CLEAN HYDROGEN MISSION

DISCUSSION PAPER

Launched at COP 26 for public consultation and open for responses

Mission Innovation

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Preface

Mission Innovation is a global initiative of 22 countries and the European Commission (on behalf of the European Union) to reinvigorate and accelerate global clean energy innovation, achieve performance breakthroughs and cost reductions, and provide widely affordable and reliable clean energy solutions.

On 2 June, the Mission Innovation Clean Hydrogen Mission – a new global coalition to support the development of the clean hydrogen economy – was launched at the 6th Mission Innovation (MI) Ministerial meeting, hosted by Chile. The goal of the Clean Hydrogen Mission ('the Mission') is to reduce the costs of clean hydrogen to the end user to USD 2/kilogram by 2030, with certain applications and locations becoming competitive before others. This will be achieved through both innovation and by delivering at least 100 large-scale integrated hydrogen "valleys" worldwide. These valleys or clusters would involve large scale hydrogen production, infrastructure and end use applications and can pave the way for economies of scale and commercial viability, reducing cost and enabling market adoption. The MI Clean Hydrogen Mission launched for an initial period of five years and, depending on progress, may be extended for a further five years to support the delivery of its key objectives by 2030.

The Mission will build a dynamic and ambitious alliance between countries, businesses, investors, and research institutes to accelerate innovation on clean hydrogen. This will include international collaboration on research, development, and innovation to further develop hydrogen valleys and accelerate building a global clean hydrogen economy. As the Mission is established, a key priority is to avoid duplication and to leverage the strengths of other global hydrogen partnerships.

This Discussion Paper provides an overview of proposed key innovation priorities and areas of focus for the Mission's Action Plan, which will be developed and adopted in 2022. These are based on member and stakeholder feedback (Appendix 1), preliminary findings on hydrogen technology innovation by the Commonwealth Scientific and Industrial Research Organisation (CSIRO, Appendix 2), as well as an initial assessment of key barriers and strategies to address them conducted by Carbon Trust (Appendix 3).

The key priorities and areas of focus are set out against the Mission's three key pillars of activity, and the document ends with a series of potential Mission actions for discussion. Readers of this Discussion Paper are invited to contribute to subsequent revisions and share their feedback and ideas via EC-MI-CLEAN-HYDROGEN-MISSION@ec.europa.eu (submission close 9 December 2021). The final version of the paper will build on the comments received by MI members, the broader stakeholder community, and wider outcomes of COP26.

1. Introduction and background

Clean hydrogen[i] has the potential to decarbonise hard to abate sectors, such as heavy industry and transport, which are responsible for approximately 60% of global emissions[ii]. As countries look to options to reduce their emissions, hydrogen is expected to be a good complement to electrification for decarbonisation of certain applications. For example, studies have found that the estimated overall technical potential for hydrogen may be higher than electricity for decarbonising industrial processes[iii]. There are also benefits from clean hydrogen beyond decarbonisation including increasing energy resilience, helping to unlock the full potential of renewable energy through its improved integration into existing systems, and enhancing energy system flexibility. It is expected that the adoption of clean hydrogen will be a key contributor in efforts to stay within the 1.5°C limit set out by the Paris Agreement with a critical role in the transition to Net Zero energy systems.

Despite being an important decarbonisation pathway for hard-to-abate sectors, clean hydrogen is currently not cost competitive. The cost of clean hydrogen today, depending on specific regions, can be up to three times more expensive than hydrogen produced directly from fossil fuels. Clean hydrogen production methods, including from renewable energy via electrolysis, conversion of fossil fuels using gasification[1] and reformation[2] with carbon capture technologies, and many other existing and emerging technologies, differentially affect end-cost. The IEA (2021) analysis shows that countries have quite diverse visions on how clean hydrogen should be produced[iv]. Hydrogen production from electricity is

[1] Such as coal gasification or co-gasification with biomass/wastes
[2] Including steam methane reforming, autothermal reforming, and other processes

common to all strategies, in some cases being the preferred route in the long term. Some prioritise renewable power while others are less specific about the origin of the electricity (so long as it is low emissions in origin). While several governments have set a significant role for the production of hydrogen from fossil fuels with CCUS, others consider this option for only the short and medium term to reduce emissions from existing assets while supporting the parallel uptake of renewable hydrogen. Current production, use, and trade of clean hydrogen are not sufficiently scaled to address this cost differential. Cost reductions and further efficiencies are also needed in handling, transporting, and storing hydrogen to enable it to become competitive for various end use applications.

End-to-end cost represents the key tipping point[v] as a vital factor determining the scale of uptake of clean hydrogen. A report by the Hydrogen Council estimates the various break-even costs at which hydrogen application becomes cost competitive against low-carbon alternatives in given segments (Figure 1), showcasing the significant role hydrogen could play as an energy vector in the future energy mix. It estimates that a hydrogen production cost of 2.5 USD/kg could make hydrogen a cost-competitive decarbonisation option for around 8% of global energy demand by 2030, increasing to approximately 15% of global demand at a production cost of 1.8 USD/kg[vi].

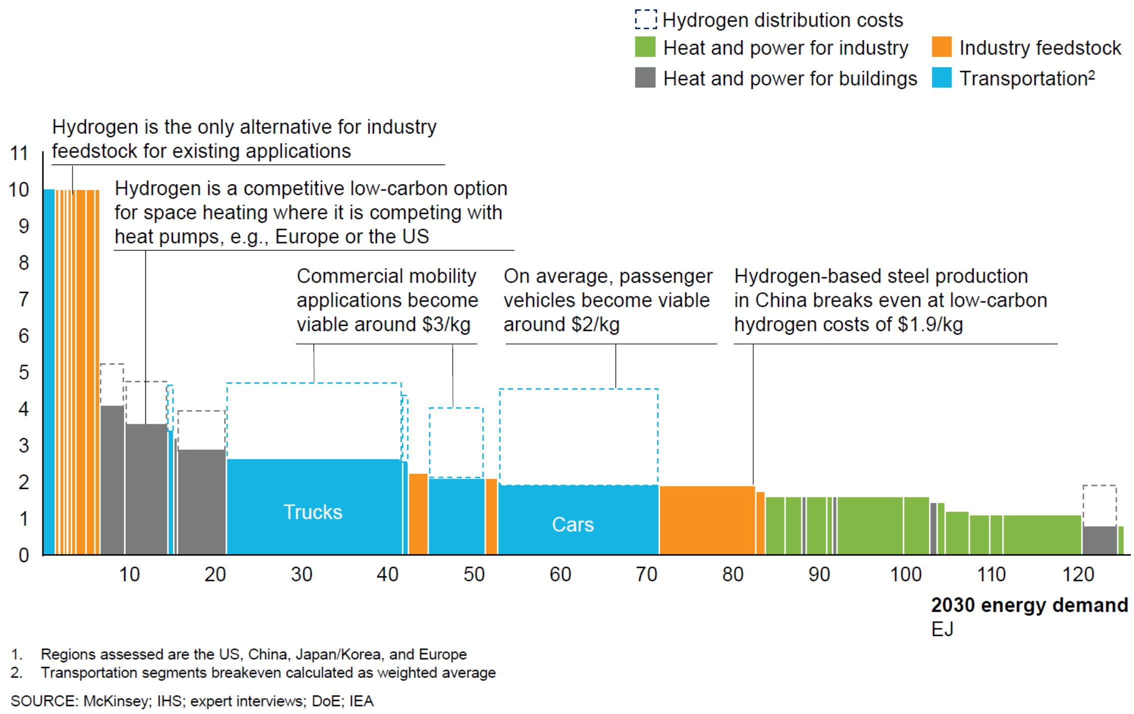


Figure 1. Breakeven hydrogen costs (USD/kg) at which hydrogen application becomes competitive against low-carbon alternative in a given segment (Source: Hydrogen Council (2020). *Path to Hydrogen Competitiveness.* [vii])

There is significant economic opportunity from a successful global hydrogen market. For example, Baker McKenzie's 2020 report estimates the hydrogen market to be worth USD 25 billion by 2030.[viii] The Hydrogen Council, a group of more than 100 global companies supporting hydrogen technologies, projects a potential 2.5 trillion USD in revenue and 30 million jobs worldwide by 2050 as a result of scaling up hydrogen technologies.[ix]

The Clean Hydrogen Mission seeks to stimulate innovation, knowledge exchange, and international cooperation, and will facilitate investment in specific areas of research, innovation, development, and demonstration to accelerate progress towards a global clean hydrogen economy. The Mission is technology neutral as to how clean hydrogen is produced and used, offering full flexibility and autonomy to identify target value chains.

For clean hydrogen, the end-to-end cost of USD 2/kg is considered by the Mission to be the tipping point in unleashing its potential to reduce global emissions, as this is the point when it starts to become cost-competitive with other energy

vectors in different industries across production, transportation, storage and end-use.

To facilitate the 2 USD/kg tipping point, the Mission organises its activity into three key pillars (Figure 2) targeting:

- the promotion of research, development and innovation, including within the areas of production, distribution and storage, and end-use applications (Pillar 1);
- demonstration of different production, storage and transportation methods by working with relevant stakeholders to explore sector coupling and creating concentrated demand centres through integrated clean hydrogen valleys (Pillar 2); and
- identifying 'demand-pull' efforts to diffuse and deploy solutions, facilitate the creation and dissemination of non-technological and non-commercial knowledge and create positive engagement from relevant stakeholders (Pillar 3).

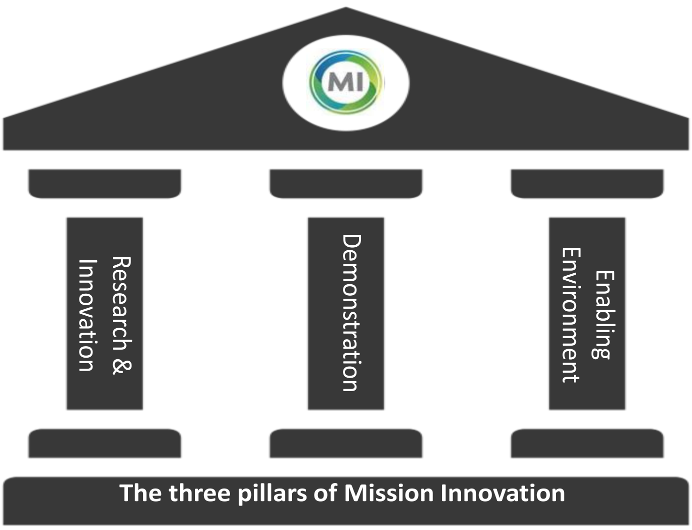


Figure 2: Clean Hydrogen Mission, 3 Pillar structure.

Consistent with other Missions, the structure includes a steering committee, mission director, other functional roles, and specific working groups within each pillar. For example, working groups under Pillar 1 include: Production; Distribution and Storage; and End Use Applications; a working group on clean hydrogen valleys is proposed under Pillar 2; and potential working groups on Policies and

Financing and Best practices & Lessons learned are proposed under Pillar 3. As priorities are further defined and as work streams are accomplished, working groups may be created or disbanded as needed.

The Mission is actively working with its member countries, partner organisations, and initiatives towards the delivery of each of these objectives. An important early step has included independent research and international expert-level consultations to map the current clean hydrogen policy landscape and to gather an evidence-base of key R&I priorities and sector challenges needed for driving cost reductions. Some preliminary findings and analysis from this work are presented in this Discussion Paper. These initial efforts provide a closer look into the strategic drivers shaping the clean hydrogen policy across many parts of the globe.

It is important to highlight that this work is at an early stage of development. Further engagement will be undertaken in the following months to expand the evidence base and broaden the scope of the work. The initial analysis presented in this paper includes findings from research undertaken by Carbon Trust to identify R&I priorities (with a special focus on innovation needs in clean hydrogen production), inputs received from Member countries, and strategic stakeholder mapping by CSIRO.

This Discussion Paper also presents a list of innovation priorities and areas of potential action by the Mission. While various activities are recognised as early priorities for action, the Mission recognises that many more aspects of the hydrogen value chain will have a significant impact on reaching the tipping-point. Different regions may also have distinct regional R&I priorities.

The Mission recognises that different countries have varying levels of ambition and areas of focus, including the extent to which they may intend to import and export hydrogen.

The Mission seeks feedback on the priorities presented in this paper as a part of its consultation. These responses will serve to validate the initial findings and will be used to shape the delivery of activities after COP 26.

1.1 Global overview and strategic priorities of Clean Hydrogen

Reaching the 2 USD/kg tipping point for clean hydrogen to stimulate clean energy transitions across hard-to-abate sectors requires increased global efforts to grow scale and reduce cost along the value chain. The Mission is actively working with its members to build a dynamic, ambitious and delivery-focussed alliance between countries, corporations, investors and research institutes to accelerate innovation on clean hydrogen research.

To support the Mission's goal, MI members are committed to developing and implementing national hydrogen strategies for their countries. Over 30 countries, accounting for over 70% of global GDP, have either released or have in preparation national hydrogen-specific strategies, roadmaps, or similar documents. This underscores the global view that hydrogen is expected to play a key role in the decarbonisation pathways of many economies. The emergence of an increasing number of national strategies in recent years is depicted in Figure 3 below.

Figure 3: National hydrogen visions, strategies and roadmaps recently released[x]

Private sector project announcements mirror this activity by governments. In mid-2021, project announcements with total associated investment through 2030 estimated at US$500 billion were identified by the Hydrogen Council[xi], an increase of over US$100 billion since the beginning of 2021.

These projects cover the full spectrum of end uses – in exports, mobility, electricity generation, industry and heating. The imperatives woven into various policy documents and announcements focus in large part on hydrogen industry market

activation and continued technology development in driving the transition from emerging technology to commercial assets. A common theme is the critical importance of investment in Research, Development, and Innovation (RD&I) with a focus on reducing costs and other barriers to hydrogen technology deployment. RD&I including investment in technology development, skills, infrastructure, knowledge generation and sharing and stakeholder engagement will be vital to bringing costs down and for driving technological breakthroughs.

Enhanced levels of ambition will be needed to support and carry out pioneering RD&I into a more competitive end-to-end clean hydrogen value chain and infrastructure. The 3-pillar structure of this Mission (figure 2) was designed to tackle the barriers that currently limit the scale-up required for achieving cost-competitiveness. By stimulating knowledge exchange and international cooperation the Mission seeks to facilitate the required innovations and support relevant industries and business towards a global clean hydrogen economy. The knowledge base being gathered through the ongoing consultations is an important step in this direction.

2. Clean Hydrogen research, demonstration, and innovation highlights and priorities

To maximize near term impact, RD&I actions that support hydrogen technology deployment across diverse industry value chains have been identified by several countries (Figure 4).

A recent report from Australia's Commonwealth Scientific and Industrial Research Organisation, CSIRO, examined these key RD&I themes[xii] (*Hydrogen research, development, and innovation*, 2021, Appendix 2) through the lens of technology deployment challenges and opportunities. The findings may be summarised as:

- **Significant reductions in clean hydrogen production costs over the course of this decade are pivotal to successful deployment**. Key hydrogen production RD&I priorities include development of low-cost, large-scale electrolyser manufacturing approaches, and, for countries pursuing blue hydrogen production pathways,

development of hydrogen focussed CO2 capture technologies and geological CO2 storage resources.

- **Reaching full global supply chain development requires large-scale, low-cost hydrogen storage and distribution systems, and supporting infrastructure**.
  RD&I in this area includes:
  - Efficient conversion and reconversion to and from derivative hydrogen carriers and improved compression and liquefaction technologies, which can help to reduce the costs for hydrogen storage, distribution and dispensing.
  - Optimising large hydrogen storage and distribution infrastructure between production facilities and loading sites/ports, including through new underground hydrogen storage approaches will also require further work.
  - Development of direct use approaches for hydrogen carriers such as ammonia and methanol in applications such as power generation and chemicals production can also improve roundtrip efficiencies through reduction in energy penalties resulting from reconversion to hydrogen.
- **RD&I-driven improvements in fuel cell technology integration and refuelling infrastructure, to support mobility applications targeted for initial deployment (e.g. heavy road transport);** RD&I efforts will also be required to support the longer-term use of hydrogen and hydrogen-based fuels in marine and aviation applications.
- **Substitution and use of clean hydrogen as a fuel and chemical feedstock in industrial processes (e.g. ammonia, chemicals production, and steel making). This will be a key driver of hydrogen demand.** Near term 'low hanging fruit' opportunities lie in RD&I, which allows clean hydrogen to replace unabated hydrogen in existing processes, including in ammonia production and petroleum refining. Other hard-to-abate industrial processes require sustained RD&I efforts to allow clean hydrogen to displace incumbent fossil fuels.
- **Clean hydrogen substitution in domestic and industrial gas uses through blended or potential use of 100% hydrogen in gas networks**: This represents a potentially large scale early deployment opportunity for clean hydrogen use, but requires RD&I actions focussed on understanding and mitigating impacts on pipeline and network materials, domestic and commercial appliances, and metering systems.

- **Clean Hydrogen in Electricity System support:** Clean Hydrogen can support faster uptake of renewables in electricity systems through 'balancing services'(matching electrolyser use to available renewable energy supply) and short-term network stability support as well as providing a means of seasonal energy storage (e.g. hydrogen produced from solar generation in summer (when output is high) can be stored for use in electricity generation in winter). This requires RD&I which delivers advances in large scale stationary fuel cell technology, turbine/engine and storage systems, and better understanding of grid integration issues.

- **National strategies highlight the importance of progressing 'cross-cutting' research activities in a time scale that is complementary to technology deployment and scale-up:** Cross-cutting research in fields such as the environment, social license and safety, policy and regulation, and modelling (including technoeconomic) is required across the whole hydrogen value chain (and applicable to all deployment RD&I themes noted above).

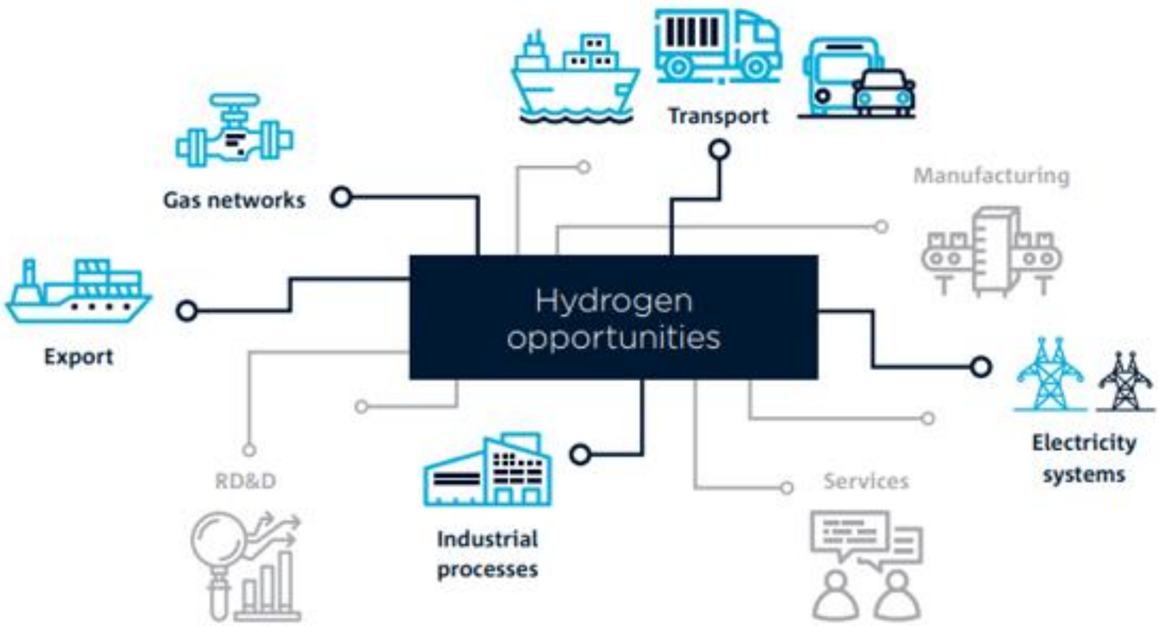


Figure 4: Hydrogen presents a decarbonisation opportunity across a diverse range of sectors (industrial sectors in blue and others in grey). Reproduced with permission from: *Hydrogen Research, Development and Demonstration: Priorities and Opportunities for Australia*, 2019.[xiii]

2.1 Global trends in hydrogen publications and patents

One of the distinguishing features of the Clean Hydrogen Mission, in comparison to other international partnerships, is its focus on research and innovation. Recognising the importance of, and need for, innovation breakthroughs, one of the first contributions to the Mission through the work of CSIRO was to assess the status of global research publications and patents related to hydrogen.

Global trends in hydrogen publications as a function of supply-chain area are shown in Figure 5 below and demonstrate a significant rise in global publication and patenting activity. Reflecting the importance of reducing the cost of hydrogen production, publications related to hydrogen production dominates (around 60,000 publications over the period 2010-2020) against approximately 40,000 publications for utilisation and 18,000 for storage and distribution.
In the decade to 2020, annual publications, using search criteria reported in the study, have more than tripled for hydrogen production and have roughly doubled in the case of both utilisation and storage and distribution. Growth in publications output has been strongest in hydrogen production over the past decade, which has exhibited a broadly consistent output growth profile over the 2010-2020 period.

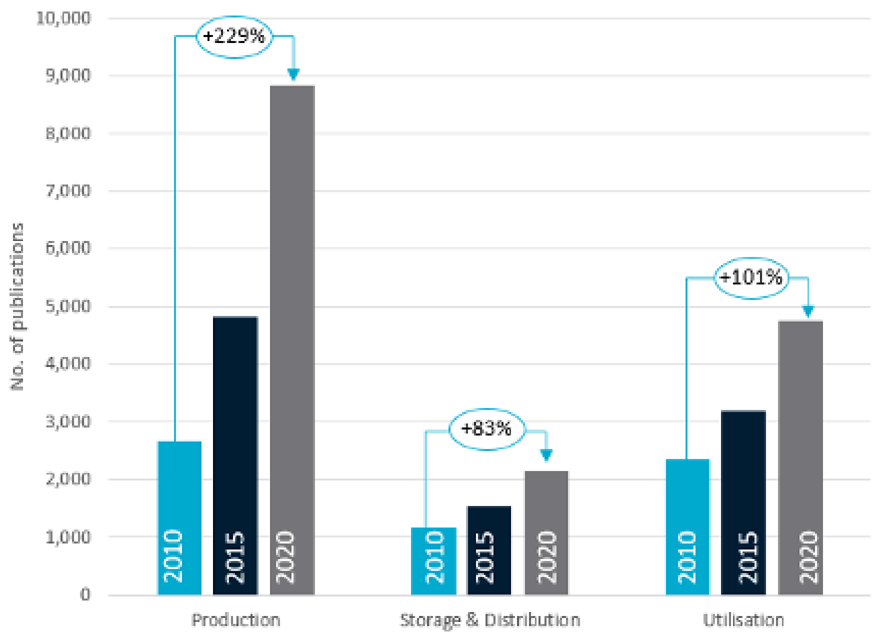


Figure 5. Global hydrogen publications output by supply-chain area[xiv]

The global patents landscape is comprised primarily of private companies that are patent assignees, while some universities and research institutions also hold patents to a lesser degree. Figure 6 highlights patent-family filing trends over the period 2010-2019, using the first filing in a patent family.

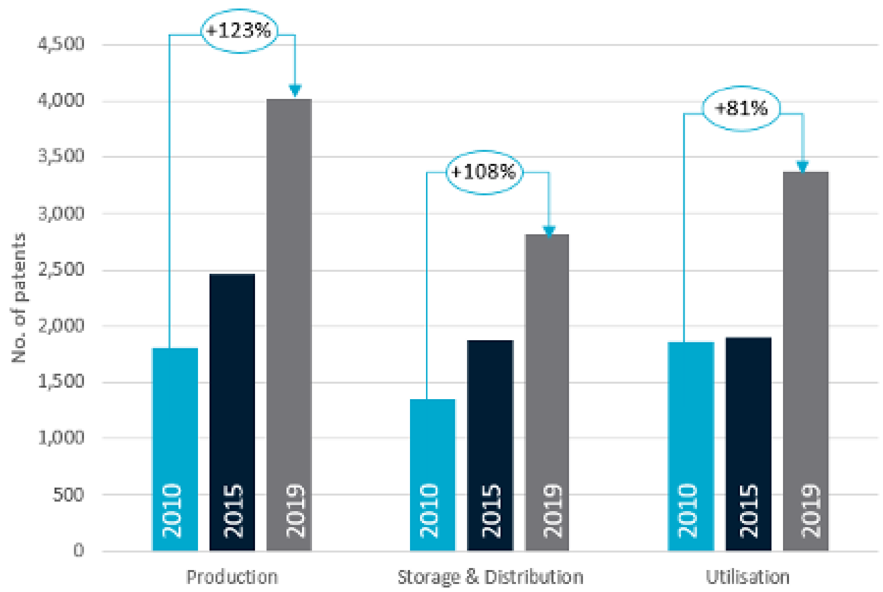


Figure 6: Global hydrogen technology patent filing over time[xv]

The count of patent families across the hydrogen value chain, after a period of virtual stagnation in the first part of the last decade, has exhibited a noticeable increase since around 2014/2015, and particularly in 2018/2019. The range of patents across value chain areas is more evenly distributed than for publications output.

Overall, the publications and patents data suggest an increased pace of knowledge enquiry and innovation in hydrogen-related areas since the middle of the last decade, which likely is reflective of the recent uptick in government and private sector investment in hydrogen technologies.

RD&I output as indicated by publication metrics has to date emphasised hydrogen production innovation, presumably because this is the area with the most tangible impact on hydrogen technology cost competitiveness. Moving forward, it seems reasonable to suggest that the areas of hydrogen storage, distribution and utilisation will show increased RD&I intensity, since innovation in

these areas will be needed to both build hydrogen demand and complete the 'hydrogen supply chain jigsaw'[xvi]. (See Appendix 2.)

Although there is reason to believe progress is being made and will continue, it will be critical for all nations with an interest in clean hydrogen to ensure that they nurture hydrogen RD&I through the current decade and into the next. Therefore, it is important to identify the key priority RD&I areas for focus which will be an important role for Mission members and stakeholders.

2.2 Tipping Point and Key Priorities and Innovation needs for Hydrogen R&I

As discussed in section 1, clean hydrogen is currently not cost competitive. Further improvements to existing technologies and step-change technological breakthroughs are needed to reduce end-to-end hydrogen costs. While storage and distribution costs contribute significantly, to the end-to-end cost, production is the highest cost-component across most regions and end-uses (Figure 1). Reducing hydrogen production cost is estimated to play a disproportionate role in unlocking cost-competitiveness of all hydrogen applications[xvii]. In most parts of the world, producing hydrogen from fossil fuels is currently the lowest-cost option. The Global Hydrogen Review by IEA (2021) estimates that the levelised cost of hydrogen produced from natural gas, depending on regional gas prices, is in the range of USD 0.50-1.70/kg hydrogen, and hydrogen produced using renewables in most places is in fact much costlier, at USD 3.00-8.00/kg hydrogen (figure 7 shows the most recent IEA analysis). Substantial carbon capture and use or storage is needed for the production of fossil-derived hydrogen to be considered clean. Depending on gas prices, natural gas with CCUS entails a production cost of USD 1.00-2.00/kg H2 – about USD 0.50/kg hydrogen higher than without CCUS. However, the price gap between production methods is expected to shrink with falling costs of renewable electricity and electrolysers.

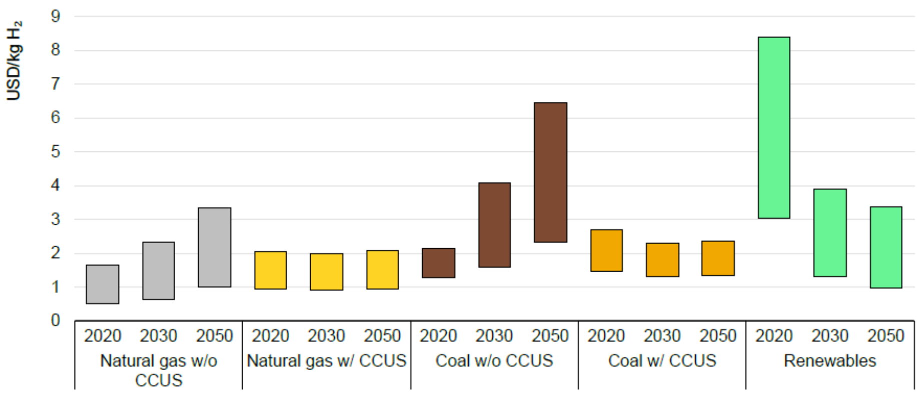


Figure 7: Levelised cost of Hydrogen Production by Technology in 2020 and in the Net Zero Emissions Scenario, 2030 and 2050 (Source: IEA, reproduced with permission)

The Mission recognises that the cost of hydrogen will vary by application and region, and that several external factors – such as climate policy and its effects on the costs of alternatives such as electrification – will affect clean hydrogen's ability to become cost-competitive. breakeven costs also show significant variance for different end-uses (Figure 1). The Mission is technology neutral as to how clean hydrogen is produced and used, offering full flexibility and autonomy to identify target value chains.

While multiple factors will play a role in determining the future cost of hydrogen, as shown in analysis by the Hydrogen Council, a 2 USD/kg production cost is achievable with 1.4 to 2.3 USD/kg projected by 2030.[xviii] The largest component of the end-to-end cost in these scenarios is the production cost of hydrogen, which will be major factor in achieving a 2 USD/kg end-to-end cost. However, depending on end-use, other costs such as the cost of compression, dispensing, and purification, would also need to be considered. As such, identifying clearly defined innovation needs in clean hydrogen RD&I (across production, distribution and storage, and end-use applications) is an ongoing focus of the Mission.

2.2.1. Production

As a part of this ongoing series of activities, Carbon Trust was commissioned by the UK Government on behalf of the Clean Hydrogen Mission to conduct desktop research and lead two international, expert-level, consultation workshops to identify and validate key R&I priorities and sector challenges, with a specific focus on production.

The focus was on production innovation needs because, whilst storage and distribution contribute to the end-to-end cost, production is the highest cost component across most regions and end-usesxix. The Hydrogen Council states that "reducing hydrogen production costs will play a disproportionate role in unlocking the cost competitiveness of all hydrogen applications", and that production costs are likely to fall by up to 60% between now and 2030 with appropriate advances in innovation.

In light of the Mission's 2030 goal, the focus was on identifying clearly defined innovation needs that could be addressed quickly within this decade i.e. technological innovation needs in the two most utilised clean hydrogen production routes: Natural Gas Reformation + Carbon Capture and Storage (NGR+CCS) and low carbon electrolysis. The analysis considered: how impactful an innovation could be at reducing the cost of clean hydrogen; how much international collaboration was required to progress an innovation; the urgency with which an innovation needs to be deployed to support the Mission's 2030 cost target; and the level of activity already occurring. The order in which the categories of innovation needs were prioritised was verified and refined by the sector experts during the workshops. The innovation needs identified were:

- For **NGR + CCS:** Innovation concerning carbon storage capabilities was found to be the highest priority. This was determined by the large scope for international collaboration in this sector, and because a rapid increase in demand for carbon storage is expected as countries legislate on industrial decarbonisation and transition to cleaner pathways. This was followed by innovation to reduce the costs and/or use of process materials comprising the reformation and carbon capture units, and innovation to improve carbon capture processes. Innovation concerning new process technology and integration was seen as lower priority in mature technologies, where lots of activity is already taking place, and there is little scope for international collaboration due to the clearly defined and easily replicable innovation needs.

- For **low carbon electrolysis**: It was concluded that innovation should be initially targeted at the electrochemical components because the predicted scale-up of hydrogen production and low availability of the materials required for electrolysis, namely precious metals and critical materials, could place constraints on rapid scale up of mass manufacturing. Innovation is needed to find alternative, abundant replacement materials or novel methods to re-use the constrained materials. Additionally, automation of electrolyser production and the

implementation of new manufacturing techniques will unlock large cost reductions by facilitating equipment production at scale. Electrochemical engineering innovation and innovation targeting the electrolysis process itself were found to be lower priorities given the scale of impact on the MI cost goal, lower scope for international collaboration and lower urgency with which they would need to be addressed to help facilitate the 2030 cost goal.

Table 1 provides a summary of these findings, and the full Carbon Trust report can be found in Appendix 3. Further engagement to broaden the scope and test and refine the findings will take place at the relevant working groups for inclusion in the Action Plan in 2022.

Categories of innovation needs for NGR+CCS		
Highest priority	**Carbon storage capabilities-** innovation addressing the identification and/or development of carbon stores and the minimisation of CO_2 leakage	• Re-characterising of old wells • Deploying sub-sea installations instead of platforms to enhance carbon storage capabilities
	Process materials- innovation concerning reducing use and/or cost of the materials comprising the reformation and carbon capture units	• Finding/developing alternative materials to use instead of expensive, rare materials • Developing ways to recycle process materials • Developing processes with advanced solvents to reduce catalyst regeneration costs and corrosion effects
	Carbon capture capabilities - innovation aimed at improving carbon capture process efficiency, technology, and/or carbon capture processes themselves in order to increase the percentage of CO_2 captured.	• Developing fuel cells to enhance post-combustion capture processes • Optimising the process of separating carbon dioxide and hydrogen to enhance carbon capture rates • Developing next generation, high pressure pre-combustion carbon capture technologies
Lowest priority	**Process technology -** innovation related to maximising the hydrogen yield by designing/integrating new technologies into the process or finding the optimal reaction sequencing.	• Deployment of technologies such as ceramic membranes for sorption-enhanced water-gas shift • Integration of gas heated reforming into the ATR process at scale • Improving hydrogen purification at different points in the process
Categories of innovation needs innovation needs for low-carbon electrolysis		
Highest priority	**Electrochemical components -** innovation concerning the components comprising the electrolyser. These innovation needs are mostly related to reducing costs by enhancing and recycling materials used in electrolyser equipment	• Creating catalysts from less scarce materials • Recycling of electrolysers and materials circularity • Using nickel-based alloys • Reducing the thickness of the electrolyser diaphragm • Increasing the specific surface area of electrodes and catalysts • Catalyst delamination or dissolution • Reducing interface resistances from the catalyst layer to the porous transport layer (PTL) • Making electrolysers easier to maintain
	Electrolyser production - innovation aimed at increasing the efficiency and reducing the cost of the electrolyser manufacturing processes	• Using advanced manufacturing methods
	Electrochemical engineering - innovation targeting electrolyser design and integration into the wider energy system	• Reducing the gap between electrodes • Increasing stack density • Increasing module size • Utilising recovered waste heat • Integration of electrolysers with intermittent renewable assets • Innovating the cooling process • Developing more reliable, low-maintenance water deionisation systems
Lowest priority	**Electrolysis process -** innovation targeting the reactions and processes comprising electrolysis to optimise the hydrogen yield and reduce the electricity consumed	• Faster ramping of alkaline electrolysers • Increasing lower heating value efficiency • Developing and using new hydrolysis routes • Optimising design of the electrolyser plant

Table 1: Priority areas and Innovation needs for Hydrogen Production identified by Carbon Trust

As the Mission develops and refines specific pathways to achieve its cost goals, scenarios such as those provided by the Hydrogen Energy Earthshot (Box 1) and other initiatives can be invaluable as experts across industry, academia, and national institutes aim to accelerate and focus on key technical barriers.

Box 1: The U.S. Department of Energy's Hydrogen Energy Earthshot, or Hydrogen Shot, seeks to reduce the cost of clean hydrogen by 80% to $1 per 1 kilogram in 1 decade ("1 1 1") The Mission will leverage relevant member initiatives and programmes to reach its goals, such as the Hydrogen Shot[1] launched by the US in June 2021 (Figure 8). The initiative aligns with the Mission goal through its development of pathways to reduce the cost of clean hydrogen production to 1 USD per kg in 1 decade ("1 1 1"). Over 34 countries and 3,200 stakeholders recently attended the Hydrogen Shot Summit in September 2021 and the Mission will continue to engage closely with this initiative as strategies are developed to reduce cost and meet collective goals.

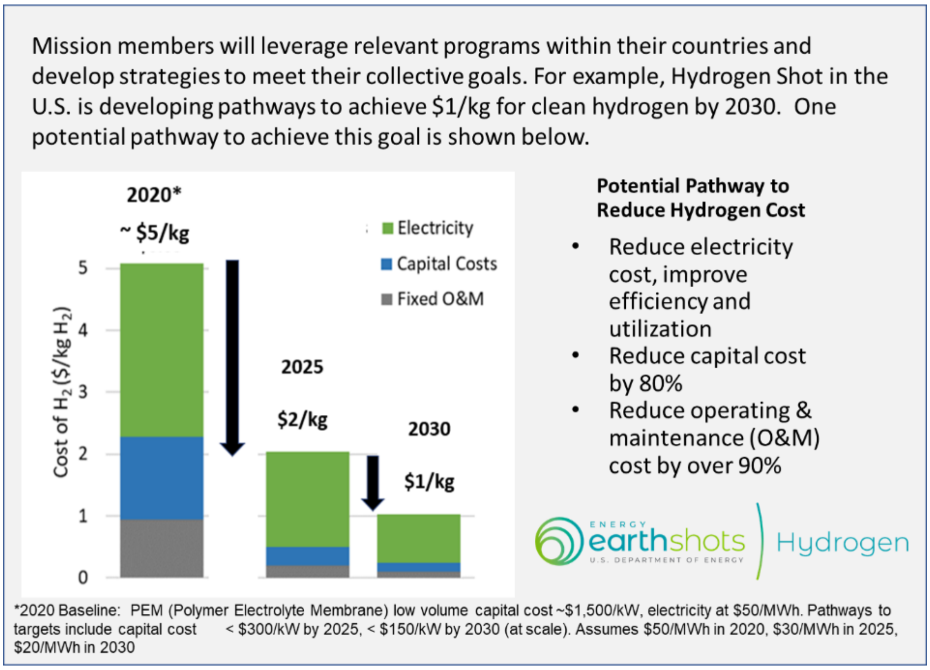


Figure 8: The U.S. Department of Energy's (DOE's) Energy Earthshots Initiative launched on June 7, 2021—Hydrogen Shot—seeks to reduce the cost of clean hydrogen by 80% to $1 per 1 kilogram in 1 decade ("1 1 1")[1]

2.2.2 Distribution and Storage

While identifying priority areas and innovation needs relevant to cost reduction in production, innovation and demonstration in other parts of the value chain will be

equally significant, storage and distribution can contribute significantly to the end-to-end cost for decentralised end-uses.

Box 2: Innovation priorities in Distribution & Storage and End-Use Applications identified by Carbon Trust

Based on Carbon Trust's preliminary findings, a range of opportunities with potential to reduce costs in distribution and storage and end-use application are being presented here for further comments. These will also be validated through the work that will be carried out within Mission Working Groups over the next several months. (For further information and references to Carbon Trust findings please refer to Appendix 1: Carbon Trust, 'Prioritisation of hydrogen cost reduction innovation needs', 2021;)

Key innovation priorities in distribution:

- Rehabilitating the existing gas network (i.e., finding materials and processes to avoid hydrogen embrittlement).
- Developing distribution networks compatible with pure hydrogen (e.g. using polymer materials).
- Scaling up and increasing the utilisation of hydrogen pipe infrastructure.
- Further developing hydrogen carriers (e.g., hydrides or liquid organic hydrogen carriers) in order that hydrogen can be distributed as Liquid Organic Hydrogen carriers (LOHCs).
- Improving hydrogen conversion/compression efficiencies and developing alternative compressors (i.e., ionic liquid, electrochemical) compatible with hydrogen utilisation. Currently, if hydrogen is converted into ammonia for distribution and back into hydrogen before use, energy losses of 72 – 73% are incurred. Losses of 0.5 – 11% are incurred for compression.
- Optimising pressure levels across hydrogen production and distribution infrastructure by using the optimal compression levels and correctly sizing components.
- Increasing tube trailers' nominal tube pressure which can reduce the cost of delivering hydrogen for transport applications.
- Increasing the efficiency of liquid hydrogen tankers to reduce the cost of long-distance hydrogen delivery. This can be achieved with better vessel insulation, higher-pressure levels.

Key innovation priorities in storage:

- Developing LOHCs and ammonia which can be used as energy storage options as well as mediums for hydrogen distribution (see the innovation needs in the above section 'Distribution')
- Developing material-based storage technologies characterised by high volumetric energy density, such as metal hydrides and porous sorbents. Also need to address liquefaction efficiency.

The Mission will focus on low cost and safe approaches for hydrogen distribution (including pipelines, liquid hydrogen, and carriers such as Liquid Organic Hydrogen Carriers (LOHCs) and ammonia) and hydrogen storage (including gaseous, liquid, geological storage, and materials-based storage such as metal hydrides, sorbents, and other carriers) with potential to meet the $2/kg production to end use cost goal. Examples from the Carbon Trust assessment are shown below.

2.2.3 End-use applications

In addition to focusing on R&I for clean hydrogen production, distribution, and storage, R&I will also be needed to enable commercially viable and competitive end use applications that result in overall emissions reductions, particularly in hard to decarbonize sectors. Figure 9 shows the most recent scenario published by IEA on the amount of hydrogen required for various end use applications to meet global net zero emissions by 2050.

Given the broad range of areas that the Mission could cover, to focus efforts, is its proposed that the Mission would focus on activities not already covered through other partnerships and leverage activities initiated by other partnerships as needed.

Based on the Mission Members' feedback, heavy duty off-road equipment such as mining vehicles, agriculture and construction equipment may be hard to electrify and will require hydrogen and fuel cell technology. Government and industry technology developers worldwide are realizing the potential for hydrogen off-road equipment applications including decarbonizing heavy-duty agricultural, construction, and mining equipment using fuel cells. For instance, mining operations account for an estimated 1% of global greenhouse gas emissions[xx]. The Mission would also focus on hard-to decarbonize applications where hydrogen is one of the only options. Another high priority group of areas, and one receiving global attention, is decarbonizing steel, ammonia, and cement manufacturing.

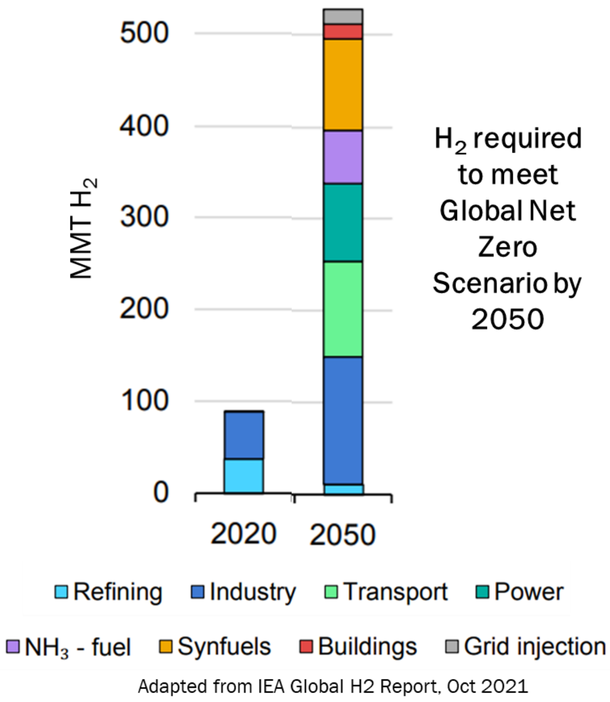


Figure 9: Hydrogen End Uses in 2020 and projected for 2050 for Net Zero Emissions, IEA Global Hydrogen Review 2021[xxi]

Box 3: Mission Innovation Hydrogen Fuel Cell Off-Road Equipment and Vehicles Virtual Workshop, September 22-24, 2021

Off-road equipment (also sometimes referred to Non-Road Mobile Machinery) such as mining vehicles was found to not be addressed through other partnerships. The End Use Working Group therefore convened its first workshop on this topic (September 22-24, 2021). The event was co-hosted by the Ministry of Energy of Chile, the Department of Industry, Science, Energy and Resources of Australia, the European Commission, and U.S. Department of Energy's Hydrogen and Fuel Cell Technologies Office. At this workshop, thirty presentations on agriculture, construction, and mining equipment and infrastructure were given focusing on the use of fuel cell power and hydrogen fuel. Two key innovation priorities in end-use applications that emerged from the workshop were:

- Developing low cost, safe, and efficient end use equipment for in situ hydrogen fuelling
- Reducing the cost and improving the durability and efficiency of fuel cell technologies for off road applications.

3. Building a global hydrogen economy through clean hydrogen valleys

3.1 Delivery of 100 clean hydrogen valleys worldwide

The Mission has committed to facilitate the delivery of at least 100 large-scale clean hydrogen valleys worldwide by 2030. These valleys are sometimes referred to as 'hubs' or 'clusters' in some countries.

One aspect of reducing the end-to-end costs of clean hydrogen is successfully demonstrating economically viable applications and end uses for clean hydrogen in globally different geographical onshore and offshore locations, enabling the build-up of scale resulting in further cost reductions.

The Mission's goals can be achieved through cohorts of clean hydrogen valleys to combine different production, storage and transport methods with the aim of reaching critical scale and unlocking learning curve effects. Valleys co-locate either or both suppliers and end-users of hydrogen, achieving economies of scale through shared infrastructure and creating a source of concentrated demand for clean hydrogen. Other benefits include improved ability for sector coupling, building international linkages, and stimulating trade. Valleys can become a focal point for the innovation and skills development needed to unlock barriers to a growing hydrogen economy.

Clean hydrogen valleys would cover the entire value chain: production, storage, distribution, and end use. Valleys typically require multi-millions to billions in €/$ investment, spread across a defined geographic scope and covering a substantial part of the value chain from hydrogen production, storage and transport to end-use in various sectors. Demonstrating the integration of demand and supply in a sufficient number of places or regions will inspire confidence of producers and users to stimulate necessary investments in infrastructure, new facilities and retrofitting of existing ones.

Over recent years, the European Fuel Cells and Hydrogen Joint Undertaking (FCH JU) has been stimulating the set-up of several hydrogen valleys, in collaboration with European cities and regions. Hydrogen Valleys have started to form the first regional "hydrogen economies", as bottom-up stepping-stones in the development of a global hydrogen economy.

The Innovation Challenge 8 (Renewable and Clean Hydrogen) of Mission Innovation developed the Hydrogen Valley Platform (www.h2v.eu), a global information sharing platform providing valuable data. Already more than 30 hydrogen valleys are presented in this platform. An analysis of these valleys has been performed and findings are presented in the report 'Hydrogen valleys – insights into the emerging hydrogen economies around the world'[xxii]. Figure 10 depicts the common characteristics of the constituent elements of a Hydrogen Valley, noting that Hydrogen Valley concepts are adaptable to cater to specific regional circumstances and objectives of specific projects.

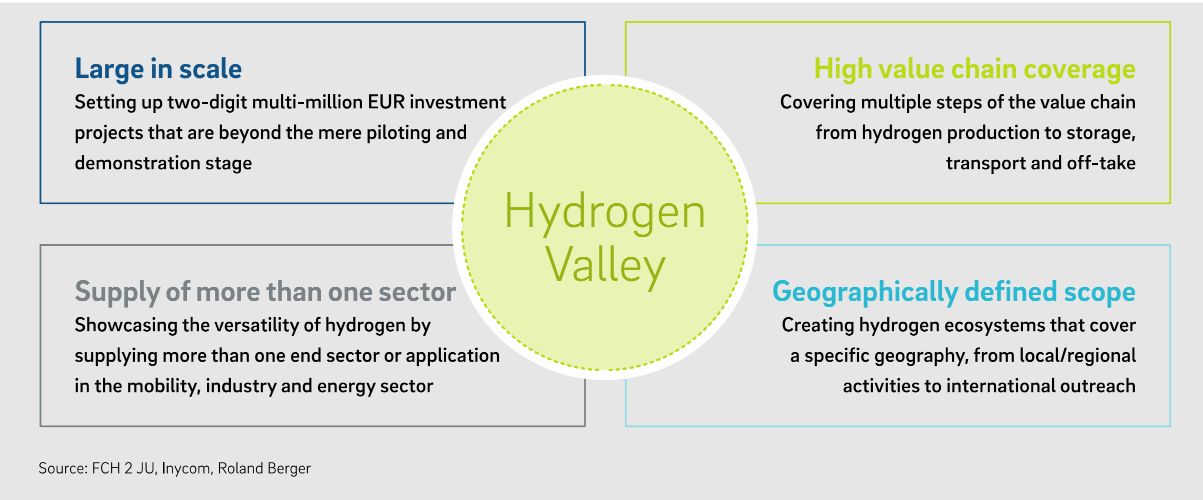


Figure 10: What makes a Hydrogen Valley[xxiii]

Hydrogen valleys will significantly mature over the 2020s, due to an increasing number of projects overall and because announced projects themselves grow in size and complexity (e.g., by hydrogen production volume, planned investment, etc.). While in the earlier phases of hydrogen deployment, projects were mostly driven by public authorities or public-private initiatives, today more than 50% of projects are led by the private sector that views projects as strategic investments into a new business area. In addition, hydrogen valleys are gravitating towards

typical value chain set-ups where different foci promise near-term commercial business cases. Three archetypal setups observed are (i) local, smaller-scale and mobility-focused projects, (ii) local, medium-scale and industry-focused projects, and (iii) large-scale and international export-focused projects; figure11 (below) illustrates.

3.2 Five factors for successful hydrogen valley development

Five factors are particularly key for the successful project development of Hydrogen Valleys.

A Hydrogen Valley needs:

1. a convincing project concept with a hydrogen value chain coverage that leverages local assets (e.g., abundant renewable energy sources) and addresses local needs (e.g., the decarbonisation of local industrial production),

2. to develop a viable business case linking competitive clean hydrogen production with the off-takers' willingness to pay.

3. public support and/or funding, (potentially from multiple sources) that closes any remaining funding gaps.

4. effective partnering and stakeholder cooperation during project development, ensuring continuous commitment from all parties involved; and

5. political backing from policy makers and support by the general public.

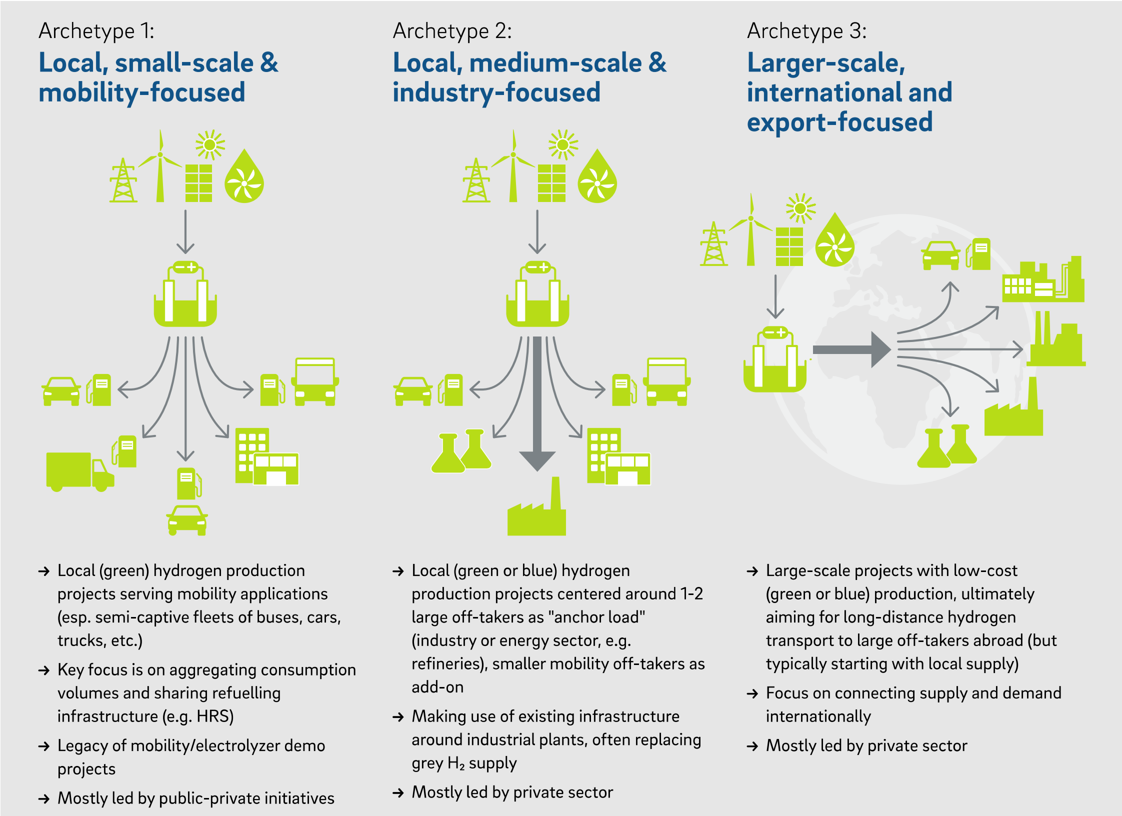


Figure 11: Hydrogen Valley Archetypes[xxiv]

3.3 Five barriers to hydrogen valley development

There are five prominent barriers to the development of hydrogen valleys – yet they are not insurmountable.

The first and most prominent barrier is securing public funding. Among the methods used by hydrogen valleys to overcome this challenge, creating awareness about the technology with funding entities, initiating proactive dialogues about funding criteria, and remaining flexible regarding the potential adaptation of the project concept to tailor it to public funding requirements proved to be particularly successful.

Secondly, securing off-take commitments for clean hydrogen is a key barrier. Credible investment plans complemented by engagement with many potential off-takers from various sectors are among the best practices reported to reach the required off-take quantities.

Thirdly, to secure private funding, hydrogen valleys rely on a structured development approach, early involvement of off-takers and equity partners that de-risk the project as well as early feedback from the lending community. Involving local private investors might additionally be attractive for locally anchored hydrogen valleys.

A fourth barrier to overcome is to mitigate technological readiness and technological performance barriers including availability and reliability of products (e.g., fuel cell vehicles); it is essential for hydrogen valleys to remain flexible regarding the project's general direction. For example, including other applications into the project's portfolio.

A fifth barrier is regulatory provisions. While the global policy landscape is increasingly favourable for hydrogen valleys, barriers still exist regarding permits and regulation affecting hydrogen valleys directly as well as indirectly (e.g., as the respective policy affects conventional competitors or off-takers). Almost 40 per cent[3] of hydrogen valleys still experience regulatory provisions as a challenge. The hydrogen valleys insights report presents four recommendations for policy makers, namely:

(i) have a clear vision of the country's future hydrogen economy in a national hydrogen strategy that sets the frame for hydrogen valley development,

(ii) create a regulatory environment conducive to their development,

(iii) close the gaps in permitting procedures, and

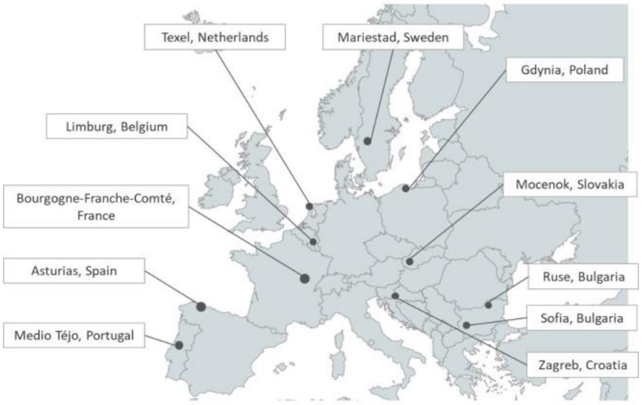
(iv) act as a local matchmaker to enable the setup of hydrogen valleys.

In supporting the development of hydrogen valleys in Europe the FCH JU piloted a Project Development Assistance (PDA) facility enabling local authorities from across the European Union to develop their concepts for regional hydrogen and fuel cell projects into detailed work plans, see Box 3. The aim of the PDA service was to provide general information on hydrogen technology characteristics and potential, exchange of experiences and best practice, procurement and financing strategies, project development, business case development, funding via national support mechanisms, and to set-up joint activities.

[3] Based on data available in report issued during the setup of the "Mission Innovation Hydrogen Valley Platform" (www.h2v.eu) and developed by the Fuel Cells and Hydrogen Joint Undertaking. by FCH 2 JU, Inycom, Roland Berger.

Box 4: Project Development Assistance (PDA) for Regions and Cities: Thinking Global, Acting Local

The Project Development Assistance programme, coordinated by the Fuel Cells and Hydrogen Joint Undertaking (FCH JU), was conceived to help European local authorities develop and implement concrete plans that would later allow regions to benefit from the use of clean hydrogen technologies in a local hydrogen ecosystem.



https://www.fch.europa.eu/page/going-fch-ju-pda-regions

Outcomes PDA (2020-2021)

- 35 applications from regions across 18 European countries
- 11 local authorities, 5 of which newcomers from Central and Eastern Europe, received funded consultancy support to develop integrated hydrogen projects
- A wide variety of relevant end-use applications and business cases
- Concrete plans developed for the 11 regions could materialise into an overall CAPEX estimated at around EUR 700 million

In a survey among the members of the Clean Hydrogen Mission, the need for knowledge sharing on lessons learned from hydrogen hubs/valleys, and for sharing details on sector coupling-intelligent co-optimizations of the production and use of hydrogen across different uses and sectors was clear. Also, the need to build an international network to enable a dialogue and exchange of experiences and to inspire new international projects/hydrogen supply chains/nuclei for clustering hydrogen technologies was evident.

4. Building an enabling environment for a global clean hydrogen economy

4.1 The need for building an enabling environment

The use of hydrogen sourced from fossil fuels in industrial processes is already a well-established global market with fluidly functioning technology providers, project developers, operators, producers, supply chains and end-users. This international market is governed by codes, certifications and standards that regularise and legalise this product from production and storage through to transportation and final use. It also gives security to financiers and investors providing capital throughout the supply chain.

In 2020, global hydrogen demand was around 90 Mt, which was met almost exclusively with unabated fossil fuel-based hydrogen[4]. Clean hydrogen production, from either renewable energy-powered electrolysis or carbon captured from fossil fuels, is not only technically viable but will be increasingly deployed. As the share of clean hydrogen production continues to grow from its current nascent stage into an international market supplying an expanding demand, it will require similar codes, certifications, regulations, and standards as its fossil fuel-based counterpart.

Currently, the international clean hydrogen arena is filled with a mixture of private sector actors, national governments, international organizations, industry associations and other mixed collaborations that are attempting to define the regulatory landscape to enable clean hydrogen. With some minimal exceptions, almost all countries share a similar vision for the role of clean hydrogen in their energy systems.

[4] IEA estimates that clean hydrogen produced using fossil fuels with CCS and low carbon electrolysis accounted for less than 1% of the share in 2020.

This consensus on the growing role that clean hydrogen will play, particularly in decarbonisation, underscores the necessity of collaboration and coordination between the national, state, private sector, and organisational actors to create a clear and coherent enabling environment to speed up clean hydrogen growth and use.

4.2 Monitoring and aligning with other international efforts

To create a better environment for scaling up the global hydrogen economy, activities under Pillar 3 of the Clean Hydrogen Mission (Enabling Environment) will be aligned with other initiatives. One option could be for the Mission to build a collaborative knowledge-exchange platform to overcome common, non-technological and non-commercial challenges to market creation and scale-up. Activities within Pillar 2 (Hydrogen Valleys) and 3 (creating an enabling environment) could be effective in facilitating these connections between participants involved in RD&I and those focusing on hydrogen valleys.

The Mission will also leverage information from partner initiatives to identify additional activities that may be undertaken to facilitate clean hydrogen market valuation and international trade by outlining a common approach. This includes linking up with initiatives such as the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE) ; Clean Energy Ministerial Hydrogen Initiative, the World Economic Forum (WEF), the International Renewable Energy Agency (IRENA) and the European Clean Hydrogen Alliance.

IPHE has a Hydrogen Production Analysis Task Force (H2PA) to develop a common analytical methodology for determining the Green House Gases (GHGs) associated with hydrogen production as well as transport, including using chemical carriers.[xxv] IPHE's Regulations, Codes, Standards, and Safety Working Group's (RCSS WG) analysis provides insights into the RCSS related gaps that need to be addressed to enable deployment of hydrogen technology (Figure 12). IPHE's Education and Outreach Working Group and Early Career Network that consists of over 200 students, postdoctoral candidates, and early career professionals across 10 countries, and fosters the development of a next generation workforce for hydrogen and related technologies is another helpful initiative.

Hydrogen Infrastructure						Hydrogen for Mobility/Transportation		
Hydrogen injection at transmission level	Hydrogen injection at distribution level	Methanation and injection of Methane (SNG) via methanation from hydrogen at transmission / distribution level	H2 refilling station (HRS)		Maritime Infra	Mobility infra (tunnel, bridge, underground parking…)	Heavy Duty vehicles	H2 and H2-based fuel vessels
Legal framework: permissions and restrictions (and Ownership constraints (unbundling))	Legal framework: permissions and restrictions (and Ownership constraints (unbundling))	Legal framework: permissions and restrictions (and Ownership constraints (unbundling))	Land use plan (zone prohibition)		Off-shore refueling	Restrictions & Incentives	Type approval & Individual vehicle registration - Process	Legal framework: permissions and restrictions (and Ownership constraints (unbundling))
Permission to connect/ inject	Permission to connect/ inject	Permission to connect/inject	(LH2) Permitting requirements/ process	(GH2) Permitting requirements/ process	On-shore refueling		Restrictions & Incentives	Safety requirements (compliance with safety regulation/ risk control expectations)
Safety requirements and process (safety distances internal / external)	Safety requirements and process (safety distances internal / external)	Safety requirements (compliance with safety regulation / risk control expectations)	(LH2) Safety requirements and process (safety distances internal/ external)	(GH2) Safety requirements and process (safety distances internal/ external)			Service and maintenance	H2 on-board storage
Gas quality requirements	Gas quality requirements	H2/ SNG quality requirements	H2 quality requirements					
			Quality measurement requirements					

Figure 12: Heat map of critical areas as identified by the IPHE RCSS Working Group. Note: red is considered the most critical, orange is moderately critical and yellow is less critical.[xxvi]

The Clean Energy Ministerial Hydrogen Initiative can provide lessons learned on enabling environments through its work streams such as the Global Ports Coalition and H2 Twin Cities initiative. WEF and IRENA recently released an Enabling Measures for Green Hydrogen Roadmap designed to assist countries take action through implementing a set of measures to develop green hydrogen on country and regional levels. Its initial recommendations include: providing clarity on standards through certifications scheme on hydrogen products and throughout the value stream; removing critical cost and regulatory barriers; focussing innovation and R&D to drive scale; and driving efficient allocation of capital. These are major tools for policy makers linked to the work on

certifications, regulations, codes and standards and can be incorporated directly within the pillars of the Clean Hydrogen Mission.

The European Clean Hydrogen Alliance also released a recent report bringing together the results of the Alliance's six roundtables on the main barriers that impact the roll out of renewable and low carbon hydrogen production, transmission, distribution and use across Europe, and the most relevant mitigation measures that should be addressed in the short or medium term to guarantee the ambitions of the European Hydrogen Strategy.

As the Mission further defines its work scope, a key aspect in future discussions and decisions will include leveraging other international partnerships. The landscape of international hydrogen partnerships and delineation based on technology versus policy and markets focus, as developed by IPHE, is shown below in Figure 13.

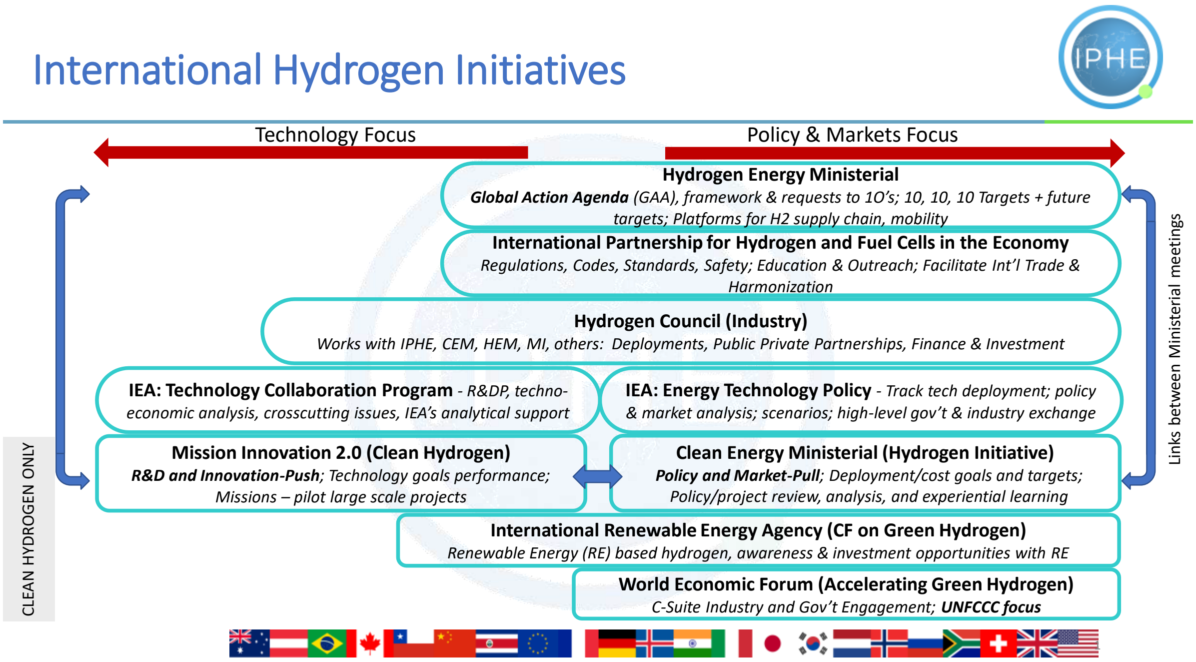


Figure 13: International Hydrogen Initiatives (Source: used with permission from the IPHE) [xxvii]

5. Potential Clean Hydrogen Mission Actions

The Clean Hydrogen Mission will develop and publish an Action Plan based on member and stakeholder input in 2022. A preliminary list of potential priority actions that may be undertaken by the Mission is presented below for consideration and feedback.

Pending feedback from members and stakeholders, these actions may be revised, and additional details may be provided. In addition, members may review the Appendix which provides specific topic areas proposed in early 2021 that may be considered in developing actions and next steps.

5.1 Potential Actions – Research & Innovation

With innovation being a cornerstone of the Mission Innovation platform, Members will focus on specific actions to foster innovation and develop strategies to achieve the overarching goal of 2 USD per kg of hydrogen. The Mission proposes convening Working Groups on hydrogen production, distribution and storage, and end use applications to address key innovation gaps working collaboratively with other partnerships and alliances. Examples of possible actions by the working groups include:

- Monitoring global R&I initiatives and continuously identifying specific strategies and activities to accelerate cost-reductions and technological breakthroughs, including in hydrogen production, distribution, storage and end-use applications. An initial set of priority areas and innovation needs that will have a step-change effect on cost reduction have been outlined by Carbon Trust (Appendix 3). These will be considered more closely by the working groups for inclusion in Action Plan in 2022.

- Establishing knowledge exchange networks with MI member countries to foster collaboration on relevant programmes and initiatives.

- Conducting webinars with MI member countries presenting on relevant programs and initiatives.

- Working with MI Members to develop a database of clean hydrogen production R&I projects by members to prioritise potential areas for enhanced collaboration.
- Identifying gaps where the Mission can add value and leverage other activities and partnerships such as IEA's TCP as applicable to avoid duplication and accelerate progress

5.2 Potential Actions – Hydrogen valleys

As agreed by Mission members, hydrogen valleys are a key deliverable. Possible actions to be defined by the Demonstration Pillar are presented below. Mechanisms for coordination and information sharing such as a Mission Innovation's Hydrogen Valley Platform could be an effective tool for monitoring progress. It would ideally need to be integrated with other international partnerships to leverage resources and avoid duplication. A platform with up-to-date information on hydrogen valley project developments globally will serve as a project incubator and collaboration enabler between mature hydrogen valleys. Potential actions that could be pursued within this pillar include:

- Continuation of the Hydrogen Valley Platform and including additional functionalities to play a role as incubator for emerging Hydrogen Valleys and enhance cross border and international cooperation.
- Developing concepts and options for a Global Hydrogen Valley Project Development Assistance Network. MI Members may already plan to set up PDA services at a national level but, through a global network, exchange of experiences and knowledge can be stimulated to build more effectively on the clean hydrogen valleys.
- Building on the results of the Mission's hydrogen valley insights report to create a central repository of best-practice, or a 'toolbox' for creating enabling environments for valleys, including business models, market structures and other systemic rules.
- Supporting the development of 100 hydrogen valleys globally by concerting action with other international initiatives, such as, the CEM Global Ports Hydrogen Coalition, MI Shipping Mission and Green Powered Future Mission.

5.3 Potential Actions – Enabling Environment

Coordination with other international partnerships to avoid duplication and leverage resources will be critical. As described above, efforts are underway through IPHE and other initiatives to address barriers including safety, codes, and standards, and facilitating international trade for hydrogen. Examples of potential actions include:

- Continuing stakeholder outreach and engagement to define priorities to be undertaken within the Mission and to foster an enabling environment for both the R&I and Demonstration Pillars.
- Providing further evaluation of the publication and patent analyses undertaken by CSIRO to determine how to foster innovation and the exchange of new ideas that could result in potential breakthroughs.
- Engaging with universities and institutes, in addition to industry, to develop mechanisms that promote international collaboration and facilitate personnel exchange.
- Working with other entities or partnerships such as HySafe, the Center for Hydrogen Safety, and the International Conference on Hydrogen Safety (ICHS), to identify and address key issues regarding hydrogen safety, codes, and standards.
- Conducting webinars and workshops to help disseminate information through other initiatives, such as through co-branded events with IPHE, WEF, CEM, IEA, IRENA, the Hydrogen Council, and others.

6. Conclusion and next steps

The Discussion Paper presented an overview of proposed key innovation priorities and areas of focus set out against the Mission's three pillars for the Action Plan, which will be developed and adopted in 2022.This Mission is well placed to stimulate international cooperation and drive consensus on innovation needs and priorities that will provide the greatest impact in reducing hydrogen costs towards 2030. While ambitious, the Mission's overarching goal is feasible if key gaps and sectoral challenges are addressed in a coordinated and time-critical manner. The Mission will continue to work collaboratively towards tackling these through its three pillars of activity. To strengthen this work, the Mission is now also releasing this report for wider consultation and is inviting engagement and comments from all interested stakeholders.

6.1 Consultation process and timelines

While general response is sought on all aspects identified in this report, specific responses are also invited on the following questions:

1. Which innovations could be most effective in reducing the cost of clean hydrogen and reaching the tipping point of USD 2 per kg by 2030?
2. Which areas of innovation will benefit most from international collaboration?
3. What are some of the most noteworthy success-stories and most innovative solutions with significant cost-reduction potential for clean hydrogen?
4. What are the key actions that should be prioritised within the Clean Hydrogen Mission?
5. What services, advisory activities, or networking tasks would members and stakeholders like to see the Mission undertake, to help enabling a beneficial environment for the deployment of hydrogen valleys?

Please respond to this consultation by 9 December 2021 by sending your responses to EC-MI-CLEAN-HYDROGEN-MISSION@ec.europa.eu

ENDNOTES

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i Clean hydrogen is used to denote fossil-based hydrogen with carbon capture and electricity-based hydrogen. The production routes described don't form an exhaustive list, as other methods of hydrogen production with significantly reduced full life-cycle greenhouse gas emissions compared to existing hydrogen production are also classed as clean by this Mission. Significant reduction is to be understood as being equal to or below the well-to-gate greenhouse gas emissions of steam reforming of natural gas with CCS with 90% capture, which is 1 kgCO2eq/kgH2 (IEA, 2019). The definition of Clean Hydrogen continues to be discussed between co-leads and may be subject to further changes.

ii https://www.iea.org/articles/the-challenge-of-reaching-zero-emissions-in-heavy-industry
iii Element Energy and Jacobs

iv https://www.iea.org/reports/global-hydrogen-review-2021
v Tipping point is defined in the Merriam Webster dictionary as "the critical point in a situation, process, or system beyond which a significant and often unstoppable effect or change takes place".

vi Hydrogen Council (2020) https://hydrogencouncil.com/wp-content/uploads/2020/01/Path-to-Hydrogen-Competitiveness_Full-Study-1.pdf

vii Hydrogen Council (2020) https://hydrogencouncil.com/wp-content/uploads/2020/01/Path-to-Hydrogen-Competitiveness_Full-Study-1.pdf

viii Baker M McKenzie (2020) https://www.bakermckenzie.com/-/media/files/insight/publications/2020/01/hydrogen_report.pdf?la=en

ix https://hydrogencouncil.com/wp-content/uploads/2017/11/Hydrogen-scaling-up-Hydrogen-Council.pdf))

x CSIRO HyResource, policy, international < https://research.csiro.au/hyresource/policy/international/>

xi Hydrogen Council (2021) https://hydrogencouncil.com/wp-content/uploads/2021/07/Hydrogen-Insights-July-2021-Executive-summary.pdf

xii CSIRO, Hydrogen *research, development and innovation*: *global priorities in support of clean hydrogen industry development*, 2021.

xiii Srinivasan, V., Temminghoff, M., Charnock, S., Hartley, P. (2019). Hydrogen Research, Development and Demonstration: Priorities and Opportunities for Australia, 2019.

xiv CSIRO, Hydrogen Research Development and Innovation: Global priorities in support of clean hydrogen industry development
There will be some overlap of key words searched across the supply chain areas, indicating that an overall hydrogen publications output tally would not align perfectly with a simple aggregation of the individual areas. The key words search structure developed is intended to lessen this overlap.

xv *ibid.*
xvi *ibid.*
xvii Hydrogen Council, 2020. Path to hydrogen competitiveness: A cost perspective
xviii https://hydrogencouncil.com/wp-content/uploads/2021/02/Hydrogen-Insights-2021.pdf

xix Hydrogen Council, 2020. Path to hydrogen competitiveness: A cost perspective;
xx McKinsey (2020) https://www.mckinsey.com/business-functions/sustainability/our-insights/climate-risk-and-decarbonization-what-every-mining-ceo-needs-to-know

xxi https://www.iea.org/reports/global-hydrogen-review-2021

xxii Fuel Cells And Hydrogen 2 Joint Undertaking (FCH 2 JU), ‘Hydrogen valleys – insights into the emerging hydrogen economies around the world’, 2021 <https://www.fch.europa.eu/sites/default/files/documents/20210527_Hydrogen_Valleys_final_ONLINE.pdf>

[xxiii] *Ibid.*
[xxiv] *Ibid.*

[xxv] IPHE WP Methodology Doc Oct 2021 | iphe

[xxvi] IPHE, Compendium of Regulatory Areas for Action in Hydrogen Infrastructure and Mobility/Transportation Technologies: A Working Paper Prepared by the IPHE Regulations, Codes, Standards and Safety Working Group, 2021 < https://1fa05528-d4e5-4e84-97c1-ab5587d4aabf.filesusr.com/ugd/45185a_f6e26899e84e4881b712f953e15e6a21.pdf>

[xxvii] IPHE, presentation: *IPHE at International Renewable Energy Agency Meeting of the Collaborative Framework on Green Hydrogen: IPHE’s Role, Global Developments, and Opportunities*, September 2020. < https://1fa05528-d4e5-4e84-97c1-ab5587d4aabf.filesusr.com/ugd/45185a_9a9f02cd23a546f48a2319aaf8ca1862.pdf>