum for zero-emission road transport and hydrogen energy applications
- Clear industry standards for HRS installation and operation, as well as metering
- Clarity on purity requirements for energy applications (e.g. 100% hydrogen pipelines)

Legend
- Action
- Interim target
- Role for EU programme

Key technologies in the distribution system: proposed areas for support

Stage of development and potential areas for support	Proposed budget	Proposed funding source
Early Stage Research Actions (TRL 2-3)		
Due to the relative immaturity of the hydrogen sector there remain a number of challenges to address with regards to H_2 infrastructure, including the storage, distribution and dispensing of H_2. Whilst systems exist today which allow the system to function, there is considerable scope for optimisation through new components and techniques. Outlined below are a number of areas where technology could benefit from research efforts: *H_2 compression* • Development of novel technologies for compression, including chemical compression (hydride thermal cycles) and electrochemical compression. • Testing of electrochemical, thermal and hydride compression at low, medium and high temperatures and pressure. • Novel cryogenic impression approaches. *H_2 purification and separation* • Development of Pt and Pd free solutions with CAPEX < €1,500/kg/day. • Concepts to increase H_2 purity levels to 99.999% with a reduction in energy wastage. • The purification of H_2 with medium and high temperature electrochemical processes. • Methodologies for separating H_2 from blended natural gas. • Development of new separation membranes.	• 8 projects • €24M budget • 100% funding rate • €24M funding	FP9
Development Research Actions (TRL 4-6)		
Validation projects need to be commissioned in order to optimise storage and distribution technologies for hydrogen. Development efforts should focus on the following areas: • Producing compression units with higher performance levels (reliability, efficiency) and in-field testing. • Development of large compression technologies for injection of H_2 into gas pipelines (30 bar to 100-200 bar). • Development of a greater accuracy within hydrogen sensors and flow meters. • Projects which could reduce the cost of H_2 separation and increase poisoning resistance. • 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.	• 9 projects • €63M budget • 75% funding rate • €47M funding	FP9
Innovation Actions (TRL 7-8)		
Demonstration of three novel concepts for hydrogen compression at a real world scale (i.e. >200kg.day for hydrogen stations 10's of tonne/day for pipeline injection).	• 3 projects • €60M budget • 50% funding rate • €30M funding	FP9

Transport logistics for hydrogen by road, ship and pipeline are optimised to deliver hydrogen at low cost.

Delivering hydrogen

Centralised hydrogen production may achieve lower production costs but delivering H_2 poses unique challenges due to its low volumetric density.

A mature market has already been established in the road transport of compressed gaseous H_2.

However, **H_2 transport remains limited by high costs and geographical distance**.

To improve large-scale H_2 distribution, key focus areas for development are **high pressure tube trailers, liquid H_2 storage and H_2 distribution via pipelines**[1].

1 – note the previous roadmap covers issues around compression, purification and metering which are relevant for delivering hydrogen

Actions and targets

- Deployment of various modes of H_2 transport to distribute large volumes of H_2 over both short and long distances, driven by demand for hydrogen.
- Projects to optimise existing technologies (e.g. reduce boil-off from liquid H_2 and liquid H_2 shipping), new higher pressure & capacity tube trailers.
- Alignment of regulations across Europe for transporting liquid hydrogen.
- Compressed gas delivery by road transport is optimised for new high pressure trailers (up to 700 bar).

2025
High pressure, high capacity road distribution networks are operating at low cost <€1/kg using pressurised hydrogen and liquid hydrogen.

2027
Improvements in liquefaction and boil-off of liquid H_2 mean optimised road (and where needed ship) networks are developing for liquid H_2.

2030
H_2 pipelines have expanded and H_2 is extracted from natural gas blends at HRS.

2030 vision

H_2 transport costs < €1/kg across all transportation methods. Road transport networks offer efficient solutions to deliver hydrogen across Europe. New large H_2 pipeline networks are serving hydrogen energy users with low carbon hydrogen.

Current state of the art

Multiple methods for delivering H_2 are available but at high cost. Novel concepts for pressurised hydrogen transport are maturing (1,100kg of H_2 at 500-bar on tube trailers), liquid H_2 transport and H_2 pipeline approaches are used in industry but require development (cost and efficiency) for energy applications.

Stage for support + funding rate	EU budget funding
Early stage research 100%	€3M
Development research 75%	€11M
Innovation actions 50%	€10M
Market deployment 25%	-
Total	**€24M**

Overview of hydrogen transport logistics: vision, current status and supply chain

Introduction

H_2 presents unique challenges for transportation and distribution due to its low volumetric density. However, if H_2 is to become a widespread energy carrier, distributed from centralized production facilities in high volumes across large geographic areas, these obstacles must be overcome in a cost-effective and efficient way. Development efforts are therefore vital to advance logistic options and develop novel transportation methods optimized for large scale H_2 delivery. This relates to improvements in:

- **Road transport for gaseous hydrogen** – most tube trailers in operation today deliver small quantities of compressed H_2 gas (<300kg of H_2 per delivery) at a low pressure (<200 bar). There is a need to develop higher pressure tube trailers with a greater capacity, which will reduce costs per kg H_2 delivered. A number are already on the road, including the Linde tube trailer which has a 1,100kg H_2 capacity with 500 bar pressure, with moves to allow higher capacity 700 bar tube trailers (c. 1,500kg) in the coming years
- **Transport of liquefied hydrogen (see liquid carriers roadmap for details of liquefaction)** – H_2 in liquid form is the most conventional means of transporting bulk hydrogen on the road and could be suitable for ship transport. The H_2 is stored at -253°C in super-insulated 'cryogenic' tankers. However, liquefaction is energy intensive and storage/transport of the H_2 often results in energy losses due to 'boil-off' or evaporation. There is potential to reduce boil off losses, as illustrated by NASA's tests on integrated refrigeration and storage[1].
- **Pipelines** – for delivering large volumes of hydrogen over land, (e.g. within industrial complexes or from centralized production to distributed users) pipelines are a leading option. Such pipelines could be dedicated hydrogen lines, serving industry initially (of which there are already >1000 km in Europe), and in the longer term deliver hydrogen to buildings and hydrogen refueling stations. Development of materials and valves for pure H_2 pipelines could help to improve operation. Alternatively, H_2 could be injected into the natural gas network (volumes up to 20%) where the use of methane – hydrogen blends is practical (see pages 89-91).

European supply chain

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

2030 vision
H_2 transport costs < €1/kg across all transportation methods. Road transport networks offer efficient solutions to deliver hydrogen across Europe. New large H_2 pipeline networks are serving hydrogen energy users with low carbon hydrogen

1 – Notardonato, W., Swanger, A., Fesmire, J., Jumper, K., Johnson, W. and Tomsik, T. (2017). Zero boil-off methods for large-scale liquid hydrogen tanks using integrated refrigeration and storage. *IOP Conference Series: Materials Science and Engineering*, 278, p.012012.

Hydrogen transport logistics: detailed technology roadmap[1]

Actions and interim targets

2020 | **2025** | **2030**

Current State of the Art

Road (tube trailers)
Tube trailers with capacity > 1,100kg H_2 (at >=500bar)
Liquid H_2 tanker capacity of 4,000 kg of H_2

Ships (liquid)
No liquid H_2 ships in operation. Kawasaki are designing a large ship to transport liquid H_2.

Pipeline
H_2 dedicated pipeline cost c €1M per km

Actions and interim targets

- Action: Optimisation of existing road and ship transport technology to optimise efficiency (loading and unloading time) and cost
- Interim target: Tube trailer CAPEX 0.45M€/tonne capacity (@1,000kg and 500 bar)[MAWP] Charge/discharge efficiency> 88%
- Interim target: Tube trailer CAPEX 0.3M€/tonne capacity (@1,500kg and 700 bar)
- Action: Development of novel high pressure lightweight composite materials H_2 tanks
- Interim target: Demands of 1,000's kg per day at HRS networks create scale needed to reduce transport costs to <<€1/kg
- Substantial increase in H_2 demand for transport and building applications
- Action: Improvements in transport vessels for liquid H_2 (temperature control and minimal boiling loss)
- Interim target: Little/no boil-off of H_2 in transportation
- Interim target: Liquid H_2 storage container capex €0.2M/tonne capacity
- Action: Demonstration of very high capacity gaseous tube trailers e.g. 700 bar, including required changes to existing regulations
- Role for EU programme: **EU programme supports R&D to optimisation of high pressure and liquid H_2 storage for road and maritime transport**
- Interim target: Most promising liquid carrier options are being adopted in commercial projects
- Regulations for on-road liquid transport of hydrogen are harmonised across the EU to facilitate transport of liquid H_2
- Action: Next generation of road and maritime transport with liquid H_2
- **EU programme support demonstration of integrated hydrogen logistics** → Action: Demonstration of intermodal hydrogen transport to optimise system components
- Devise regulations and safety standards to allow the integration of 100% H_2 into the natural gas grid pipelines and the more widespread deployment of H_2 dedicated pipelines
- Action: UK's Hy4Heat and H21 programs test viability of conversion of existing (low pressure) gas pipes to run on hydrogen
- Interim target: Deployment of H_2 dedicated pipelines for energy applications
- Action: Development of novel components/welding processes for high pressure H_2 pipelines, as well as practical solutions to problems identified around converting existing pipelines to hydrogen
- Role for EU programme: **EU programme supports R&D to develop new components/practices for H_2 pipelines**

2030 vision

H_2 transport costs < €1/kg across all transportation methods. Road transport networks offer efficient solutions to deliver hydrogen across Europe. New large H_2 pipeline networks are serving hydrogen energy users with low carbon hydrogen

Background assumptions:
- Continued policy support and industry momentum for zero-emission road transport and hydrogen energy applications
- Demand driven increase in H_2 production (from transport and housing energy demands)
- Clarity on purity requirements for energy applications (e.g. 100% hydrogen pipelines)
- Regulatory support for H_2 pipelines

Legend
- Action
- Interim target
- Role for EU programme

1 - The previous roadmap covers issues around compression, purification and metering which are relevant for delivering hydrogen

Transport logistics for hydrogen: proposed areas for support

Stage of development and potential areas for support	Proposed budget	Proposed funding source
Early Stage Research Actions (TRL 2-3)		
The transport of H_2 by road (compressed gas tube trailers and liquid H_2) is a relatively advanced sector. Due to this, no early phase projects are proposed to further these technologies. However, early phase development for H_2 pipelines will be required to support the development of new materials for pipes and valves, including devising welding processes consistent with a high or 100% H_2 content.	• 1 project • €3M budget • 100% funding rate • €3M funding	FP9
Development Research Actions (TRL 4-6)		
Development work is needed to optimise the transport and storage of liquid hydrogen for road transport, aiming to improve temperature control to minimise H_2 loss by evaporation. Learnings from this work should be able to be transferred to transporting liquid H_2 in ships. Development work is also required to devise and deploy very high capacity pressurised tube trailer concepts (e.g. at 700 bar).	• 2 projects • €14M budget • 75% funding rate • €11M funding	FP9
Innovation Actions (TRL 7-8)		
The transfer of hydrogen between different modes of transport needs to be addressed to optimise systems components and reduce hydrogen losses. An intermodal demonstration project will aim to demonstrate hydrogen transport by best in class examples of pipelines, containers designed for ships and road.	• 1 project • €20M budget • 50% funding rate • €10M funding	FP9 CEF ETS-IF
Market Deployment Actions (TRL 9)		
Growing markets for hydrogen and hydrogen applications should provide the pull needed to reach volumes for distribution methods. In some places there may be an argument for Member State/European support for e.g. optimised gas networks as part of programmes like CEF.	No funding proposed	

Liquid hydrogen carriers develop and provides a safe and affordable means of distributing hydrogen to end users

Liquid hydrogen carriers

Current methods of transporting hydrogen include **liquefaction** (at -253°C) in large scale plants or compression to high pressures.

There are alternative liquid carriers which are safer to transport, and can use existing fuel distribution infrastructures.

There is interest in a range of chemistries which could provide an **energy efficient, safe and practicable solution to transporting hydrogen**.

Liquid organic hydrogen carriers are a promising area, with potential for low energy losses.

Ammonia is also an area of interest, both as a hydrogen carrier and also as an energy carrier in it's own right, with potential to use ammonia directly in high temperature fuel cells, gas turbines and other applications.

Actions and targets

- Commercial scale projects are rolled out with improved liquefaction technology and alternative liquid hydrogen carriers operating at commercial prices.
- Regulatory changes facilitate transport of ammonia and LOHCs such as toluene from ship to road at ports.
- Demonstration projects validate liquid carriers to deliver hydrogen to HRS and other applications at scale.
- R&D on chemistries and technologies that hold high potential for energy efficiency.

Current state of the art
Large scale liquefaction plants operate with energy requirements c. 12 kWh/kg. Research on other carriers but as yet no real-world scale demonstrations.

2023-25
Liquid carriers have been developed and demonstrate charge/discharge efficiency above 88% and discharge energy use below 5 kWh/kg H_2.

2027
Liquefaction with 6-9 kWh/kg efficiency developed at scale and with low cost (<€1/kg).

2030
Most promising liquid carrier options are being adopted in commercial projects.

2030 vision

A range of liquid hydrogen carriers are being used commercially to transport and store hydrogen at low cost and with <10% energy lost from loading/unloading.

Stage for support + funding rate	EU budget funding
Early stage research 100%	€12M
Development research 75%	€11M
Innovation actions 50%	€20M
Market deployment 25%	-
Total	**€43M**

Overview of liquid hydrogen carriers: vision, current status and supply chain

Introduction

Hydrogen is one of the most energy dense fuels by mass, but it is extremely light and so the volumetric energy density in standard conditions is very low. Conventional hydrogen delivery solutions solve this problem by either compressing and delivering a pressurized gas, or by liquefaction and delivery of a liquid. These methods have significant energy and cost implications, as well as safety considerations. They also are unsuited to very long term storage of hydrogen (due to high cost of containers and also boil-off losses for liquid hydrogen), and for the same reasons not suited to distribution over long distances and in bulk. For these reasons, there is research on other methods of transporting hydrogen in hydrogen carriers. This roadmap focusses on those options which are in a liquid phase, as they have the major advantage of being able to transport and distribute the material using infrastructure familiar to mineral-oil based fuel industries. Key liquid carriers include **liquid organic hydrogen carriers (LOHCs) and ammonia**. Methanol is an option, an of interest for maritime applications, but as there are CO_2 releases it is not an option for full decarbonisation. Because there is scope for improvement of conventional liquefaction of hydrogen, it is included here. The transport of liquid hydrogen is covered in the previous roadmap (pages 35-38).

Hydrogen carriers store hydrogen by hydrogenating a chemical compound at the site of production and then dehydrogenating either at the point of delivery or potentially onboard the fuel cell vehicle for transport applications. They are largely at the research stage and have yet to be proven as cost or energy efficient. There is interest in direct use of ammonia in a range of applications, including turbines and certain types of fuel cells.

Current status of the technology and deployments

Conventional liquefaction of hydrogen is a mature technology but has not been subject to significant innovation in recent decades. There is therefore scope to improve cost and efficiency, with the FCH JU IDEALHy project concluding that it should be possible to halve energy consumption.

A number of companies, notably Hydrogenious, Areva H2Gen, are developing liquid organic chemistries and reformation products, none of which have yet been deployed in real world applications or demonstration projects. The FCH-JU HySTOC project aims to test the technology in a commercially operated HRS in Finland.

European supply chain

Large industrial gas companies such as Linde and Air Liquide (based in Europe) have expertise in liquefaction technologies and are well placed to exploit this market. European SMEs such as Hydrogenious and Areva H2Gen are active in developing liquid hydrogen carriers and could capitalise on this with the continued research and development in this market.

2030 vision
A range of liquid hydrogen carriers are being used commercially to transport and store hydrogen at low cost and with <10% energy lost from loading/unloading

Whilst there is interest in a variety of chemistries for hydrogen carriers, the additional energy requirements can be significant…

Energy requirements (today's state of the art)

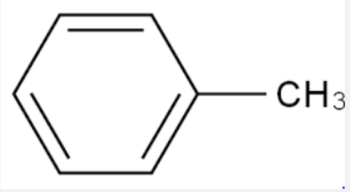
Liquefaction

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. When stored as a liquid, some hydrogen is lost as evaporative "boil off".

12kWh/kg based on current technology
6kWh/kg possible with improved technology

= 15-30%
Of H_2 energy

LOHCs

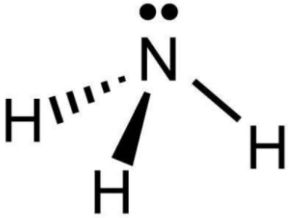


LOHCs are typically hydrogen-rich aromatic and alicyclic molecules, which are safe to transport. The hydrogenation reaction occurs at elevated hydrogen pressures of 10-50 bar, and is exothermic. Dehydrogenation is endothermic and occurs at low pressures. The unloaded carrier is returned to the production site for reloading

10 kWh/kg based on Hydrogenious estimates for Dibenzyltoluene
Range is due to the assumption that the heat from the exothermic reaction can be used

= 5-30%

Ammonia

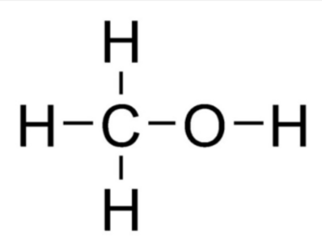


Ammonia production via renewable hydrogen is receiving increasing interest in particular as costs of solar energy drop at low latitudes. Conventional ammonia production via the Haber-Bosh process is energy intensive, new processes have significant potential to reduce this. Ammonia cracking is done in the presence of a catalyst and results in the loss of c. 15% of H_2

Enthalpy of ammonia synthesis reactions = 12kWh/kg H_2. System energy requirements can be reduced by direct synthesis of NH_3.
Ammonia cracking + losses = 4 kWh/kg H_2

= 30-50%

Methanol



Conventionally methanol is produced by reforming of natural gas at temperatures of c. 200-300°C. There are a range of other production methods including biomass gasification, and using captured CO_2 with H_2. Dehydrogenation is done via reforming at high pressures and temperatures of c. 200°C (and also releases CO_2). With methanol is made from inputs such as biomass or captured CO_2, it could be considered a CO_2 neutral process.

12kWh/kg for hydrogenation
6 kWh/kg for dehydrogenation (both based on reaction energetics)

= c. 45%

Liquid hydrogen carriers: detailed technology roadmap

Actions and interim targets

2020 | 2025 | 2030

Current State of the Art

Liquefaction KPIs:
Energy consumption: 12 kWh/kg
Cost: c.€1.5/kg
IDEALHy

Most liquid carrier concepts <TRL 5

Hydrogenious have deployed a 30kW unit in a micro-grid environment

Liquefaction

- Next generation of liquefaction technology developed (cryogenic vessels, high efficiency etc)
- High efficiency liquefaction demonstration project to validate next gen technologies
- ★ Liquefaction with 6-9 kWh/kg efficiency developed at scale and with low cost (<€1/kg)
- Improvements in storage of liquid H_2 to reduce boil-off losses (see previous roadmap)
- Roll-out of next generation liquefaction technology to new bulk hydrogen production plants

EU programme supports R&D&D on these technologies

Regulation

- Regulatory changes facilitate transport of ammonia and LOHCs such as toluene from ship to road at ports

Liquid carriers

- Demonstration activities to prove the viability of existing liquid carrier chemistries including ammonia, LOHCs & methanol
- ★ Large scale ammonia project operating, with conversion costs <€5/kg
- Continued research on carrier chemistries which show potential for reduced energy use, and on reducing raw material requirements for catalysts
- Most promising concepts in terms of safety, cost and performance are developed
- ★ Most promising liquid carrier options are being adopted in commercial projects
- Most promising next generation chemistries and catalysts are demonstrated in HRS with 100kg/day capacity and €5/kg cost

EU programme supports R&D&D on these technologies and concepts

- ★ Carriers have charge/discharge efficiency above 88% and discharge energy use below 5 kWh/kg H_2
- Techno-economic work based on early trials to conclude on most appropriate liquid option for different scales of demand/production and also distance travelled (from short distance to intercontinental energy transport)
- ★ Carriers have charge/discharge efficiency above 90% and total additional cost of €1/kg

2030 vision

A range of liquid hydrogen carriers are being used commercially to transport and store hydrogen at low cost and with <10% energy lost from loading/unloading

Background assumptions:
- Demand for H_2 grows in line with projections in other roadmaps

Legend
- Action
- ★ Interim target
- **Role for EU programme**

IDEALHy: Efficient liquefaction of hydrogen: Results from the IDEALHy project, 2013.

Liquid hydrogen carriers: areas for support

Stage of development and potential areas for support	Proposed budget	Proposed funding source
Early Stage Research Actions (TRL 2-3)		
Liquefaction: Energy efficiency improvements and cost reductions could come from next generation materials for liquefaction, e.g. cryogenic vessels. Support would target innovations with the potential to reduce energy cost of liquefaction, reduce boil off losses, improve efficiency and improve reliability. ***Liquid carriers:*** More research is needed to develop novel chemistries and reduce the amount of expensive raw materials needed in hydrogenation/dehydrogenation reactions.	• 4 projects • €12M budget • 100% funding rate • €12M funding	FP9
Development Research Actions (TRL 4-6)		
Liquefaction: No development work proposed here – instead the innovations identified in early stage projects will be demonstrated (see TRL 7-8) ***Liquid carriers :*** Most promising concepts from early stage work will be developed into working prototype systems, with a focus on new chemistries with improved safety, cost and performance	• 2 projects • €14M budget • 75% funding rate • €11M funding	FP9
Innovation Actions (TRL 7-8)		
Liquefaction: One demonstration project will be supported, based on the solutions validated in the early stage R&D projects ***Liquid carriers :*** Most promising concepts which have been developed will be deployed in a real-world application, supplying 100kg/day H_2 to an HRS, at a cost of €5/kg	• 2 projects • €40M budget • 50% funding rate • €20M funding	FP9
Market Deployment Actions (TRL 9)		
Market entry support may be required once the technology readiness has improved and the costs have been lowered, though in practice the various hydrogen transport options would be expected to compete for end-use markets established by the end-use specific market activation work which is defined in these roadmaps…	N/A	

HRS

Hydrogen refuelling stations are deployed across Europe, reliably dispensing fuel at an affordable cost

Hydrogen refuelling stations

Hydrogen refuelling stations are being deployed across Europe at an accelerating pace.

Further deployment programs focussing on public stations will be required to allow mainstream deployment of hydrogen passenger cars, vans and trucks. There is scope for improvements in the reliability, cost and footprint of stations through novel design concepts and the introduction of new components[1] (e.g. liquid hydrogen pumps for liquid stations).

In addition, novel station designs are required for the very high hydrogen capacity needed for the **heavy duty applications in bus depots, trucks, rail and ships**.

1 – New components such as novel compressors are already covered in the key technologies for distribution roadmap.

Actions and targets

- European manufacturers continue their global lead in HRS production and operation.
- Hydrogen stations are initially deployed in clusters catering to urban captive fleets. These stations are eventually joined together in coordinated national programs to form nationwide networks. Initial market activation supported by Europe.
- Novel fuelling station concepts with large throughput, improved reliability and reduced cost are validated.
- Large initiative coordinated by the EU to roll-out 1000 public HRS across Europe.
- R,D&D aims to reduce footprint & cost, improve reliability.

2020-25
Continued expansion of public HRS networks.

2025
1000 public HRS deployed.

HRS for heavy-duty applications: 10’s ultra-high capacity stations are deployed and tested, proving the ability to deploy tons of hydrogen per day to trains, ships etc.

2030
4,500 public stations are deployed, enabling continent wide driving

>500 ultra-high capacity HRS for trains, ships.

Current state of the art
Viable HRS have been deployed in limited national networks (~100 stations across Europe). HRS availability in excess of 99% achieved for bus stations <95% for passenger cars stations.

2030 vision

4,500 HRS installed across Europe, achieving continent wide coverage and enabling sales to private car customers. HRS cost decreased by >50% compared to today >99% reliability.

Stage for support + funding rate	EU budget funding
Early stage research 100%	€3M
Development research 75%	€16M
Innovation actions 50%	€50M
Market deployment 25%	€250M
Total	**€319M**

Hydrogen refuelling stations: vision, current status and supply chain

Introduction

The hydrogen refuelling station is an essential part of the hydrogen mobility proposition. For widespread hydrogen mobility to be viable, it will be essential the there is a nationwide network of public hydrogen refuelling stations for passenger cars, trucks and vans. Furthermore, the larger heavy duty fuelling applications such as buses and trains will require very reliable, high capacity stations capable of delivering many tonnes each day, usually in short overnight refuelling windows. Today, we see approximately 100 refuelling stations around Europe. These stations demonstrate the ability to completely refuel hydrogen vehicles quickly and with an equivalent experience to refuelling a conventional vehicle. There are however significant issues with public stations, which can all be resolved by combined industry public sector work over the coming years :

- The cost of the stations are too high - the capital and fixed operating cost of hydrogen stations are very high, which creates a challenge in creating a viable refuelling station business model, particularly in the early years when utilisation is low.
- The station reliability (particularly for passenger cars) is too low – The refuelling station networks for passenger cars have struggled to reach availability levels in excess of 99%, whilst at least 98% is required for a viable network. This creates issues for customers who cannot rely on their hydrogen supply. This situation will be partly resolved through increased throughput at the stations, but will also benefit from improved components (particularly compressors and dispensers). By contrast, the bus refuelling stations have proven >99% reliability is possible, generally through multiply redundant design and also 350 bar designs which eliminate compressors.
- The network is not sufficiently widespread to allow sale of hydrogen cars to the private customer – this leads to a requirement for new business models based on targeting fleet customers who are “captive” to a specific region with a geographically limited network coverage
- The permitting and construction process is too long – leading to a need to improve standardisation and also levels of education and awareness amongst regulators

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.

2023 – German H_2 station map

European supply chain

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

2030 vision
4,500 HRS installed across Europe, achieving continent wide coverage and enabling sales to private car customers
HRS cost decreased by >50% compared to today
>99% reliability

HRS

Hydrogen refuelling stations: detailed technology roadmap

Current State of the Art

Circa 100 HRS installed in Europe by end of 2018

Cost of HRS ranges from €1m to €3.2m for HRs from 200kg.day (cars @700 bar) to large scale bus refueling (20 + buses @ 350 bar)

Availability >99% bus stations. <95% passenger cars stations
No validated design for high capacity trains stations

Actions and interim targets

2020 – 2025 – 2030

- Large initiative coordinated by the EU to roll-out 1000 public HRS across Europe
- Initial deployment of stations in geographically limited clusters linked to major towns with strong zero emission policies (London, Paris, Berlin, Hamburg etc)
- Early adopter Hydrogen Mobility expansion programs deliver first nationwide networks (Germany, UK, France, Scandinavia, Benelux), with Member State support
- Follower Member States launch nationwide roll-out programs (starting with large urban centres)
- Market activation program support first 1,000 stations in Europe with European + Member state funds
- New HRS designs incorporating novel components and system architecture to achieve low footprint (e.g. underground tanks), lower cost and increased reliability.
- Demonstration of stations designed for high reliability and stations incorporating low cost/low footprint components

EU programme supports R&D to reduce cost and improve reliability, & market deployment supports station rollout

- HRS for captive fleets (buses, trains, ships) situated on depot and justified based on captive demand

EU programme supports development of ultra high-capacity stations for captive fleets

- New concepts for hydrogen refuelling stations for high capacity refuelling (for trains, large bus fleets and ships
- Demonstration of stations for trains and ships, achieving very high daily capacities - >1,000kg.day
- Investment in European manufacture for series produced HRS
- Standardisation of HRS designs and interfaces (to improve component supply)
- Campaign to educate and improve the knowledge of planning and permitting officials involved in HRS consenting

Interim targets

- >1,000 public stations across Europe
- HRS consenting process reduced to 3 months
- >50 high capacity stations (>1,000kg.day) in operation proving viability of high capacity hydrogen
- >4,500 public stations across Europe, nationwide coverage in all Member States
- >2M tonnes per year dispensed for mobile applications
- Cost of HRS will be reduced by at least 50% (in comparison to present prices)
- Stations achieve >99% availability for all applications)

2030 vision

4,500 HRS installed across Europe, achieving continent wide coverage and enabling sales to private car customers

HRS cost decreased by >50% compared to today

Background assumptions:

- Continued policy support for zero-emission road transport.
- Member States commit to hydrogen as part of ZE solution
- Concurrent commitment to large volume deployment by vehicle OEMs
- Cost reductions assume increased scale of FC market and increased deployment of FCEVs

Legend

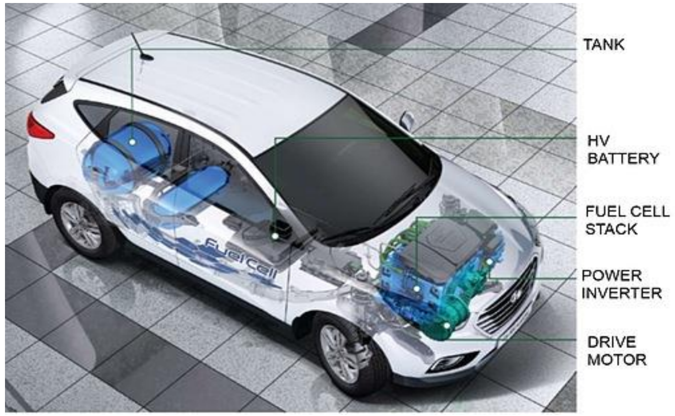
- Supporting strategy
- Action
- Interim target
- Role for EU programme

HRS

Hydrogen refuelling stations: areas for support

Stage of development and potential areas for support	Proposed budget	Proposed funding source
Early Stage Research Actions (TRL 2-3)		
Despite HRS being demonstrated in the field, there is scope for advancement to improve the efficiency and cost of refuelling stations. Better interfacing technology is required between hydrogen vehicles and HRS to ensure optimal (and safe) filling protocols.	• 1 project • €3M budget • 100% funding rate • €3M funding	FP9
Development Research Actions (TRL 4-6)		
As HRSs have reached the phase of commercial deployment, development efforts should focus on optimising station design (to reduce footprint, improve efficiency and decrease cost) and increasing station size (to allow FCEV sales to all use cases, including ships, fleets of trains and airplanes). Below are some examples of development projects which could be targeted: • Development of new approaches to decrease overall HRS footprint. • Develop high throughput stations for large scale vehicles (ships, fleets of trains, large fleets of buses or trucks), including >> 1,000kg/day capacity and individual fills in excess of 200kg (in less than 20 minutes). • Reduction in the CAPEX and OPEX of HRS through integrating innovative technological components – development work here would focus on how to integrate those components.	• 3 projects • €21M budget • 75% funding rate • €16M funding	FP9
Innovation Actions (TRL 7-8)		
Demonstration projects are key to optimising HRS technologies and testing their operational ability in real-world use cases. It is suggested FP9 focusses demonstration efforts on projects which: • Aim to standardize and industrialise HRS equipment and components. • Have a specific goal to increase the reliability and availability of HRS equipment and infrastructure. • The deployment of high throughput stations (multi-ton/day) for large scale ships, fleets of trains or large fleets of buses and trucks. • Support improved efficiency and zero boil off during H_2 transfer and H_2 distribution at a HRS based on liquid hydrogen. • Explore novel business models, for example, on-demand hydrogen refuelling and compact hydrogen mobile stations.	• 5 projects • €100M budget • 50% funding rate • €50M funding	FP9
Market Deployment Actions (TRL 9)		
Funding through market activation will help encourage HRS operators to invest in hydrogen technology by lowering the initial capital cost of HRSs and hence helping to create the initial networks required to deploy hydrogen vehicle technologies. European support (25% funding rate) is envisaged alongside Member State support (25%) for the deployment of the first 1,000 HRS in Europe.	Budget €1BN • 1000 HRS • Funding €250M	FP9 CEF

Fuel cell vehicles are produced at a price equivalent to other vehicle types: technology building blocks



Technology building blocks

The technologies required for hydrogen fuel cell based automotive systems have matured rapidly, to the point **that we now see commercial sales of hydrogen passenger cars (in volumes of 1,000's/year) and heavy duty vehicles (in volumes of 10's/year per manufacturer).**

The main issue now is to **drive down cost whilst maintaining an acceptable level of durability and efficiency.** This will be driven by two factors:

- **Scale** – economies of sale will be critical in taking cost out of the fuel cell component supply chain, with a 4x effect available in moving from today's volumes to 100,000 units/year.
- **Technology** – new lab based technologies need to progress through the TRL levels and into final products to further reduce cost.

Actions and targets

Volume increases are stimulated by a combination of market activation programs and regulations which increase the size of the market year on year.

European funding supports the acceleration of the TRL's of these components to enable new generation of European stacks and tanks, with progressively improved cost and performance.

Core technology advances stimulated by R&D aiming to ensure 2030 targets are met.

2020-25
A programme incorporating the latest technical developments into stacks and tanks demonstrates 2030 performance targets at the lab scale.

2025
Next generation European fuel cell stacks and tanks offer globally leading performance and cost dynamics.

2030
Average passenger car tank + FC system costs <€5,000.
Typical bus tank + FC system < €40k.

2030 vision

Fuel cell system and hydrogen tank components have developed to allow FCH vehicles to be offered on a cost competitive basis for both light and heavy duty markets.

Current state of the art
Technology validated in numerous European trials
Cost reduction is the key challenge e.g. current FC system costs > €200/kW for passenger cars but need to fall below €50/kW for mass market.

Stage for support + funding rate	EU budget funding
Early stage research 100%	€30M
Development research 75%	€53M
Innovation actions 50%	-
Market deployment 25%	-
Total	**€83M**

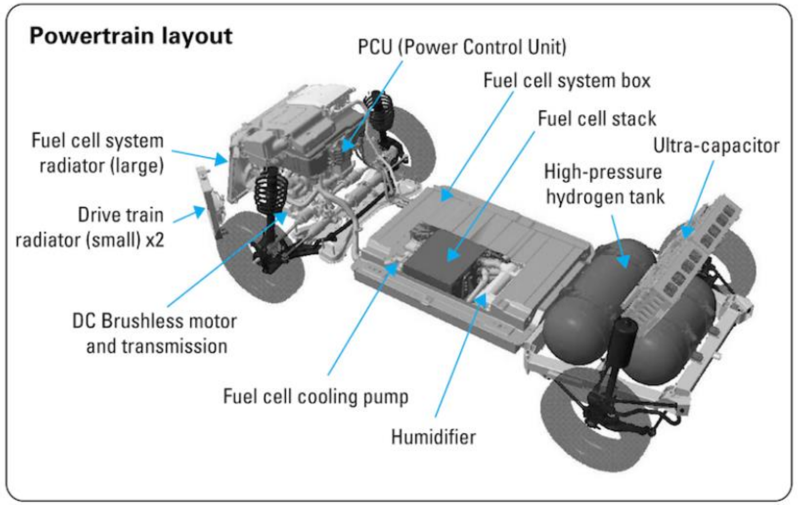
Overview of technology building blocks: vision, current status and supply chain

Introduction

Hydrogen and fuel cell technology has great potential to offer zero emission mobility for a range of transportation uses without compromising the way vehicles are refuelled today (same refuelling time, similar range).

To do this the vehicle prices will need to tend towards the prices of vehicles in use today. This in turn requires a reduction in the cost of the drivetrain components – the "technology building blocks" – the fuel cell stacks, the supporting balance of plant which makes up the "fuel cell system" and the hydrogen storage tank.

Cost reduction in these components will be driven by a combination of technology development and volume of deployment.



Current status of the technology and deployments

Researchers have developed these components to the point where they have the operational reliability to allow them to be deployed in small series production to mainstream vehicle customers (for example in the Toyota Mirai which has sold over 3,000 units into California). The fuel cell stacks operating in London's buses since 2010 have lasted for over 25,000 hours, thereby proving their longevity for heavy duty applications. The challenge now is to reduce cost through combination of increased production volume as well as technology development to improve 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 a catalyst, membrane and system level.

European supply chain

The European supply chain for fuel cell stacks and systems is not as mature as those in other countries (notably Japan and the USA). It is however developing rapidly with large tier 1 manufacturers getting involved such as Bosch, Michelin and ElringKlinger and with stack suppliers such as PowerCell, Symbio, Nedstack and Proton Motor maturing rapidly.

A number of tank manufacturer are now based in Europe, notably Hexagon and Luxfer. These manufacturers are being joined by Tier 1 suppliers such as Plastic Omnium and Faueccia

2030 vision

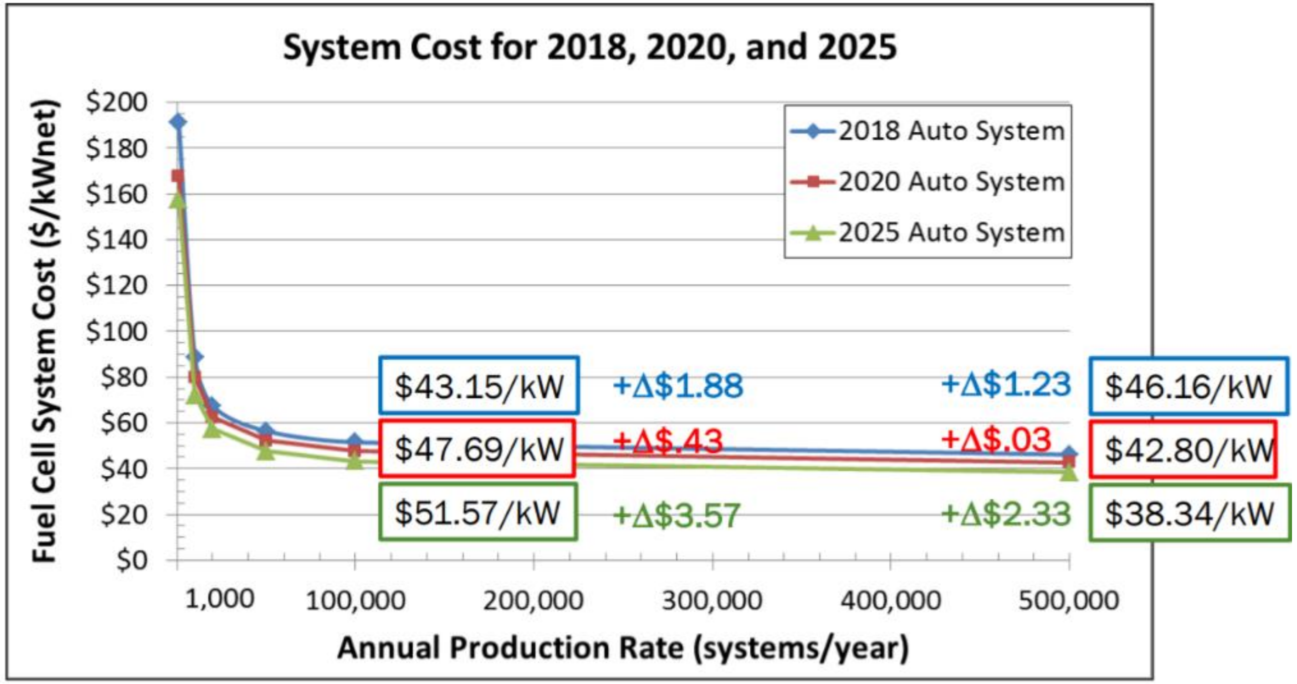
Fuel cell system and hydrogen tank components have developed to allow FCH vehicle to be offered on a cost competitive basis for both light duty and heavy duty markets

Even with today's state of technology development, volume production plays a major role in reducing cost of the building blocks

When considering the evolution of fuel cell vehicle components it is important to separate volume effects and technology development on the cost of the units

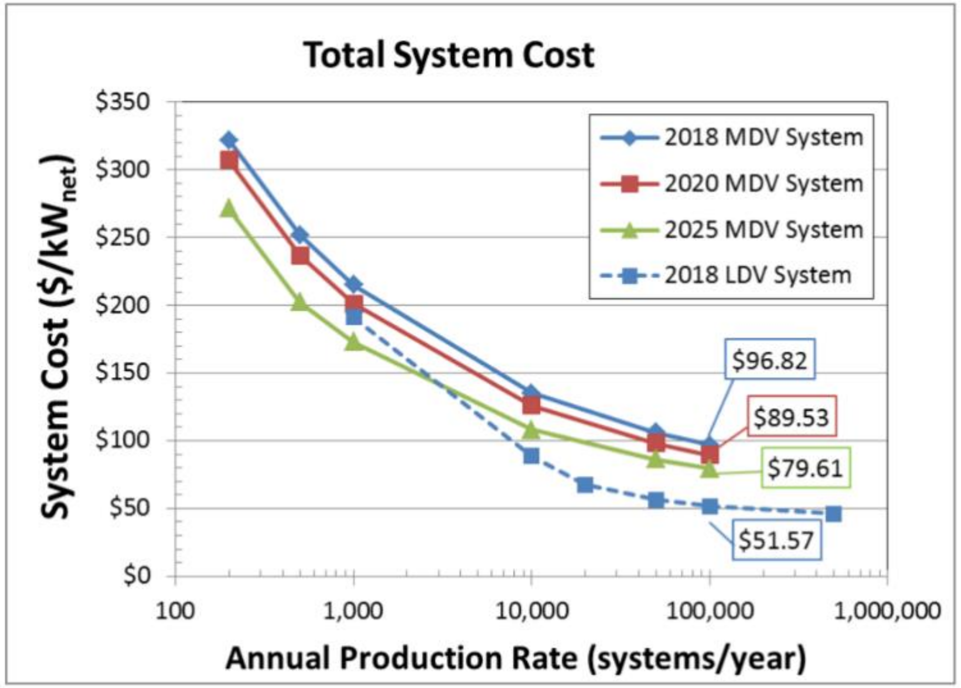
The graphs below show the impact of volume on the cost of the key fuel cell components. It is clear that increasing production volume will already today have a very significant impact on price. The data comes from the US DOE cost analysis (2018) which is accepted by global OEMs as providing an accurate review of the current status

Passenger car fuel cell systems



*Cost results shown for both 100,000 & 500,000 systems/year

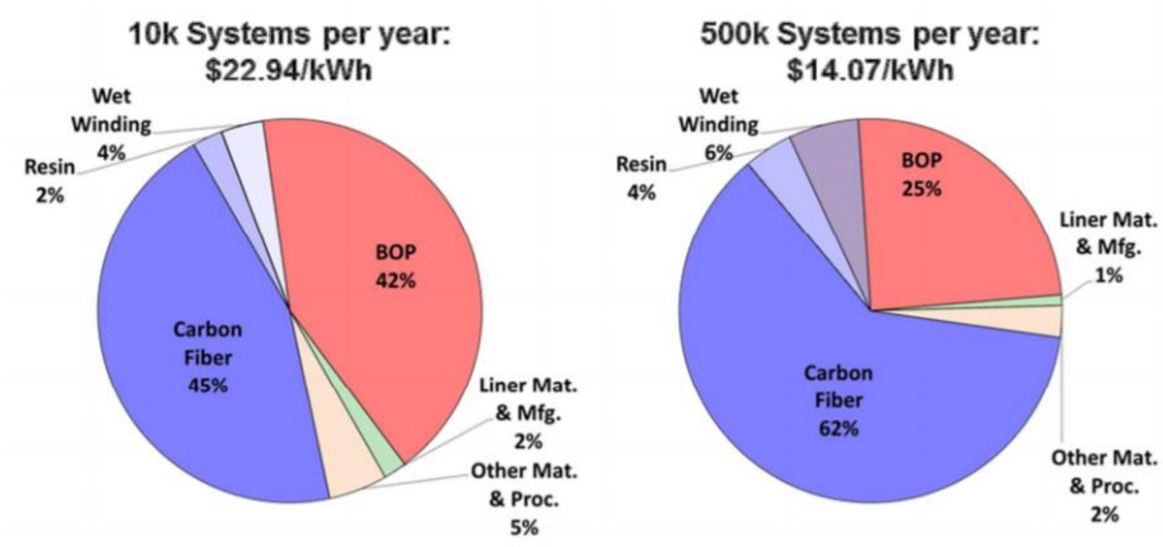
Heavy duty fuel cell systems (for trucks and buses)



Reference: Graphs are sourced from the DOE 2018 Cost Projections of PEM Fuel Cell Systems for Automobiles and Medium-Duty Vehicles, Brian James, Strategic Analysis Inc.

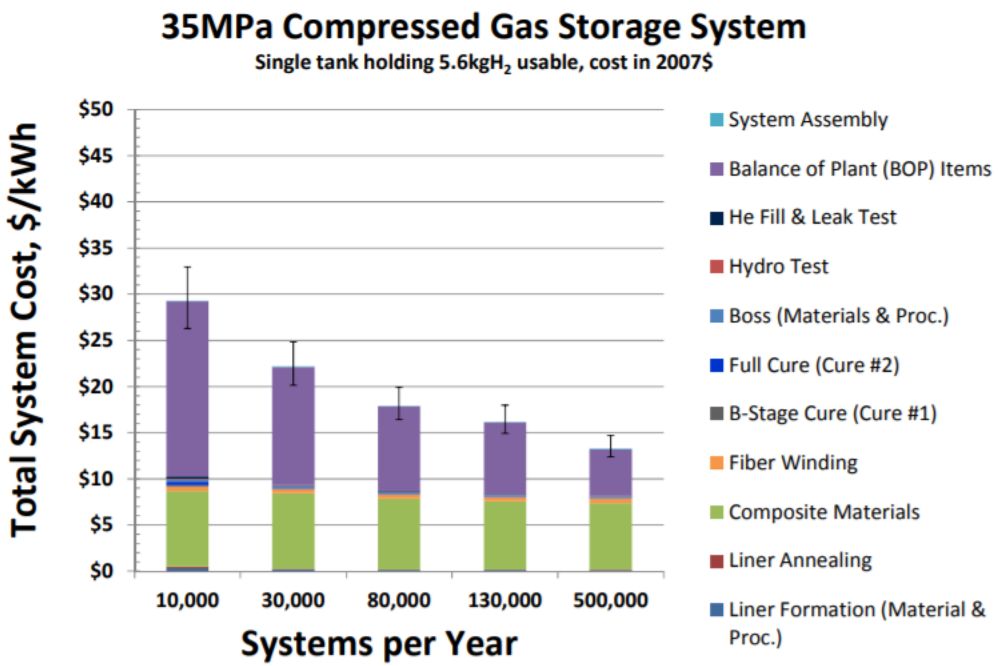
Volume production will also play a similar role for hydrogen tanks

Passenger car hydrogen tanks (700bar)



Cost breakdown for type IV 700 bar H_2 single tank storage systems with 5.6 kg usable H_2 and aspect ratio of 3.

Heavy duty tanks (350 bar)



The importance of volume is that to develop the components themselves to the correct prices, **market deployment programs to stimulate the market and allow the technology to mature along the cost curve are crucia**l.
In parallel, **technology development programs** are required to ensure the core technology progresses towards the lower bound of the cost targets.

Reference: Graphs are sourced from the DOE 2016 Hydrogen Storage System Cost Analysis, Brian James, Strategic Analysis Inc.

Technology Building Blocks

Further advances in technology building blocks are available through technology developments, moving from lab scale to system level

Actions and interim targets

2020 | 2025 | 2030

Current State of the Art

Fuel cell stack
Power density $1 W/cm^2$
Pt loading 0.3g/kW:

Hydrogen store
€1-1,500/kg
Volumetric capacity 0.023 kg/l
Gravimetric capacity 5%

System costs
Passenger cars (@100k units/year) - €100/kW
Heavy duty - €1-1,500/kW (@100 units/year)

Actions

Year on year volume increases are stimulated by market activation programs and regulations – this leads to increased investment in European manufacturing capacity for components

TRL 1-3 technologies are developed for the core system components (see next page) – projects are supported where they demonstrate ability to contribute to 2030 targets

Most promising new technologies incorporated into functional stacks/tanks and proven over long duration test cycles (TRL4 to 6)

Current wave of most promising technologies at lab scale incorporated into next generation stack designs and tested in real world test cycles (TRL 4 to 6)

EU programme supports core technology development aimed at hitting cost and performance targets

Designs frozen and manufacturing systems and supply chains developed

Next generation European stack and tanks integrated into vehicles. Car stack <€50/kW (@100k units/year). Tank cost <€400/kg)

Designs frozen and manufacturing systems and supply chains developed

Following generation European stack /tanks

Interim targets (2030)

Fuel cell stack
Areal power density: $2.2 W/cm^2$
PGM loading 0.1g/kW, volumetric power density 5.5 kW/L

On-board storage:
<400€/kg H_2 at the system level, volumetric capacity 0.035 kg/l, gravimetric capacity 6%

Passenger car fuel cell system
FC system durability >7000 hrs
FC system cost @100,k units/year < €300/kW,

Heavy duty fuel cell system
FC system durability >30,000 hours
FC system cost < €250/kW (@1k/year)

2030 vision

Fuel cell system and hydrogen tank components have developed to allow FCH vehicle to be offered on a cost competitive basis for both light duty and heavy duty markets

Background assumptions:

- Continued policy support for zero-emission road transport.
- Cost reductions assume increased scale of FC market
- Programs in member states to help stimulate manufacturing capacity expansion from European manufacturers

Legend

Action

Interim target

Role for EU programme

Vehicle technology building blocks: areas for support

Stage of development and potential areas for support	Proposed budget	Proposed funding source
Early Stage Research Actions (TRL 2-3)		
Fundamental improvements are available for all of the fuel cell vehicle components. Key areas of research include: *Fuel cell stack technology* • Improvements in aerial and volumetric power density of fuel cells (single cell level). • Improvements in fuel cell durability, reliability and lifetime performance.(single cell level). • Specific attention to new needs of marine and rail applications. *Fuel cell system technology* • Low cost BoP components (ionic exchanger, humidifier, air filter, etc.). • Volumetric & gravimetric density of FC systems. *On board storage technology* • Development of new fibres and polymers for the tank lining. • Development of novel storage concepts, including hybrids of solid stores and pressurised tank. Attention will also be paid to developing systems for scaled up fuel cell manufacturing plants.	• 10 projects • €30M budget • 100% funding rate • €30M funding	FP9
Development Research Actions (TRL 4-6)		
Development projects will work on existing technologies deployed in real systems, including: *Fuel cell stack technology* • Stack level improvements to increase fuel cell system durability and reliability. • Developing a low cost stack concept and improving stack manufacturability. *Fuel cell system technology* • Developing FC system manufacturability. • Optimisation of the FC system to different use cases (e.g. hybridized drive trains, ranger extender etc.). *On board storage technology* • Validation programmes on final dimension storage prototypes and developing mounting and integration concepts. • Mounting and integration concepts, safety by design, fire detection and innovative manufacturing issues. • Integration of low cost and reliable safety sensors.	Budget €112M • 10 projects • €70M budget • 75% funding rate • €53M funding	FP9

Fuel cell vehicles are produced at a price equivalent to other vehicle types: Cars, 2-3 wheeled vehicles & vans

Fuel cell vehicles

FCEVs provide a **viable alternative to conventional diesel vehicles with no compromise in terms of refuelling time or range** and have been successfully deployed in cities across Europe in fleets of 10's-100's.

Vehicle sales are low due to high capital cost and limited refuelling infrastructure.

Capital costs for FCEVs are expected to decrease as economies of scale are accessed, reducing the **total cost of ownership and becoming competitive with diesel equivalents by 2030.**

The high capital cost issue will be resolved through increased volume, improvements in the components and optimisation of manufacturing and packaging H_2 system components in the vehicles.

Actions and targets

- Regulations in city centres and at a national level drive adoption of fuel cell based cars and vans, initially for fleet users before migrating to private customers as costs decrease and the HRS network expands.
- Support for developing and deploying new concepts for FC integration into vehicles & demonstration of FCs in different use cases: small cars, vans, scooters.
- Business models are developed for specific use cases such as taxis operating in city centres, driving uptake.
- European market activation expands sales, initially to fleet customers based in large cities with clusters of fuelling station.

2020-23
FCEV sales reach 10,000's per year.

2027
FCEV sales reach 100,000's per year.

1,000,000 FCEVs operating in Europe.

2030
FCEV sales reach 750,000 pa (~5% new vehicle sales).

2030 vision

FCEVs offer lowest ownership cost ZE option in many vehicle classes.

European stock of 5 million FCEVs operating by 2030 (1.5% of total stock).

1 in 5 new taxis are FCEVs.

Current state of the art
Passenger cars: TRL 9, range 550km and top speed of 178 km/h,
cost approximately 100% of equivalent diesel model.
Vans: 330km range and 130 km/h top speed.

Stage for support + funding rate	EU budget funding
Early stage research 100%	-
Development research 75%	€11M
Innovation actions 50%	€20M
Market deployment 25%	€75M
Total	**€106M**

Overview of fuel cell cars, vans & 2-3 wheelers: vision, current status and supply chain

Hydrogen offers a zero compromise, zero emission alternative to fossil fuels in road transport

Introduction

Hydrogen fuel cell vehicles have been developed through a number of vehicle generations to the point where they are now in small series production with a number of OEMs worldwide. The technology has proven capable of offering drivers a zero emission driving experience in vehicles which meet the standards of today's passenger cars and do all of this without comprising on range or refueling time. This is a key differentiator from the battery electric vehicles which are achieving commercial take-off today and leads to an expectation that fuel cell cars will be favoured for larger longer range vehicles in the early stages of their introduction.

Despite these positives, the cost premium of FCEVs and the initial refueling infrastructure required still presents a significant barrier to market entry. The capital cost premium is expected to be resolved through economies of scale and foreseeable introduction of new technologies. The hydrogen infrastructure issue has led to strategies where hydrogen vehicles are initially rolled out to "captive fleets" able to make use of a geographically limited cluster of stations. These clusters will expand to enable full national and Europe-wide driving.

Current status of the technology and European deployments

There are a limited number of OEMs currently offering fuel cell vehicles to the market. Toyota and Hyundai currently dominate the car market, with new series produced models expected in 2018 from Daimler and in the early 2020's from BMW and Audi. In the van sector, Symbio, working with Michelin and Renault offer a range extended Kangoo van, whilst StreetScooter are planning to offer a fuel cell version of their electric delivery van.

Approximately 500 fuel cell vehicles are in operation across Europe, many of these have been funded by European programs. The largest of these - Hydrogen Mobility Europe (H2ME) is deploying over 1,400 FCEVs of different specification and models by 2020 to demonstrate the viability of hydrogen mobility across multiple use cases.

European supply chain

With expertise at each stage of the FCEV supply chain, including FCEV integration and PEM stack components, Europe could play a vital role in the FCEV market. Although the level of deployment of European car manufacturers is slightly behind leading companies in Japan and Asia, Europe is still expected to hold a 30% market share of worldwide FCEV sales by 2030.

2030 vision
FCEVs offer lowest ownership cost ZE option in many vehicle classes
European stock of 5 million FCEVs operating by 2030 (1.5% of total stock).
1 in 5 new taxis are FCEVs

Cars, vans and 2-wheelers: detailed technology roadmap

Current State of the Art

Toyota Mirai passenger car: TRL: 9 Top speed: 178 km/h, 500km range[1]

Symbio RE-EV vans: Top speed: 130 km/h Range: 330km[1]

Suzuki Burgman scooters: Top speed: 80km/h Range: 120km

Legend

Action

Interim target

Role for EU programme

Actions and interim targets

2020 | 2025 | 2030

Hydrogen infrastructure expansion, initially in clusters in select regions, followed by nationwide expansion, beginning in early adopter countries and spreading across Europe (see HRS roadmap – pages 45 – 48)

- >150 HRS in clusters across Europe
- >1,000 HRS Europe wide
- >4,500 HRS Europe wide

Improvements in FC stack technology to increase reliability and lifetime (see technology building block roadmap – pages 50-55)

- Improved technical KPIs: FC stacks: > 7,000 hrs lifetime, <€50/kW at 100k units/year, H_2 tank: €400/kg H_2
- 2030 technical KPIs met FC stacks: <€45/kW at 100k units/year, H_2 tank: €300/kg H_2

Incentives for fleet and private users to highlight the viable business case of FCEVs and decrease H_2 cost, using European and national fund as well as national and city level regulation – initial focus on fleet users in cities, migrating to general public use as HRS network expands.

EU programme supports market deployment to scale up technology and improve ownership costs

- 500,000 passenger FCEVs and up to 150,000 FC-RE vehicles globally
- Over 1.5 million passenger FCEVs sold each year, with 5 million FCEVs operating across Europe in 2030. European global market share >30%

Optimisation of technology to specific use cases (e.g. passenger cars of different sizes, autonomous vehicles)

Optimisation of manufacturing process to allow scale-up of FCEV production lines

Demonstration projects on less mature FCEV applications (autonomous vehicles)

EU programme supports TRL 4-6 concepts to improve packaging and manufacturing processes and demonstration of novel concepts

- 10 new FCEV models of which 5 produced in Europe
- FCEV capex premium vs incumbent is less than 10%
- Lowest ownership cost ZE option for vehicles above class D, premium vs incumbent <5%

European OEMs invest in European FC vehicle manufacture and associated European component supply chain

2030 vision

FCEVs offer lowest ownership cost ZE option in many vehicle classes

European stock of 5 million FCEVs operating by 2030 (1.5% of total stock)

1 in 5 new taxis are FCEVs

Background assumptions:

- Continued policy support for zero-emission road transport.
- Cost reductions assume increased scale of FCEV market & accompanying decrease in H_2/HRS costs
- Battery electric vehicles remain limited by range requirements and recharging times.
- National regulations in place to allow for HRS installation

FCEVs

Cars, 2-3 wheeled vehicles & vans: areas for support

Stage of development and potential areas for support	Proposed budget	Proposed funding source
Early Stage Research Actions (TRL 2-3)		
Due to the high technical maturity of FCEVs, there is not a case for early phase development projects at the whole vehicle level. Component support is discussed in the preceding section…	Covered in the "technology building blocks" section	
Development Research Actions (TRL 4-6)		
Support is targeted at improving the integration of fuel cells into vehicles, specifically: • System integration into different vehicle types (classes), development of BoP components, bench test validation of complete drivetrains, packaging and vehicle integration. • Supplier identification, benchmarking and standardization at a component level.	• 2 projects • €14M budget • 75% funding rate • €11M funding	FP9
Innovation Actions (TRL 7-8)		
Due to the support of the FCH JU and H2020 funding, multiple demonstration projects have already been able to prove the reliability and readiness of FCEVs. Due to this, the only demonstration projects needed over 2021-2027 will be demonstrating the capability of less mature technologies such as autonomous FCEVs and demonstrating less developed use cases such as FC vans.	• 2 projects • €40M budget • 50% funding rate • €20M funding	FP9
Market Deployment Actions (TRL 9)		
Cost represents a major barrier to the introduction of FCEVs into the mass market. Through market activation targeted at proven use cases (e.g. captive fleet operation in markets with a regulatory push towards ZE vehicles (e.g. taxis in large urban centres)), economies of scale can be accessed, reducing the capital cost of purchasing FCEVs and making them more accessible to private users.	Budget €500M • Incentivising uptake of 10,000 FCEVs • Funding rate begins at 20% for first 5,000 vehicles and reduces to 10% for next 5,000 vehicles • €75M funding	FP9 CEF

Fuel cell vehicles are produced at a price equivalent to other vehicle types: Buses, coaches & minibuses

Fuel cell buses

FC buses are electric buses with **zero harmful tailpipe emissions**. They offer **long range** (600km+) and **fast refuelling** (5–10 minutes), making them a drop-in replacement for diesel buses with **no operational compromises**.

FC buses have been successfully demonstrated through many years of operations. A **commercialisation process** is now underway based on **increasing scale**, to reduce cost and to lead to supply chain maturity. **Building on this success** and improving vehicle range will **accelerate the development of FC coach and minibus options** for long-distance driving.

European manufacturers are well placed to capitalise on market growth for FC buses.

Actions and targets

Fuel cell solutions fully validated in a wide range of urban buses, coaches and minibuses. Regulation drives uptake – zero emission regulation drives the urban bus market whereas private procurements drive the long distance coach & mini-bus markets.

Market deployment programme supports roll-out of 1,000 FC coaches and minibuses.

Continued growth in demand for FC buses in cities with commitments to rolling out zero emission fleets.

R&D accelerates development of FC coaches and minibuses.

Current state of the art
Fleets <10 buses. C. 90 fuel cell buses in day-to-day operations across Europe. Plans in place to deploy several hundred FC buses in European cities by early 2020’s. FC bus price c.€600k–€650k.
No FC minibuses or coaches available.

2023-25
>1,000 FC buses in operation in Europe. FC coach & minibus demonstration projects operational.

2027
>5,000 FC buses operating in Europe. FC coaches gain traction in ZE long distance mobility markets.

2030
Mature market for FC urban buses, >1,000 FC coaches & minibuses in operation.

2030 vision

European fleet of FC buses and coaches is 15,000 (1.5% of total).

By 2030 new sales of 10,000 per annum based on growing demand for zero emission solutions and continued technology development.

Stage for support + funding rate	EU budget funding
Early stage research 100%	-
Development research 75%	€16M
Innovation actions 50%	€30M
Market deployment 25%	€100M
Total	**€146M**

Overview of fuel cell buses, coaches & minibuses: vision, current status and supply chain

Fuel cell buses & coaches offer a zero emission public transport solution with no operational compromises

Hydrogen fuel cell buses are a type of electric bus in which the electricity to power the drivetrain is generated from hydrogen stored on board. With relatively long ranges and short refuelling times, these vehicles offer a zero emission solution with no operational compromises compared to today's diesel vehicles (no overnight charging needed, no on-street infrastructure, excellent fit with bus operators' standard operations).

Significant progress has been made to date in demonstrating the performance of the technology and reducing costs (from >€1m/bus in c.2014/15 to c. €600k/bus in 2017/18). However, further progress on cost reduction and overall operational performance is needed for the full potential of fuel cell buses to be realised. There are also no FC products on the market for coaches & minibuses, and so transferring the successes of the FC bus market into these segments is key.

Current status of the technology and deployments

CHIC · JIVE ZERO EMISSION · HyTransit · HIGHVLOCITY · 3EMOTION environmentally friendly, efficient, electric motion

FC bus demonstrations: nearly 400 FC buses deployed / planned in >35 cities across 12 European countries

The technical performance of fuel cell buses and associated refuelling infrastructure has been validated via several multi-year real world trials focused on urban buses, which have shown that hydrogen fuel cells are capable of meeting the needs of even the most demanding bus operations. However, fuel cell buses are not yet a fully commercial proposition, mainly due to the relatively high costs (capital and operating costs) of vehicles. This in turn is due to the limited volume production methods for the buses themselves and the drivetrain components. Improvements in the overall maintenance and support supply chain are also expected with volume, which will bring the reliability of the buses up to the standard set by diesel vehicles..

The latest demonstration projects (JIVE programme) are designed to allow the sector to begin to scale up and achieve the economies of scale needed for more cost effective fuel cell buses. These activities are fully aligned with a commercialisation vision set out by stakeholders in the sector, which envisaged increasing scale via joint procurement as a stepping stone towards deployment of thousands of fuel cell buses by the mid-2020's.

European supply chain

Many European bus OEMs have FC bus development programmes and are therefore well placed to meet the growing demands for zero emission buses. Particularly active players include Van Hool, Solaris, VDL, EvoBus, Wrightbus, Solbus and Alexander Dennis. While most FCs in buses deployed in Europe to date come from non-European suppliers, there is significant potential for European companies (e.g. Proton Motor, Symbio, Hymove, ElringKlinger) in this area.

2030 vision

European fleet of FC buses and coaches is 15,000 (1.5% of total).

By 2030 new sales of 10,000 per annum based on growing demand for zero emission solutions and continued technology development

Fuel cell buses, coaches & minibuses: detailed technology roadmap

Actions and interim targets

2020 | 2025 | 2030

Current State of the Art

Typical FC bus efficiency 9-10kgH_2/100km

FC bus price: €650k per vehicle

Largest operational fleets: 10 vehicles (Aberdeen, London); plans for 45+ buses in Cologne

Actions and interim targets

- Action: Current and planned deployment projects prove technology at scale of tens of buses per site
- Action: Cost reductions via economies of scale and development of standardised products
- Interim target: Improved technical KPIs achieved (12m bus):
  - Average fuel efficiency below 7.5kgH_2/100km
  - FC system lifetime >20,000 hours
  - Vehicle availability equivalent to diesel buses
- Action: Further economies of scale from commercial deployments
- Interim target: FC buses (12m) below €300k
- Action: Support available to encourage new entrants
  - **EU programme supports development of new drivetrain and vehicle concepts**
- Interim target: FC buses available for prices below €400k per vehicle – lowest ownership cost ZE bus
- Action: Coordinated support for expanded fleets of FC buses (1,000's)
  - **EU programme provides support for market activation, helping to reach fully commercial volumes and therefore prices**
- Interim target: >1,000 FC buses operating in daily services in Europe
- Interim target: Total fleet of 15,000 FC buses. New sales of 10,000 vehicles per year across Europe

Learning + successes from urban bus deployments trigger more rapid advances in coach and minibus products and deployments

- Action: FC solutions developed / adapted for other bus applications (in addition to urban buses) – i.e. coaches, minibuses
  - **EU programme supports R&D on these technologies and concepts**
- Interim target: FC coaches and minibuses developed and optimised, ready for market activation phase
- Action: Large-scale validation testing in real world environments of FC coaches and minibuses
  - **EU programme supports demonstration projects at increasing scale of new vehicles**
- Interim target: >100 FC coaches / minibuses demonstrated

2030 vision

European fleet of FC buses and coaches is 15,000 (1.5% of total).

By 2030 new sales of 10,000 per annum

Background assumptions:

- Cities with strong environmental commitments continue implementing policies to support uptake of zero emission buses.
- Final stage of technology demonstration of FC city buses achieved via the JIVE projects.
- Hydrogen <€5/kg

Legend

- Action
- Interim target
- **Role for EU programme**

Buses

Fuel cell buses, coaches & minibuses: areas for support

Stage of development and potential areas for support	Proposed budget	Proposed funding source
Development Research Actions (TRL 4-6)		
Fuel cell solutions for urban bus applications are successfully developed and demonstrated within the scope of activities of the FCH (2) JU. The focus of development phase projects required to allow the vision outlined above to be met should be on: ***Coaches**:* • Adapting fuel cell systems from other vehicles (urban buses / cars) for long distance coaches, developing solutions for integrating fuel cell based powertrains into coaches without compromising utility of the vehicles and certifying hydrogen-fuelled coaches in line with existing regulations governing conventional coaches. ***Minibuses:*** • Adapt fuel cell systems from other vehicles (cars / vans) for minibuses, developing solutions for integrating fuel cell based powertrains (including FC system, electric drivetrain, hydrogen tanks) into minibuses, whilst maintaining passenger carrying capacity, range, etc.	• 3 projects • €21M budget • 75% funding rate • €16M funding	FP9
Innovation Actions (TRL 7-8)		
Support for deployment of European heavy duty fuel cells in the bus market, and support for new entrant bus OEMs and novel drivetrain concepts. Demonstration will be required for new entrant OEMs, fuel cell coaches and minibuses in the 2020's. The scope of these activities will include: • Validation of technical performance in real world operational environments. • Optimising solutions and modifying designs based on feedback from trials. • Confirming that KPIs (technical & economic) can be met and providing compelling economic and environmental case for end users of the technology.	• 3 projects • €60M budget • 50% funding rate • €30M funding	FP9, CEF
Market Deployment Actions (TRL 9)		
The fuel cell bus market based on urban buses requires a phase of market activation across European Member States. The aim will be to provide a sufficient subsidy to achieve parity with the incumbent bus. In so doing, the European bus sector and associated supply chain can achieve the economies of scale needed to begin offering the commercially viable fuel cell bus. Market deployment support targeted at cities willing to deploy large fleets of FC buses which help to reduce the cost of hydrogen production and distribution equipment. A programme to introduce 1,000 fuel cell buses, with an average funding rate of €100k per vehicle, would unlock commercialisation of fuel cell buses in a sector with very few viable alternatives for decarbonisation and with benefits from the other FC sectors which are expected to mature later.	Budget €500M • Support for 1000 buses • 20% funding rate • €100M funding	FP9, CEF

Trucks

Fuel cell vehicles are produced at a price equivalent to other vehicle types: fuel cell trucks

Fuel cell trucks

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

There has been limited OEM activity and there are currently no fully demonstrated fuel cell trucks on the market in Europe. This is set to change with an **FCH-JU supported demonstration project due to begin in 2019 involving multiple major European truck OEMs.**

The most promising applications are in long-haul, heavy duty (26-40 tonne) applications and logistics, where FC options can provide the range and flexibility required.

Actions and targets

Fuel cell solutions fully are validated in a range of use cases, refuse vehicles, long haul heavy duty trucks and a range of logistics trucks. Procurement policy of haulage companies etc drives uptake.

Market deployment leads to an accelerated uptake of FC trucks so that the total fleet size grows to tens of thousands of vehicles by 2030 and FC trucks account for a meaningful proportion of new truck registrations.

Development and demonstration of activity on FC trucks in most promising use cases: long haul 26-40 tonne trucks and logistics.

2030
FC trucks lowest cost ZE option for long haul 26-40 tonne applications.

2026
10,000 FC trucks deployed in Europe.

2023
>500 FC trucks operating in Europe across a range of applications include refuse vehicles and long-haul 26-40 tonne applications.

Current state of the art
A limited number of small-scale FC truck development and demonstration projects are underway in Europe. Vehicles are yet to be fully tested and validated in real world operations. No OEM FC trucks available on the market in Europe.

2030 vision

European fleet of FC trucks is 95,000 (2% of total).

By 2030 new sales of 10,000's per annum (c. 7% of annual sales).

Stage for support + funding rate	EU budget funding
Early stage research 100%	-
Development research 75%	€11M
Innovation actions 50%	€40M
Market deployment 25%	€50M
Total	**€101M**

Overview of fuel cell trucks: vision, current status and supply chain

Fuel cell trucks are one of very few options to decarbonise haulage

Introduction

Hydrogen fuel cells are well suited to applications where long range and/or high payloads are required due to the relatively high energy density of compressed hydrogen. In its *Hydrogen Scaling Up* study (2017), the Hydrogen Council identified the truck sector (along with buses / coaches and large cars) as being a key market for FC technology over the period to 2050. In much the same way as fuel cell buses provide a no compromise zero emission solution for public transport operators, fuel cell trucks are a potential drop-in replacement for diesel trucks as they can be refuelled in minutes and achieve a range of hundreds of kilometres. Furthermore, there is growing interest in zero emission logistics in Europe, particularly from major retailers and their transport solutions providers – this helps to provide an early market. The FC truck sector is composed of a wide range of segments; the most promising for FCs are: long haul 26-40 tonne trucks, logistics applications, and refuse collection trucks.

Current status of the technology and deployments

Concept for a 27t rigid FC truck by VDL

Source: www.nweurope.eu/projects/project-search/h2share-hydrogen-solutions-for-heavy-duty-transport/#tab-1

A small number of vehicle OEMs have developed FC trucks to a TRL of 5/6 via prototyping and demonstration activities. Examples include trials by La Poste in France of a Renault Maxity electric truck (4.5t) with a range extender added by Symbio FCell, a conversion of a 34t MAN truck by engineering and prototyping company ESORO and trials with Coop in Switzerland, plans to deploy a fleet of four 27t FC trucks from Scania (for use by ASKO in Norway), and VDL's development of a 27t FC truck in the H2-Share project.

The FCH JU project REVIVE will test 15 fuel cell refuse trucks in 7 locations. An FCH JU funded project due to start in 2019 will develop and demonstrate at least 15 FC heavy duty trucks. These vehicles will be run for a minimum of two years in real world operations, with the intention of reaching a TRL of 8 by the end of the project and thus preparing for wider uptake in the 2020's.

European supply chain

Many European OEMs have relevant experience in this area and are well placed to respond to the growing demand for zero emission trucks. This includes IVECO, MAN, Scania (VW), Daimler, and VDL. Several European FC system / component suppliers are also active in this sector, e.g. Swiss Hydrogen (provider of the FC system for the ESORO / MAN truck) eTrucks, Symbio FCell and ElringKlinger (a partner in the *GiantLeap* project along with Bosch Engineering and VDL).

2030 vision

European fleet of FC trucks is 95,000 (2% of total)

By 2030, there are 10,000's of new sales of FC trucks per year (c. >7% of annual sales)

Trucks

Fuel cell trucks: detailed technology roadmap

Current State of the Art

No OEM vehicles available from European suppliers.

One-off prototypes have been tested in limited trials.

Small fleet demonstration projects are in planning stages

Actions and interim targets

2020 | 2025 | 2030

- Action: Demonstrate OEM FC trucks in real world operations in key applications for multiple years
- Action: Homologate vehicles and prepare case for continued uptake
  - Interim target: Real world tests of vehicles from at least five European OEMs completed
- Action: Prove the operational viability of truck refuelling concepts sufficient for large fleet deployment
  - Interim target: European supply chain for all FC truck components is validated and ready for scale up
- Interim target: FC trucks achieve:
  - >1,000km range (for 44 tonne)
  - <10 minute refill time (44 tonne)
  - Capex <50% premium compared to the incumbent diesel product
- Action: Further FC truck prototyping, development, optimisation, and test activities involving a growing number of vehicle OEMs and truck types
  - **European support for R&D on these technologies and concepts**
- Action: Extended, large-scale truck deployments (100's) validate the technical and commercial performance of FC trucks
  - **European support for deployment projects at increasing scale**
- Interim target: Commercial launch of FC trucks from multiple European OEMs and in multiple weight categories
- Interim target: >500 FC trucks operating in Europe
- Interim target: 10,000+ FC trucks deployed in Europe
- Action: Ongoing optimisation and cost reduction of FC truck drivetrains
  - **European programme provides support for ongoing development of the FC truck drivetrain and integration of best in class components**
- Interim target: Competitive market for FC trucks established
- Uptake driven by regulation in vehicles using city centres, procurement policies in long-haul applications

2030 vision

European fleet of FC trucks is 95,000 (2% of total)

By 2030, there are 10,000's of new sales of FC trucks per year (c. >7% of annual sales)

Background assumptions:

- Successful development and demonstration of FC trucks in a range of weight classes from multiple OEMs.
- Continued growth in demand for zero emission trucks (e.g. due to policies restricting the use of diesel vehicles in cities).
- Deployment of hydrogen infrastructure suitable for trucking

Legend

- Action
- Interim target
- **Role for EU programme**

Trucks

Fuel cell trucks: areas for support

Stage of development and potential areas for support	Proposed budget	Proposed funding source
Development Research Actions (TRL 4-6)		
Building on the development work already underway in this sector, a targeted programme of support can help to cover the costs of further development activities and attract a growing number of suppliers. There is a case for funding to support non-recurring engineering costs and prototyping / development activities, including: • Establishing FC truck specifications required to meet users' needs for a range of truck sizes and duty cycles, system modelling and optimisation. • Prototyping activities, development of control systems, interfaces between sub-systems and integration of FC systems into trucks.	• 2 projects • €14M budget • 75% funding rate • €11M funding	FP9
Innovation Actions (TRL 7-8)		
Given the similarities and synergies between the FC truck sector and the FC bus sector, demonstration projects in this area can learn from previous real world trials. Further demonstrations in the post-2020 period should focus on: • Validating the performance of the technology in a range of real world operations, specifically KPIs such as availability, lifetime, efficiency and ownership costs. • Preparing the market for wider roll-out, e.g. by training technicians to maintain the vehicles etc. • Collecting and analysing empirical evidence on performance (technical and commercial) of vehicles and associated refuelling infrastructure. • Ensuring the range of truck types are trialled (i.e. different weight classes, niches such as refuse trucks).	• 4 projects • €80M budget • 50% funding rate • €40M funding	FP9 CEF
Market Deployment Actions (TRL 9)		
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 truck roll-out programme in the mid 2020's. Funding of around €100k per vehicle is anticipated to be sufficient to catalyse the uptake of around 500 FC trucks, creating the scale required for this sector to reach a commercial footing. Key priorities in the market activation phase include developing and implementing innovative commercial models to manage risk appropriately and supply chain development to ensure that the vehicles are fully supported throughout their operational lives.	Budget €500M • Support for 500 trucks • 10% funding rate • €50M funding	FP9 CEF

Material Handling

Fuel cell vehicles are produced at a price equivalent to other vehicle types: material handling vehicles

Material Handling Vehicles

Material handling vehicles include forklifts, mixed size vehicles in factories, and heavy duty vehicles (operating at ports & airports).

Incumbent forklift trucks are either diesel or battery electric. Both of these technologies have problems – harmful emissions for diesel, and frequent battery changes affecting duty cycles for electric. There are also applications which have not yet been decarbonised, in particular heavy duty vehicles.

Fuel cell vehicles offer distinct advantages - with no harmful emissions at point of use (only water) and quick refuelling times (similar to diesel).

In the US, >10,000 FC forklifts are in use and FC is the go to technology for large 24 hour operations.

Further scale-up of the European fuel cell forklift sector will further reduce costs and develop a commercial market in Europe.

Actions and targets

There is pressure today for environmental improvements in factories, ports, warehouses and airports. This continued pressure leads to roll-out and reduced costs through economies of scale.

European support for market activation by part-funding 10,000 forklift deployments.

Support for development of heavy duty material handling applications for ports and airports.

Current state of the art
Current cost of fuel cell forklift systems c.€2,500/kW, with c.400-600 fuel cell forklift vehicles currently deployed in Europe.

2023-25
Successful demonstration of mixed size and heavy duty applications.

2027
Fuel cell forklifts reach commercial prices in Europe
Mixed size & heavy duty material handling vehicles begin to gain market traction.

2030
Capital cost of fuel cell forklift <€450/kW. FC forklifts become technology of choice for all large fleets.

2030 vision

Fuel cell forklift vehicles are the prime choice for large production floors (29%) and achieves 50% market share within ZE fleets for harbours and airports.

Stage for support + funding rate	EU budget funding
Early stage research 100%	-
Development research 75%	€21M
Innovation actions 50%	€20M
Market deployment 25%	€15M
Total	**€56M**

Overview of material handling vehicles – vision, current status, and supply chain

Fuel cell material handling vehicles offer operational advantages over battery vehicles with no harmful emissions and are zero carbon when fuelled by green hydrogen

Hydrogen fuel cell material handling vehicles have environmental and health benefits over diesel vehicles as they emit no harmful emissions and when sourced from green hydrogen emit no well-to-wheel CO_2 emissions. They also offer improved range and performance over battery electric vehicles, which require time consuming battery replacements and suffer performance loss towards the end of the battery charge. For forklift trucks, fuel cell products can be designed to fit into the battery compartment of conventional electric trucks to allow simple replacement of the battery. The benefits of this technology have been demonstrated through a number of European projects and global deployments, however unlike the US market, the European fuel cell forklift market has not yet reached commercial volumes or prices. There is a wide range of types of material handling vehicles: mixed size vehicles used in factories, as well as ports and airports, and heavy duty vehicles at ports and airports used for lifting heavy loads.

Current status of the technology and deployments

There have been a number of FCH 2 JU backed deployment projects including the Don Quichote project which has deployed 75 fuel cell forklifts at Colruyt's facility in Belgium, powered from an on-site electrolyser connected to a wind turbine.

Similar projects include deployment of hydrogen fuel cell fork lifts through the FCH 2 JU HyLift project for French supermarket chain Carrefour (150 forklifts) and logistics companies; FM Logistic's (47 forklifts), Prélodis, (50 forklifts).

The European market has not yet reached commercial levels, with c.400-600 fuel cell forklifts currently deployed in comparison to North America (c. 20,000 fuel cell forklifts). This is partly due to the US Government subsidy which was available until 2017 for material handling vehicles ($3,000/kW) and the European CE marking requirement which places commercial liability on the whole product for forklift manufacturers who want to integrate a fuel cell developed by another company.

European supply chain

European manufacturers are well placed to capitalise upon growth in the EU market for fuel cell material handling vehicles, with several material handling manufacturers in Europe involved in demonstrations of fuel cells into their material handling vehicles, including Still, Jungheinrich, Linde Material Handling and Kalmar. The market for fuel cell supplies is currently dominated by US companies Plug Power and Nuvera. However, there are European based fuel cell stack manufacturers/integrator, who have developed fuel cells for material handling applications, including Powercell, Ajusa, ElringKlinger and Proton Motor.

2030 vision

Fuel cell material handling vehicles are the prime choice for materials handling in large scale facilities.
Zero emission material handling fleets are introduced in commercial operation in harbours and airports, with FCs taking a 50% share of these ZE markets

Material handling vehicles: detailed technology roadmap

Current State of the Art

- c. 400-600 fuel cell forklifts currently deployed in Europe
- Fuel cell cost c.€2,500/kW
- Finnish cargo company Kalmar are developing medium range fuel cell forklift with Swedish steel manufacturer SSAB, using fuel cells from Swedish company Powercell

Actions and interim targets

2020 — 2025 — 2030

Actions:

- There is pressure today for environmental improvements in factories, warehouses, ports and airports. This continued pressure leads to roll-out and reduced costs through economies of scale
- FCH JU current deployment projects continue to demonstrate high level of technology maturity
- European OEMs achieve cost reductions due to scale up and parallel FC system improvements
- Deployment of 1,00's of FC forklifts and mixed size vehicles supported to reach commercial volumes
- Range of larger fuel cell material handling vehicles developed (e.g. 50 tonne reach stackers and front loaders for port operations)
- Demonstrate fuel cell airport ground support equipment (e.g. pushback tractors and container loaders)
- Roll-out of fuel cell airport vehicles
- Demonstration of fuel cell material handling vehicles in European harbour and ports
- Roll-out of fuel cell material handling port vehicles
- Demonstration of multiple uses of hydrogen refuelling infrastructure (e.g. refuel forklifts and trucks from same site).

European support for demonstrations of FC in a range of material handling use cases, and market deployment to increase scale of demand

Interim targets:

- Forklift FC system cost <€1,250/kW
- Capital cost <€450/kW for 10 kW forklift fuel cell system
- Fuel cell forklift vehicles achieve 29% market share of European fleet
- 50% of the ZE market for harbours and airports
- Fuel cell fork lifts able to offer commercial proposition for large 24 hour operations in Europe
- 10,000 FC forklifts deployed in Europe
- Fuel cell fork lifts achieve lowest cost option for >30 unit fleets

2030 vision

Fuel cell forklift vehicles are the prime choice for large sites

50% market share within ZE fleets for harbours and airports

Background assumptions:
- Low cost hydrogen available at forklift sites
- Continued political motivation to reduce greenhouse gas emissions and improve air quality drives move companies away from diesel vehicles.

Legend
- Action
- Interim target
- **Role for EU programme**

Material handling vehicles: areas for support

Stage of development and potential areas for support	Proposed budget	Proposed funding source
Development Research Actions (TRL 4-6)		
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. There is a case for funding to support non-recurring engineering costs and prototyping/development activities, including: • Establishing FC mixed size vehicle specifications required to meet users' needs for a range of vehicle sizes and use cases, system modelling and optimisation. • Establishing FC heavy duty vehicle specifications required to meet users' needs for a range of use cases, system modelling and optimisation. • Prototyping activities, development of control systems, interfaces between sub-systems and integration of FC systems into material handling vehicles. • Prototype deployment of early mixed size and heavy duty vehicle concepts.	• 4 projects • €28M budget • 75% funding rate • €21M funding	FP9
Innovation Actions (TRL 7-8)		
Development and demonstration of larger heavy duty materials handling vehicles for ports and airports, including: • Early fleet trials. • Deployment in larger material handling trials involving multiple materials handling vehicles and common fuelling facilities.	• 2 projects • €40M budget • 50% funding rate • €20M funding	FP9
Market Deployment Actions (TRL 9)		
Market entry support which promotes the environmental and health benefits to on-site operators of hydrogen fuel cell materials handling vehicles and helps them to scale-up production and establish supply chains to reduce capital costs of materials handling vehicles.	Budget €45M • Support for 10,000 fuel cell forklift vehicles • Funding rate 33% of additional FC cost • €15M funding	FP9

Fuel cell vehicles are produced at a price equivalent to other vehicle types: hydrogen fuel cell trains

FCH trains

FCH trains could play a key role in the **decarbonisation of rail transport by providing a cost-effective, viable alternative to diesel trains.**

Demonstration projects are already underway in Germany to establish the **technical maturity of FCH trains for regional passenger services and total cost of ownership.**

As well as **regional passenger trains**, there FCH trains can provide viable zero emission options for **local freight trains and shunting locomotives.**

Europe is in a leading position to develop this technology further with expertise in FC drivetrain integration and the provision of large scale infrastructure.

Actions and targets

Zero Emission trains (or hydrogen trains) are specified as a requirement in new procurements for trains on non-electrified routes.

Market deployment supports the rollout of FCH regional passenger trains on European rail networks, aiming to reach fully commercial volumes and therefore prices.

Regulations are to be developed across Europe to allow hydrogen train operation across the European network.

R&D on components for local freight and shunting locomotive applications.

2030
1 in 10 trains sold for non-electrified railways are powered by H_2.

2027
H_2 drivetrain <150% diesel capex.
>500 FCH trains operating.

2023-25
> 200 FCH regional passenger trains operating by 2025
Demonstrations of local freight and shunting locomotives operating successfully.

Current state of the art
Two European companies are developing new hydrogen fuelled fuel cell trains. Use cases based on this technology indicate that costs be within 10-20% of conventional options (depending on cost of hydrogen).

2030 vision

Hydrogen is recognised as the leading option for trains on non-electrified routes, with 1 in 10 locomotives powered by hydrogen in 2030.

Stage for support + funding rate	EU budget funding
Early stage research 100%	-
Development research 75%	€11M
Innovation actions 50%	€30M
Market deployment 25%	€50M
Total	**€91M**

Overview of hydrogen fuel cell trains: vision, current status and supply chain

Hydrogen trains can deliver reductions in air pollution, CO_2 emissions and noise, at equivalent cost to diesel options

Introduction

The majority of trains operating today are either diesel powered or electrified via overhead lines. Whilst electrification offers zero emissions at the point of use, electrification of railway lines is expensive and logistically complex. Hydrogen offers several advantages over electric locomotives, e.g. freedom of the locomotives to roam, relatively little infrastructure required and the option to secure a zero carbon fuel supply. **Hydrogen is key to decarbonising rail transport as it can provide the most cost-effective solution for certain lines that are still operated with diesel trains.** The technology requires further demonstration and optimisation of integrated FCH components into trains, and market deployment support to increase volumes and reduce costs. There is also considerable effort required around regulation for use on railways. Low cost renewable hydrogen is essential, and so achieving the vision of the electrolysis roadmap (see pages 14-17) is needed to decarbonise rail.

Siemens Mireo train

Current status of the technology and deployments

Alstom iLint FCH train

The Alstom iLint FCH train (pictured, left) has a 400 kW FC, and a range of 600-800 km (350 bar hydrogen, c. 180kg stored on board) and can accommodate up to 300 passengers. Capital costs are c. €5.5M (excluding H_2 infrastructure). It has recently been approved for commercial operations in Germany. Prototypes have now entered into pilot operation with passenger service. 14 trains have been ordered for delivery in 2021, and letters of intent for a total of 60 trains have been signed.

Siemens are also working on a fuel cell version of their Mireo train (pictured, above), 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)

European supply chain

Europe has adopted a leading position on the integration and assembly of FC trains thanks to the work of Alstom and Siemens. Whilst there is passenger train demonstration activity in Asia and Canada, it appears Europe has a lead in this area especially with regards to the integration of the fuel cell drivetrain, the provision of large scale infrastructure (e.g. Linde, Air Liquide, Nel) and regulation to allow the use of hydrogen on the railways.

2030 vision

Hydrogen is recognised as the leading option for trains on non-electrified routes, with 1 in 10 locomotives powered by hydrogen in 2030

Rail

Hydrogen fuel cell trains: detailed technology roadmap

Current State of the Art

Range: 600-800km

Consumption: 0.25 – 0.3 kg/km

Cost: €5.1 M - €5.5 M

Two 400 kW FC trains in Germany (TRL: ca. 6), 14 ordered for 2021

Legend

- Action
- Interim target
- **Role for EU programme**

Actions and interim targets

2020 | 2025 | 2030

- Zero Emission trains (or hydrogen trains) specified as a requirement in new procurements for trains on non-electrified routes
- Heavy duty stacks and H_2 tank improvements and cost reductions
- ★ FC train shown to offer lowest ownership cost ZE option for majority of long, non-electrified routes
- Development of specific technology and integration improvements to rail applications
- 2nd generation train development, cost optimised (freight and passenger)
- **EU programme supports 2 development projects to advance specific train technologies**
- Large scale infrastructure for trains developed (>5,000 kg/day, 200kg fills in <10 mins)
- First deployments of FCH rail applications across Europe (city, trams, regional trains and freight)
- ★ >100 passenger trains and >10 freight locos operating by 2023
- ★ H_2 train drivetrain <150% diesel capex Green H_2 < €5/kg
- Further deployments aim to optimise technology solutions and reduce TCO
- **EU programme supports 2 deployment projects to demonstrate optimised and integrated solutions for hydrogen trains**
- Pre-normative work on safety aspects related to hydrogen on trains (hydrogen in tunnels, venting strategies in the event of a crash etc)
- Introduction to new European networks, including gaining regulatory acceptance
- **EU programme provides support for market deployment phase, aiming to reach fully commercial volumes and therefore prices**
- Regulations developed across Europe to allow hydrogen train operation across the European network
- ★ >200 H_2 trains by 2025
- ★ >1000 H_2 trains by 2030

2030 vision

Hydrogen is recognised as the leading option for trains on non-electrified routes, with 1 in 10 locomotives powered by hydrogen in 2030

Background assumptions:

- -Increasing requirement ZE from rail authorities.
- -Electrification of lines remains challenging on all but busiest lines.
- -$CO_{2=}$ included as a key factor in rail purchasing decisions
- -Safety standards adapted to allow H_2.
- -Cost decreases assume volumes for H_2 train and other heavy duty H_2 applications are achieved.

Hydrogen fuel cell trains: areas for support

Stage of development and potential areas for support	Proposed budget	Proposed funding source
Early Stage Research Actions (TRL 2-3)		
Due to the FCH train already achieving a high TRL (6) no early phase development projects will be funded.	N/A	
Development Research Actions (TRL 4-6)		
There is potential to reduce costs of FCH systems for trains through technological developments such as: • Devising new concepts for on board bulk hydrogen storage e.g. cryo-compressed hydrogen or liquid storage. • 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 scope to optimise (e.g. space for hydrogen storage, use of waste heat) in purpose built designs.	• 2 projects • €14M budget • 75% funding rate • €11M funding request	FP9
Innovation Actions (TRL 7-8)		
Projects need to be implemented across Europe to demonstrate that FCH trains could create cost-savings in comparison to diesel and electric trains. Demonstration projects will help to illustrate the technology's potential to: • Ensure early deployment of trains of different types including local freight and shunting locomotives. • Validate the commercial and environmental performance of the trains (and hence the claim of being the lowest cost zero emission option for non-electrified routes). • Test very high capacity refuelling stations. Such projects could also help to develop maintenance and support strategies for the vehicles and provide a basis to develop regulations to enable FC train and hydrogen use across Europe.	• 3 projects • €60M budget • 50% funding rate • €30M funding	FP9 CEF
Market Deployment Actions (TRL 9)		
Market entry support to promote the deployment of ~100 trains across Europe to enable OEMs to begin standardised production and establish the technology as a mainstream option for Europe's train specifiers. Initial financial aid will help increase the scale of the technology across Europe as well as support the integration of hydrogen refuelling infrastructure across the continent.	Budget €500M • Support for 100 trains • 10% funding rate • €50M funding	FP9 CEF

Maritime

Fuel cell applications make a meaningful contribution to decarbonization: Maritime applications

Fuel cell marine applications

10% of transport-related GHG emissions are attributable to maritime transport.

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

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

Development work will focus on improving access to the market for H_2 and FCs on smaller vessels and advancing the components and fuelling systems required for larger ship types.

Actions and targets

Standards and regulations work will be required to approve the use of FCs (and associated fuels) within the maritime sector. Once the technology is proven (commercially and operationally), regulatory pressure will be needed to encourage early adoption within the market.

Demonstration projects to test the viability of FCH technology in small ships. The primary focus for larger vessels is on design studies, progressing to trials for partial power supply and increasing the proportion as FC systems and refuelling technologies progress.

R&D into marinization of FC components

2023-2025
Demonstration projects lead to 10's of small FC ship trials (in-land and coastal)

2027
~100 small FC ships operating in Europe.
Consensus on preferred fuel options for larger ships

2030
FCs are a mainstream option for the maritime sector.

Current state of the art

FCs and H_2 have been demonstrated in a number of small in-land and near coastal vessels, proving the viability of the technology. In addition, demonstration projects on small ferries are under construction. Larger vessels are generally at the design study stage and a range of fuels and fuel cell types are currently being tested.

2030 vision

FC passenger ships reach mass market acceptance for small in-land and coastal vessels, using hydrogen as a preferred fuel.

Larger vessels select FCs as a preferred zero emission propulsion solution, using a range of fuel types

Stage for support + funding rate	EU budget funding
Early stage research 100%	-
Development research 75%	€72M
Innovation actions **75%**	€90M
Market deployment <25%	-
Total	**€162M**

Overview of FCH maritime applications: vision, current status and supply chain

FC and hydrogen technologies can provide a commercially viable option for zero-emission marine transport in certain use cases

GHG emissions from maritime applications are expected to increase by 50-250% above 2012 levels by 2050. Fuel cell and hydrogen technologies will play an important role in mitigating this increase by providing a zero emission option for propulsion and/or auxiliary power on ships.

The shipping sector involves a wide range of use cases, with both the autonomy and power requirements of small vessels and large cruise ships differing by three orders of magnitude. This highlights the importance of defining different strategies for zero emission propulsion for each vessel type. **For the smaller in-land or near coastal vessels (Type 1 and 2),** the hydrogen option has been demonstrated and there are the beginnings of a consensus that hydrogen as a fuel, with PEM fuel cells and/or modified combustion engines, offers the best zero emission (and low carbon) option. In these vessels, there is a need for demonstration programs to prove the use of hydrogen and fuel cells for different end users. Projects to develop and marinise the core FC components and to devise new refuelling solutions for these vessels are also required. These will inevitably begin with smaller vessels and progress to increasingly larger vessels in the Type 1 & 2 categories.

For larger vessels (Type 3 & 4), there are still a multitude of options; these include the use of fuel cells with other liquid and gaseous fuels (ammonia, methanol, liquefied natural gas etc.) as well as the use of hydrogen in a more dense format (liquid hydrogen, organic carriers). There is also the challenge of defining propulsion options capable of meeting the power needs of a very large vessel (many 10's of MW). As a result, the focus here is on new design work to assess different options for larger vessels and the use of fuel cells for specific power applications on large ships (e.g. the hotel loads on ships). **As a result two roadmaps are proposed, differentiated by vessel size and use.**

PowerCell fuel cell and Viking's cruise ship

European supply chain

In light of this opportunity, the European supply chain is beginning to scale up, with large joint ventures announced between fuel cell suppliers and shipping powertrain providers such as PowerCell & Siemens and ABB & Ballard. Norwegian company HyOn has been formed specifically to target this market (including partners: PowerCell, Nel and Hexagon).

With multiple demonstration projects on-going/in preparation, Europe could become the market leader for optimised technological solutions for maritime applications. This is exemplified by the range of European companies that are active in the fuel cell maritime space, such as Fincantieri, Ferguson Marine, Viking Cruises, Kongsberg Maritime and Brødrene AA.

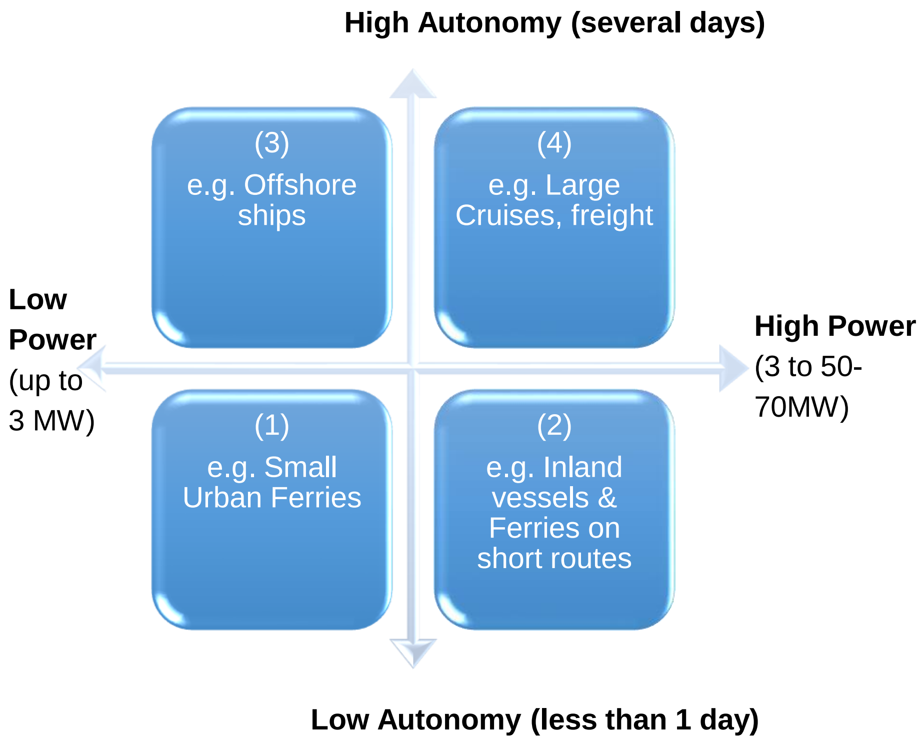
First applications of FCs and hydrogen in maritime applications

The FCS Alsterwasser in Hamburg provides evidence of long term, real-world operation. Between 2008 and 2013 this vessel combined two 48 kW PEM fuel cells and a battery pack to transport up to 100 passengers across Lake Alster[1]. More recently, in July 2018, the €12.6M HySeas III project was commissioned in Orkney, Scotland to build a car and passenger ferry using hydrogen and fuel cells. Fuel cells have also been considered for auxiliary power on large cargo and cruise ships, with a number of projects now in the design phase.

1 – Zemships (2013) One hundred passengers and zero emissions: the first ever passenger vessel to sail propelled by fuel cells

In the marine sector, four different users can be distinguished due to different implications for on board power and refuelling

FCs could provide a viable power alternative in all maritime applications and are key to enabling future reductions in GHG emissions in the marine transport and shipping sector



(1) Small ships with reduced autonomy needs

Small passenger and urban ferries which do not require large amounts of power (~1MW) or energy storage constitute this category. They are likely to be the early adopters of fuel cells in this sector. These ships can be served with a dedicated "back to port" fuelling infrastructure and thus do not require large on-board energy storage; this increases the range of applicable fuels. Although regulatory issues need to be addressed, the development of Type 1 FC vessels will demonstrate the reliability of this solution before further up-scaling is undertaken.

(2) Inland navigation or short route ferries

Small to medium size ships navigating on fixed routes will be the sequential adopters due to the possibility of relying on fixed bunkering points along their routes. Fuel distribution networks can be developed in parallel with the progressive introduction of these new ships. Larger power generation units will be required (from 1MW to 15-20MW), based on the scaling up of small scale applications. On board storage will not be an issue thanks to shorter/fixed routes with frequent bunkering options.

(3) Offshore ships and infrastructures

There are a large number of ship types that serve traditional maritime sectors (e.g. fishery, oil & gas, and tourism coastal activities) or that enable large-scale activities (e.g. offshore marine renewable energy, aquaculture, nautical leisure, etc.) that constitute this category. These ships and are generally characterised by reduced hull dimensions and a very high number of systems and equipment on-board. Power needs are therefore dominated by propulsion and the operation of on-board equipment. These vessels could be served in distinct clusters (e.g. from a fishing port) to minimise infrastructure costs. Nevertheless, these ships will still require considerable on-board energy storage.

(4) Large Ships with high autonomy

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

The possible fuel options for fuel cell marine vessels will vary depending on power and autonomy requirements

H_2 has been accepted as a viable low carbon fuel for smaller marine vessels, but for larger vessels the best fuel for decarbonisation is undetermined

H-H

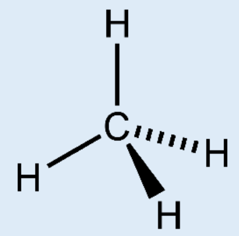
Type 1 & 2 vessels - main fuel options

Hydrogen

- For small vessels there is agreement that H_2 should be the main fuel choice for propulsion.
- Low power demands and low degrees of autonomy for small vessels means that the low volumetric energy density of H_2 is not a disadvantage.
- Current development and demonstration projects are testing the viability of H_2 as a fuel for Type 3 & 4 vessels, with a focus on using H_2 to provide partial power supply to large vessels.
- Regulatory measures will be required to allow the storage and use of H_2 in marine vessels.

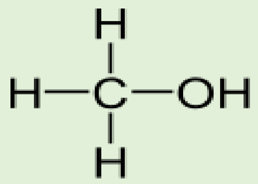
LNG + CNG

- Applicable across all vessel types.
- Has been used in modified combustion engines for a number of years.
- Suitable for use in fuel cells.
- Widely available & inexpensive.
- Wide distribution network for LNG/CNG at ports could facilitate the uptake of FCs in maritime applications, using LNG/CNG as a fuel.
- However, natural gas provides limited carbon savings, with a maximum achievable reduction of 25% in CO_2 emissions (in comparison to heavy fuel oil)



Degree of maturity

Type 3 & 4 vessels - main fuel options



Methanol, Ammonia (sustainable hydrogen based energy carriers)

- Can be used in fuel cells.
- Higher volumetric energy density than hydrogen makes them more suitable for Type 3 & 4 vessels (see liquid energy carriers roadmap).
- Regulatory changes will need to be made to allow use on board marine vessels.

Detailed technology roadmap: smaller vessels (Type 1 & 2)
Full power loads can be replaced by FCH technologies

Current State of the Art

HySeas III FC ferry cost: €12.6M. TRL 6.

PowerCell have made a 3MW PEM system for FC propulsion or APU on ships

Actions and interim targets

2020 | 2025 | 2030

- Numerous ongoing demonstration programs already underway – generally in small ships and scheduled ferries
  - ★ Trials demonstrate the viability of different FC configurations and fuels for ships (generally smaller near coast and inland ships) – at least 10 ships will be in operation in a number of representative use cases (ferry, fishing, in-land waterway etc.)
- Increasingly strict CO_2 and air pollutant emission regulations in the maritime industry

Development work focuses on deploying novel FCH technologies in small boats

- Core fuel cell and hydrogen component programs are modified to ensure the needs of the marine sector are met (marinized components, larger tanks etc)
- Development of 2nd generation maritime fuel cell system, hydrogen storage and balance of plant concept designs based on learnings from first demonstrations (for larger and more autonomous ships)
- **EU programme supports R&D projects to develop novel hydrogen and fuel cell technologies for propulsion applications on small boats (Type 1 & 2)**
- User requirements for hydrogen and fuel cell vessels are investigated with a range of Type 1 & 2 ship owners and operators
  - ★ FCH ship ownership cost achieves parity with diesel cost for small vessels (Type 1 & 2) in regulated markets

- High capacity refuelling options and on board hydrogen storage for vessels are developed and tested at a prototype level

Demonstrations aim to optimise technologies in a wide range of use cases

- High capacity hydrogen infrastructure is demonstrated in trial ports (>5,000 kg/day, 1,000kg individual fills).
- New demonstration projects are initiated to enable tests of European hydrogen and fuel cell based vessels. The specific aim is to ensure that a range of use types are covered and to test novel concepts for hydrogen refuelling and drivetrain design
- **EU programme supports demonstration projects to optimise technologies for a range of use cases**
  - ★ >100 ships in operation using fuel cells, use in larger Type 1 & 2 vessels started
- Increasing commercial deployment of hydrogen and fuel cells for smaller vessels (Type 1 & 2)
- Define standards and rules on hydrogen and FC technology in maritime applications (i.e. ship specifications, storage of H_2 on-board accepted)
  - ★ A solid definition of the regulatory framework is devised based on the technical evidence from demonstration projects

2030 vision

For small ships (Type 1&2), hydrogen and fuel cells are the mainstream option for zero emission ships. Mass market acceptance is achieved due to parity of ownership cost in regulated markets

Background assumptions:
- Development of regulations requiring improved air quality and CO_2 emission cuts within the maritime sector.
- Cost reductions assume increased scale of FC applications and the success of other heavy duty H_2 applications.
- Movement to mass market requires a strict regulatory framework in place that defines the target specifications for H_2 ships and allows the introduction and storage of H_2 as a fuel.

Legend
- Action
- ★ Interim target
- **Role for EU programme**

Maritime

Detailed technology roadmap: larger vessels (Type 3 & 4)
Proportion of power load delivered by FCH technologies increases to 2030

Actions and interim targets

2020 | 2025 | 2030

Current State of the Art

Project MARANDA testing 2x85 kW fuel cells as APU's for a large research vessel

Viking Cruises are planning to operate an ocean going cruise ship with liquid hydrogen fueled PEM cells

Commercial pressure from certain sectors (e.g. cruises) for quieter, lower emission energy systems on-board large vessels

Increasingly strict CO_2 and air pollutant emission regulations in the maritime industry

Ongoing design studies for larger ships involving a range of fuel cell types (solid oxide, molten carbonate, PEM) and fuels (liquid hydrogen, ammonia methanol, natural gas)

★ Initial design studies reach their conclusions on viable and non-viable technology options

★ First commercial use of fuel cells for auxiliary power applications on very large commercial vessels

★ Project evidence aids selection of optimum FC technologies and related fuel

Development work focuses on increasing proportion of large vessel power which can be delivered by FCH technologies

Development of new concepts for on-board energy storage and fuel cell integration for large ships requiring days of autonomy and 10's of MW of power

Detailed design studies for the integration of fuel cell systems (and/or hydrogen as a fuel) into very large ships

Development of bunkering (refuelling) solutions the fuel supply chain to achieve widespread roll-out of fuels which appear most viable for larger vessels

First demonstrations of fuel cell systems (and fuelling) in very large vessels for auxiliary loads and increasing proportions of propulsion power to test the most promising fuel types and fuel cell options

EU programme supports R,D&D projects to develop and integrate FC systems into large ships and demonstration projects to prove the viability of FCs in large maritime use cases

Define standards and rules on FC technology in maritime applications (i.e. ship specifications, storage of fuels on-board)

Economic assessment and business planning work for roll-out of high capacity refuelling infrastructure at ports worldwide, including analysis on an achievable price of H_2

Technical evidence supports regulatory decision making

Work to achieve an industry consensus on best fuel options for different vessel sizes and use types, including techno-economic analyses for different use cases

Regulations developed and implemented to enable worldwide fuelling of FC ships (working with International Maritime Organisation)

2030 vision

Fuel cells are accepted as the most viable option to achieve zero emission shipping in large vessels

Background assumptions:

- Development of regulations requiring improved air quality and CO_2 emission cuts within the maritime sector.
- Cost reductions assume increased scale of FC applications and the success of other heavy duty H_2 applications.
- Movement to mass market requires a strict regulatory framework in place that defines the target specifications for H_2 ships and allows the introduction and storage of H_2 as a fuel.

Legend

Action

★ Interim target

Role for EU programme

Maritime vessels: areas for support

Stage of development and potential areas for support	Proposed budget + funding source
Early stage (TRL 2-3)	
The early TRL stage work will be carried out as part of the work defined in the "technology building blocks" roadmap. Special attention will be paid within these tasks to the specific needs of FCs in maritime applications, focussing on novel FC stacks and systems and the modular scale up of technology.	Included in "technology building block" roadmaps
Development phase (TRL 4-6)	
The maritime sector has a diversity of use cases with different demand profiles. Existing technology used in demonstration projects for Type 1 & 2 vessels (in-land, near coastal ships) will therefore require substantial development work to optimise and expand the use of FCs to all maritime use cases (i.e. Type 3 & 4, larger cargo, freight and cruise ships). In addition it will be important to undertake studies to determine H_2 prices at ports/harbours and the impact of this on the ship owner's business case. For smaller ships (Type 1 & 2), two development projects should focus on optimising FC modules for maritime use cases, including work on the balance of plant. A further development project should work on how to optimise FCs for primary propulsion power and the installation of novel, light-weight H_2 storage on-board ships. For Type 3 & 4 ships, which require higher autonomy and power, extensive development of existing technology is required. Projects could include: • Two design studies for ships using different combinations of fuel cells (or modified engines) and novel balance of plant configurations to increase operational flexibility and FC durability. • A development project to improve the modular scalability of FC stacks to enable the scale up of the technology to meet the power demands of Type 3 & 4 ships. This will involve PEM fuel cells as well as SOFC and MCFC systems capable of using a range of fuels. • Another development project should focus on how to integrate large FCs, on a MW scale, into both new and existing large ships to provide partial power supply for propulsion or electrical and heating needs. • Two projects should investigate how to store and dispense large volumes of energy either as hydrogen or as other fuels compatible with fuel cell use (ammonia, methanol, methane) at ports. This should be accompanied by a full costing and business case development exercise to test the viability of progressively larger and more autonomous zero emission vessels (and the associated refuelling infrastructure required).	• 9 projects • €96M budget • 75% funding • €72M funding FP9
Demonstration phase (TRL 7-9)	
For smaller, Type 1 & 2 vessels, demonstration activity is already underway to prove the technology and associated refuelling infrastructure. However, further demonstration projects will be required before the technology reaches the market. Three projects should work on applying hydrogen FCs and H_2 storage into new vessels and installing the associated high capacity refuelling infrastructure into ports. For larger ships (Type 3 & 4), projects will be needed to validate the technical readiness of FCs and to determine the preferred fuel option for large vessels. Two demonstration projects should focus on integrating large FCs and novel storage containers to store and use a range of fuels (e.g. hydrogen, methane, ammonia etc) to provide partial power for large ships (e.g. APU's, hotel loads, hybrid drivetrains). A further demonstration project should focus on H_2 as a fuel, testing the viability of H_2 to provide a share of a ship's propulsion power, using novel H_2 storage tanks and large-scale FCs.	• 6 projects • €120M budget • 75% funding • €90M funding FP9 CEF
Market activation phase (TRL 10)	
Market entry support will be required by the FC maritime industry once technological readiness has been established and fuel costs are lowered. This is mainly expected to come through a combination of regulation and commercial pressure on ship operators to offer cleaner solutions.	No funding requested.

Aviation

Fuel cell applications make a meaningful contribution to decarbonisation: aviation

Aviation

There are a number of near-term options for integrating FCH technologies in aviation to reduce GHG emissions: auxiliary power units (APUs), ground power units (GPUs), FCs for propulsion; and H_2 for generation of synfuels to replace jet fuels. Emissions from planes on the ground at airports are important and offer near-term possibilities for improvements.

Technical immaturity and strict regulations set by aviation authorities mean these technologies will need considerable development effort.

Demonstration projects have already begun, concentrating on small scale applications such as **on-board power, emergency power units, unmanned aerial vehicles** (UAVs)/drones & **small passenger planes** (<25 seats).

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.

Actions and targets

Regulatory pressures need to be in place early to drive the development of low-emission aviation technologies to the commercial market. Clear standards and regulations will need to be implemented to allow the integration of synfuels and FC technology (and the associated fuel) on board aircraft.

Demonstration projects prove the viability of FCHs in small-scale aviation applications (i.e. APUs, GPUs, UAVs & small passenger aircrafts) with the aim to further the technology for larger scale applications in the future (post-2030).

R&D efforts to further aviation specific FC technologies (i.e. novel FC systems and H_2 tanks for APUs or propulsion applications in UAVs).

2023-25
Demonstration projects for on-board GPUs for civil aircraft leads to tens of FCH applications in prototype operation.

2025
Projects expand to in-flight non-critical applications & ground hotel loads increased with increased capability.

2030
Demonstrations of FC in-flight critical applications
FCs for UAVs and 2-4 passenger aircraft are mature

Current state of the art
FC applications have been demonstrated on small-scale aviation applications: drones/UAVs. Demonstration projects are progressively targeting larger applications (i.e. passenger aircrafts with < 25 seats and FC auxiliary power units on business jets).

2030 vision

FCs are increasingly used for auxiliary power units & ground power units in civil aircraft
A selection of FCH aviation models achieve full certification and are in real-world operation, including small passenger planes (<5 seats)

Stage for support + funding rate	EU budget funding
Early stage research 100%	-
Development research 75%	€26M
Innovation actions 50%	€30M
Market deployment 25%	-
Total	**€56M**

Overview of FCH aviation applications: vision, current status and supply chain

Hydrogen could provide a viable zero-emission source of power in a range of aviation applications

Introduction

There are limited options for decarbonising aviation. Hydrogen and other fuels for FCs are already a viable option for fuelling unmanned aerial vehicles (UAVs) and there have been early demonstrations of small passenger planes. In particular, the higher volumetric and gravimetric energy density of hydrogen compared to lithium ion batteries can give longer range for UAVs, although there is work to be done to reduce costs and improve hydrogen storage options. Fuel cells can also play a role on commercial passenger flights by providing auxiliary power for 'hotel loads'. This could improve the fuel efficiency of flights as little/no jet fuel would be required for non-propulsive applications, particularly on the ground where emissions issues are most severe. However, both of these technologies remain immature and require significant development efforts to reach the high safety standards set by aviation authorities. Changes in regulations will also be needed to drive this market. For these reasons, estimates for market development are for the late 2020's onwards for UAVs and APUs and 2030 onwards for other applications (i.e. FC propulsion on larger planes).

Another option for H_2 powered aviation is the integration of renewable synthetic fuels, or 'synfuels', into aeroplane combustion engines. By reacting H_2 and CO_2, a hydrocarbon fuel can be produced with properties that mimic fossil fuels. If CO_2 from CCS is used in this process, a closed carbon cycle can be created meaning the fuel is 'carbon-neutral' upon combustion.

The use of FCHs in aviation applications is already being tested in multiple demonstration projects across different use cases. However, due to the unique challenges posed by aviation (i.e. extremely large energy demands) projects to date focus on light, small-scale UAVs and passenger airplanes (<5 passengers). For example, the Hy4 (pictured left) project is the world's first four-seat passenger aircraft powered by FC technology. With 4 FC modules and a large battery pack the aircraft can reach a top speed of 200km/hr with a range of 750 to 1,500km.

APUs in aviation applications have also been tested through the HYCARUS project (2013-2018). Supported by the FCH JU, this project aimed to develop a Generic Fuel Cell System (GFCS) for use as auxiliary power on larger commercial aircrafts and business jets. Flight tests of the GFCS will be carried out in 2018 on-board the Dassault Falcon.

European supply chain

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

2030 vision

FCs are increasingly used for auxiliary power units & ground power units in civil aircraft

A selection of FCH aviation models achieve full certification and are in real-world operation, including small passenger planes (<5 seats)

FCH aviation applications: detailed technology roadmap

Current State of the Art

Hy4 project – passenger aircraft: Top speed: 200km/h Range: 750-1500 km H2 storage tank weight: 170kg

Ion Tiger (UAV) energy density: 1.3 kWh/kg Flight time: 26 hours

HYCARUS system: On-board power generator, 17 kW to power non critical systems

Actions and interim targets

2020 — 2025 — 2030

- Increasingly strict CO_2 and air pollutant emission regulations in the aviation industry
- Numerous demonstration and development programs already underway for passenger planes – generally focussed on small-scale applications (i.e. UAVs, on board power generation, and small passenger aircrafts (<5 seater))
- Hydrogen fuel cells finding commercial traction for Ground Power Units for civil aviation, APUs and commercial and military drones requiring long run times
  - ★ Trials demonstrate the viability of FCH both for propulsion for passenger vehicles (at least 10 in operation)
- H2 fuelling stations are deployed at airports and feed "out-of-the-airport" applications (bus, taxi) as well as demonstration inside the airport; normative frame is build for H2 infrastructure in the airport
  - ★ Hydrogen infrastructure increasingly available at airports
- Development of specific technologies for aviation applications (i.e. light weight FC stacks, adaption of FC system for aviation, lightweight tanks, development of specific BOP components)
- **EU programme supports development projects to advance and optimize FC technologies in aircraft applications**
- Detailed plans for the integration of a modular approach to fuel cells for APU in large aircraft and prime power in small passenger aircraft (i.e. new designs for aircrafts wherein motors can be distributed throughout the airframe to increase efficiency and performance)
  - ★ Specific FC system cost €1,500/kW, Lifetime of FC system: 40,000 hrs
- Demonstration of GPUs/APUs/drones in real-world operation to develop aviation-specific FC technology
- **EU programme supports demonstration projects will focus on smaller applications to prepare the technological foundations for larger scale applications**
  - ★ Commercial deployment of fleets of X,000's of mid-range UAVs + up to 5 aircraft with FC APUs
- Deployment of FC applications on progressively more critical functions ★
- R&D on synfuels based on hydrogen precursors for integration into conventional combustion engines
  - Synfuels accepted as a viable alternative to jet fuel
- Transform recommendations on FC technology in aviation applications (i.e. aircraft specifications, storage of H2 on-board accepted, regulations over safety and collisions) into applicable standards and rules by working with FAA and EASA
- Techno-economic evaluation of the different zero emission options for different applications
- Industry consensus on best option for decreasing GHG emissions in aircraft applications
- Regulations developed to allow certification and commercial operation

2030 vision

FCs are increasingly used for auxiliary power units & ground power units in civil aircraft
A selection of FCH aviation models achieve full certification and are in real-world operation

Background assumptions:
- Technology meets safety standards
- Intensive work initiated now to build the regulatory framework for FCH technologies in aviation (i.e. certification process)
- Development of regulations in the aviation sector to reduce CO_2 emissions
- Cost reductions assume increased scale of FCH applications and the success of other heavy duty H2 applications.
- Lithium ion batteries in aviation applications remain limited by range

Legend
- Action
- ★ Interim target
- **Role for EU programme**

FCH aviation applications: areas for support

Stage of development and potential areas for support	Proposed budget	Proposed funding source
Early Stage Research Actions (TRL 2-3)		
No dedicated early stage development projects for aviation (as these are covered by the early stage recommendations on the core technologies). However, in supporting the development of various H_2 components, attention will be placed on those which can meet the specific demands of aviation applications, including developments of ultra light-weight H_2 storage tanks and the optimisation of fuel cell systems and stacks.	No funding proposed	
Development Research Actions (TRL 4-6)		
Development projects will focus on small scale aviation applications (i.e. GPUs, APUs, UAV, and small passenger aircrafts) initially. Promising areas within which development work would focus on are: *GPUs, APUs + small airplanes (<5 seaters)* • Adaption of FC system to optimise performance. • Development of specific BoP components to reduce FC system costs. • Development of FC system that can comply with aeronautic regulations (i.e. very large temperature variations, low pressure environments, extended operational ranges). *UAVs and drones* • Adaption of existing FC systems used in on-going demonstration projects. • Development of clear methods for integration of FC technology.	• 5 projects • €35M budget • 75% funding rate • €26M funding	FP9
Innovation Actions (TRL 7-8)		
Due to the technical immaturity of FCH applications in aviation, all development efforts will focus on small scale applications (i.e. two projects on GPUs or APUs in civil aircraft and one project on small passenger aircrafts). These will aim to highlight the viability of FCHs in aviation applications and demonstrate their use in real world applications. It will also pave the way for new standards and approvals processes for hydrogen and other fuels, as well as fuel cells themselves in aviation.	• 3 projects • €60M budget • 50% funding rate • €30M funding	FP9
Market Deployment Actions (TRL 9)		
Market activation on FCH aviation applications is not proposed.	No funding proposed	

The following roadmaps cover a number of related technologies for hydrogen in gas grids & for heat & power in a range of use cases

Use case

- *Hydrogen in gas grids*
- *Domestic & commercial heat & power*
- *Industrial*
  - *Baseload heat & power requirements*
  - *Cycling power & heat requirements*
  - *Heat only*

Technology

Green hydrogen production

See pages 14 & 23

Blends of hydrogen in natural gas

- **Conventional appliances** no modification needed at low % H_2. Replacement burners needed as %s of H_2 increases
- **FC CHP** minor modification a higher % blends, most efficient solution
- **Gas turbine CHP** Flexible fuel burners needed as %s of H_2 increase
- **FC CHP** Minor modification to existing natural gas fired systems
- **Gas burners** Flexible fuel burners needed as %s of H_2 increase

100% hydrogen in the grid

- **Conventional appliances** Modification of burners and boilers needed, piping and metering infrastructure may also need upgrade
- **FC CHP** Dedicated hydrogen fuelled product can be easily adapted from existing gas fired systems
- **Gas turbine CHP** New burners & combustion chambers needed
- **FC CHP** Hydrogen fuelled system easily adapted form existing designs
- **Gas burners** New burners required. Some processes may need adaptation to work with H_2 vs CH_4 flame

See pages 89-91

See pages 96-97

See pages 99-102

Hydrogen is meeting demands for heat and power at a meaningful scale: hydrogen in gas grids

Hydrogen in gas grids

Hydrogen is one of the lowest cost solutions for decarbonising heat [1,2]. Putting hydrogen into gas grids will serve as a **valuable energy store for renewably produced hydrogen** and **ensure continued use of the public gas grid assets in a** low carbon future.

There are two ways hydrogen can be used to directly decarbonise the gas grid:

- **Blending H_2 with methane:** Blends of hydrogen up to 20% by volume are possible without pipeline or appliance conversion in the majority of gas grid.
- **Conversion to 100% hydrogen grid:** conversion programme of the network and appliances needed, similar to town > natural gas conversions of the last century. Purification advances (see roadmap on page 31) would allow a 100% hydrogen grid to deliver fuel for transport as well as heating.

Innovations are needed to improve metering accuracy and H_2 pipeline components, to support increasing the levels of hydrogen in the gas grid.

Actions and targets

Viability in this market is crucially dependent on the cost of the input fuel – either H_2 prices at €2/kg or below, or regulatory pressures will be required to drive the market.

Public awareness campaigns and regulatory changes support increasing use of H_2 – CH_4 blends and 100% hydrogen in gas grids.

Metering developments needed to accommodate variable volumes of H_2 in the gas grid.

Current state of the art
There are a small number of demonstration projects injecting hydrogen into natural gas grids, generally at <5% by volume.

2023

Hydrogen is being blended in the gas grid in >5 EU MS.

2025
Hydrogen blends become more widespread (>10 EU MS).
2 EU regions have 100% hydrogen pipelines for residential uses.

2030
>10 EU regions have or are implementing 100% hydrogen grids.

2030 vision

30 TWh pa H_2 is blended into the natural gas grid.

>10 EU regions implementing 100% H_2 for residential & industrial sectors.

Clean H_2 use for heat saves 7 $MtCO_2$/pa.

Stage for support + funding rate	EU budget funding
Early stage research 100%	-
Development research 75%	€11M[3]
Innovation actions 50%	-
Market deployment 25%	-
Total	**€11M**

1 - 2050 Energy Scenarios, KPMG for the Energy Networks Association, 2016. 2 - Cost analysis of future heat infrastructure, UK National Infrastructure Commission, 2018. 3 - Description of areas for support is given on page 97

Overview of hydrogen in gas grids: vision & current status

Hydrogen could enable deep decarbonisation of heat, using gas grids to store large amounts of renewable energy

Using hydrogen for heat may be one of the lowest cost options for decarbonising heating. Heating and cooling is the largest single energy use in Europe, covering half of final energy demand. Power-to-gas systems (using electrolysis) have the potential to couple the electricity and gas grids, transferring clean energy from constrained electricity networks, storing and using it in the gas networks.

Injecting a proportion of hydrogen into the natural gas grid is technically feasible today up to certain volumes, usually considered to be c. 10-20% by volume, without major overhaul of pipelines or appliances. This has the benefit of reducing the CO_2 intensity of the gas grid, and also using existing assets with large seasonal storage potential.

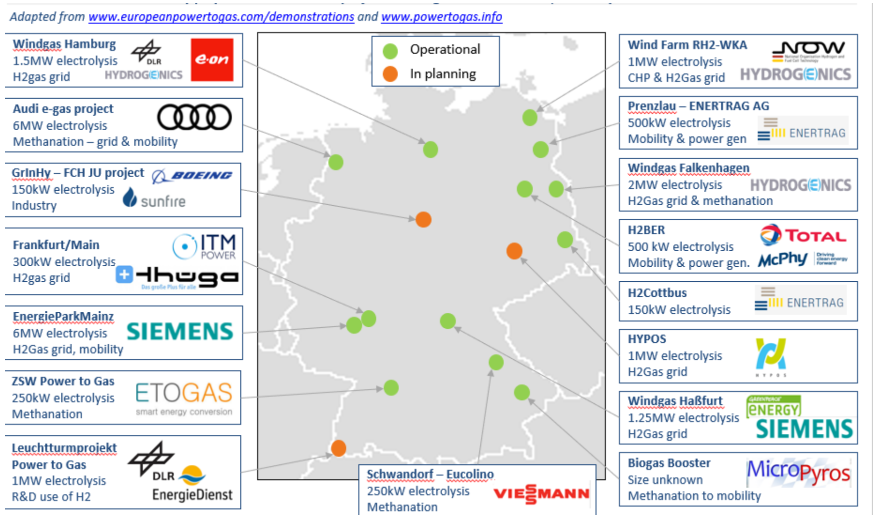
For deeper decarbonisation, 100% hydrogen could be used by industry for cogeneration of heat and power using fuel cells. Low & medium grade heat requirements can also be met using hydrogen/flexible fuel burners/boilers with retrofitted components. For some high-T applications H_2 direct combustion is viable, but the technology needs to be developed to ensure compatibility with the underlying process. H_2 turbines for power and heat generation exist as product offerings today. Conversion of gas grids to 100% hydrogen is also possible and under consideration in parts of the UK (see below), & interest is growing in other countries such as the Netherlands.

Falkenhagen project (DE) is injecting 2% H_2 by vol. into the gas grid

The H21 Leeds City Gate project

The H21 Leeds City Gate study aimed to determine the technical and economic feasibility of converting the existing natural gas network in Leeds, UK, to 100% hydrogen.
The first phase of the project reported in 2016[1] and concluded that the conversion is feasible. **As well as supporting decarbonisation, 100% conversion of the gas network could be an enabler of other markets – hydrogen for transport or industry.**
The project is continuing to attract very significant political interest in the UK. Funding has been secured and a project team assembled to deliver c. €60 million of further work on detailed feasibility, FEED studies, demonstration scale tests, regulatory change, financing etc. The partners estimate that 2025 is the earliest feasible date for conversion to natural gas.

Power-to-gas projects: Germany



There is a wide range of power-to-gas (and power-to-X) projects happening in Germany[2], including hydrogen injection into the gas grid (see above)

1 - H21 Report, July 2016, see www.northerngasnetworks.co.uk

2 - *Adapted from www.europeanpowertogas.com/demonstrations and www.powertogas.info*

Hydrogen in gas grids: detailed technology roadmap

Current State of the Art

Permitted injection limits vary by country and by region depending on pipe composition and presence of CNG refueling stations etc.

P2G plants in Germany are injecting up to 15% H2 by volume

Actions and interim targets

Today | 2020 | 2025 | 2030

- Viability in this market is crucially dependent on the cost of the input fuel – either H2 prices at €2/kg or below, or regulations are needed to incentivize/reward the energy storage services that P2G systems provide
- Public awareness campaigns support increasing use of H_2 – CH_4 blends and 100% hydrogen in gas grids
- Regulatory changes needed to allow increased % of blends or 100% hydrogen in networks

Hydrogen blends

- Determine appropriate hydrogen % depending on pipeline materials & planned infrastructure upgrades, taking into account gas standard work and needs of CNG vehicles
- Meters need to be developed to accommodate variable volumes of H_2 in the gas grid
- **EU programme supports development of components needed to increase % of hydrogen in the gas grid[1]**
- Gas DSOs will need to make investments on additional pipeline monitoring & maintenance measures
- ★ Hydrogen is being blended in the gas grid in >5 EU MS
- ★ Hydrogen blends become widespread (>10 EU MS)

100% hydrogen

- Conversion programmes in 1-2 EU regions with suitable pipeline materials (plastic) upgrade appliances & meters
- ★ 2 EU regions have 100% hydrogen pipelines for residential uses
- ★ >10 EU regions have or are implementing 100% hydrogen grids
- Feasibility & engineering studies on conversion of specific regions
- Programmes to replace old (metal) gas pipes with plastic pipes facilitate other regions considering 100% conversion programmes
- Conversion programmes being rolled out across suitable regions

2030 vision

30 TWh pa H_2 is blended into the natural gas grid
>10 EU regions implementing 100% H2 for residential & industrial sectors
Clean H2 use for heat saves 7 $MtCO_2$/pa

Background assumptions:

- Regulation changes to incentivise energy storage and allow electrolysis plants to access cheap electricity (e.g. German regime)
- Large scale SMR + CCS produces H_2 at >€2/kg to kickstart this market whilst electrolyser costs reduce

Legend

- Action
- ★ Interim target
- **Role for EU programme**

1 - much of the activity to realise this roadmap will occur in the gas sector & with mature components, and so there is a limited role for an FCH programme. The projects proposed here are detailed in page 97

The efficiency of stationary fuel cells reduces energy needs, and reversible fuel cells link the electricity and gas networks

Stationary fuel cells

Stationary fuel cell CHP units use gas (methane or hydrogen) to meet power & heat needs. They can also provide power in remote locations or as back-up power to displace diesel generators.

Fuel cell CHP units have **high overall efficiency (>90%) and electrical efficiency (>60%),** reducing energy used for power & heat in buildings. Deployed today, they can provide **30-50% of the CO_2 savings required from energy use in buildings.**

As the **gas grid becomes decarbonised, stationary fuel cells produce increasingly low CO_2 power and heat for decentralised applications and buildings.**

Reversible fuel cell systems (gas > heat + elec., or elec. > gas) offer the ability for localised energy storage with **large scope to decentralise energy systems and put control into the hands of the consumers.**

Actions and targets

- Building regulations recognise the value of FC CHP efficiency in reducing the environmental impact for new build and retrofit.
- Market activation increases scale of demand and production for fuel cell micro-CHP, reducing costs and driving the uptake. Demonstration of next generation of commercial scale products (0.1 – 1MW).
- Development of reversible fuel cell concepts leads to deployment of distributed commercial systems capable of linking electricity and gas grids at medium and low voltage levels.
- R&D on new stack technologies & components to reduce costs & improve flexibility in operation.

2023-25
Fuel cell stack design with 75,000 hours lifetime and €5,500/kW.

2027
Fuel cell power plants >100 kW installed in Europe at €1,500/kW
Reversible fuel cell systems operating at a range of scales.

2030
>100,000 units/year for at least 3 European stationary FC manufacturers.

Current state of the art
Current cost of fuel cell-micro CHP c.€13,000/kW, with >2,000 fuel cell-micro CHP systems installed to date and another 2,500 by 2021
Largest FC power plant operating in Europe is 1.4 MW.

2030 vision

Widespread uptake for domestic and commercial buildings, with 0.5 million FC CHP units deployed. Numerous European manufacturers producing >100,000 sales/year.

Stage for support + funding rate	EU budget funding
Early stage research 100%	€24M
Development research 75%	€68M
Innovation actions 50%	€30M
Market deployment **20%** **€800M of the investment will come from industry**	€200M
Total	**€322M**

Overview of stationary fuel cells current status, supply chain and vision

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

- **CHP** - Fuel cells (typically gas fuelled) can be installed in a Combined Heat and Power (CHP) system to provide heat for buildings as well as high efficiency electricity - fuel cells have been designed for “Micro-CHP” applications, powering residential and small commercial buildings (0.3-5kW), for medium sized application up to 400kW (typically for a large commercial building or small district heating network) and for very large scale applications at power levels over 1MW.
- **Back-up power** (typically hydrogen or methanol fuelled) – because of their fast response times, fuel cells are an ideal component of back-up power systems. Key markets are back-up systems for telecom and data centre sites, where there is a premium on reliable and clean power.
- **Prime power** (gas or hydrogen fuelled) – fuel cells can also be used as prime power providers. In Europe there have been limited prime power applications, but in the US and Asia, applications such as data centres and large corporate campuses have seen significant uptake. There is also a niche market associated with the use of waste hydrogen from chlor-alkali plants.
- **Energy system coupling and flexibility** Reversible fuel cells are under development which could operate in prime power and electricity system markets, storing electricity via hydrogen, and also using grid gas/biomass-derived gas as an alternative energy input.

Deployment in Europe of stationary fuel cells has been limited compared to other geographies, for example in Japan where over 100,000 fuel cell CHP systems have been installed under the ENEFARM program which is backed by considerable government subsidy. In the US and Korea, incentive programs have led to many tens of >1MW fuel cell systems, whilst in Europe there are fewer than 5 installed to date.

The most significant European deployments have occurred due to incentive programs, notably the FCH JU funded Ene.field project which has installed ~1,000 fuel cell CHP units and the PACE project which is a successor aiming at 2,500 units, with a view to decreasing costs by >30%. German Government support for small fuel cells is also now encouraging increased pace of uptake.

ene.field
Fuel Cells x Combined Heat and Power

PACE

European supply chain

There is a strong European based supply chain for fuel cell micro-CHP, which has been developed in part due to FCH JU funded projects. It includes micro-CHP system integrators such as; Bosch, Valliant, Ceragen, SOLIDpower, Viessmann, as well as stack developers such as Elcomax, ElringKlinger, Serengy; Ceres Power, Sunfire and Hexis. For larger systems there is more limited experience, though companies such as AFC (alkaline FCs for waste hydrogen) are expanding and companies such as Fuel Cell Energy and Doosan have established European operations.

2030 vision

Widespread uptake for domestic and commercial buildings, with 0.5 million FC CHP units deployed. Numerous European manufacturers producing >100,000 sales/year

Stationary fuel cells: detailed technology roadmap

Current State of the Art

- >2,000 fuel cell-micro CHP systems installed, with c.2,500 planned to be installed by 2021
- Cost of residential micro-CHP c. €13,000/kW
- Largest fuel cell plant in Europe is 1.4 MW power plant in Germany

Actions and interim targets (Today – 2020 – 2025 – 2030)

- Action: Building regulations recognise the value of FC CHP efficiency in reducing the environmental impact for new build and retrofit
- Action: FCH JU PACE project deploys c.2,000 fuel cell-micro CHP
- Interim target: Fuel cell production capacity of >1,000 units/manufacturer/year
- Interim target: Stationary fuel cell increased production of >10,000 units/manufacturer/year. Capital costs reduce with volume of production
- Action: Design for manufacture and mass manufacturing processes reduces fuel cell stack costs
- **EU programme supports market activation with widespread deployment of fuel cell micro-CHP**
- Action: Develop OEM/Tier supply chain to further reduce costs of fuel cell stacks and related components
- **EU programme supports cost reductions via supply chain development** **(see page 104)**
- Interim target: Fuel cell stack cost for micro-CHP (0.3 – 5kW) <€5,500/kW
- Interim target: Fuel cell stack cost for micro-CHP (0.3 – 5kW) <€3,500/kW
- **EU programme supports R&D & demonstration on new technologies and use cases**
  - Action: Research on new stack technologies & components to reduce costs & improve flexibility in operation
  - Action: Demonstrate next generation of commercial/industrial scale (>100kW) fuel cell power plant at €1,500/kW
- Interim target: Large-scale fuel cell power plant installed at <€1,500/kW
- Action: Research & development on reversible cell concepts for grid balancing
- Action: Demonstrate reversible cells integrated at RES sites and/or with biogas
- Interim target: Reversible power plants with efficiency >50% and cost €5,000/kW
  Deployment of distributed commercial systems linking LV & MV grids with gas grids
- Action: Commercial sales of stationary FC to specific use cases continue (back-up power for sensitive electronics, use of waste hydrogen etc.)
- Increased H_2 and biogas content in the gas grid furthers the decarbonisation of stationary fuel cells
- 100% hydrogen gas grids emerge and further decarbonisation potential with stationary fuel cells

2030 vision

Widespread uptake for domestic and commercial buildings, with 0.5 million FC CHP units deployed. Numerous European manufacturers producing >100,000 sales/year

Background assumptions:

- Hydrogen and biogas is blended into the gas grid across European countries and reduces the carbon footprint of the gas grid, improving the CO_2 emission of NG based fuel cells
- Emergence of 100% hydrogen gas networks.

Legend

- Action
- ★ Interim target
- **Role for EU programme**

Stationary Fuel Cells

Stationary fuel cells: proposed areas for support

Stage of development and potential areas for support	Proposed budget	Proposed funding source
Early Stage Research Actions (TRL 2 – 3)		
Research into new stack technologies, components and processes for fuel cell micro-CHP systems to improve system flexibility and increase robustness of components under flexible operation. Research to develop reversible cell concepts, focussing on reversible pressurised solid oxide concepts.	• 8 projects • €24M budget • 100% funding rate • €24M funding	FP9
Development Stage Research Actions (TRL 4 – 6)		
Support to drive cost reductions in the balance of plant components and in-operation processes such as predictive maintenance and development of fuel cell systems that are integrated with smart grids and decentralised renewable energy sources. Develop a commercial/industrial scale CHP unit (100 kW – 1 MW) to demonstrate this. Integration work on reversible cell concepts, in particular to integrate a range of gas inputs (hydrogen – methane blends, biogas, syngas), to improve the round trip efficiency to above 50% and to develop concepts at a range of scales.	• 13 projects • €91M budget • 75% funding rate • €68M funding	FP9
Innovation Actions (TRL 7 – 8)		
Demonstrate the deployment of the next generation of commercial/industrial scale fuel cell CHP units from European suppliers (100 kW – 1 MW). Demonstrate reversible cell concepts at sites with renewable generation and/or biogas/syngas inputs.	• 3 projects • €60M budget • 50% funding rate • €30M funding	FP9
Market Deployment Actions (TRL 9)		
European market deployment support for the roll-out of domestic scale fuel cell micro-CHP, in concert with market activation activities in other Member States (notably Germany). This type of programme, along with supply chain support (see page 104) has the potential to ensure European dominance in solid oxide FC markets. Where possible, market support should be aimed at gas grids with a program to maximise the concentration of green hydrogen or biogas, to build on the decarbonisation benefits of gas fired fuel cell-micro CHP. As 100% hydrogen gas grids are developed, the market activation support program should look to ensure a role for fuel cell micro CHP and also larger fuel cells on these gas grids.	Budget €1000M • Market deployment of 100,000 units aiming for commercial volumes and prices for FC micro-CHP • Funding rate 20% • €200M funding	FP9 CEF

Hydrogen is meeting demands for heat and power at a meaningful scale: hydrogen in domestic and commercial burners[1]

Domestic & commercial burners

In some cases, FC CHP may not be the best option for providing buildings with the heat they need – e.g. retrofitting of old building stock.

As blends of hydrogen increase in the gas grid and conversion programmes for 100% hydrogen in the grid begin, there will be a need for **domestic and commercial fuel flexible hydrogen boilers and burners** (e.g. for gas cookers).

Whilst some development work is needed, the majority of the actions are around standards and regulations.

Actions and targets

- As this roadmap is linked to hydrogen in the gas grid, viability for hydrogen in this market is crucially dependent on the cost of the input fuel and regulatory pressures will be needed to drive the market.
- Training hydrogen-safe gas engineers.
- Development of standards for hydrogen fuel in domestic settings, & regulations covering appliance installation.
- Development work on key components for flexible fuel H_2 burners.

2023
Hydrogen is being blended in the gas grid in >5 EU MS.

2027
Flexible fuel and full H_2 boilers and burners offered by >10 manufacturers.

2030
Range of products available to support domestic and commercial heat needs.

2030 vision

Range of fuel flexible and 100% H_2 products readily available to support increasing concentrations of hydrogen in the gas grid.

Current state of the art
Some hydrogen boilers available but with limited availability. R&D work is underway on flexible fuel burners and boilers.

Stage for support + funding rate	EU budget funding
Early stage research 100%	-
Development research 75%	€11M
Innovation actions 50%	-
Market deployment 25%	-
Total	**€11M**

1 – This roadmap covers the end-user technologies needed to accommodate hydrogen in the gas grids, excluding FC CHP which is covered separately on the previous roadmap. As the actions & standards that relate to a FCH programme are limited, there is no detailed roadmap for this specific application.

Hydrogen in the gas grids, domestic & commercial burners: areas for support

These actions describe the potential areas for funding from 2 roadmaps: hydrogen in gas grids (pages 89-91), and hydrogen in domestic & commercial burners (page 96)

Stage of development and potential areas for support	Proposed budget	Proposed funding source
Early Stage Research Actions (TRL 2-3)		
No case for early stage research actions in this area.	N/A	
Development Research Actions (TRL 4-6)		
To accommodate an increasing amount of hydrogen for heat there is a case for development work in the following areas: *Hydrogen blends in the natural gas grid* • Development of a fuel flexible or pure H_2 burner for boilers, capable of accepting a growing percentage of H_2 in natural gas and with zero NOx emissions (domestic & commercial scales). • Development work on metering for hydrogen blends to ensure that customers are accurately charged for the energy content received, which will vary when the hydrogen content varies.	• 2 projects • €14M budget • 75% funding rate • €11M funding	FP9
Innovation Actions (TRL 7-8)		
No innovation actions are proposed.	N/A	
Market Deployment Actions (TRL 9)		
No market deployment actions are proposed.	N/A	

Hydrogen is actively displacing fossil fuels as a clean energy input into a wide range of industrial processes

Hydrogen in industry

Clean hydrogen is an essential component of efforts to decarbonise industry[1].

Approx 7 Mt/yr of hydrogen (SMR) is currently used in Europe in a wide range of industrial processes (mainly refining & ammonia manufacture). All of this could be replaced by clean hydrogen (from RES + electrolysis and/or SMR + CCS).

Hydrogen can also replace fossil fuels as a feedstock in a range of other industrial process – for heat and power, as well as replacing coke as a reducing agent in the steel manufacturing process.

Hydrogen can be combined with CO_2 (from capture plants) to replace oil and gas in a range of petrochemical applications such as:

- Producing liquid fuels: methanol, gasoline, diesel, jet fuel.
- Producing important petrochemicals such as olefins (e.g. ethylene, propylene) or BTX (aromatic hydrocarbons which are key components of manufacturing nylon & polyurethane).

Developing these applications could put Europe at the forefront of a clean industrial revolution.

1 – Electrolysis using renewable energy is essential for decarbonizing industry. Elements relating specifically to electrolysis are covered in the earlier roadmaps on pages 14-17 & 23-24

Actions and targets

Regulations (e.g. Renewable Energy Directive) recognise the value of renewably-produced hydrogen in decarbonising industry.

Market deployment supports demand for large scale (50-200MW) electrolysis plants supplying H_2 to industrial processes and industrial heat and power applications.

Development of synthetic liquid fuels for transport, aviation & shipping applications.

Demonstration projects proving electrolysis and H_2 for heat across key industrial processes.

2023
>5 H_2 demonstration projects operating across the range of industrial applications (including those currently planned).

2027
Full scale tests of hydrogen use as an alternative to coke in iron and steel manufacture.

2030
100's MW scale electrolysis plants operating in industry across Europe.

Current state of the art
1-10 MW scale projects integrating electrolysis into refineries and steel plants are being planned/under construction. Baseload electrolysis for ammonia is a mature technology. Key technical challenges relate to integrating variable electrolyser operation (due to variable RES input) with continuous industrial processes and/or making CCS derived hydrogen available for these applications.

2030 vision

Clean hydrogen replaces fossil-fuel derived hydrogen in industrial uses, saving c.60 $MtCO_2$pa.

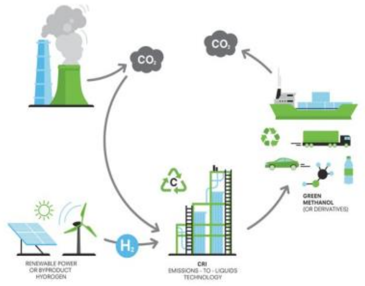
Use of H_2 in steel and petrochemicals has been successfully demonstrated, and hydrogen provides 30 TWh/year energy input into these processes.

Stage for support + funding rate	EU budget funding
Early stage research 100%	-
Development research 75%	€47M
Innovation actions 50%	€150M
Market deployment <25%	€211M
Total	**€408M**

Overview of hydrogen in industry: vision, current status and supply chain

Clean H_2 is key for the decarbonisation of industry and the transfer of renewable fuels to other sectors

Current status of the technology and deployments



Hydrogen has been used as a feedstock for industrial processes for many years – most importantly in ammonia production and refining operations. There is now increasing interest in using clean hydrogen in a wide variety of industrial applications, including replacing natural gas for heat and power, and replacing fossil-fuel based inputs in other industrial processes. There remains a cost premium for clean hydrogen, which will need to be overcome for the fuel use to become widespread. This will involve both cost reductions in production (see pages 14-21) and regulatory pressures or incentives. Multiple projects are underway to highlight the use, and associated benefits, of green H_2 as a feedstock for industry. Below are some examples across different industries:

- **Carbon Recycling International** – Located in Iceland, the George Olah Plant is the world's largest commercial CO_2 methanol plant. The plant uses renewable electricity from geothermal and hydropower sources to produce green H_2, and combines it with captured carbon in a catalytic reaction to produce methanol. With a capacity of 4 Mt pa of methanol, the plant recycles 5,500 tonnes of CO_2 per annum. The production and use of this low-carbon methanol as an automotive fuel releases 90% less CO_2 than a comparable amount of energy from fossil fuel.
- **GrInHy –** Project to support the design, manufacture and operation of a high-temperature electrolyser as a reversible generator (reversible Solid Oxide Cells) to provide H_2 for heat treatment in the steel industry and grid stabilizing services. In June 2017 the rSOFC achieved >7,000 hours of operation with a high efficiency of ~80% LHV.
- **Refhyne** – Project to install a 10MW electrolyser at the Shell Rhineland refinery complex in Germany to produce H_2 for processing and upgrading products at the refinery, as well as regulating the electricity use of the plant. When operational in 2020 this will produce 1,300 tonnes of H_2 per year, reducing CO_2 emissions and proving the polymer membrane technology on a large industrial scale.
- **HyBrit** – In 2016, SSAB, LKAB and Vattenfall formed a joint venture project with the aim of replacing coking coal in ore-based steel making with H_2. In 2018, a pilot plant was planned and designed in Lulea and the Norbotten iron ore fields to provide a testing facility for green H_2 (produced by electrolysis) to be used as a reducing agent in steel-making. Project partners state that using this production method could make steel-making technology fossil-free by 2035, reducing Sweden and Finland's CO_2 emissions by 10% and 7% respectively.

European supply chain

With multiple demonstration projects taking place in Europe, those involved (such as Air Liquide, ITM Power, Vattenfall, SSAB) will have unrivalled expertise in the integration of clean H_2 as a feedstock for industry. Europe could become a market leader in the use of clean H_2 in industry, producing revenues of €13.5bn and 202,000 jobs by 2030

2030 vision

Clean hydrogen replaces fossil-fuel derived hydrogen in industrial uses, saving c.60 $MtCO_2$pa.

Use of H_2 in steel and petrochemicals has been successfully demonstrated, and hydrogen provides 30 TWh/year energy input into these processes

H_2 in Industry

Hydrogen in industry: detailed technology roadmap

Current State of the Art

CRI (George Olah plant)
4M tpa methanol production using clean H_2 and captured carbon (~5,500 tpa CO2 recycling)

Refhyne
10MW electrolyser in construction to produce 1, 300tpa H_2 in 2020 for refinery operations. Budget €20M

HyBRIT
FF free steel pilot plant using H_2 as reducing agent under construction.

Actions and interim targets

Today — 2020 — 2025 — 2030

- Increased industry and national pressure to reduce GHG emissions from H_2 production
- CCS implemented for H_2 production with SMR. Captured carbon reacted with H_2 to produce synthetic hydrocarbons
- Low cost electricity accessible (~€40-50/ MWh)
- Large scale electrolysers installed (1-10MW) on industrial sites with rapid response technology to produce green H_2 from renewable energy and help energy system flexibility and stability
  - ★ Revenues from energy system services realised
- Development of more efficient production methods for synthetic fuels (i.e. improvements in catalyst and reactor design, development of low temp catalysts)
  - ★ Regulations permit use of alternative fuels in road, maritime & aviation
- Prototypes for smart cogeneration of pressurized steam & power by FC CHP at scales 1-100 MW
- Demonstration projects on cogeneration for specific applications e.g. biotech, food
- Development of fuel flexible and 100% H_2 burners & combustion chambers with zero NOx emissions for industrial scale burners & boilers
- Demonstration of 100% H2 burners for high-T heat at 10-100 MW scales
- Pure H_2 burner components integrated into hydrogen turbines
  - ★ Range of FCH options & products available for industrial heat & power
- Current & future demonstration projects prove the economic and technical viability of green H_2 in existing key industry processes (e.g. in ammonia and methanol production, refineries)
  - ★ >10 industry projects using H_2 produced by electrolysis across multiple industries (i.e. chemical, refineries, steel)
- Research and demonstration projects into the use of H_2 as a reducing agent in iron and steel production (in replacement of coke or natural gas)
- Commercial roll-out of H_2 in iron and steel industry
  - ★ 100,000 tons of H_2 used per year as a reducing agent
- Second generation demonstrations with optimised electrolysers for large H_2 production in industry (i.e. large scale electrolysers, 50-200MW)
- Regulations (e.g. Renewable Energy Directive) recognise renewable H_2 as key to the decarbonisation of industry
- Introduction of low carbon H_2 as a feedstock for industry across Europe

EU programme supports development & demonstration projects to optimize green H_2 + FC use industry

EU programme supports market activation to commercialise green H_2 production

2030 vision

Clean hydrogen replaces fossil-fuel derived hydrogen in industrial uses, saving c.60 $MtCO_2$pa.

Use of H2 in steel and petrochemicals has been successfully demonstrated, and hydrogen provides 30 TWh/year energy input into these processes

Background assumptions:
- Continued pressure to decrease GHG emissions in industry
- Policy changes allow electrolysis plants to access cheap electricity (e.g. German regime)
- Resolution to Renewable Energy Directive include synthetic fuel as renewable

Legend
- Action
- ★ Interim target
- Role for EU programme

Hydrogen in industrial processes: areas for support

Stage of development and potential areas for support	Proposed budget	Proposed funding source
Early Stage Research Actions (TRL 2-3)		
Any early stage development projects for clean H_2 in industry relate to electrolysis, covered in pages 14-17.	No funding proposed	
Development Research Actions (TRL 4-6)		
Industrial heat and power: There is a case for development work on: • Prototypes for the smart cogeneration of pressurized steam and electricity by FC CHP at 1, 10 and 100 MW scales. • Development of a fuel flexible H_2 burner for industrial scale boilers, with zero NOx emissions. • Development of a pure H_2 burner for refurbishing existing industrial scale boilers. **Other industrial processes:** A suite of projects should research technology concepts which could be used to produce synfuels (i.e. improvements in catalyst reactions) and steel (i.e. testing H_2 as a reducing agent).	• 9 projects • €63M budget • 75% funding rate • €47M funding	FP9
Innovation Actions (TRL 7-8)		
Industrial heat and power: Demonstration projects could include: • A number of demonstration projects on cogeneration of pressurized steam and electricity by FC CHP in a variety of application environments, e.g. food, biotech. • A number of demonstration projects on pure H_2 burners providing high-grade process heat, at scales of 10-100 MW. **Other industrial processes:** Demonstration projects could include: • Integrating large scale electrolysers (50-200 MW) into industrial production plants, demonstrating dynamic operation. • Clean H_2 for refining crude oil into complex fuels (e.g. kerosene/jet fuel). • Ammonia and methanol production with clean H_2 to decrease GHG emissions and managing energy loads. • Production of synthetic petrochemicals (e.g. olefins and BTX) using green H_2 from electrolysis and captured carbon. • Assessing the ability of H_2 as a reducing agent in iron and steel production (replacing fossil fuels such as coal and gas).	• 15 projects • €300M budget • 50% funding rate • €150M funding	FP9 ETS-IF
Market Deployment Actions (TRL 9)		
Market entry support will be needed to: • Begin the widespread roll-out of integrating green H_2 into industry and to displace existing fossil-fuel based processes (Budget €500M for 6 very large scale projects, with 25% funding rate, €125M funding). • Begin the widespread roll-out of hydrogen based FC CHP for power & low/medium grade heat requirements in industry, aiming to deploy at least 100 MW (Budget €424M, >100MW total deployments, variable funding rate, €86M funding).	Budget €924M • Range of deployments • < 25% funding rate • €211M funding	ETS-IF

Actions on supply chain development will trigger inward investments & other actions are important to underpin success

Supply chain development is key to securing inward investment and maintaining competitiveness

The FCH sector includes a series of **highly successful SMEs** that have developed products and are eager to move to large scale manufacturing to enable cost reductions and market penetration. This typically requires investments between €10-40 million. When they turned to private European investors, these SMEs face hesitation and risk aversion and too often they turn outwards to overseas investors. **Private European investments could be facilitated by a combination of EU grants and debt**. This would be in line with the objective of the framework programme, the recommendation of the Lamy report (the so-called "FAB" dimension) and in line with the discussions around the Innovation Council, which aim at supporting technology development along the complete innovation chain from R&D to market.

We propose:

- 4 large scale industrialization projects, total budget of €400M, funding of €100M (25% funding rate) **to support fully automated manufacturing facilities** with the potential to reduce costs of key components.
- 12 medium scale projects, total budget of €240M, funding of €120M (50% funding rate), to **support capacity increases in manufacturing of fuel cells, electrolyser components**, and other core components of FCH systems
- 14 development research projects, total budget €98M, funding of €74M (75% funding rate), to undertake studies and small scale experiments
- 8 early stage research projects, total budget €24M, funding €24M (100% funding rate), developing sensors and actuators to **improve real-time quality control** in the manufacturing process

Stage for support	EU budget funding
Early stage research	€24M
Development research	€74M
Innovation	€120M
Market deployment	€100M
Total	**€318M**

Actions on cross-cutting issues will support the development of the hydrogen sector

We propose the following actions:

- **Education and public understanding of hydrogen as a mainstream fuel**: 7 projects will prepare and disseminate material for education, media and decision makers whilst surveys will gauge public understanding.
- **Pre-normative research and regulations, codes and standards:** 9 projects on research and standards. Examples include harmonised standards for the public use of hydrogen, hydrogen valorisation and metering and refuelling protocols.
- **Safety:** 7 projects to improve safety aspects. Examples include guidelines for indoor installation of hydrogen systems for FCEVs, optimal deployments of sensors, certification for applications involving combustion of H_2.
- **Monitoring and databases:** Recording performance of FCH technologies is essential for determining the direction of and potential for future involvements. 6 projects will continue the work on existing databases and develop new ones where required

Stage for support	EU budget funding
Early stage research	€24M
Development research	€110M
Innovation	-
Market deployment	-
Total	**€134M**

Annex – summary of the programme budget by technology

Target	Technology roadmap	Research Actions (TRL 2-3, 100% funding) Budget, €MN	Research Action (TRL 4-6 75% funding) Budget €MN	Innovation Action (TRL 7-8, 50% funding) Budget €MN	Market Deployment Action (TRL 9, 25% funding) Budget €MN	Total budget €MN	Total public contribution €MN
Low carbon hydrogen production	1. Electrolysis	42	126	80	500	748	302
	2. Alternative H_2 production	30	56	80	100	266	137
Hydrogen production increases renewable use	3. Energy system electrolysis	Costs of support are included in electrolysis budget given above					
	4. Large scale H_2 storage	6	28	60	0	94	57
Hydrogen is delivered at low cost	5. Technical: metering etc	24	63	60	0	147	101
	6. Transport of H_2 by road etc.	3	14	20	0	37	24
	7. Liquid H_2 carriers	12	14	40	0	66	43
Affordable hydrogen refuelling	8. Hydrogen refuelling stations	3	21	100	1,000	1,124	319
Fuel cell vehicles (road, rail, ship) are competitively priced	9. Technology building blocks	30	70	0	0	100	83
	10. Cars, 2-3 wheelers, vans	0	14	40	500	554	106
	11. Buses & coaches	0	21	60	500	581	146
	12. Trucks	0	14	80	500	594	101
	13. Material handling	0	28	40	45	113	56
	14. Rail	0	14	60	500	574	91
	15. Maritime	0	96	120	0	216	162
	16. Aviation	0	35	60	0	95	56
Decarbonising the gas grid & heat	17. Hydrogen in the gas grid	0	14	0	0	14	11
	18. Stationary fuel cells	24	91	60	1,000	1,175	322
	19. Burners	0	14	0	0	14	11
Decarbonising industry	20. Hydrogen in industry	0	63	300	924	1,287	408
Horizontal actions support hydrogen development	21. Supply chain development	24	98	240	400	762	318
	22. Cross-cutting issues	24	147	0	0	171	134
		222	**959**	**1,420**	**5,969**	**8,732**	**2,984**