REPORT

Hydrogen Production Innovation Priorities

For the Mission Innovation 2.0 Clean Hydrogen Mission

November 2021

Acknowledgments

The Carbon Trust wrote this report based on an impartial analysis of primary and secondary sources, including expert interviews.

The Carbon Trust would like to thank everyone that has contributed their time and expertise during the preparation and completion of this report.

This report was sponsored by the UK Government. For the avoidance of doubt, this report expresses independent views of the authors.

Who we are

We are a trusted, expert guide to Net Zero, bringing purpose led, vital expertise from the climate change frontline. We have been pioneering decarbonisation for more than 20 years for businesses, governments and organisations around the world.

We draw on the experience of over 300 experts internationally, accelerating progress and providing solutions to this existential crisis. We have supported over 3,000 organisations in 50 countries with their climate action planning, collaborating with 150+ partners in setting science-based targets, and supporting cities across 5 continents on the journey to Net Zero.

The Carbon Trust's mission is to accelerate the move to a decarbonised future.

Authors:

Serene Esuruoso

Associate

Serene.Esuruoso@carbontrust.com

Beatrice Stockport

Intern

Beatrice.Stockport@carbontrust.com

Contributors:

Tom Jennings

Director

Tom.Jennings@carbontrust.com

Nadia Montoto

Manager

Nadia.Montoto@carbontrust.com

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Abbreviations

ATR + CCS	Autothermal reforming with CCS
ATR + GHR + CCS	Autothermal reforming with gas-heated reforming and CCS
BECCS	Biomass gasification with CCS
BEIS	Department for Business, Energy and Industrial Strategy
CAPEX	Capital expenditure
CCS	Carbon capture and storage
CO_2	Carbon Dioxide
FCDO	Foreign, Commonwealth and Development Office
H_2	Hydrogen
LOHCs	Liquid organic hydrogen carriers
NGR + CCS	Natural gas reformation with CCS
NiH	Nickel hydrogen
OPEX	Operational expenditure
PEM	Polymer electrolyte membrane electrolyser
PTL	Porous transport layer
R&I	Research and innovation
SMR + CCS	Steam methane reforming with CCS

Executive Summary

Hydrogen is a versatile energy vector that can be used to decarbonise traditionally hard to abate sectors such as industry and transport. Clean hydrogen, which includes renewable-based hydrogen, other low carbon electricity-based hydrogen and fossil-based hydrogen with carbon capture and storage[1], will play an important complementary and enabling role to electrification in decarbonisation. This will be especially crucial in sectors where electrification is not feasible or is too costly. Consensus has not yet been reached on the definition of clean hydrogen and the International Partnership for the Hydrogen Economy (IPHE) is working towards an internationally agreed upon methodology to define the greenhouse gas emissions associated with the production of clean hydrogen[2]. In the long term, clean hydrogen can also help the international community to stay within the 1.5ºC limit set out by the Paris Agreement. To harness this potential of clean hydrogen is the objective of Mission Innovation 2.0 Clean Hydrogen Mission.

Mission Innovation 2.0 aims to bring together governments, public authorities, corporates, investors and academia to strengthen global cooperation on clean energy innovation. As the main intergovernmental platform, Mission Innovation has become a catalyst for action and investment in research, development and demonstration to reduce the cost of clean energy and make it globally accessible.

As part of Mission Innovation 2.0, the Clean Hydrogen Mission is working with partner initiatives and organisations to decrease the cost of clean hydrogen to the end-user by reducing its end-to-end[3] cost to 2 USD/kg by 2030. This cost represents a tipping point with the potential to drive economies of scale and reduce costs further, therefore enabling clean hydrogen to play a complementary role to other clean energy vectors in reaching net zero. Achieving a cost for clean hydrogen of 2 USD/kg by 2030 is an ambitious target that, once reached, would make clean hydrogen a commercially viable alternative to fossil fuels and hydrogen produced with unabated emissions, the current industry standard. This can be reached by identifying and addressing innovation needs in the international hydrogen landscape. Reaching this target also depends on the input fuel costs (e.g. renewable electricity), the price of which cannot be reduced by technological innovation.

The Carbon Trust was commissioned by the UK Government, as one of the co-leads of the Clean Hydrogen Mission, to conduct desktop research and lead two international, expert-level, consultation workshops to identify key global R&I priorities and challenges in the hydrogen sector, with a specific focus on production. This report intends to inform the Clean Hydrogen Mission's COP26 Discussion Paper and recommend broad

[1] This is the definition of clean hydrogen given in the Mission Innovation 2.0 Clean Hydrogen Mission's Joint Mission Statement. However, governments and industry use a variety of definitions for clean hydrogen, with a lack of consistent analysis methodology. .

[2] Methodology for Determining the Greenhouse Gas Emissions Associated With the Production of Hydrogen, International Partnership for the Hydrogen Economy, October 2021.

[3] The "end-to-end" cost of hydrogen (sometimes referred to as the "delivered" cost) is defined by the Clean Hydrogen Mission as the cost of hydrogen paid by the user. This includes the production, storage and distribution costs of hydrogen.

areas of innovation for all co-leads of the Clean Hydrogen Mission to consider. Correspondingly, a high-level and qualitative approach has been used.

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-uses. 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, this project focussed 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 with 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 it; the urgency with which an innovation should be deployed to support the 2030 cost target; and the level of activity already occurring.

Prioritised Innovation Needs

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 cost 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 design 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**, Innovation should be initially targeted at the electrochemical components as 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.

In summary, this work has identified broad areas of innovation for NGR + CCS and low carbon electrolysis and suggested a priority order in which to address them. The nature of this report has been high-level and intended as a preliminary document for the Clean Hydrogen Mission to use when taking the next steps towards shaping its COP26 Discussion Paper and programme of activities. It is left to the Clean Hydrogen Mission’s discretion to decide on specific areas of innovation as it sees fit.

Introduction

In the wake of the Paris Agreement and countries legislating on net zero emissions targets, decarbonisation has become of paramount importance. Clean hydrogen, which includes renewables-based hydrogen, other low carbon electricity-based hydrogen and fossil-based hydrogen with carbon capture and storage[4], is a versatile energy vector that can be used to decarbonise industrial processes, power, transport, and heating systems. However, the benefits of using hydrogen extend far beyond decarbonising individual sectors to increasing energy resilience, improving integration of renewable energy into existing systems and enhancing energy system flexibility. Consensus has not been reached on the definition of clean hydrogen and the International Partnership for the Hydrogen Economy (IPHE) is working towards an internationally agreed upon methodology to define the greenhouse gas emissions associated with the production of clean hydrogen. Viewed comprehensively, clean hydrogen can help the transition to clean energy systems, playing an important complementary and enabling role to electrification. This will be especially crucial in sectors where electrification is not feasible or is too costly, for example, when decarbonising industrial processes[5]. Harnessing this potential of clean hydrogen is the focus of Mission Innovation 2.0 Clean Hydrogen Mission.

Mission Innovation 2.0 aims to bring together governments, public authorities, corporates, investors and academia to strengthen global cooperation on clean energy innovation. As the main intergovernmental platform, Mission Innovation has become a catalyst for action and investment in research, development and innovation to reduce the cost of clean energy and make it globally accessible. As part of Mission Innovation 2.0, the Clean Hydrogen Mission is working with partner initiatives and organisations to increase the cost-effectiveness of clean hydrogen to the end-user by reducing its end-to-end[6] cost to 2 USD/kg by 2030. This cost represents a tipping point with the potential to drive economies of scale and reduce costs further, therefore enabling clean hydrogen to play a complementary role to other clean energy vectors in driving net zero. Achieving a cost for clean hydrogen of 2 USD/kg by 2030 is an ambitious target that, once reached, would make clean hydrogen a commercially viable alternative to fossil fuels and hydrogen produced with unabated emissions, the current industry standard. This can be reached by identifying and addressing innovation needs in the international hydrogen landscape. Reaching this target also depends on the input fuel costs, e.g. renewable electricity, the price of which cannot be reduced by technological innovation.

Research and innovation (R&I) - including investment in technologies, skills, infrastructure, knowledge generation and sharing, and stakeholder engagement - will be vital to reducing the cost of clean hydrogen and driving technological breakthroughs. Clear policy support for clean hydrogen and promoting innovation

[4] This is the definition of clean hydrogen given in the Mission Innovation 2.0 Clean Hydrogen Mission's Joint Mission Statement. However, governments and industry use a variety of definitions for clean hydrogen, with a lack of consistent analysis methodology. For example, the EU's taxonomy for sustainable activities definition of clean hydrogen is 3kgCO_{2eq}/kg. The Clean Hydrogen Mission's definition will be used in this Discussion Paper.

[5] Element Energy and Jacobs, 2018. Industrial Fuel Switching Market Engagement Study: Final report for Business, Energy & Industrial Strategy Department

[6] The "end-to-end" cost of hydrogen (sometimes referred to as the "delivered" cost) is defined by the Clean Hydrogen Mission as the cost of hydrogen paid by the user. This includes the production, storage and distribution costs of hydrogen.

can further accelerate the development and demonstration of better technologies and remove barriers to their adoption. An appropriate policy environment that generates positive market signals and fosters strong partnerships between relevant stakeholders will help near-to-market innovations in clean hydrogen to play a critical role in decarbonising global energy systems. However, new technologies and processes have longer lead times and therefore urgent action to identify and address key R&I priorities and challenges will be needed now to achieve the Clean Hydrogen Mission's goal.

In keeping with the Clean Hydrogen Mission's objectives to "increase the cost-competitiveness of clean hydrogen by reducing end-to-end costs to 2 USD/kg by 2030" and "catalyse cost reductions by increasing research and development in hydrogen technologies and industrial processes […] to unleash a global clean hydrogen economy"[7], its Members have been leading targeted activities across the topics shown in Figure 1[8]. 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. These innovation needs are targeted at achieving the Clean Hydrogen Mission's goal of an end-to-end cost of 2 USD/kg for clean hydrogen by 2030[9]. Ultimately, this report will support the Clean Hydrogen Mission in its creation of an Action Plan of activity from now up until 2030.

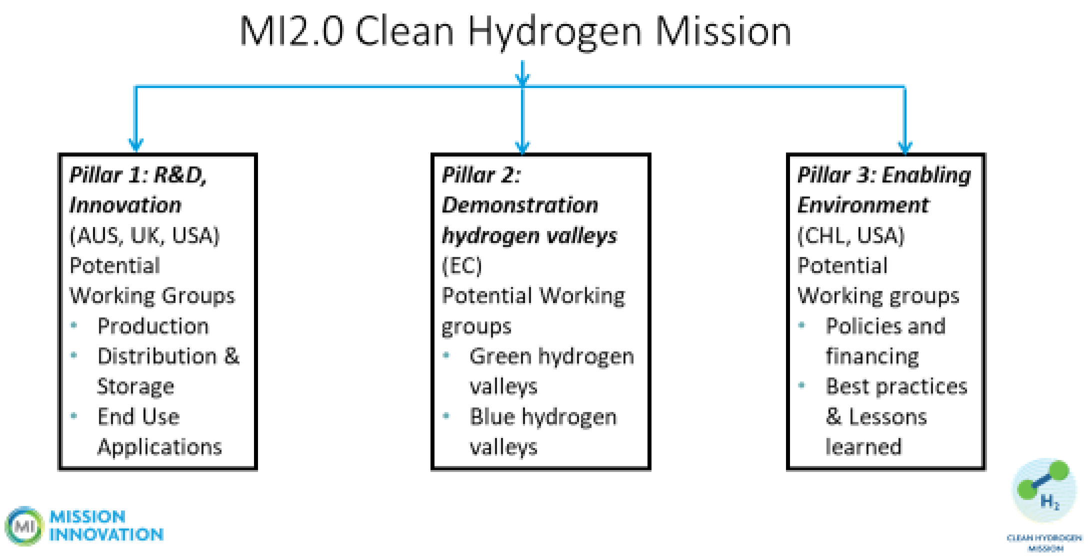

Figure 1: Mission Innovation 2.0's Clean Hydrogen Mission Pillars.

Hydrogen can be produced using several different processes, namely: thermochemical, electrolytic, photolytic and biological (see Table 1). The two main routes to produce clean hydrogen covered in this

[7] Mission Innovation, 2021. Clean Hydrogen Mission

[8] Please visit Mission Innovation's page on the Clean Hydrogen Mission for more details of the activities being carried out by the Mission Coalition.

[9] This is one of the Clean Hydrogen Mission's two targets; the second of which is to deploy 100 hydrogen valleys by 2030.

report are natural gas reformation with carbon capture and storage (NGR + CCS) and low carbon electrolysis. According to the IEA, approximately 60% of global hydrogen is produced via NGR[10]. It is the primary method of production. However, the carbon dioxide (CO_2) emissions from this process are typically unabated[11]. Less than 5% of hydrogen is produced by electrolysis[12]. A global shift to low carbon hydrogen is required to accelerate decarbonisation efforts and the creation of a global, clean hydrogen marketplace. Governments around the world are facilitating this in different ways, including through the work of the Clean Hydrogen Mission.

In light of the Clean Hydrogen Mission's 2030 target, this project focussed 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: NGR + CCS and low carbon electrolysis.

The Clean Hydrogen Mission's goal of an end-to-end cost of 2 USD/kg by 2030 should be achieved in order to make NGR + CCS and low carbon electrolysis commercially viable when compared to cheaper, unabated SMR and other high-carbon fuels [13]. The most efficient way to do this is by targeting innovation at hydrogen production because, whilst storage and distribution contribute to the end-to-end cost, production is the highest cost component across most regions and end-uses[14]. 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[15]. This report will therefore primarily focus on identifying the innovation needs in hydrogen production.

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10 59% of NGR hydrogen production is unabated. The emissions from 1.1% of NGR hydrogen production are captured with CCS.

11 IEA, 2021. Global Hydrogen Review 2021

12 IEA, 2020. The Future of Hydrogen: Seizing today's opportunities

13 Mission Innovation, 2021. Clean Hydrogen Mission

14 Hydrogen Council, 2020. Path to hydrogen competitiveness: A cost perspective; Energy Transitions Commission, 2021. Making the Hydrogen Economy Possible: Accelerating Clean Hydrogen in an Electrified Economy; BloombergNEF, 2020. Hydrogen Economy Outlook: Key messages

15 Hydrogen Council, 2020. Path to hydrogen competitiveness: A cost perspective

Table 1: Different methods of clean hydrogen production[16].

		Hydrogen Production Route	Description
Natural Gas Reformation (NGR)		Steam methane reforming with CCS (SMR + CCS)	In this process, methane and steam are input into a reactor, where hydrogen and carbon dioxide are generated at the end of three sequential reactions. The output gas enters a post-combustion carbon capture system, where the carbon dioxide generated in the SMR reactor is removed and subsequently stored, leaving low-carbon hydrogen.
		Autothermal reforming with CCS (ATR + CCS)	ATR is a low-carbon hydrogen production route in which a hydrocarbon feedstock (usually natural gas) is reacted with oxygen and steam to produce hydrogen and carbon dioxide. The carbon dioxide from this synthesis gas can be captured and stored by either a pre- or post-combustion carbon capture system. ATR is similar to SMR as both are natural gas reformation technologies, however ATR is now being proposed as the preferred technology for new low-carbon hydrogen production facilities because it allows for a higher percentage of carbon dioxide emissions to be captured compared to conventional SMR.
		Autothermal reforming with gas-heated reforming and CCS (ATR + GHR + CCS)	This production route follows the same process as ATR + CCS, however the addition of GHR technologies produces a synthesis gas with a higher hydrogen-to-carbon dioxide ratio. This is achieved by increasing the ratio between steam reforming and partial oxidation and, consequently, the percentage of carbon dioxide that can be captured and stored is maximised.
Electrolysis	Low-carbon electrolysis	Renewable electrolysis	Electrolysis is the process of using electricity to split water modules into hydrogen and oxygen in an electrolyser – equipment consisting of an anode and a cathode separated by an electrolyte. There are different types of electrolyser, typically differentiated by the material used for the electrolyte, however they all produce hydrogen. When electricity from renewable resources is used, electrolysis provides a route for carbon-free hydrogen production.

[16] Energy Transitions Commission, 2021. Making the Hydrogen Economy Possible: Accelerating Clean Hydrogen in an Electrified Economy

		Nuclear-powered electrolysis	Here, the process of hydrogen production from electrolysis is as outlined above, however the electricity required for electrolysis is provided by nuclear power. Although this route produces carbon-free hydrogen, it has been differentiated from electrolysis using renewable electricity due to other environmental implications associated with nuclear power.
	Variable-carbon electrolysis	Grid-powered electrolysis[17]	Similarly, the process of hydrogen production from electrolysis is as outlined above, but the electricity required for electrolysis is provided by the grid instead of renewable resources. Although this significantly reduces the cost of hydrogen production, this route does not always output clean hydrogen because the carbon intensity of the grid may be higher than the clean hydrogen threshold.
Biomass gasification with CCS (BECCS) **Not in scope of this report[18]**		Biomass gasification with CCS (BECCS)	Biomass gasification is the process of converting renewable, organic resources (i.e. biomass) into hydrogen and carbon dioxide using high temperatures and a supply of oxygen and/or steam. The resultant bioenergy enters a post-gasification carbon capture process, where the carbon dioxide is captured and stored, leaving clean hydrogen as the output. Additionally, because some biomass sources will absorb carbon dioxide during their lifetime, BECCS can result in negative emissions of carbon dioxide.

[17] The carbon intensity of grid-powered electrolysis depends on the carbon intensity of the electricity in the grid used to power the process. This can be low-carbon. As such, many of the innovation needs identified for low carbon electrolysis can be applied to grid-powered electrolysis.
[18] BECCS has not been included in the scope of this report because, in light of the Clean Hydrogen Mission's goal of achieving an end-to-end cost of 2 USD/kg for clean hydrogen by 2030, looking at more developed hydrogen production methods has been prioritised.

1. Methodology

This project was carried out in four stages:

- A cost baseline for the current and projected costs of hydrogen produced via NGR + CCS and low carbon electrolysis was formulated.
- Innovation needs for NGR + CCS and low carbon electrolysis were identified and categorised.
- The innovation needs were prioritised using a bespoke framework.
- The identified and prioritised innovation needs, alongside the prioritisation framework, were verified and refined by sector experts during two workshops.

The approach to these stages has been outlined below.

1.1 Cost Baseline

An analysis of four reports[19] was carried out to estimate the current and future cost of hydrogen produced by NGR + CCS and low carbon electrolysis[20]. These reports were chosen due to their alignment with the Clean Hydrogen Mission's global scope[21] and the authoring organisation's expertise and credibility. The maximum and minimum values provided in these reports for the cost of hydrogen today and the predicted costs for 2030 and 2050, were shown on a graph to illustrate the cost baseline for each of these time periods. The cost baseline generated can be seen in Figure 2. This cost baseline was crucial to view the long-term trajectory of the cost of hydrogen produced via NGR + CCS and low carbon electrolysis, and to understand the pace at which innovation would be required to achieve the Clean Hydrogen Mission's target of 2 USD/kg by 2030. The cost baseline was also used to verify if there was consensus in the hydrogen sector on whether a cost of 2 USD/kg by 2030 was realistic.

[19] The reports were: The Energy Transitions Commission's "Making the Hydrogen Economy Possible: Accelerating Clean Hydrogen in an Electrified Economy" (2021), BloombergNEF's "Hydrogen Economy Outlook: Key messages" (2020), The International Renewable Energy Agency's "Hydrogen: A renewable energy perspective" (2019), and The Hydrogen Council's "Path to hydrogen competitiveness: A cost perspective" (2020). Please refer to these reports for further details on the calculation methodology employed by each.

[20] Please note, the values given by these reports were specific to SMR + CCS and renewable electrolysis and, therefore, the cost baseline is specific to these subdivisions of NGR + CCS and low carbon electrolysis, respectively. The terminology used in Section 2 reflects this.

[21] The Clean Hydrogen Mission has a global scope, but the costs of hydrogen from NGR + CCS and low carbon electrolysis are highly region-specific. Therefore, to ensure that the baseline created was specific to the Clean Hydrogen Mission, only values from reports with a global scope were used.

1.2 Identifying Innovation Needs

The innovation needs for NGR + CCS and low carbon electrolysis were initially identified through desktop research. Innovation needs which were deemed most relevant to the Clean Hydrogen Mission in light of its goal to achieve an end-to-end cost of 2 USD/kg for clean hydrogen by 2030 and its focus on international, collaborative R&I were selected for a longlist. These innovation needs were compiled from reports and hydrogen literature from governments and multi-laterals (which have been referenced throughout)[22]. Clearly defined, solutions-focused, technological innovations were identified for a shortlist (e.g. "re-characterising of old wells"), whereas higher-level, less specific gaps requiring innovation were referenced in-text (e.g. "improving techniques and processes for CCS"). This distinction was made to highlight innovations that can be actioned quickly, in light of the Clean Hydrogen Mission's 2030 targets, whilst also recognising areas requiring innovation but which need more initial research and development.

The shortlisted innovation needs were then categorised. For NGR + CCS, the innovation needs were grouped into the following:

- **Carbon storage capabilities** – innovation addressing the identification and/or development of carbon stores and the minimisation of carbon dioxide leakage.
- **Process materials** – innovation concerning reducing use and/or cost of the materials comprising the reformation and carbon capture units.
- **Carbon capture capabilities** – innovation aimed at improving the carbon capture process efficiency, technology, and/or carbon capture processes themselves in order to increase the percentage of carbon dioxide captured.
- **Process technology** – innovation related to maximising the hydrogen yield by designing/integrating new technologies into the process or finding the optimal reaction sequencing.

For low carbon electrolysis, the innovation needs were grouped into the following:

- **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.
- **Electrolyser production** – innovation aimed at increasing the efficiency and reducing the cost of the electrolyser manufacturing processes.
- **Electrochemical engineering –** innovation targeting electrolyser design and integration into the wider energy system.

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[22] Whilst factors influencing the cost of hydrogen are location dependent, innovation needs for hydrogen production routes are not. As a result, innovation needs from region-specific stakeholders were included here. The reports referenced can be seen in the Annex.

- **Electrolysis process** - innovation targeting the reactions and processes comprising electrolysis to optimise the hydrogen yield and reduce the electricity consumed.

1.3 Prioritising Innovation Needs

The categorised innovation needs for NGR + CCS and low carbon electrolysis were prioritised using a framework considering the following factors:

- How impactful an innovation would be at reducing the cost of clean hydrogen to 2 USD/kg.
- How much international collaboration would be required to progress an innovation.
- The urgency with which an innovation needs to be deployed, i.e. whether the innovation would be required within the next 1 – 3 years so that it has time to be developed, tested and proved at scale before coming online and delivering cost savings for clean hydrogen production by 2030.
- The level of activity already occurring concerning the innovation, and the subsequent additionality of activity from the Clean Hydrogen Mission.

Each of the innovation categories was qualitatively assessed and given a rating of red, amber or green (RAG) against each metric.

Table 2: Overview of how the impact metric was assessed and what the RAG ratings mean.

How impactful is the innovation to reducing the end-to-end cost of hydrogen to 2 USD/kg by 2030?			
Assessed based on the **number of innovation needs identified in a category** (a higher number of innovation needs might suggest more impact), **frequency of mentions in select literature**[23] (higher mentions might suggest more consensus over impact), and **input from workshop attendees**.	Addressing the innovation needs category will likely have a high impact on cost reduction efforts.	Addressing the innovation needs category will likely have a medium impact on cost reduction efforts.	Addressing the innovation needs category will likely have a low impact on cost reduction efforts.

[23] Reports from credible sources were referred to exclusively.

Table 3: Overview of how the international collaboration metric was assessed and what the RAG ratings mean.

Would international R&D collaboration be additional to progressing this innovation?			
Assessed based on whether the innovation need scope was **clearly defined** and **how easily an innovation could be replicated** once implemented (more ambiguous and/or complex innovations which cannot be easily replicated might suggest international collaboration will be helpful and/or necessary). Also assessed based on **requirements for international territory** (requirements for international space suggests international collaboration will be helpful and/or necessary).	International collaboration will likely be helpful and/or necessary for the innovation needs category to be addressed.	International collaboration could be helpful and/or necessary for the innovation needs category to be addressed.	International collaboration is less likely to be helpful and/or necessary for the innovation needs category to be addressed.

Table 4: Overview of how the timeliness metric was assessed and what the RAG ratings mean.

Does this innovation need to happen within the next 1 – 3 years in order to reach the 2030 cost target?			
Assessed based on **how quickly an innovation need would precipitate cost reductions** leading to onset economies of scale by 2030[24], and whether an innovation need would **reduce CAPEX** directly or otherwise, leading to economies of scale (as economies of scale are typically accompanied by significant cost reductions).	Addressing the innovation needs category in the next 1 – 3 years will likely be instrumental in enabling the Mission to reach its cost target by 2030.	Addressing the innovation needs category in the next 1 – 3 years may be instrumental in enabling the Mission to reach its cost target by 2030.	Addressing the innovation needs category in the next 1 – 3 years is unlikely to be instrumental in enabling the Mission to reach its cost target by 2030.

[24] Creating longer lead times to grow economies of scale will give the Mission the greatest opportunity to maximise the cost reduction benefits available ahead of the 2030 time limit.

Table 5: Overview of how the additionality metric was assessed and what the RAG ratings mean.

What level of activity is already taking place in the sector?			
Assessed based on the **frequency** with which the **innovation needs were referenced in literature** (a higher frequency might suggest more activity) and **input from the sector experts** during the workshops.	There is not much activity taking place in the sector, so activity from the Mission is likely to be additional.	There is some activity taking place in the sector, so activity from the Mission may (or may not) be additional.	There is considerable activity taking place in the sector, so activity from the Mission is unlikely to be additional.

The category of innovation needs with the highest number of green-rated and lowest number of red-rated metrics was classified as the highest priority. Conversely, the category of innovation needs with the highest number of red-rated and lowest number of green-rated metrics was classified as the lowest priority. This prioritisation does not infer the lower-priority categories are unimportant, but rather that the higher-priority categories should be prioritised by the Clean Hydrogen Mission based on the international nature of R&I it fosters, and its end-to-end cost target of 2 USD/kg for clean hydrogen by 2030. A low priority ranking suggests that other sector actors (e.g. governments, industrial stakeholders etc) are likely to be better positioned to address these innovation needs. As this piece of work is a high-level preliminary assessment, the approach used was correspondingly high-level.

1.4 Stakeholder Workshops

The identified and prioritised innovation needs, alongside the prioritisation framework, were presented to industry leaders and innovators, representing the full hydrogen value chain, via two workshops[25]. The two workshops engaged with sector experts from the UK and across Europe. Here, the innovation needs and their prioritisation were verified or refined. This stage was crucial to equip members of the Clean Hydrogen Mission with an accurate, informed list of prioritised innovation needs.

[25] See the Annex for information on the workshop participants.

2. Cost Baseline

The Clean Hydrogen Mission's goal of an end-to-end cost of 2 USD/kg by 2030 is a stretch target. This cost represents a tipping point in unlocking the potential for clean hydrogen to reduce global emissions, where clean hydrogen would be cost competitive with other energy vectors across production, transportation, storage and end-use. Achieving this stretch target will drive economies of scale and reduce costs further, thus catalysing the development of a global clean hydrogen economy. Today, the cost of hydrogen produced by unabated SMR is between 1 USD/kg and 2 USD/kg[26]. As these figures don't include storage and transportation costs, the hydrogen industry believes that clean hydrogen can be cost competitive with hydrogen produced by unabated SMR and other energy vectors once an end-to-end cost of 2 USD/kg is achieved[27].

The different components (i.e. production costs, storage costs and distribution costs) contributing to the end-to-end cost of clean hydrogen are discussed below.

2.1 Global Production Costs

Using the method outlined in Section 1.1, the current cost and predicted costs for 2030 and 2050 of hydrogen produced via SMR + CCS and renewable electrolysis were identified. These values have been displayed in Figure 2. Additionally, Figure 2 shows that the current cost of hydrogen from renewable electrolysis has a much bigger spread and is generally higher than SMR + CCS. The differences in cost between these production routes are a result of the regional variations in the cost of gas and carbon storage, the carbon price for SMR + CCS and the cost of electricity for renewable electrolysis[28]. All of these factors vary globally by location.

Figure 2 shows that SMR + CCS and renewable electrolysis reach cost parity by 2030. This is probably because policy decisions will continue to evolve in support of lower carbon solutions, causing the cost of renewable electricity and electrolysis to decrease. On the other hand, solutions with higher carbon intensities will become more expensive due to the rising cost of carbon. Despite this, SMR + CCS is likely to still be important for many countries near term to transition to a clean hydrogen economy, as the rapid economies of scale SMR + CCS can achieve have the potential to provide the foundation for other clean hydrogen production routes to be deployed cost-competitively at scale[29]. However, this will depend on national priorities and policy decisions in each country.

[26] IEA, 2020. Hydrogen production costs using natural gas in selected regions, 2018
[27] Mission Innovation, 2021. Clean Hydrogen Mission; IEA, 2020. The Future of Hydrogen: Seizing today's opportunities;
[28] Hydrogen Council, 2020. Path to hydrogen competitiveness: A cost perspective
[29] Oxford Institute for Energy Studies, 2020. Blue hydrogen as an enabler of green hydrogen: the case of Germany

Although the lower bound of the price for hydrogen produced by SMR + CCS and renewable electrolysis appear to be equal by 2030, it is possible that actual prices will differ. Analysis from the UK's Climate Change Committee suggests the stagnation in cost reduction of hydrogen produced by SMR + CCS could be a result of the predicted increase in the cost of gas and carbon, which could cause the cost of hydrogen produced by SMR + CCS to increase by 2% a year on average from 2025 to 2040[30]. However, this may vary across regions, based on local gas costs, carbon prices, and the wider policy landscape.

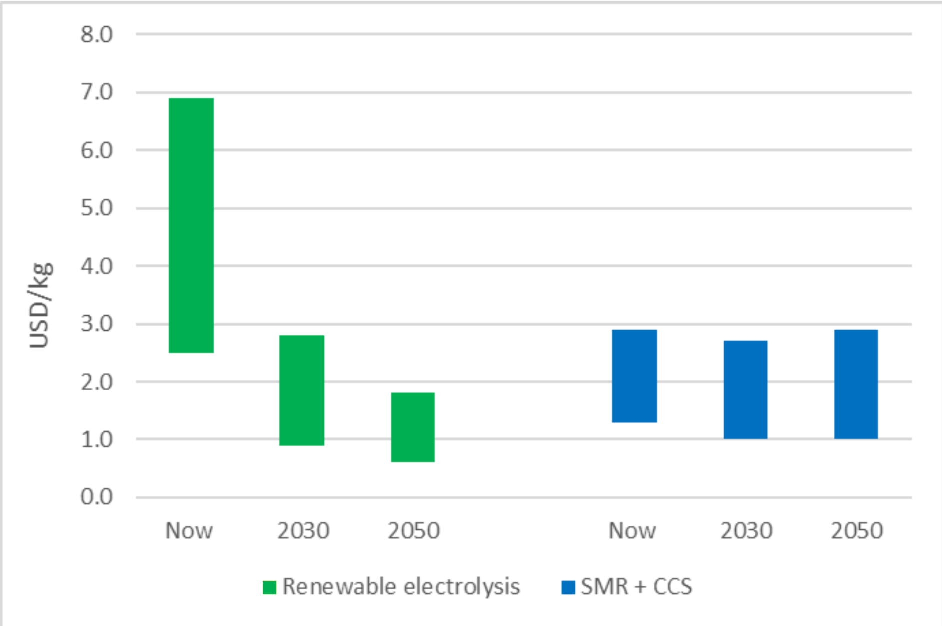


Figure 2: The production cost of hydrogen from renewable electrolysis and SMR + CCS in three timeframes: today, 2030 and 2050.

Based on the projected costs of hydrogen production shown in Figure 2, an end-to-end cost of 2 USD/kg by 2030 is achievable[31]. However, innovation gaps must be addressed. This is possible through innovation and demonstration, two of the Clean Hydrogen Mission's Pillars. As such, the work of the Clean Hydrogen Mission will be crucial in unlocking the end-to-end cost reductions available through innovation.

Biomass gasification with CCS (BECCS) is likely to be another key production route in the clean hydrogen economy but is less likely to contribute to the Clean Hydrogen Mission's cost target of 2 USD/kg by 2030. Some of the most recent figures available on the predicted cost of hydrogen via BECCS are available in a report by BEIS. Whilst this report focuses on the UK, the up-to-date data made it an attractive source. This report concluded that in the UK, the expected cost of hydrogen via BECCS will be between 3.31 USD/kg and

[30] Climate Change Committee, 2018. Hydrogen in a low-carbon economy; As this report is being written (October 2021), there is a shortage of gas globally leading to rising gas prices. The long-term cost implications of this crisis are still unclear.

[31] Please see The Energy Transitions Commission's "Making the Hydrogen Economy Possible: Accelerating Clean Hydrogen in an Electrified Economy" (2021), BloombergNEF's "Hydrogen Economy Outlook: Key messages" (2020), The International Renewable Energy Agency's "Hydrogen: A renewable energy perspective" (2019), and The Hydrogen Council's "Path to hydrogen competitiveness: A cost perspective" (2020) for more details on the assumptions and conditions used in each report to generate cost figures.

5.75 USD/kg by 2030[32], excluding storage and distribution costs. Please note that, whilst these cost predictions are specific to the UK, it is likely that regions with comparable resources will achieve similar costs. Regions that have different resources may end up with different production costs. As this report is focused on innovation for hydrogen production that can bring end-to-end costs down to 2 USD/kg by 2030, BECCS was deemed out of scope.

2.2 Global Storage and Distribution Costs

As shown in Figure 3[33] and Figure 4[34], the majority of the end-to-end cost of hydrogen across different regions and end uses comes from hydrogen production. Consequently, across most scenarios, the largest opportunities for cost reduction lie in reducing the cost of clean hydrogen production.

However, in some cases (particularly in transport applications), storage and distribution can contribute significantly to the end-to-end cost for decentralised end-uses, as shown in Figure 4[35]. This approach is one that is already widely utilised today, as currently, there is limited large-scale hydrogen infrastructure for storage and distribution as most hydrogen use is captive (i.e. production assets are co-located with end-use applications).

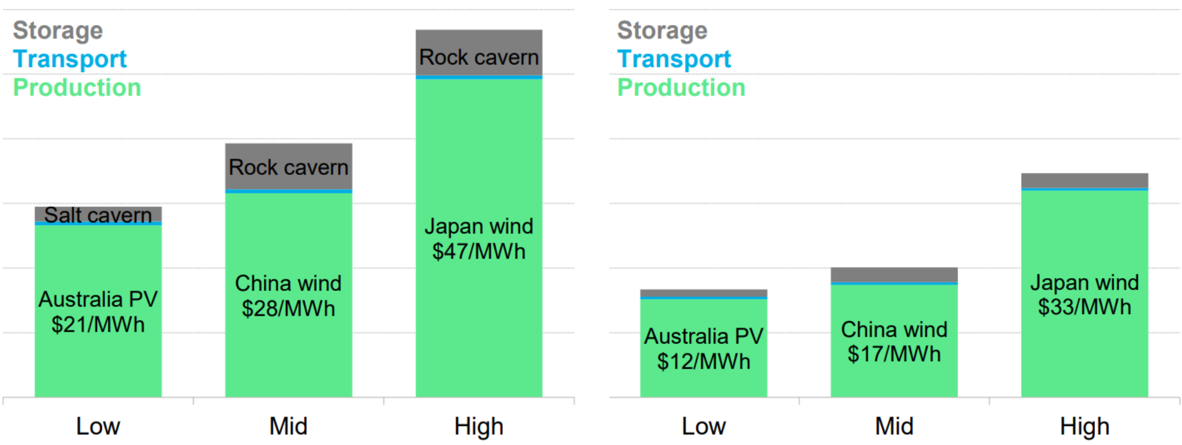
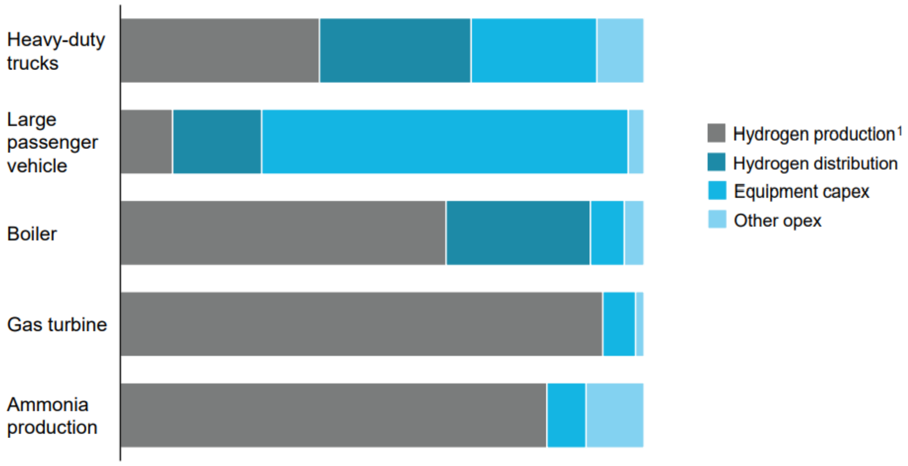


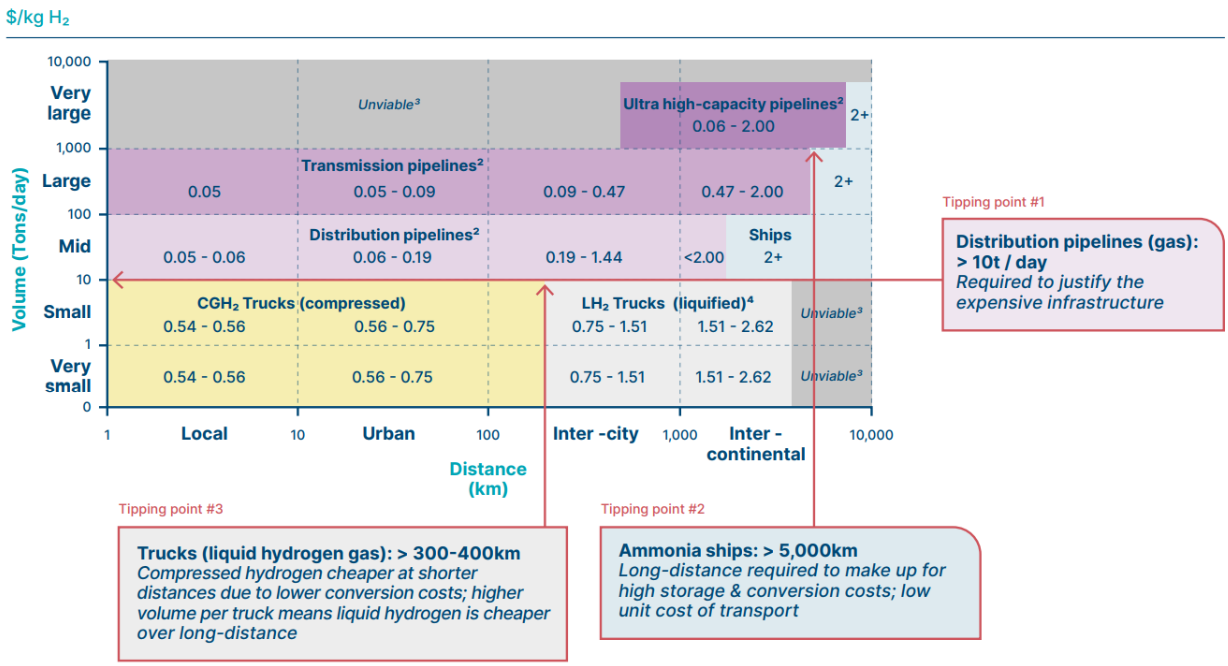
Figure 3: Predicted large scale end-to-end cost of hydrogen produced by renewable electrolysis based on different electricity costs (shown) in different locations and delivered to industrial users. The graph on the left and right show the predicted cost for 2030 and 2050, respectively. (Modified from BloombergNEF, 2020)

[32] UK Government's Department for Business, Energy and Industrial Strategy, 2021. Hydrogen Production Costs 2021
[33] BloombergNEF, 2020. Hydrogen Economy Outlook: Key messages
[34] Hydrogen Council, 2020. Path to hydrogen competitiveness: A cost perspective
[35] Hydrogen Council, 2020. Path to hydrogen competitiveness: A cost perspective



1. Assumes 50/50 blend of low-carbon and average renewable hydrogen

Figure 4: Cost breakdown of hydrogen applications. Costs are shown as a proportion of the total cost in 2020 (Modified from Hydrogen Council, 2020)



NOTE: [1] Including conversion and storage; [2] Assumes salt cavern storage for pipelines; [3] Ammonia assumed unsuitable at small scale due to its toxicity; [4] While LOHC (liquid organic hydrogen carrier) is cheaper than liquid hydrogen for long distance trucking, it is unlikely to be used as it is not commercially developed.

Figure 5: Lowest cost form of hydrogen transportation (including conversion and storage) based on volume and distance (Energy Transitions Council, 2021)

There are different modes of hydrogen distribution, including pipelines, trucking, shipping and rail. The most appropriate distribution method is dependent on the production method and end-use. Similarly, there are different modes of hydrogen storage, including salt caverns, canisters, tanks and undersea storage in disused oil and gas fields. Each method of distribution and storage will have different contributions to the end-to-end cost of hydrogen in different scenarios, as shown in Figure 5[36].

Whilst an overview of innovation needs concerning the storage and distribution of hydrogen has been presented in Section 3.3 of this report, this project focuses on the innovation needs in hydrogen production because it is usually the largest contributor to the end-to-end cost of clean hydrogen[37] (see Figure 3) and so an in-depth cost analysis of storage and distribution has not been carried out for this report.

[36] Energy Transitions Commission, 2021. Making the Hydrogen Economy Possible: Accelerating Clean Hydrogen in an Electrified Economy

[37] Energy Transitions Commission, 2021. Making the Hydrogen Economy Possible: Accelerating Clean Hydrogen in an Electrified Economy; BloombergNEF, 2020. Hydrogen Economy Outlook: Key messages; Hydrogen Council, 2020. Path to hydrogen competitiveness: A cost perspective.

3. Innovation Needs

Due to the nascent nature of the hydrogen sector, there are a variety of innovation needs in NGR + CCS and low carbon electrolysis that could be addressed to reduce the cost of clean hydrogen. These cost reductions are primarily driven by technological learning, learning-by-doing, and creating economies of scale[38]. It is worth noting that the nature of the internationally collaborative approach adopted by the Clean Hydrogen Mission creates the option for the Mission to join up with and support/be supported by other forums facilitating international collaboration[39]. However, this was not factored into the identification or prioritisation of innovation needs for the Clean Hydrogen Mission to address.

The innovation needs identified for hydrogen produced by NGR + CCS and low carbon electrolysis have been detailed in this section, with an emphasis on technological innovation. However, innovation needs in storage and distribution have also been provided, alongside non-technological innovations concerning policy, standards and regulations. Whilst production innovation will be crucial to reducing costs (as evidenced in Section 2), the nascency of the hydrogen sector means different types of innovation are required along the value chain to unlock further cost reductions. These innovation needs are out of scope for this piece of work and have therefore not been explored in as much depth as production innovation needs, but they have been included in this report to provide a more comprehensive view of the hydrogen innovation landscape.

3.1 Natural Gas Reformation with Carbon Capture and Storage (NGR + CCS)

Currently, SMR is the standard industry production route of hydrogen, where the site of production is largely co-located with end use. However, ATR + CCS offers a more cost-effective production route due to its higher rate of carbon dioxide capture[40]. In light of this, some experts believe that new hydrogen production assets should use ATR + CCS, while other sector experts believe new SMR + CCS assets should still be built. It is therefore likely that new ATR + CCS and SMR + CCS hydrogen production plants will be built as well as existing SMR assets being retrofitted with CCS technologies. The Energy Transitions Council estimate that, by 2025, over 150 SMR + CCS projects are likely to be in early development and, by 2030, over 50% of unabated SMR plants will be converted to SMR + CCS plants[41]. Through this combination of retro-fitting and new production assets, well-established, stable demand centres (likely to be found in the industrial sector)

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[38] UK Government's Department for Business, Energy and Industrial Strategy, 2021. Hydrogen Production Costs 2021

[39] For example, the CEM Hydrogen Initiative could offer useful, enlarged testing beds, and the IPHE's methodology work and contributors may provide helpful inputs on topics such as leakage and carbon capture.

[40] ATR + CCS can be cheaper hydrogen production route than SMR + CCS, because a higher degree of separation between the hydrogen and carbon dioxide molecules is achieved during the process. Money is consequently saved as SMR + CCS requires higher levels of purification and incurs higher levels of hydrogen loss.

[41] Energy Transitions Commission, 2021. Making the Hydrogen Economy Possible: Accelerating Clean Hydrogen in an Electrified Economy

can then act as a nucleator for the hydrogen economy and subsequently provide the foundation for new clean hydrogen production methods to be deployed at scale[42].

The UK Government's report, "Hydrogen production costs", indicates that the scope for cost reduction in SMR + CCS is limited compared to the scope to reduce the cost of ATR + CCS because SMR is an older and more established technology[43]. This suggests that innovation should also mainly target new ATR + CCS assets. The consensus among experts is that innovation needs in policy, regulations and standards are the biggest barriers to cost parity. However, technological innovation needs are still important to cost reduction.

Because both SMR + CCS and ATR + CCS are natural gas reformation processes integrated with carbon capture, the innovation needs concerning SMR + CCS are also largely applicable to ATR + CCS. Technological innovation needs for both production routes include:

- **Finding/developing alternative materials to use** instead of expensive, rare materials.
- **Developing ways to recycle process materials.**
- **Re-characterising** of **old wells**[44]**.**
- **Developing processes with advanced solvents** which has the potential to reduce catalyst regeneration costs and corrosion effects, therefore preventing product degradation.
- **Developing fuel cells** (e.g. molten carbonate fuel cells) **to enhance post-combustion capture processes.**
- **Deploying sub-sea installations instead of platforms** to enhance carbon storage capabilities[45].
- **Thermal and mechanical integration of gas heated reforming**, which can reduce costs for improving efficiency and optimising separation processes.
- Deployment of technologies such as **ceramic membranes for sorption-enhanced water-gas shift** to provide high-purity hydrogen streams[46].

Some additional innovation needs identified by industry experts in the workshops were:

- **Optimising the process of separating carbon dioxide and hydrogen**, thereby **optimising carbon capture rates.**
- **Improving hydrogen purification** at different points in the process, particularly at the end of the pipeline/point of dispensing.

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[42] Oxford Institute for Energy Studies, 2020. Blue hydrogen as an enabler of green hydrogen: the case of Germany
[43] UK Government's Department for Business, Energy and Industrial Strategy, 2021. Hydrogen Production Costs 2021
[44] Vivid Economics and partners, 2019. Energy Innovation Needs Assessment: Overview report
[45] Vivid Economics and partners, 2019 Energy Innovation Needs Assessment: Carbon capture, usage and storage
[46] Vivid Economics and partners, 2019. Energy Innovation Needs Assessment: Hydrogen & fuel cells

As highlighted in BEIS' Energy Innovation Needs Assessment[47], although ATR is an existing process, it is in an early stage of deployment in the hydrogen sector and, correspondingly, innovation is required for at-scale deployment with CCS in order to give investors the necessary confidence to invest in ATR + CCS assets. ATR + CCS-specific innovation needs include:

- **Including GHR in the deployment of ATR at scale** to maximise energy recovery, therefore reducing fuel costs.
- **Developing next generation, high pressure carbon dioxide pre-combustion capture technologies.**

These innovation needs listed were subsequently categorised into "Carbon storage capabilities", "Process materials", "Carbon capture capabilities" and "Process technology", where:

- **Carbon storage capabilities** – innovation addressing the identification and/or development of carbon stores and the minimisation of carbon dioxide leakage.
- **Process materials** – innovation concerning reducing use and/or cost of the materials comprising the reformation and carbon capture units.
- **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 carbon dioxide captured.
- **Process technology** – innovation related to maximising the hydrogen yield by designing/integrating new technologies into the process or finding the optimal reaction sequencing.

Whilst some innovation needs could arguably fit into two categories, the most appropriate category was identified so that each innovation need appears only once in the table. The categorised innovation needs were then prioritised and verified by sector experts during two workshops using the methodology described in Sections 1.3 and 1.4. The verified list of prioritised innovation needs is given in Table 6 (the original list of innovation needs can be seen in Annex A)[48]. Table 7 shows the completed framework for the NGR + CCS innovation needs, which provides the rationale for the prioritisation.

[47] Vivid Economics and partners, 2019. Energy Innovation Needs Assessment: Hydrogen & fuel cells
[48] Table 6 shows the updated list of innovation needs following input from the sector experts who attended the workshops.

Table 6: NGR + CCS innovation needs prioritised for the Clean Hydrogen Mission[49].

Highest priority ↑	**Carbon storage capabilities**	• Re-characterising of old wells. • Deploying sub-sea installations instead of platforms to enhance carbon storage capabilities.
	Process materials	• 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	• 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**	• 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.

[49] The list shown in this table is an abbreviated version of the full list on page 25. Please see page 25 for addition details (where available) on the innovation needs.

Table 7: RAG rated and prioritised NGR + CCS innovation needs.

	Assessment Criteria / Innovation Needs Category	How impactful is the innovation to reducing the end-to-end cost of hydrogen to 2 USD/kg by 2030?	Would international R&D collaboration be additional to progressing this innovation?	Does this innovation need to happen within the next 1 – 3 years in order to reach the 2030 cost target?	What level of activity is already taking place in the sector?
Highest priority	Carbon storage capabilities				
	Process materials				
	Carbon capture capabilities				
Lowest priority	Process technology				

Due to the high-level nature of this piece of analysis, innovation needs were prioritised in categories rather than individual innovation needs. The prioritised innovation needs categories and the innovation needs contained within each category (as can be seen in Table 6) were shown to an international group of sector experts for validation and the methodology was approved. There is an opportunity for future analysis to prioritise individual innovation needs, building on the prioritisation of innovation needs categories as carried out in this work.

The following tables show the RAG ratings of each of metrics for each innovation needs category.

How impactful is the innovation to reducing the end-to-end cost of hydrogen to 2 USD/kg by 2030?			
Carbon storage capabilities	Process materials	Carbon capture capabilities	Process technology

All of the innovation needs categories received a green rating for the impact metric because NGR + CCS was seen as key to rapid scale up of the hydrogen economy.

Would international R&D collaboration be additional to progressing this innovation?			
Carbon storage capabilities	Process materials	Carbon capture capabilities	Process technology

The innovation needs listed in the “Process materials”, “Carbon capture capabilities” and “Process technology” were seen as small and/or simple to varying degrees due to the clearly defined scope of the innovation needs (such as “Deployment of technologies such as ceramic membranes for sorption-enhanced water-gas shift” in “Process technology”) and/or the replicability of the deployment of the innovation needs (such as the innovation need “developing ways to recycle process materials” in “Carbon capture capabilities”), hence the amber/red ratings. The innovation needs in “Carbon capture capabilities” are more complex than those in “Process technology” and some of the innovation needs in “Process materials” have international considerations, leading to amber ratings rather than red. All of the innovation needs in “Carbon storage capabilities” have international considerations leading to a green rating.

Does this innovation need to happen within the next 1 – 3 years in order to reach the 2030 cost target?			
Carbon storage capabilities	Process materials	Carbon capture capabilities	Process technology
All of the innovation needs categories were ranked green for timeliness because, similar to the impact metric, NGR + CCS is expected to be crucial for a rapid scale up of the hydrogen economy. Scaling up is key to reducing costs before 2030, therefore all innovations targeting NGR + CCS should be prioritised.			

What level of activity is already taking place in the sector?			
Carbon storage capabilities	Process materials	Carbon capture capabilities	Process technology
Activity is taking place across all categories; however more was observed in the "Carbon capture capabilities" innovation needs category (such as "Optimising the process of separating carbon dioxide and hydrogen to enhance carbon capture rates") and "Process technology" innovation needs category (such as "Integration of gas heated reforming into the ATR process at scale") than "Carbon storage capabilities" and "Process materials". Consequently, intervention from the Mission on the latter two categories was not seen as additional.			

Consistent with the rationale above, the final prioritisation of the categories was:

1. **Carbon storage capabilities**
2. **Process materials**
3. **Carbon capture capabilities**
4. **Process technology**

Additional innovation needs specific to NGR + CCS which were less defined and, therefore, not shortlisted or categorised included:

- Improving **monitoring and pressure management of CCS assets.**
- Using technological developments to **improve the performance of absorbers**, which are the largest cost components of carbon capture units[50].

Additional, non-technological innovation needs that are specific to NGR + CCS include:

- **Full-scale demonstration of CCS in clusters** which span the hydrogen value chain (production, distribution, storage and end-use)[51].
- **Proving NGR + CCS at scale with high carbon capture rates** to de-risk technology scale-up and secure investment in new assets[52].

Operating costs of NGR plants also make a substantial contribution to the end-to-end cost of clean hydrogen. Thus, addressing innovation gaps in the running of the plant can unlock significant cost reductions, for example, via:

- **Optimising thermal energy use, water use and maintenance strategies.**
- **Deploying digital innovations** (e.g. artificial intelligence) to support predictive maintenance and automation[53].

3.2 Low carbon electrolysis

In 'Path to Hydrogen Competitiveness: A Cost Perspective'[54], the Hydrogen Council identifies three ways to reduce the cost of low carbon electrolytic hydrogen:

- The **industrialisation of electrolyser manufacturing** (responsible for up 25% of cost reductions between now and 2030).
- **Improvements in electrolyser efficiency, operations, and maintenance** (responsible for up to 10% of cost reductions between now and 2030).
- The use of **low-cost renewable electricity** (responsible for up to 20% of cost reductions between now and 2030)[55].

[50] Vivid Economics and partners, 2019. Energy Innovation Needs Assessment: Carbon capture, usage and storage
[51] Vivid Economics and partners, 2019. Energy Innovation Needs Assessment: Overview report
[52] Vivid Economics and partners, 2019. Energy Innovation Needs Assessment: Hydrogen & fuel cells; Vivid Economics and partners, 2019. Energy Innovation Needs Assessment: Carbon capture, usage and storage
[53] IEA, 2020. Energy Technology Perspectives 2020: Special Report on Carbon Capture, Utilisation and Storage
[54] Hydrogen Council, 2020. Path to hydrogen competitiveness: A cost perspective
[55] Hydrogen Council, 2020. Path to hydrogen competitiveness: A cost perspective

The Energy Transitions Commission has estimated the relative orders of magnitude required at a global level in 2025 and 2030 for hydrogen production to achieve an end-to-end cost of 2 USD/kg for clean hydrogen. It has been suggested that, by 2025, over 15 GW electrolyser capacity – equivalent to 10 large scale renewable electrolytic hydrogen clusters – could be installed. Following this trajectory, 200 GW electrolyser capacity could be installed by 2030, requiring over 40 operational electrolyser production factories greater than 2 GW[56]. However, the rapid ramp-up of clean hydrogen production cannot be achieved without addressing innovation gaps in low carbon electrolysis.

Similarly to the innovation needs of SMR compared to ATR, there are more opportunities for innovation of polymer electrolyte membrane (PEM) and solid oxide electrolysers compared to alkaline electrolysers as the latter is a more mature and established technology[57]. However, the innovation needs identified are largely applicable to all electrolysis technologies:

- **Faster ramping** of alkaline electrolysers[58].
- Creating **catalysts from less scarce materials** for alkaline electrolysers[59] and PEM electrolysers[60]. Examples of innovation include using low-titanium bipolar plates and low-platinum catalyst loading[61].
- Using **fewer critical materials in electrolyser stacks** which, similarly to changing catalyst materials, can lower end-to-end costs[62].
- Utilising **recovered waste heat** to increase process efficiency.
- **Recycling of electrolysers** to increase materials circularity and reduce the demand for new primary resources.
- **Integrating electrolysers with intermittent renewable assets** and other energy system components (such as the grid and batteries) to improve electrolyser utilisation and use electricity that would otherwise be curtailed[63].
- **Optimising catalyst loading.**

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[56] Energy Transitions Commission, 2021. Making the Hydrogen Economy Possible: Accelerating Clean Hydrogen in an Electrified Economy
[57] UK Government's Department for Business, Energy and Industrial Strategy, 2021. Hydrogen Production Costs 2021
[58] Energy Transitions Commission, 2021. Making the Hydrogen Economy Possible: Accelerating Clean Hydrogen in an Electrified Economy
[59] IRENA, 2020. Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5ºC Climate Goal
[60] Energy Transitions Commission, 2021. Making the Hydrogen Economy Possible: Accelerating Clean Hydrogen in an Electrified Economy
[61] Vivid Economics and partners, 2019. Energy Innovation Needs Assessment: Hydrogen & fuel cells
[62] IRENA, 2020. Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5ºC Climate Goal
[63] Energy Transitions Commission, 2021. Making the Hydrogen Economy Possible: Accelerating Clean Hydrogen in an Electrified Economy

- **Increasing lower heating value efficiency** to improve efficiency to contribute to cost reductions[64].
- **Innovating stack design** to achieve higher efficiency and durability, and increase production rate though a **higher current density**[65]**.**
- **Increasing stack density**[66]**.**
- **Increasing module size** which can help to achieve economies of scale for some plant components.
- **Reducing the thickness of the electrolyser diaphragm** which has the potential to improve efficiency by reducing electricity consumption. However, there is a trade-off of lower durability and safety concerns[67].
- **Increasing the specific surface area of electrodes and catalysts** to increase utilisation[68] [69].
- Using **nickel-based alloys to improve kinetics of hydrogen and oxygen evolution.**
- **Delamination or dissolution to reduce mechanical degradation of the catalyst.**
- **Finding stable polymer chemistry to produce electrodes** for alkaline electrolysers[70].
- More effectively finding and **reducing interface resistances from the catalyst layer to the porous transport layer** (PTL).
- Using **advanced manufacturing methods** such as tape casting, expanded metal cutting, hydroforming, and additive manufacturing processes to improve electrolyser production rates[71].
- **Reducing the gap between electrodes.**
- Developing and **using new hydrolysis routes** such as thermochemical water decomposition [72].
- **Optimising design of the electrolyser plant** such as balancing of the plant.

Additional innovation needs for low carbon electrolysis identified during the workshops included:

[64] Hydrogen Council, 2020. Path to hydrogen competitiveness: A cost perspective
[65] IRENA, 2020. Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5ºC Climate Goal
[66] Vivid Economics and partners, 2019. Energy Innovation Needs Assessment: Hydrogen & fuel cells
[67] IRENA, 2020. Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5ºC Climate Goal
[68] Vivid Economics and partners, 2019. Energy Innovation Needs Assessment: Hydrogen & fuel cells
[69] IRENA, 2020. Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5ºC Climate Goal
[70] IRENA, 2020. Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5ºC Climate Goal
[71] Vivid Economics and partners, 2019. Energy Innovation Needs Assessment: Overview report
[72] Vivid Economics and partners, 2019. Energy Innovation Needs Assessment: Hydrogen & fuel cells

- Developing more **reliable, low-maintenance water deionisation** systems.
- Making **electrolysers easier to maintain** more generally, which can reduce the total life cost.
- **Innovating the cooling process.**

These innovation needs listed were subsequently categorised into “Electrochemical components”, “Electrolyser production”, “Electrochemical engineering” and “Electrolysis process”, where:

- **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.
- **Electrolyser production** – innovation aimed increasing the efficiency and reducing the cost of the electrolyser manufacturing processes.
- **Electrochemical engineering** – innovation targeting electrolyser design and integration into the wider energy system.
- **Electrolysis process** – innovation targeting the reactions and processes comprising electrolysis to optimise the hydrogen yield and reduce the electricity consumed.

The categorised innovation needs were then prioritised and verified by sector experts during two workshops using the methodology described in Section 1.3 and 1.4. Table 8 shows the prioritised innovation needs categories, and Table 9 shows the framework results. The original list of innovation needs, categorisation of innovation needs and ranking of the innovation needs categories can be seen in Annex A[73].

[73] Table 7 shows the updated versions of these tables following input from the sector experts who attended the workshops.

Table 8: Low carbon electrolysis innovation needs prioritised for the Clean Hydrogen Mission[74].

Highest priority ↑	**Electrochemical components**	• 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	• Using advanced manufacturing methods.
	Electrochemical engineering	• 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**	• Faster ramping of alkaline electrolysers. • Increasing lower heating value efficiency. • Developing and using new hydrolysis routes. • Optimising design of the electrolyser plant.

[74] The list shown in this table is an abbreviated version of the full list on pages 30 – 32. Please see pages 30 – 32 for addition details (where available) on the innovation needs.

Table 9: RAG rated and prioritised low carbon electrolysis innovation needs.

	Assessment Criteria / Innovation Needs Category	How impactful is the innovation to reducing the end-to-end cost of hydrogen to 2 USD/kg by 2030?	Would international R&D collaboration be additional to progressing this innovation?	Does this innovation need to happen within the next 1 – 3 years in order to reach the 2030 cost target?	What level of activity is already taking place in the sector?
Highest priority	Electrochemical components				
	Electrolyser production				
	Electrochemical engineering				
Lowest priority	Electrolysis process				

As with the NGR + CCS prioritisation process, innovation needs were prioritised according to innovation needs category rather than individual innovation need. The prioritised innovation needs categories and the innovation needs contained within each category (as can be seen in Table 8) were shown to an international group of sector experts for validation and the methodology was approved. There is the opportunity for future analysis to prioritise individual innovation needs, building on the prioritisation of innovation needs categories as carried out in this work.

The following tables show the RAG ratings of each of metrics for each innovation needs category.

How impactful is the innovation to reducing the end-to-end cost of hydrogen to 2 USD/kg by 2030?			
Electrochemical components	Electrolyser production	Electrochemical engineering	Electrolysis process
"Electrochemical components" category had the biggest list of innovation needs leading to a green rating. Both the "Electrochemical components" and "Electrolyser production" categories have the biggest impact on cost reduction, with workshop attendees indicating that the impact of "Electrochemical components" innovation could be higher than that of "Electrolyser production". They are both rated green however, as scale up of electrolyser production can reduce costs to a point before materials costs prevent further reductions and materials innovation is required. The same is true for reducing materials costs before increasing electrolyser production. "Electrolysis process" was lower ranked than the others as addressing the other categories will bring down cost significantly. However, if other categories aren't addressed and "Electrolysis process" is, that innovation is unlikely to be hugely influential on costs.			

Would international R&D collaboration be additional to progressing this innovation?			
Electrochemical components	Electrolyser production	Electrochemical engineering	Electrolysis process
"Electrochemical components" was rated highest for international R&D as many of the innovation needs have geopolitical implications, particularly those that are materials related. The innovation needs listed are also varied and complex, meaning international collaboration would support their progression. Whilst the innovation needs in the other three categories are more clearly defined in scope (such as "Faster ramping of alkaline electrolysers" in "Electrolysis process") and/or more easily replicated (such as "Using advanced manufacturing methods" in "Electrolyser production") international collaboration could be helpful and/or necessary for the innovation needs categories to be addressed.			

Does this innovation need to happen within the next 1 – 3 years in order to reach the 2030 cost target?			
Electrochemical components	Electrolyser production	Electrochemical engineering	Electrolysis process

The timeliness ratings for the categories were the same as the impact ratings due to the similar rationale. The "Electrochemical components" and "Electrolyser production" categories have significant contributions to cost and so addressing these innovation needs categories in the next 1-3 can remove barriers to deployment, resulting in green ratings. Addressing the "Electrochemical engineering" and "Electrolysis process" innovation needs are likely to have a smaller impact and are therefore less urgent.

What level of activity is already taking place in the sector?			
Electrochemical components	Electrolyser production	Electrochemical engineering	Electrolysis process

As with NGR + CCS, the activity taking place across each of the innovation needs categories was assessed and ranked based on mentions in the literature reviewed and input from the workshop attendees. Whilst significant activity is taking place around the "Electrochemical components" innovation needs, stakeholders across both workshops highlighted that more activity is required. The same is true for "Electrolyser production" and "Electrochemical engineering" but to a lesser degree. Due to the low impact and urgency for "Electrolysis process", there is little activity taking place which led to a green rating. However, this innovation need category is still the lowest ranked as it has the highest number of red ratings.

Consistent with the rationale above, the final prioritisation of the categories was:

1. **Electrochemical component**
2. **Electrolyser production**
3. **Electrochemical engineering**
4. **Electrolysis process**

Other technological innovations specific to low carbon electrolysis that were not clearly defined in scope and, subsequently, not shortlisted or categorised include:

- **Improving poisoning/deactivation mitigation of the electrolyte's catalyst.**
- **Mitigating the formation of nickel hydrogen (NiH) on the cathode.**
- **Designing and using recombination catalysts for gas permeation**[75]**.**
- **Improving the efficiency of purification and desalination equipment** to produce purer hydrogen.
- Introducing **advanced modelling and diagnostics**[76]**.**

Additional, non-technological innovation needs include:

- **Using pilots and demonstrations** to de-risk technology scale-up and secure investment in new low carbon electrolysis plants. The experience gained from this can precipitate a streamlining of system design and operating efficiency, leading to lower CAPEX and OPEX[77].

3.3 Other innovation needs

Whilst this report has focused on innovation gaps in clean hydrogen production, innovation needs in storage, distribution, policy, regulation and standards also have the potential to reduce the end-to-end cost of clean hydrogen. These innovation needs have been identified in this section, as they could contribute to the work being carried out within other Working Groups of the Clean Hydrogen Mission[78].

Distribution and storage costs are often viewed together because they jointly make up the hydrogen infrastructure required to connect production to end-use. As such, these innovation needs have been listed together. Innovations needs for policy, standards and regulations have also been listed here because there are sector experts who believe that overcoming commercial, policy and regulatory barriers will be equally or possibly more important than technological innovation in reducing end-to-end costs [79].

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[75] IRENA, 2020. Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5ºC Climate Goal
[76] Vivid Economics and partners, 2019. Energy Innovation Needs Assessment: Hydrogen & fuel cells
[77] Vivid Economics and partners, 2019. Energy Innovation Needs Assessment: Hydrogen & fuel cells; UK Government's Department for Business, Energy and Industrial Strategy, 2021. Hydrogen Production Costs 2021
[78] The Mission's work is progressing across through three pillars: Promotion of research, development and innovation; Demonstration through building Clean Hydrogen Valleys; and Coordination for an enabling environment. There are currently three dedicated working groups within the R&I pillar: Production; Distribution and Storage; and End-use applications.
[79] BloombergNEF, 2020. Hydrogen Economy Outlook: Key messages; Energy Transitions Commission, 2021. Making the Hydrogen Economy Possible: Accelerating Clean Hydrogen in an Electrified Economy; IRENA, 2020. Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5ºC Climate Goal

3.3.1 Distribution and storage

Whilst not technological, some of the opportunities available to reduce the cost of hydrogen distribution contained in literature include:

- **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)[80].
- Scaling up and **increasing the utilisation of hydrogen pipe infrastructure[81].**
- **Further developing hydrogen carriers** (e.g. hydrides or liquid organic hydrogen carriers) in order that hydrogen can be distributed by LOHCs[82].
- **Improving hydrogen conversion/compression efficiencies and developing alternative compressors (i.e. ionic liquid, electrochemical) compatible with hydrogen utilisation[83]**. 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[84].
- **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** in order to reduce the cost of long-distance hydrogen delivery. This can be achieved through better vessel insulation and higher-pressure levels[85].

It is likely that some end-uses in the future hydrogen economy will require significant storage capacity. BloombergNEF estimates that storage capacity of up to 20% of annual hydrogen use will be required[86], which is partly a result of the long-term energy storage hydrogen can offer. Hydrogen's low density means

[80] Vivid Economics and partners, 2019. Energy Innovation Needs Assessment: Hydrogen & fuel cells
[81] Hydrogen Council, 2020. Path to hydrogen competitiveness: A cost perspective
[82] Energy Transitions Commission, 2021. Making the Hydrogen Economy Possible: Accelerating Clean Hydrogen in an Electrified Economy
[83] The percentages mentioned here show the total energy loss as a percentage of the energy in hydrogen.
[84] Energy Transitions Commission, 2021. Making the Hydrogen Economy Possible: Accelerating Clean Hydrogen in an Electrified Economy
[85] Vivid Economics and partners, 2019. Energy Innovation Needs Assessment: Hydrogen & fuel cells
[86] BloombergNEF, 2020. Hydrogen Economy Outlook: Key messages

that large scale storage is required, or compression technologies will need to be used[87]. Innovation of both options can contribute considerably to reducing the end-to-end cost. Some innovation needs include:

- **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[88].

In the workshops, a number of innovation needs related to hydrogen **storage and/or distribution** were raised such as:

- **Finding safe hydrogen storage materials.**
- **Developing compact and lightweight storage.**
- **Developing high-pressure, underground storage.**
- **Reducing the cost of liquid organic hydrogen carriers** (LOHC) which are included in end-to-end cost for certain applications and can significantly increase it.
- **Innovating compressors to be able to resist damage associated when compressing hydrogen**. As hydrogen is a lighter molecule, faster compressor speeds are required which can lead to thermal and mechanical stresses.
- **Developing liquid hydrogen tanks isolation materials** to avoid boil-off.

3.3.2 Policy, standards and regulations

Policy, standards and regulations innovations all have a critical role in reaching the Clean Hydrogen Mission's goal of 2 USD/kg clean hydrogen by 2030. Addressing policy innovations gaps will support and accelerate technological innovations. However, additional benefits will also be achieved (such as driving necessary investment, creating new business models and stimulating sector scale-up) which will reduce the end-to-end cost of clean hydrogen of their own accord. Some sector experts believe that private investment alone will be enough to drive many technological developments and subsequently, public sector innovation should focus on the policy, standards and regulatory innovation which can stimulate this[89]. BloombergNEF estimates that strong and comprehensive policy could lead to a global hydrogen demand of 696 million metric tonnes by 2050. On the other hand, only a quarter of that demand is available if weak and

[87] Energy Transitions Commission, 2021. Making the Hydrogen Economy Possible: Accelerating Clean Hydrogen in an Electrified Economy
[88] Vivid Economics and partners, 2019. Energy Innovation Needs Assessment: Hydrogen & fuel cells
[89] Energy Transitions Commission, 2021. Making the Hydrogen Economy Possible: Accelerating Clean Hydrogen in an Electrified Economy; World Energy Council, 2019. Innovation Insights Brief: New Hydrogen Economy - Hope or Hype?

piecemeal policy is deployed[90]. This emphasises the importance of policy innovations, some examples of which have been identified through desk research and included below:

- **Rules and standards on greenhouse gas emissions** for hydrogen and its derivatives. International alignment is key [91].
- **Rules and standards on purity** for hydrogen and its derivatives. International alignment is key [92].
- **Rules and standards on safety** for hydrogen and its derivatives, particularly enforcing minimum hydrogen leakage levels and supporting end-use applications (such as ammonia as a marine fuel). International alignment is key [93].
- **Local standards and certification processes** that provide safety assurance to the public on hydrogen use to support increased levels of social acceptance.
- **Clean hydrogen standards** that maximise the climate benefits of hydrogen and its derivatives, such as certification schemes that incorporate full life cycle emissions. International alignment is key.
- **Tracing and accounting methods** for hydrogen and its derivatives that support clean hydrogen standards. International alignment is key[94].
- **Regulatory reviews** to remove potential barriers to investment in the sector.
- **Supportive policy to incentivise hydrogen** such as subsidies for hydrogen use, penalties on fossil fuels[95], and grants/loans for capacity expansion.
- **Supportive policy to encourage technological innovation and scale up**. For example, platinum and cobalt-free designs are already commercially viable for alkaline electrolysers. However, policy support is needed to scale up manufacturing capacity confidently[96].
- **Regional/national hydrogen strategies** which can show government commitment, encouraging the private sector to invest. Each of the Clean Hydrogen Mission co-leads has a strategy and many other countries are going through the process of strategy development[97].

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[90] BloombergNEF, 2020. Hydrogen Economy Outlook: Key messages
[91] Energy Transitions Commission, 2021. Making the Hydrogen Economy Possible: Accelerating Clean Hydrogen in an Electrified Economy; Hydrogen Council, 2020. Path to hydrogen competitiveness: A cost perspective
[92] Energy Transitions Commission, 2021. Making the Hydrogen Economy Possible: Accelerating Clean Hydrogen in an Electrified Economy
[93] Energy Transitions Commission, 2021. Making the Hydrogen Economy Possible: Accelerating Clean Hydrogen in an Electrified Economy; Hydrogen Council, 2020. Path to hydrogen competitiveness: A cost perspective
[94] Energy Transitions Commission, 2021. Making the Hydrogen Economy Possible: Accelerating Clean Hydrogen in an Electrified Economy
[95] Hydrogen Council, 2020. Path to hydrogen competitiveness: A cost perspective
[96] IRENA, 2020. Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5ºC Climate Goal
[97] Hydrogen Council, 2020. Path to hydrogen competitiveness: A cost perspective

- **Target setting** such as manufacturing capacity targets can also show government commitment, encouraging the private sector to invest.
- Government-produced **progress trackers** which ensure transparent communication by showing how hydrogen costs change with time, as well as identifying opportunities for cost reduction that the private sector can act on[98].

Whilst the above innovation needs were not validated in the workshops as they were not the report's focus, they have been included to provide a comprehensive view of the hydrogen innovation landscape and feed into the work being carried out by other pillars of the Mission. However, workshop attendees did highlight the following policy, standards and regulations innovation needs as important:

- **Developing a hydrogen guarantee of origin certification scheme** to encourage penetration of clean hydrogen in the market.
- **Improving testing and standards for hydrogen.**
- **Harmonising hydrogen blending standards** to boost the hydrogen economy.
- **Developing roadmaps for the optimal deployment of hydrogen networks**, taking into account size and location of production units, storage, transportation and refuelling stations.

3.3.3 Out of scope

Some other innovation needs highlighted in the workshops were material contributors to the end-to-end cost of clean hydrogen but went beyond the scope of the Clean Hydrogen Mission. They included:

- Increasing the availability and **reducing the cost of renewable electricity** - the most significant cost component for producing hydrogen via renewable electrolysis.
- **Improving fuelling and metering technologies.**
- **Utilising block chain** in conjunction with the data and digitalisation innovation needs mentioned in Sections 3.1 and 3.2 were also recommended as an overarching innovation need.

[98] IRENA, 2020. Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5ºC Climate Goal

Conclusion

Today, the high cost of clean hydrogen is preventing the scale-up of a global hydrogen economy. With production costs reaching close to 7 USD/kg in some regions[99], and end-to-end costs reaching higher, the Clean Hydrogen Mission's goal of achieving a 2 USD/kg end-to-end cost of clean hydrogen by 2030 is ambitious. However, it is achievable through identifying and addressing technological and non-technological innovations across the production, storage, distribution and end-use of hydrogen. This process will be accelerated by international collaboration.

Innovation is likely to take place in waves of activity. Before 2030, clearly defined innovations for established clean hydrogen production routes should be prioritised to build the hydrogen economy. This will be reinforced by scaling-up hydrogen production, developing storage methods and expanding distribution networks. Following that, these foundations can be built upon further by implementing new hydrogen production technologies and improving existing ones. For this reason, this report has focused on identifying technological innovation needs.

Furthermore, this report focussed on innovations concerning hydrogen production because it generally contributes the largest cost component to the end-to-end cost and, consequently, addressing innovation needs in this stage of the value chain is the most efficient route to achieve a cost for clean hydrogen of 2 USD/kg by 2030. A high-level, qualitative approach has been employed for this project. There is the opportunity for future analysis to prioritise individual innovation needs, building on the prioritisation of innovation needs categories as carried out in this work. This could use a more quantitative and detailed approach as a next step.

Key Findings

Innovation concerning carbon storage capabilities is of high priority for **NGR + CCS**. 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. By contrast, innovation concerning process technology were seen as low priority because this is a mature sector, 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 NGR + CCS, innovation should target optimising the efficiency and integration of carbon capture and storage into the reformation process. The categorised innovation needs were prioritised as such:

1. **Carbon storage capabilities** – innovation addressing the identification and/or development of carbon stores and the minimisation of carbon dioxide leakage.

2. **Process materials** – innovation concerning reducing use and/or cost of the materials comprising the reformation and carbon capture units.

[99] As shown on Figure 2 of this report which illustrates a range of current production costs for clean hydrogen.

3. **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 carbon dioxide captured.

4. **Process technology** – innovation related to maximising the hydrogen yield by designing/integrating new technologies into the process or finding the optimal reaction sequencing.

Where (1) represents the innovation needs category of the highest priority and (4) represents the innovation needs category of the lowest priority.

For **low carbon electrolysis**, 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 could constrain mass manufacturing in the future. Simultaneous with the scale-up of renewable electrolysis, automation of equipment production and deployment of mass manufacturing techniques will unlock large cost reductions. Addressing these innovation needs is of high priority too. Therefore, the categorised innovation needs were prioritised as follows:

1. **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.

2. **Electrolyser production** – innovation aimed increasing the efficiency and reducing the cost of the electrolyser manufacturing processes.

3. **Electrochemical engineering –** innovation targeting electrolyser design and integration into the wider energy system**.**

4. **Electrolysis process** - innovation targeting the reactions and processes comprising electrolysis to optimise the hydrogen yield and reduce the electricity consumed.

Where, again, (1) represents the innovation needs category of the highest priority and (4) represents the innovation needs category of the lowest priority. To reiterate, this prioritisation does not infer the lower ranking categories are unimportant, rather that the higher ranking categorises should be prioritised by the Clean Hydrogen Mission based on the international nature of research and innovation collaboration it fosters, and its end-to-end cost target of 2 USD/kg clean hydrogen by 2030.

Annex

A. Original Innovation Needs Prioritisation

Please note, following comments from sector experts during the workshops, the scope of this report was broadened from SMR + CCS to NGR + CCS and renewable electrolysis to low carbon electrolysis. This was done by conducting more desktop research on other methods of NGR + CCS and low carbon electrolysis and is reflected in the change in terminology from the original RAG rating and prioritisation, seen in the Annex, to the finalised RAG rating and prioritisation, seen in Section 3 of the report.

i. Steam Methane Reforming with Carbon Capture and Storage (SMR + CCS)

Whilst there was agreement on the initial need to retrofit SMR plants with CCS technologies, attendees at both workshops suggested that newly built hydrogen production assets that reform natural gas are likely to be ATR + CCS, rather than SMR + CCS. This was a key contributor for broadening the scope of innovation needs from “SMR + CCS” to “NGR + CCS” which includes ATR + CCS.

Table 10 shows the original list of categorised and prioritised innovation needs for hydrogen produced via SMR + CCS.

Table 10: Original categorised SMR + CCS innovation needs.

Highest priority ↑	Carbon storage capabilities	• Re-characterising of old wells. • Deploying sub-sea installations instead of platforms to enhance carbon storage capabilities.
	Process materials	• Creating and using cheaper and more energy efficient materials and processes. • Developing processes with advanced solvents to reduce catalyst regeneration costs and corrosion effects.
	Carbon capture capabilities	• Developing fuel cells to enhance post-combustion capture processes.
↓ Lowest priority	Process technology	• Deployment of technologies such as ceramic membranes for sorption-enhanced water-gas shift. • Thermal and mechanical integration of gas heated reforming.

Across both workshops, there was broad consensus on the proposed prioritisation for the natural gas reforming innovation needs. However, two participants made alternative suggestions. The first recommended de-prioritising the “Carbon storage capabilities” category and prioritising the “Carbon capture capabilities” category higher. The second suggested that the “Carbon capture capabilities” category be prioritised the lowest, and the “Carbon storage capabilities”, “Process materials” and “Process technology” categories be jointly prioritised. Whilst these attendees were in the minority and so their comments have not impacted the ranking, their comments have been captured here for the Clean Hydrogen Mission’s consideration.

ii. Renewable Electrolysis

Table 12 shows the original list of categorised and prioritised innovation needs for hydrogen produced via renewable electrolysis. Table 11 shows how the categorised renewable electrolysis innovations were RAG rated against the framework and, subsequently, how they were prioritised.

Table 11: Original RAG rated and prioritised renewable electrolysis innovation needs.

	Assessment Criteria / Innovation Needs Category	How impactful is the innovation to reducing the end-to-end cost of hydrogen to 2 USD/kg by 2030?	Would international R&D collaboration be additional to progressing this innovation?	Does this innovation need to happen within the next 1 – 3 years in order to reach the 2030 cost target?	What level of activity is already taking place in the sector?
Highest priority	Electrolyser equipment				
↑	Electrolyser materials				
	Electrolyser production				
↓	Electrolyser efficiency				
Lowest priority	Electrolysis process				

Table 12: Original categorised renewable electrolysis innovation needs.

Highest priority ↑	Electrolyser equipment	• Optimisation of catalyst loading. • Innovating stack design. • Increasing stack density. • Increasing module size. • 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). • Reducing the gap between electrodes. • Optimising design of the electrolyser plant.
	Electrolyser materials	• Creating catalysts from less scarce materials. • Using fewer critical materials in electrolyser stacks. • Recycling of electrolysers and materials circularity. • Using nickel-based alloys.
	Electrolyser production	• Finding stable polymer chemistry to produce electrodes for alkaline electrolysers. • Using advanced manufacturing methods.
	Electrolyser efficiency	• Utilising recovered waste heat. • Integration of electrolysers with intermittent renewable assets. • Increasing lower heating value efficiency.
↓ Lowest priority	Electrolysis process	• Faster ramping of alkaline electrolysers. • Developing and using new hydrolysis routes.

Following discussions in the workshops on the innovation needs and the innovation needs categories, the categorisation of innovation needs was updated. The category “Electrolyser efficiency” was removed because electrolyser efficiency is contingent on improvements in electrolyser materials and electrolyser equipment and, therefore, attendees felt it could not be seen a standalone category. The “Electrolyser efficiency” innovation needs were separated into the other categories. Secondly, the innovation needs were re-categorised from “Electrolyser equipment”, “Electrolyser materials”, “Electrolyser production”, "Electrolyser efficiency" and "Electrolysis process" to "Electrochemical components"[100], "Electrochemical engineering"[101], "Electrolyser production and "Electrolysis process". A workshop participant also suggested thinking about the innovation needs in terms of technological innovation, system innovation and product innovation. This recommendation has been included as an alternative way to help the Clean Hydrogen Mission frame its thinking as it designs its Action Plan.

One workshop participant predicted that, with the scale-up of renewable electrolysis, automation of equipment production and mass manufacturing (relevant to the "Electrolyser production" innovation needs category) will unlock large cost reductions. However, the accessibility of the materials required for electrolysis, namely precious metals and critical materials, will restrict mass manufacturing in the future. Therefore, in order to facilitate the scale-up of renewable electrolysis, innovations in electrolyser materials should be prioritised. As a result of these and other supporting comments across both workshops, the "Electrolyser materials" innovation needs category was ranked higher than the "Electrolyser equipment" innovation needs category in the prioritisation framework.

During the workshops, sector experts also provided additional reports for the Clean Hydrogen Mission to consider when identifying innovation needs for an electrolyser's electrochemical components[102]. Some workshop participants, recommended categorising innovation needs for low carbon electrolysis further, by different types of electrolyser (e.g. PEM, solid oxide or alkaline) because they serve different markets.

As mentioned in Section 1.3, the innovation needs that were highlighted were those with a clearly defined scope and that were more quickly actionable. However, some workshop participants felt some innovation needs were not solution-focused enough and as such, some innovation needs were removed. The following were removed from the 'Electrochemical components' category:

- Using fewer critical materials in electrolyser stacks
- Optimisation of catalyst loading
- Finding stable polymer chemistry to produce electrodes for alkaline electrolysers

Additionally, the following was removed from the 'Electrochemical engineering' category:

- Innovating stack design

[100] Which includes innovation needs related to catalysts, membranes, electrodes and other electrolyser components. This primarily consists of the innovation needs related to electrolyser materials.
[101] This primarily consists of innovation needs related to electrolyser equipment.
[102] These reports have been listed in the Annex of this report.

B. References

The following is a complete, alphabetised list of the sources used in this report.

- BloombergNEF, 2020. Hydrogen Economy Outlook: Key messages
- Climate Change Committee, 2018. Hydrogen in a low-carbon economy
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+44 (0) 20 7170 7000

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Published in the UK: 2021