

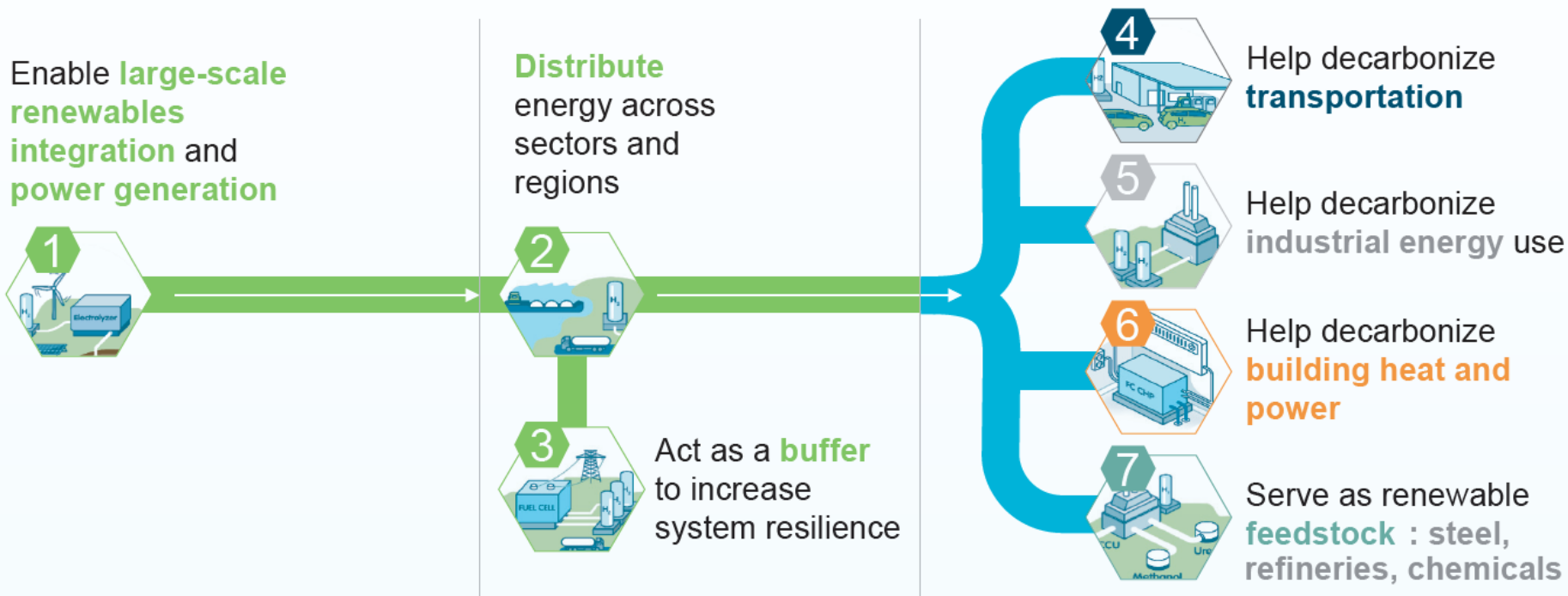
**HYDROGEN,
ENABLING A ZERO
EMISSION EUROPE**

**TECHNOLOGY ROADMAPS
SUMMARY 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

Enable the renewable energy system —————> Decarbonize 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 CO₂ 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.

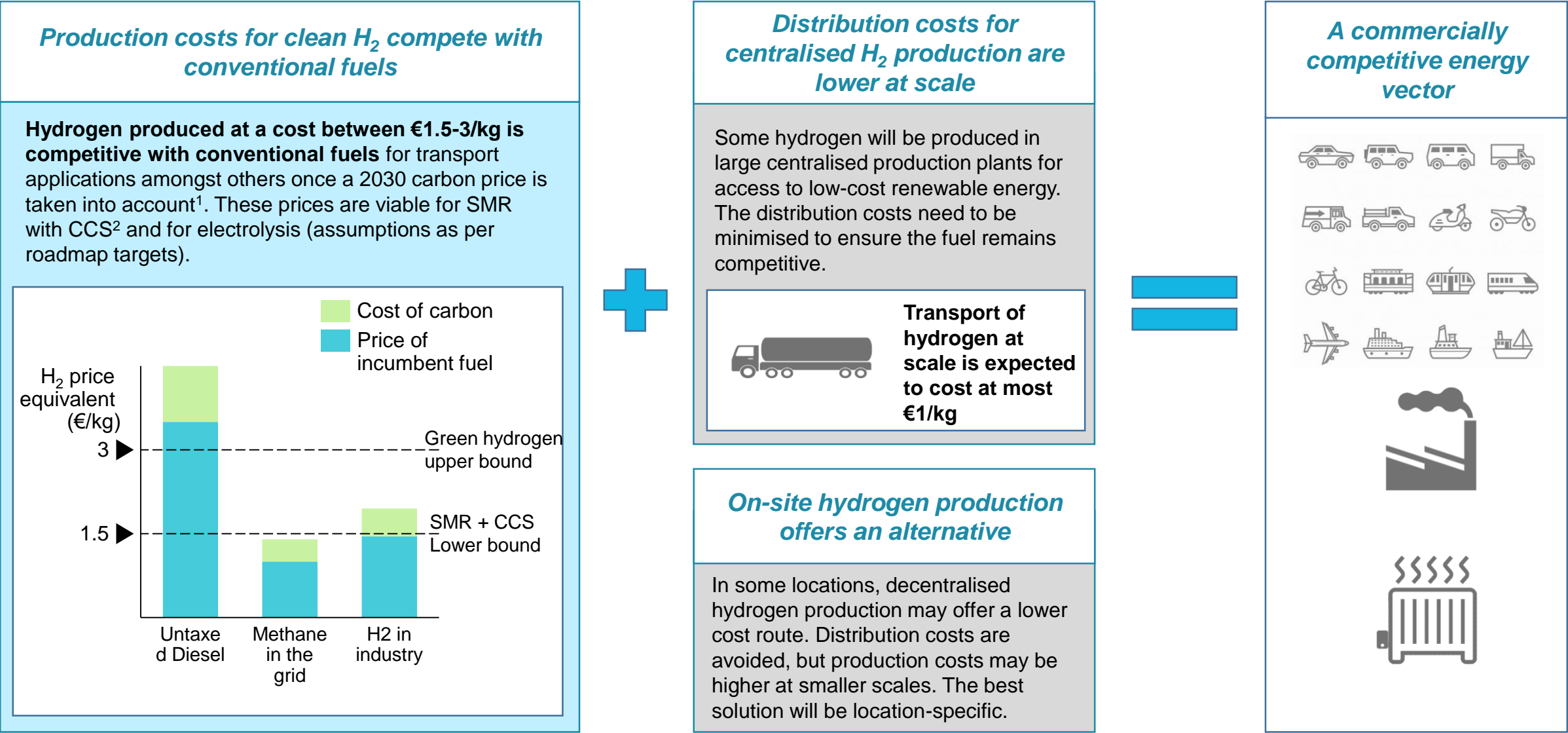
7. Hydrogen is actively displacing fossil fuels as a clean energy input into a wide range of industrial processes:

- 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...**



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 H₂ cost of €5/kg.

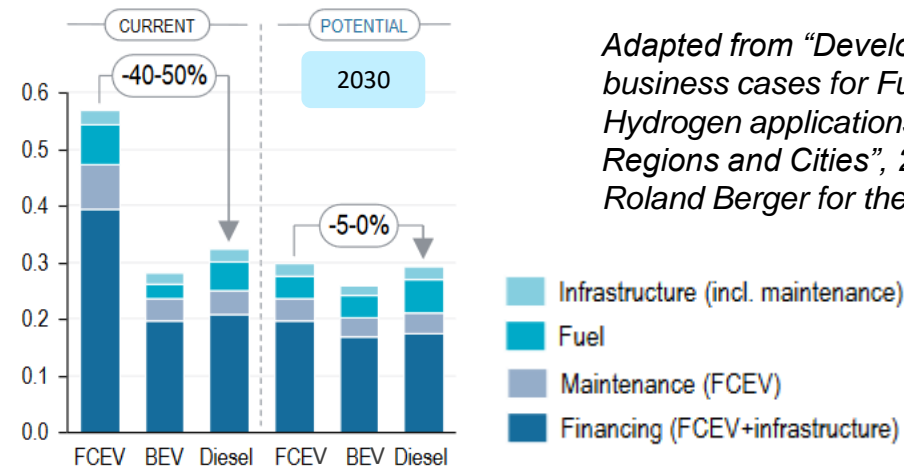


Industry and gas – clean H₂ as a feedstock can reach parity with fossil-based inputs once the cost of carbon is included.



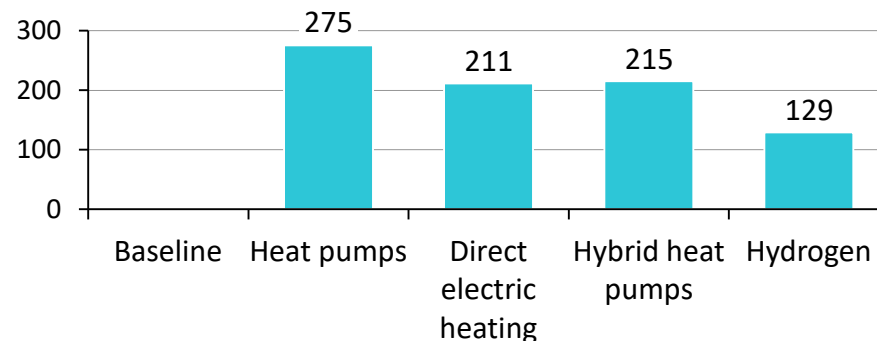
Buildings – fuel cell CHPs are high efficiency and can reduce energy use and associated CO₂ emissions even in advance of grid decarbonisation. Hydrogen may be the lowest cost way to decarbonise the gas grid.

Estimated annualised Total Cost of Ownership (TCO) [ct/km], 2017 prices



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

Net cost of CO₂ abatement for different options for decarbonising heat
€/tonne CO₂



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

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 CO₂ 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**

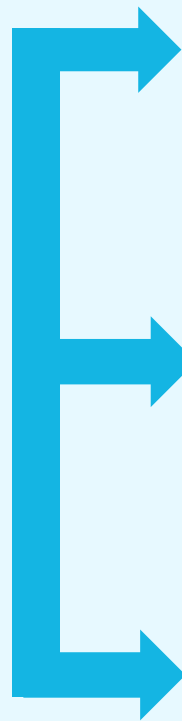
1. Clean Energy for all Europeans is being provided by a diversity of clean hydrogen production routes. Clean hydrogen provides 8% of required emissions reductions between now and 2030, and 25% by 2050.



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.
 - CO₂ 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 MtCO₂ 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**.

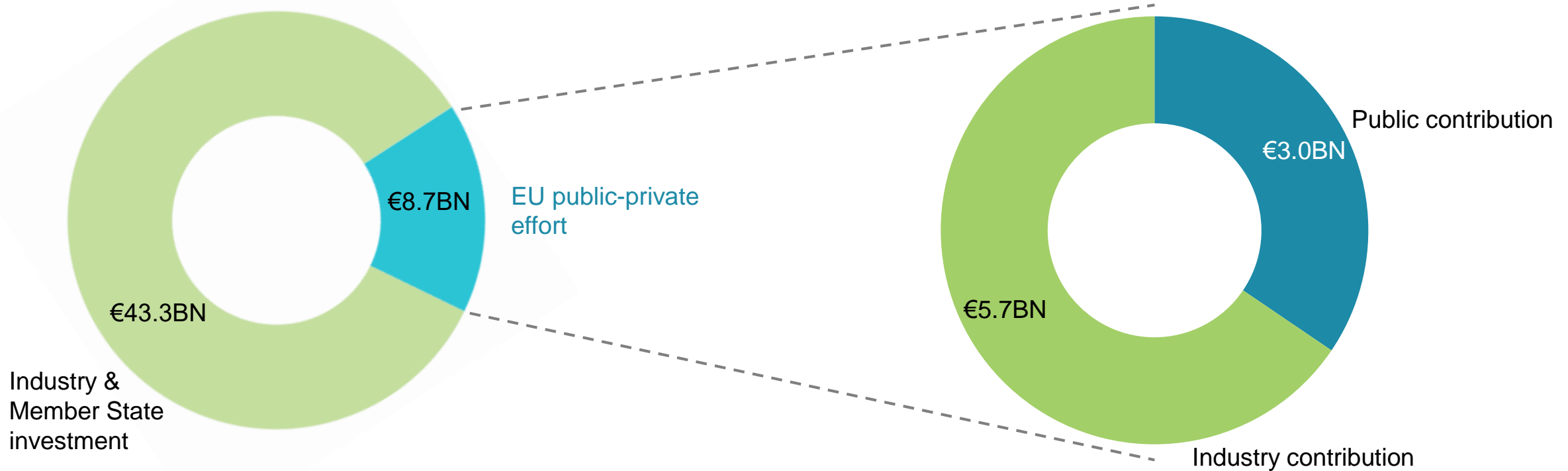
7. Clean hydrogen in industry is essential to achieving deep decarbonisation of industry, contributing to the aims of the Emissions Trading Directive and sectoral agreements on decarbonisation.



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 €52BN¹, mostly funded by Industry contributions & Member State investment

Total investment managed by Europe 2021-2027

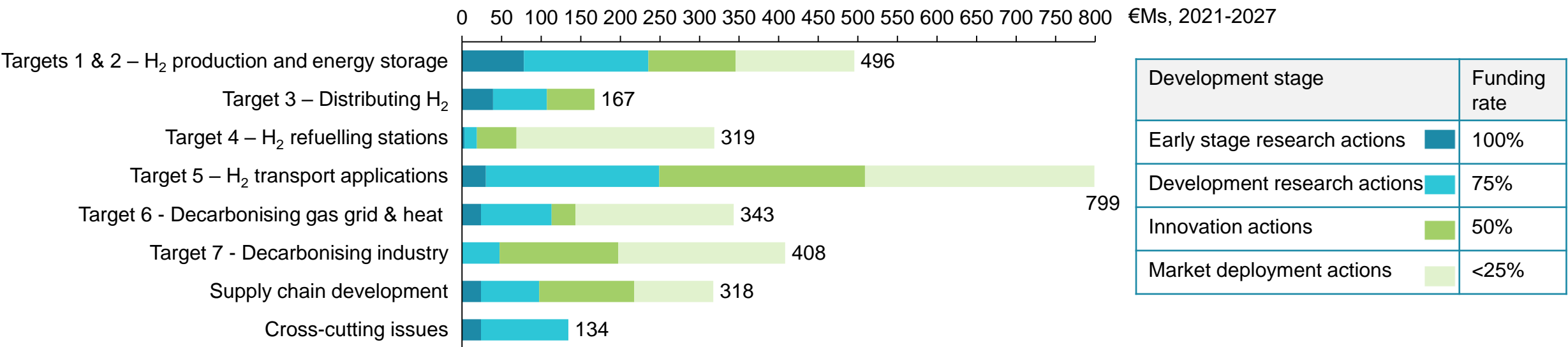


The €8.7BN programme proposed here will be 65% funded by industry and 35% supported by public contributions.

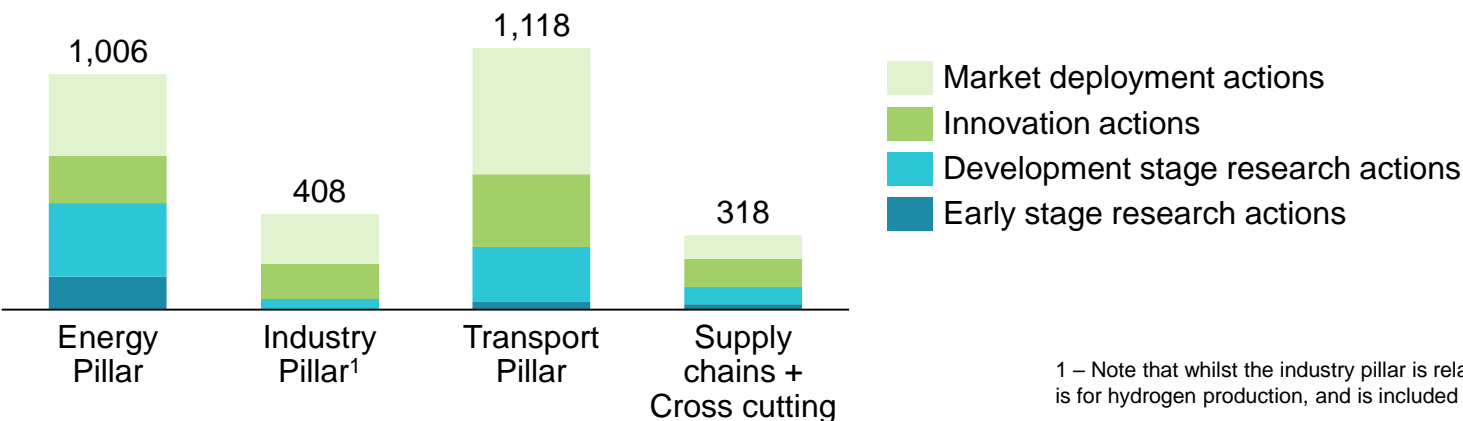
There is a strong case for public funding to support development of hydrogen as an element *sine qua non* the energy transition cannot successfully achieve the deep decarbonisation requirement to meet ambitious decarbonisation targets.

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



Total funding proposed for each core pillar of the programme

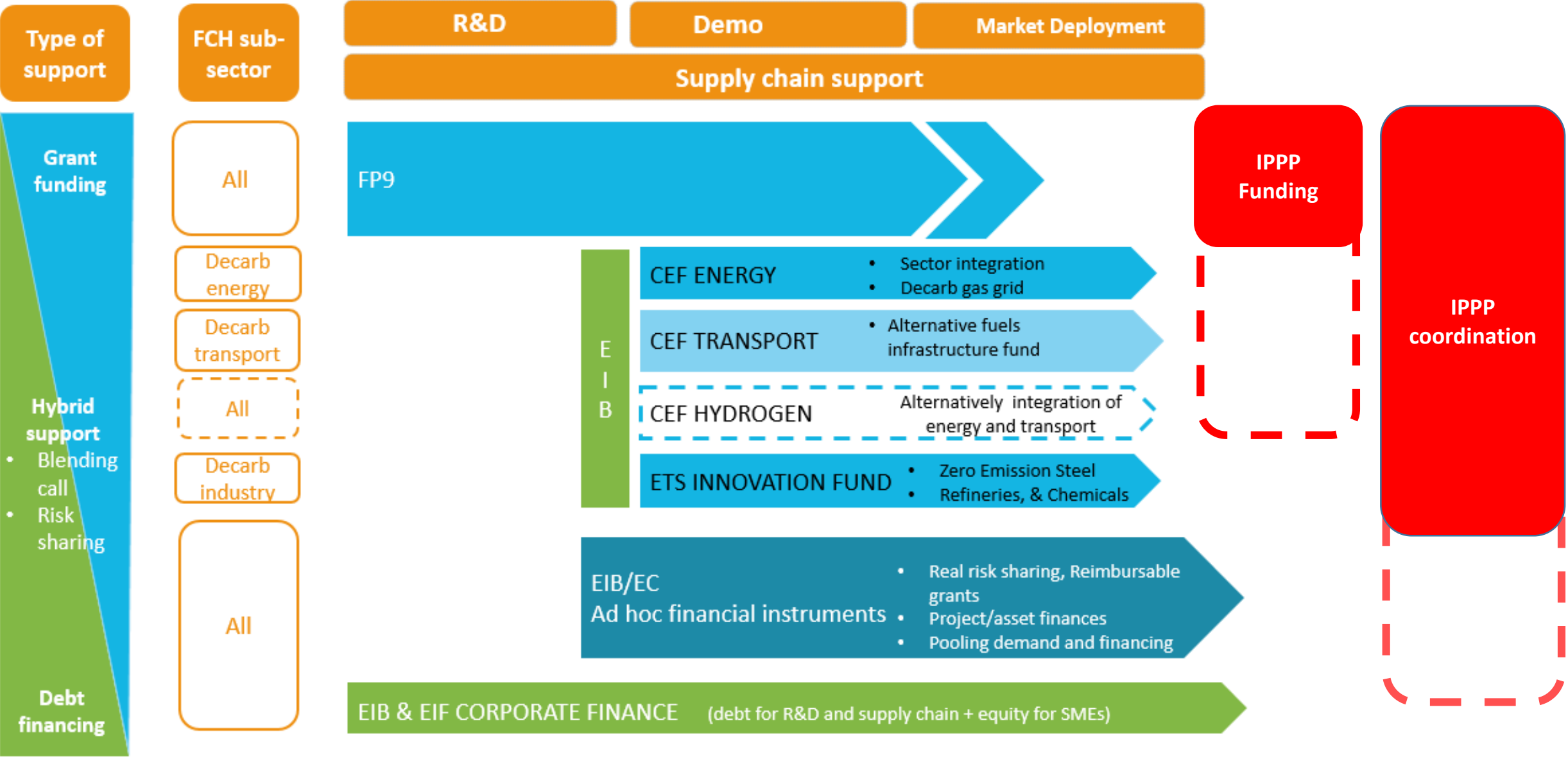


Three core pillars will be supported:

- **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)

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

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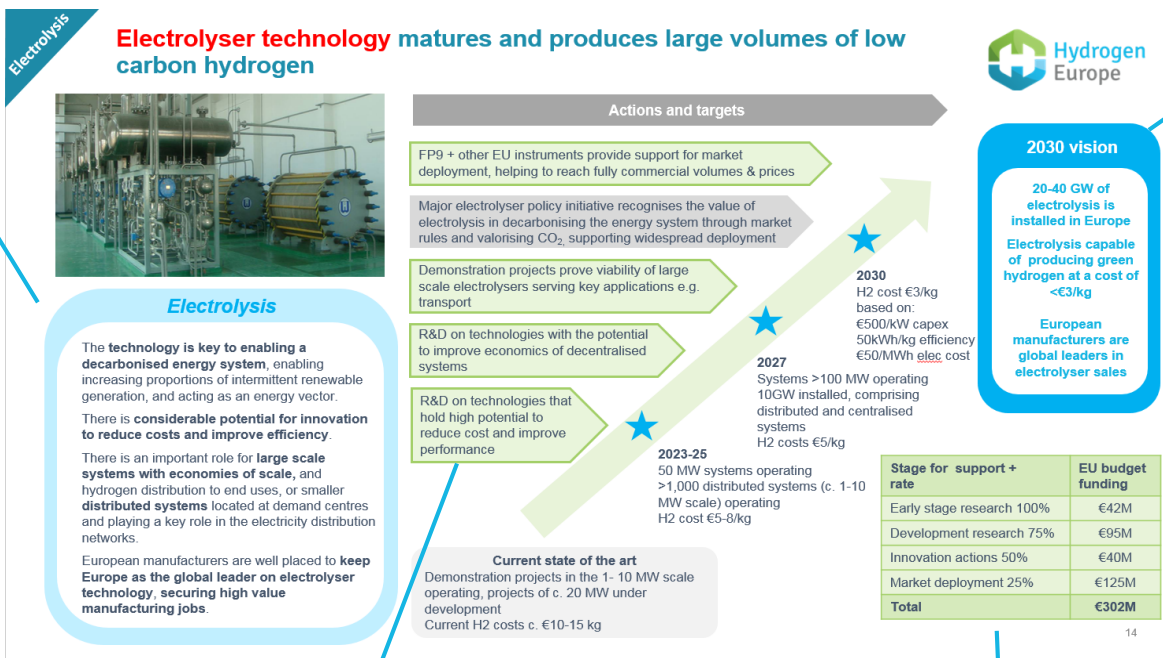
The **summary technology roadmaps** aim to show the key steps to achieve the vision, and the role for EU budget support

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 Hincio for the FCH-JU, 2015.

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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 CO₂, supporting widespread deployment.

Demonstration projects prove viability of large scale electrolyzers 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.

2023-25
50 MW systems operational.
>1,000 distributed systems (c. 1-10 MW scale) operational.
H₂ cost €5-8/kg.

2027
Systems >100 MW operational.
10GW installed, comprising distributed and centralised systems.
H₂ costs €5/kg.

2030
H₂ 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.

Current state of the art

Demonstration projects in the 1- 10 MW scale operational.
Projects of c. 20 MW under development.
Current H₂ costs c. €10-15 kg.

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

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



Other modes of H₂ production

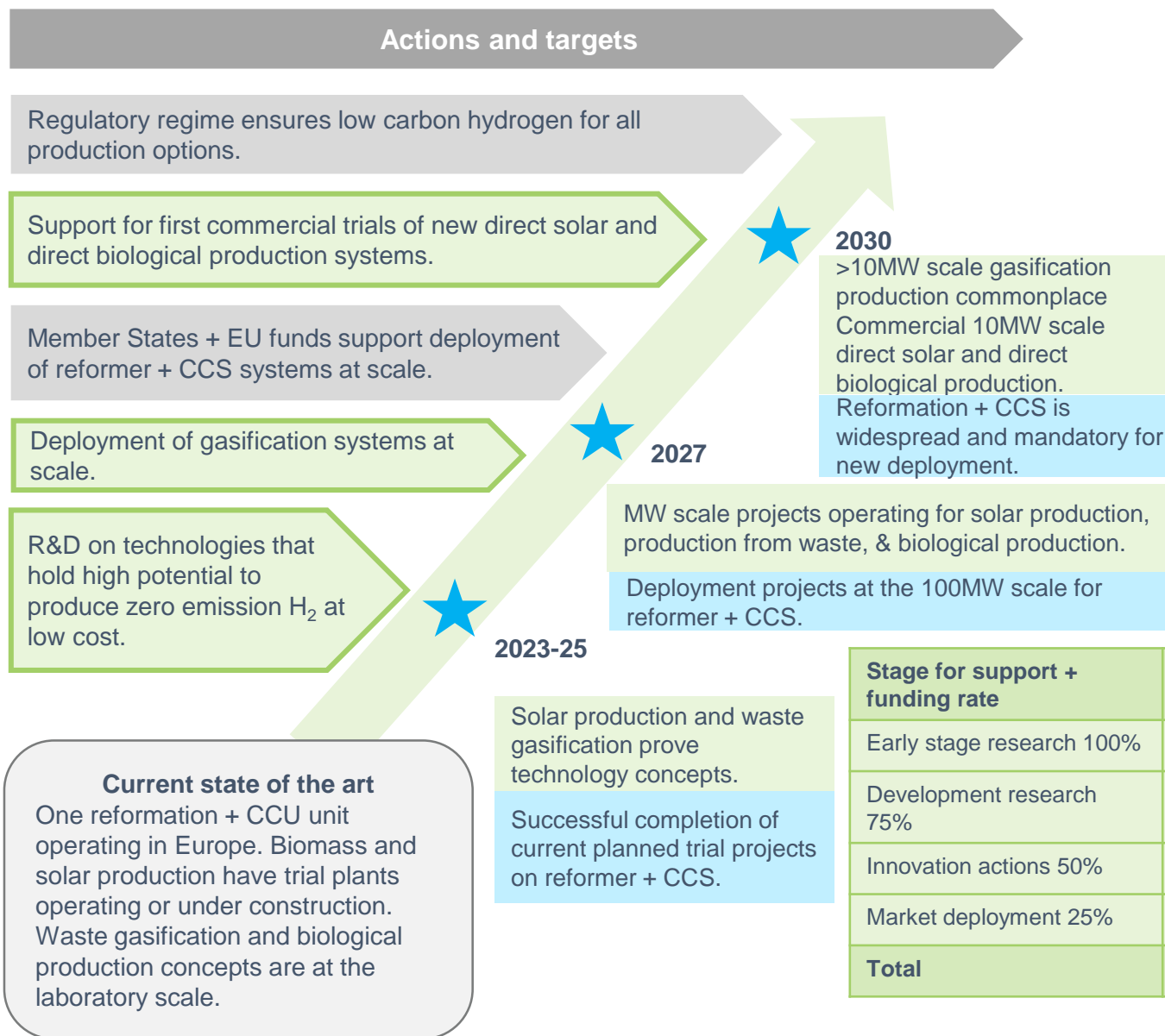
There are a range of H₂ production options which could be environmentally neutral or even positive.

New technologies (focus of this programme):

Producing H₂ 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).



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

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

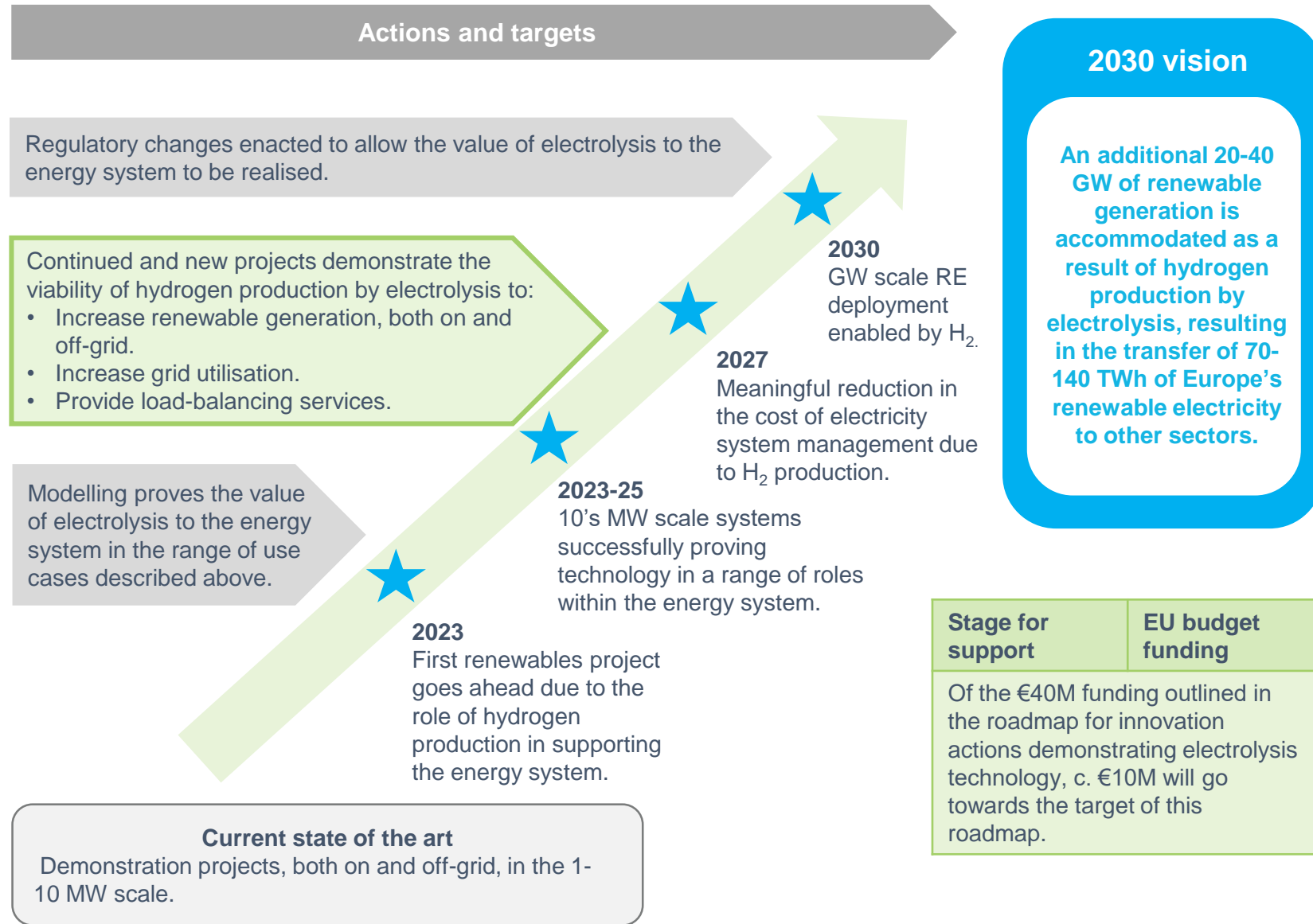


Electrolysis in the energy system

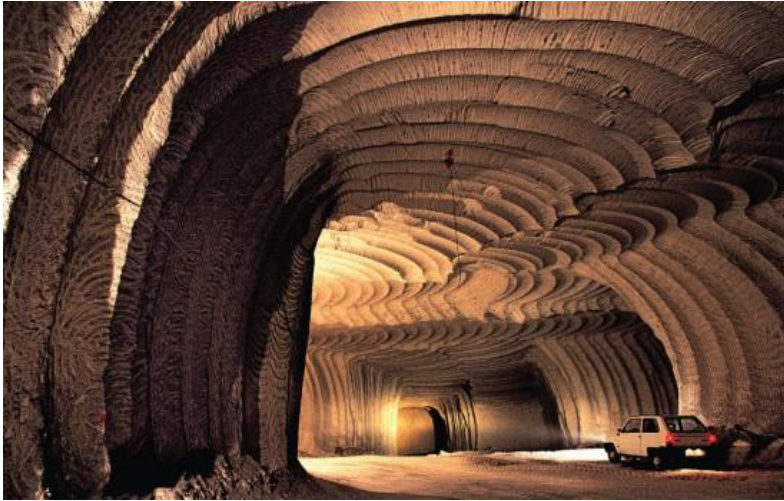
H₂ production via electrolysis offers unique advantages: it can **store energy for long periods** (e.g. in gas grids or in underground storage), and also **transfer these clean electrons into other sectors**. H₂ offers a locally produced clean energy vector for all applications, **ensuring security of 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.



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



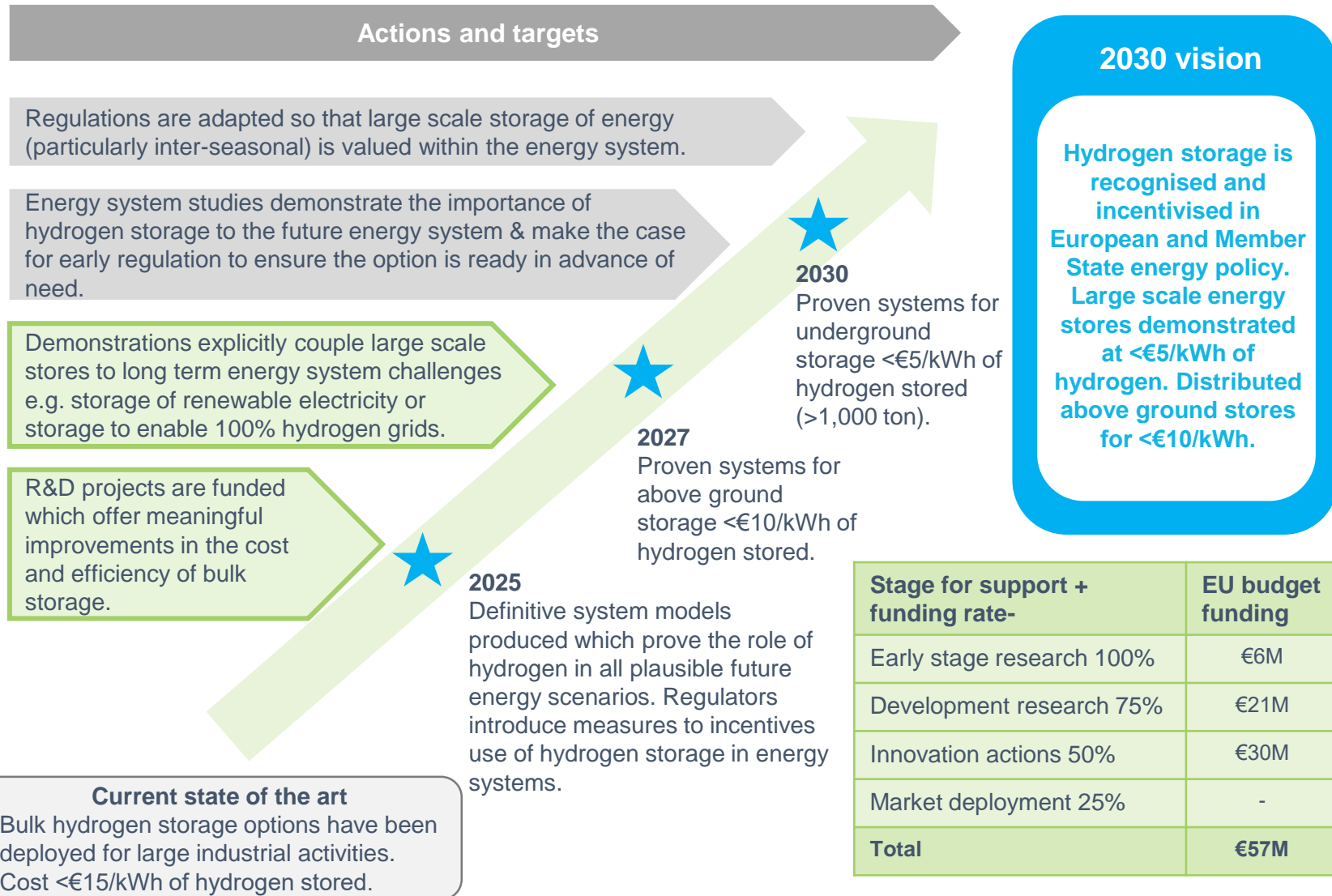
Bulk hydrogen storage

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 stores¹.



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.

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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 H₂ 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

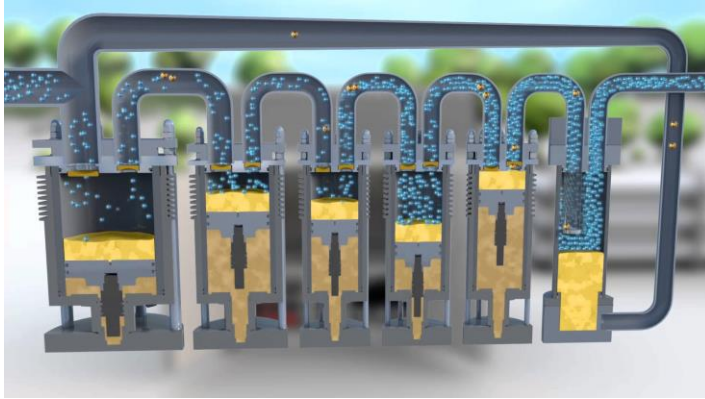
- Existing logistics e.g. road trailers carrying gaseous hydrogen will have reduced in cost. A parallel distribution infrastructure, based on liquid hydrogen or hydrogen carriers will start to appear to transport large quantities of hydrogen across Europe by ship and rail as well as road.
- Hydrogen 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

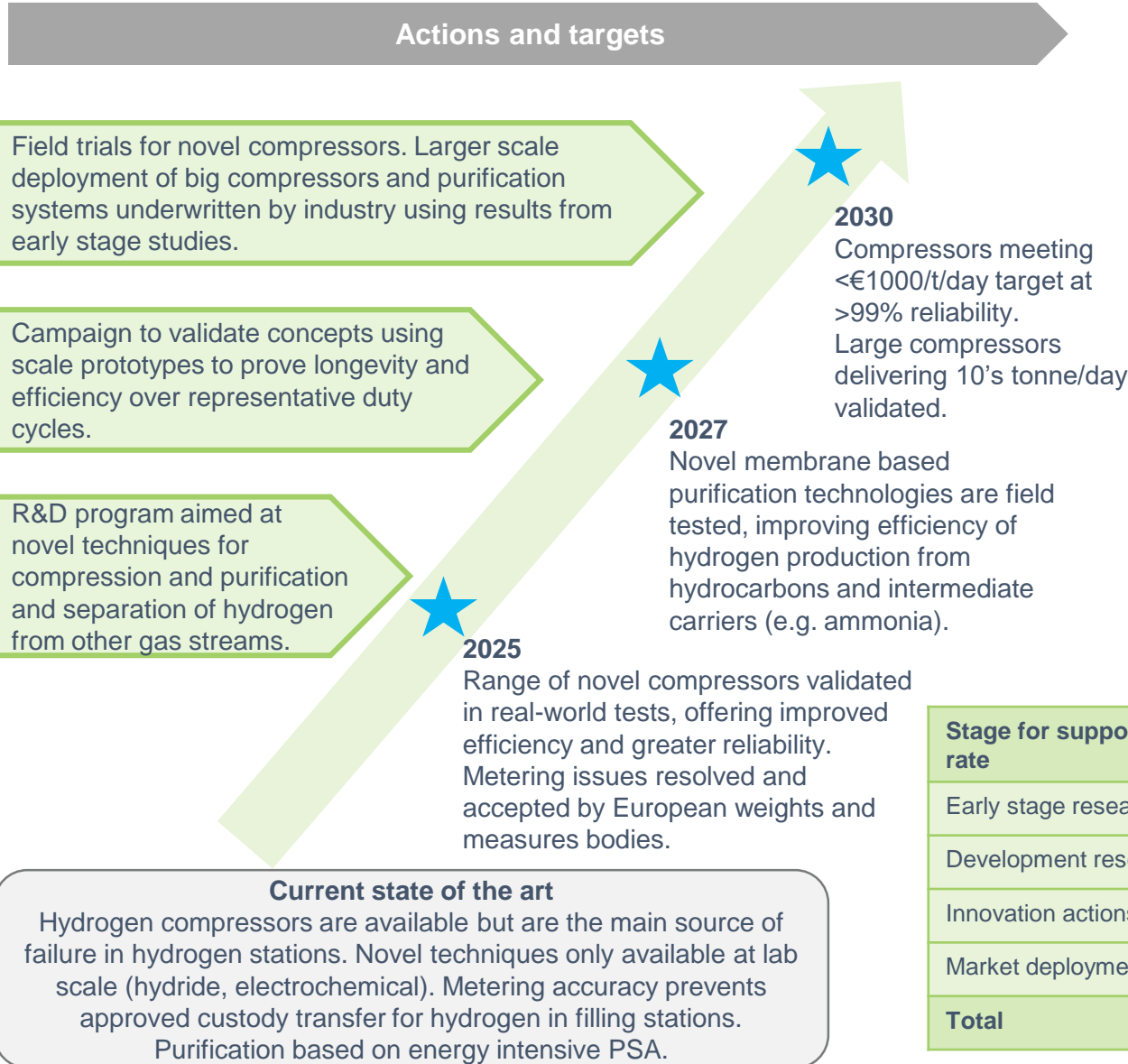


Distribution key technologies

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.



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.

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

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 H₂ poses unique challenges due to its low volumetric density.

A mature market has already been established in the road transport of compressed gaseous H₂.

However, **H₂ transport remains limited by high costs and geographical distance.**

To improve large-scale H₂ distribution, key focus areas for development are **high pressure tube trailers, liquid H₂ storage and H₂ distribution via pipelines¹.**

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 H₂ transport to distribute large volumes of H₂ over both short and long distances, driven by demand for hydrogen.

Projects to optimise existing technologies (e.g. reduce boil-off from liquid H₂ and liquid H₂ 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 H₂ mean optimised road (and where needed ship) networks are developing for liquid H₂.

2030

H₂ pipelines have expanded and H₂ is extracted from natural gas blends at HRS.

2030 vision

H₂ transport costs < €1/kg across all transportation methods. Road transport networks offer efficient solutions to deliver hydrogen across Europe. New large H₂ pipeline networks are serving hydrogen energy users with low carbon hydrogen.

Current state of the art

Multiple methods for delivering H₂ are available but at high cost. Novel concepts for pressurised hydrogen transport are maturing (1,100kg of H₂ at 500-bar on tube trailers), liquid H₂ transport and H₂ 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

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.

2023-25

Liquid carriers have been developed and demonstrate charge/discharge efficiency above 88% and discharge energy use below 5 kWh/kg H₂.

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.

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.

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

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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 components¹ (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.

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.

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.

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.

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

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

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

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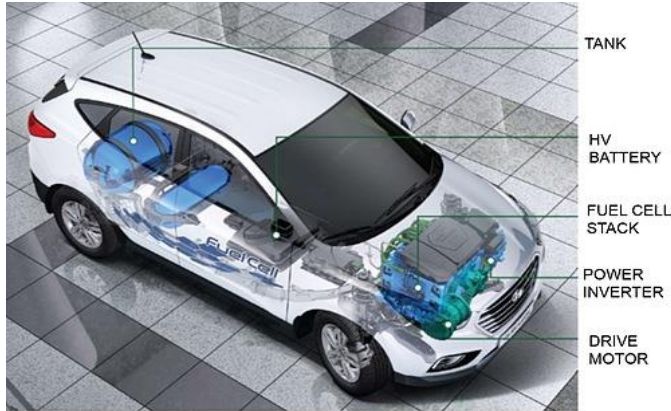
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Fuel cell vehicles are produced at a price equivalent to other vehicle types: **technology building blocks**



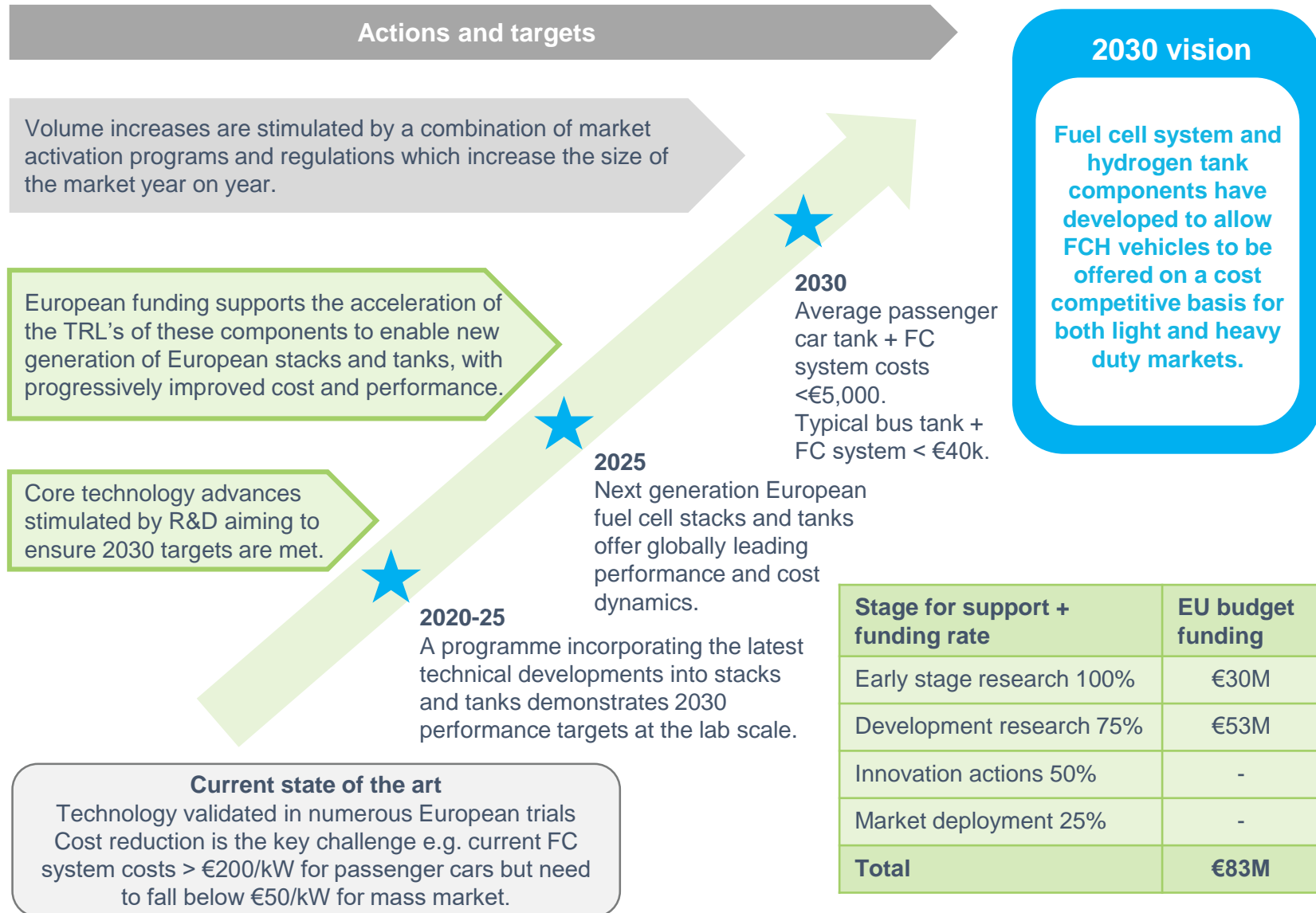
Technology building blocks

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.



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 H₂ 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).

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.

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.

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

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

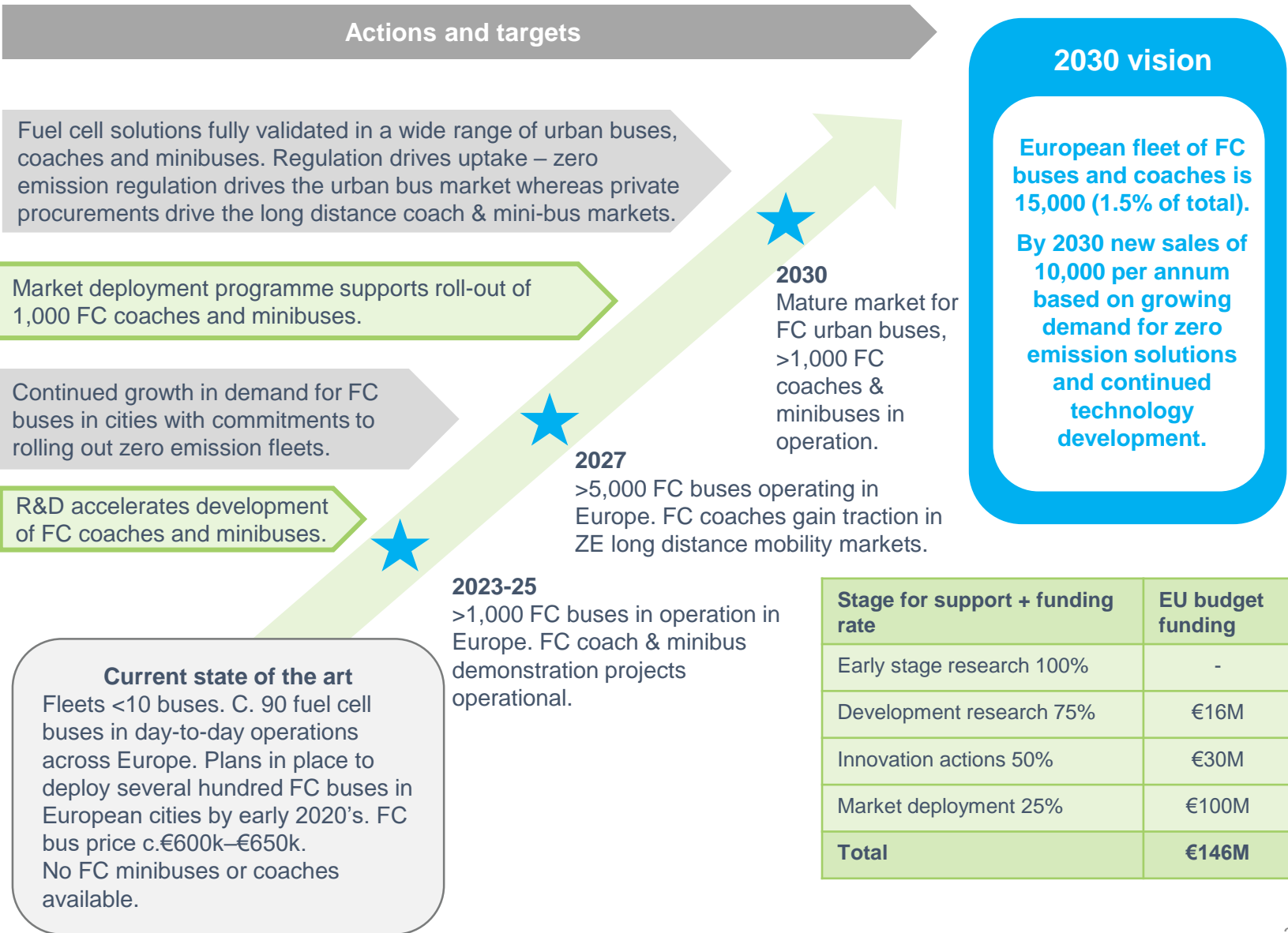


Fuel cell buses

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.



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

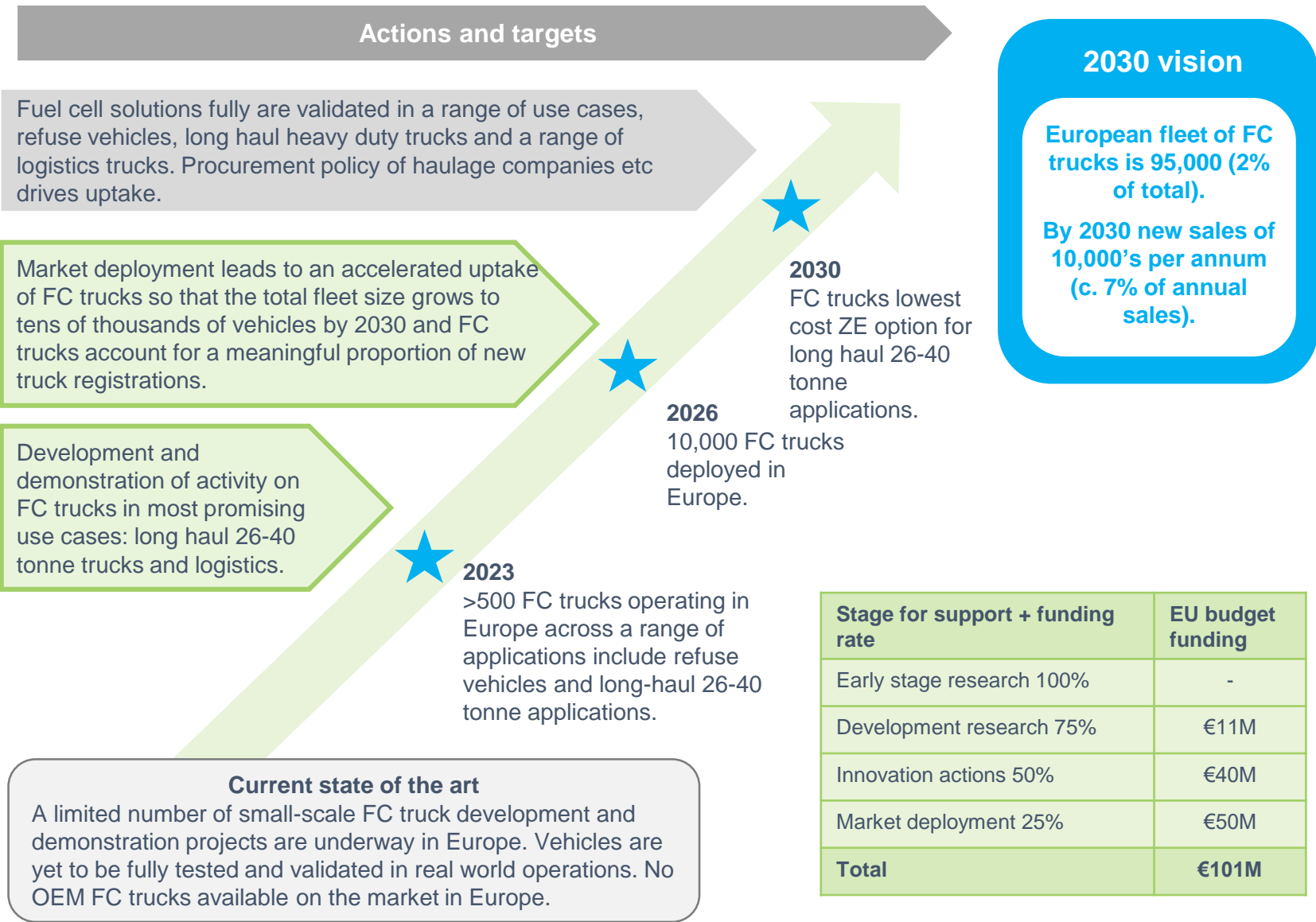


Fuel cell trucks

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.



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.

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.

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.

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

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.

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

2027
H₂ drivetrain <150% diesel capex.
>500 FCH trains operating.

2030
1 in 10 trains sold for non-electrified railways are powered by H₂.

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.

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).

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

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 H₂ 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 H₂ 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 H₂ 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.

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

Current state of the art

FCs and H₂ 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.

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

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 H₂ 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 H₂ 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

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

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6 Hydrogen meets demands for heat and power

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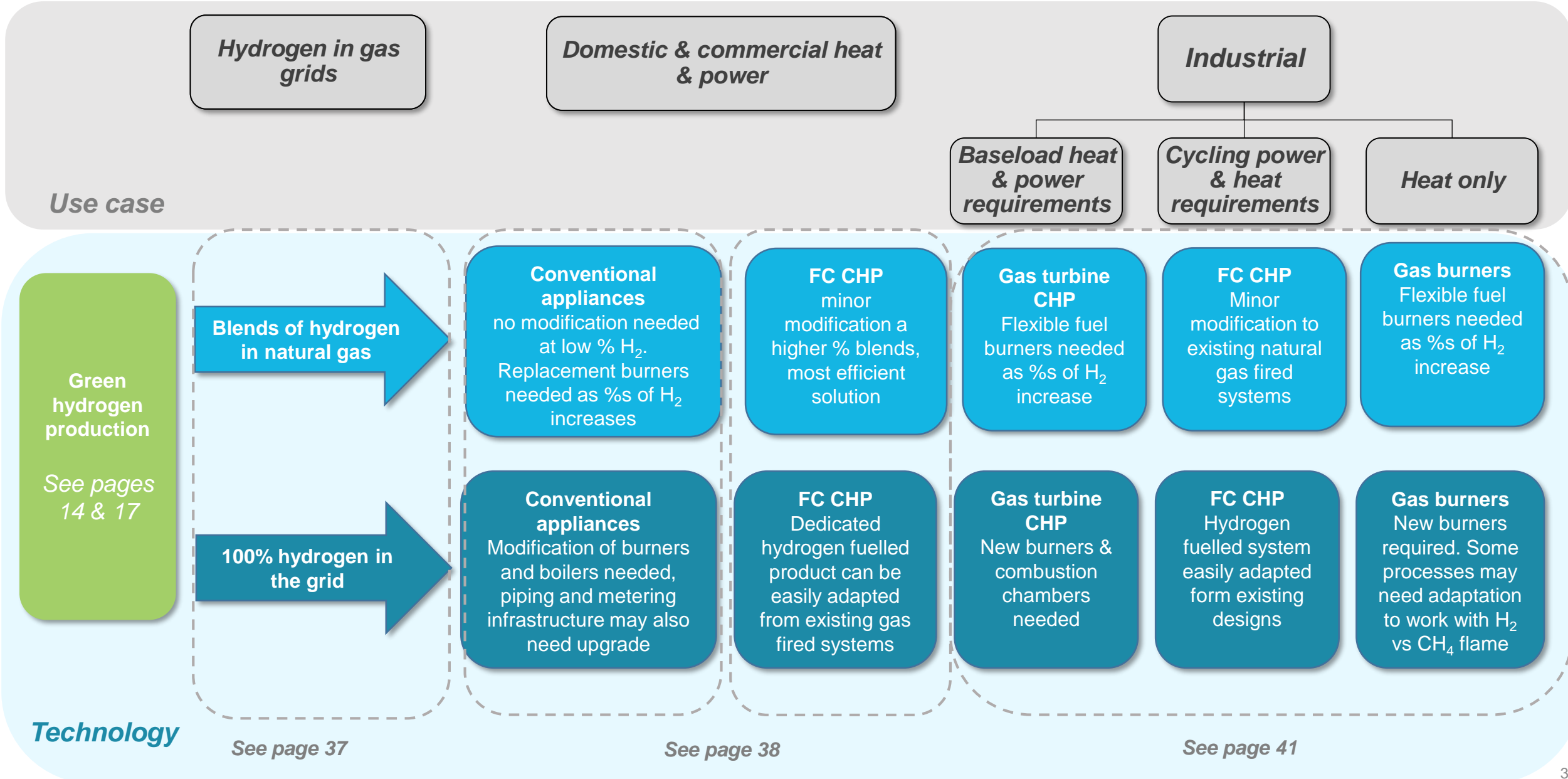
7 Hydrogen decarbonises industry

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8 Horizontal activities support the development of hydrogen

Supply chains & other cross cutting issues	Page 43
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The following roadmaps cover a number of **related technologies for hydrogen in gas grids & for heat & power** in a range of use cases



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 H₂ 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 21) would allow a 100% hydrogen grid to deliver fuel for transport as well as heating.

Innovations are needed to improve metering accuracy and H₂ 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 H₂ 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 H₂ – CH₄ blends and 100% hydrogen in gas grids.

Metering developments needed to accommodate variable volumes of H₂ in the gas grid.

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 H₂ is blended into the natural gas grid.

>10 EU regions implementing 100% H₂ for residential & industrial sectors.

Clean H₂ use for heat saves 7 MtCO₂/pa.

Current state of the art

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

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

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



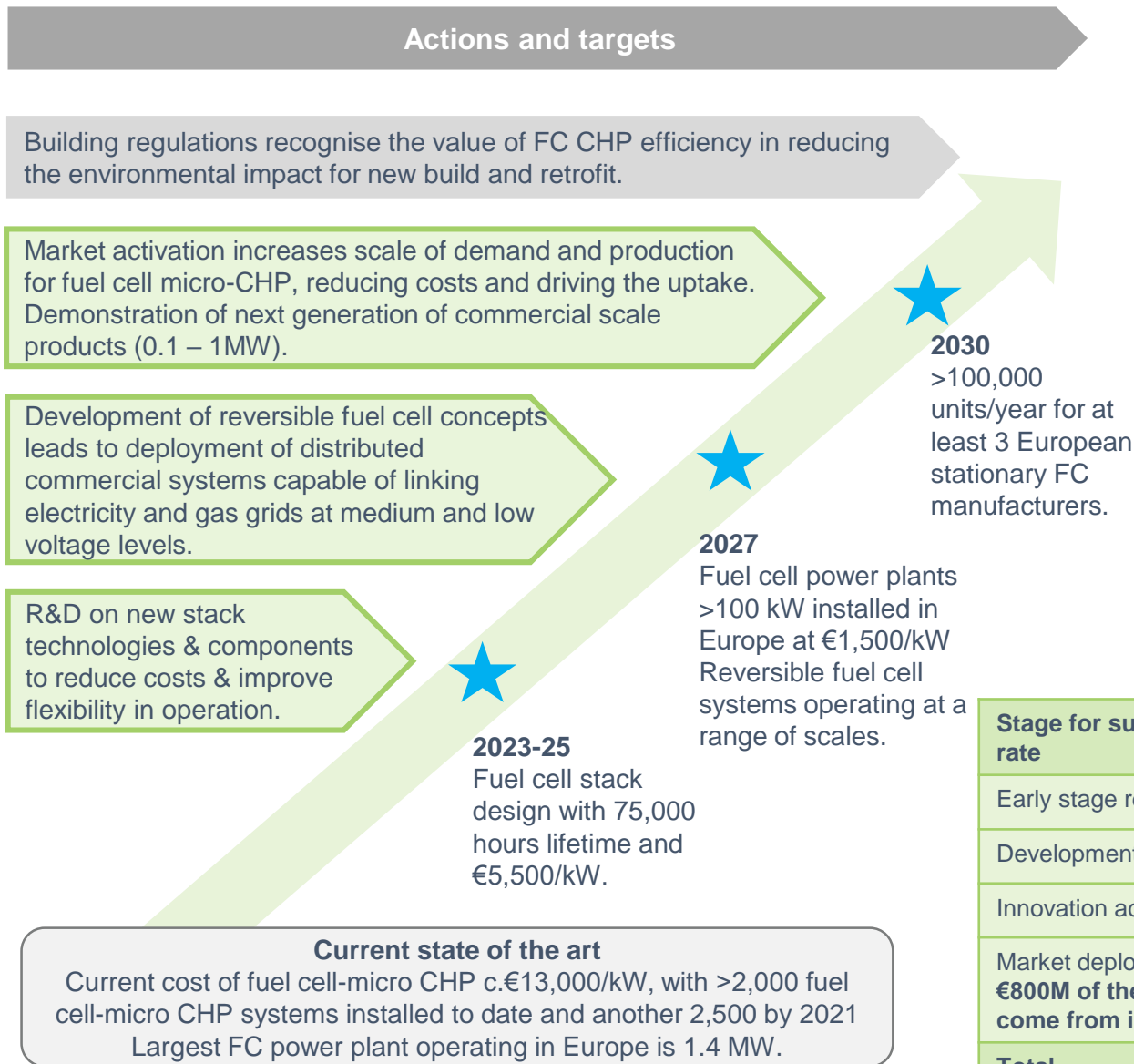
Stationary fuel cells

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 CO₂ savings required from energy use in buildings.**

As the **gas grid becomes decarbonised**, stationary fuel cells produce increasingly low CO₂ 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.**



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

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 H₂ burners.

2023

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

2027

Flexible fuel and full H₂ 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% H₂ 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.

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

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8 Horizontal activities support the development of hydrogen

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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 industry¹.

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 CO₂ (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

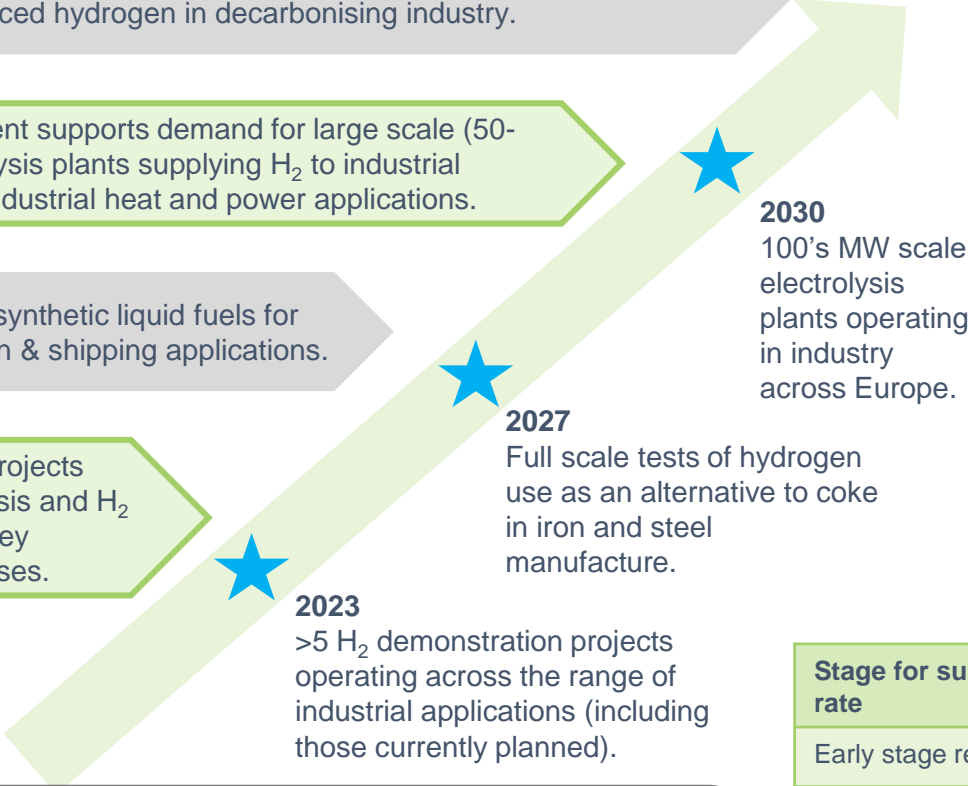
Actions and targets

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 H₂ to industrial processes and industrial heat and power applications.

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

Demonstration projects proving electrolysis and H₂ for heat across key industrial processes.



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 MtCO₂pa.

Use of H₂ 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

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

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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

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 H₂.
- **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	€74M
Innovation	€120M
Market deployment	€100M
Total	€318M



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
	9. Technology building blocks	30	70	0	0	100	83
	10. Cars, 2-3 wheelers, vans	0	14	40	500	554	106
Fuel cell vehicles (road, rail, ship) are competitively priced	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