# 8

# The Hydrogen Economy

FIONA J. BECK, DAVID GOURLAY, MICHELLE LYONS AND
MAHESH B. VENKATARAMAN

## Executive Summary

The global energy system will have to undergo a significant transformation over the next few decades to reduce greenhouse gas emissions and avoid dangerous climate change. There is an urgent need to find carbon-free forms of energy that can be produced cheaply, used across multiple emissions sectors and stored to balance energy grid intermittency. Hydrogen is a particularly interesting candidate for a zero-carbon energy vector, as it has a high energy density and can be produced and used in a variety of ways.

Hydrogen is already used extensively by industry, and techniques for production and handling are well established. However, the current supply chain is relatively simple and relies heavily on fossil fuels, resulting in large amounts of carbon dioxide emissions.

The value chain for a future hydrogen economy will be more complex and require different technologies to be further developed and scaled up. These include:

- hydrogen production processes with low or no carbon emissions;
- methods for large-scale storage and transport to allow hydrogen to be widely and safely traded across the world; and
- technologies to enable hydrogen to be used in a wide range of new applications in industry, transport, heating and cooking, and the electricity sector.

The emergence of the hydrogen economy faces a number of economic, social acceptance and regulatory challenges. Governments around the world have a role to play in providing policies to address potential market failures, socialising the widespread use of hydrogen and establishing international regulations and standards.

Hydrogen produced with zero-carbon emissions has the potential to be a major new globally traded commodity which could enable countries with high energy needs and limited renewable energy potential to decarbonise their economies. As hydrogen can be produced and exported by a broad range of countries, it could diversify the global energy supply and increase energy security.

International cooperation and governance will be needed to facilitate the development of the hydrogen economy. A wide variety of public multilateral and national institutions are working in this space to provide information and analysis for decision makers, build technical capacity, coordinate research, development and demonstration funding, provide international financing and set international standards.

## 8.1 Introduction: Why Hydrogen, and Why Now?

The hydrogen economy was first described in a visionary paper by Bockris and Appleby in 1972 (Bockris and Appleby 1972). Their concept is simple: electricity from renewable sources like wind and solar should become the primary source of global energy, and where direct electrification is not feasible, fossil fuels should be replaced with hydrogen generated from renewable energy.

Global momentum to develop a hydrogen economy has never been stronger. All countries have committed to the Paris Agreement, which seeks to limit global temperature increases to reduce the risks and impacts of climate change.[1] In 2018, the Intergovernmental Panel on Climate Change (IPCC) issued a stark warning: global greenhouse gas (GHG) emissions must reach net zero by 2050 to limit global temperature levels to 1.5 °C above pre-industrial levels and avoid the worst effects of climate change (IPCC 2018). This will require a rapid transformation of the current global energy system, which is highly dependent on fossil fuels.

Investments in renewable electricity generation are already driving the energy transformation. However, current renewable energy sources are mostly intermittent (e.g. solar photovoltaic (PV) and wind energy) and not easily stored or transmitted over long distances. As the proportion of renewable energy on electricity grids increases, so does the need for grid-balancing services, including electricity storage. Additionally, not all emissions sectors can directly replace fossil fuel use with renewable electricity. These include heavy freight, aviation and industries like iron and steel, cement, chemicals and aluminium. A third of global energy emissions currently have no commercially viable alternative to fossil fuels (IRENA 2018). To truly decarbonise, we need to find carbon-free energy vectors and fuels that can replace fossil fuels across the spectrum of emissions sectors.

Hydrogen is a particularly promising candidate for a carbon-free energy vector. It has a high specific energy (i.e. energy per unit mass) and is very versatile in terms of how it can be produced and used. In particular, it can be generated from the electrolysis of water using renewable energy, resulting in a gaseous fuel similar to fossil fuel sources like natural gas, but without the same carbon dioxide ($CO_2$) emissions or supply limitations. Hydrogen produced in this way could allow renewable energy to be stored on a very large scale, mitigating the intermittency of resources like wind and solar, and opening up the possibility of exporting local renewable resources around the world. Hydrogen could play a role in decarbonising a wide range of previously hard-to-abate emissions sectors, including domestic heating and cooking, transportation and heavy industrial processes, where it

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[1] *Paris Agreement Under the United Nations Framework Convention on Climate Change*, opened for signature 16 February 2016. Available at: https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement.

can be used as both a fuel and a feedstock. This versatility has led IRENA to identify hydrogen as the possible 'missing link' in the energy transition (IRENA 2018: 45).

This chapter provides an overview of pathways and implications of a future hydrogen economy. It explores current and future options for hydrogen production, storage, transport and use, including future supply and demand scenarios. It analyses economic, social and regulatory barriers to hydrogen uptake and examines potential policy responses and international governance mechanisms to assist governments and international organisations to overcome these barriers. It also considers the positive impacts a renewable hydrogen industry would have on global energy security and international trade.

## 8.2 The Hydrogen Value Chain

In 2018, nearly 70 million tonnes of pure hydrogen were consumed, mostly for ammonia production and petrochemical refining (IEA 2019d). Hydrogen for these industrial applications is generally produced on-site from fossil fuels. The value chain in a future hydrogen economy will be much more complicated, requiring production methods with low or no carbon emissions, and for hydrogen to be stored and transported across the world for use in a range of sectors.

This section outlines a variety of technologies for production, transport and utilisation that will need to be developed and integrated at scale to enable the hydrogen economy, with a focus on the relative challenges and opportunities.

### *8.2.1 Production*

#### *8.2.1.1 Current Production Techniques*

Global hydrogen production is currently dominated by thermochemical processes requiring carbon-based feedstock. Fossil fuels contain hydrocarbons (organic compounds made up of carbon and hydrogen), which are reacted with water at high temperatures to produce hydrogen and $CO_2$.

The most common technology, responsible for almost half of total dedicated hydrogen production, is steam methane reforming (SMR), which uses natural gas as the feedstock. Steam methane reforming is a high-temperature process (700–1000 °C) in which steam reacts with methane in natural gas in the presence of a catalyst to produce hydrogen, carbon monoxide and a relatively small amount of $CO_2$. A further reaction between the carbon monoxide and steam produces more $CO_2$ and pure hydrogen. This is an endothermic process, and the heat is provided by burning a part of the fossil fuel feedstock, resulting in additional $CO_2$ emissions. Steam methane reforming is up to 75% efficient[2] and is currently the cheapest hydrogen production technology; however, the cost is very sensitive to gas prices.

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[2] Throughout the chapter, efficiency is defined as the usable energy output compared to all energy inputs, assuming the lower heating value (LHV) of hydrogen.

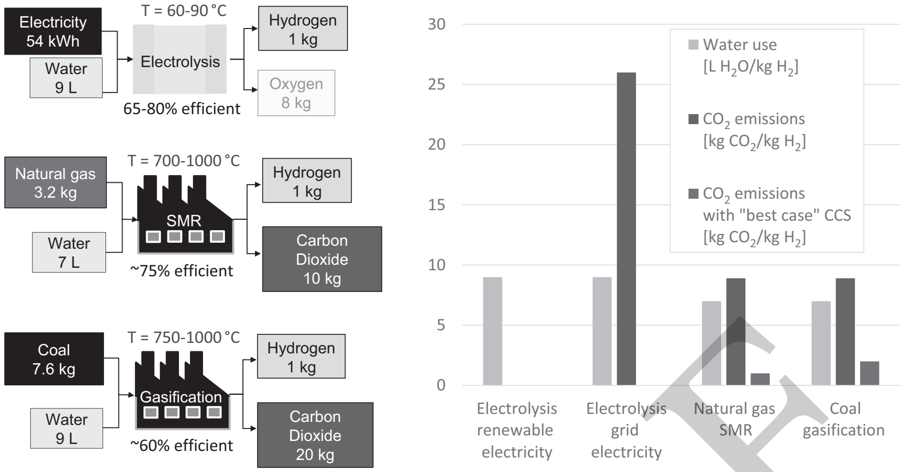

Figure 8.1 Comparison of SMR, coal gasification and electrolysis hydrogen production technologies, showing process inputs, temperatures and outputs. Bar chart compares water usage and $CO_2$ emission intensities for the different processes with and without 'best-case' CCS, equivalent to 90% $CO_2$ capture and retention rate.

*Source*: Authors' analysis; emissions and water use for different production techniques is taken from IEA (2019d); fossil fuel inputs taken from Milbrandt and Mann (2009). For a colour version of this figure, please see the colour plate section.

Another roughly 30% of hydrogen is generated by partial oxidation of hydrocarbons (POX). In POX, methane (e.g. from natural gas) or other heavy hydrocarbons are partially combusted in a low-air atmosphere to produce 'syngas', which is further reformed to produce pure hydrogen. A further 18% of global hydrogen is produced by coal gasification. During gasification, coal is reacted with oxygen and steam, at high temperature (and in some cases high pressures), to form syngas, which again is further refined to form pure hydrogen. All of these methods produce $CO_2$ as a by-product of the process.

The GHG emissions from current hydrogen production are significant (see Figure 8.1). Producing 1 kg of hydrogen with SMR generates 9–12 kg of $CO_2$ (Cetinkaya et al. 2012; Committee on Climate Change 2018), not including the fugitive emissions from the extraction of the natural gas. Coal gasification is even more emission-intensive, at 19–23 kg $CO_2$/kg $H_2$ (per kilogram of hydrogen) (Muradov 2017; Committee on Climate Change 2018). The IEA calculated the total annual $CO_2$ emissions from hydrogen production to be 830 MT (megatonnes) of $CO_2$ per year (IEA 2019c), which is comparable to the total annual $CO_2$ equivalent emissions from Germany in 2018.

### 8.2.1.2 *Low-Carbon Hydrogen*

In order to be a low-carbon process, existing fossil-fuel-based hydrogen production technologies can be coupled with carbon capture and storage (CCS). The use of CCS, an integrated suite of technologies, can prevent large quantities of $CO_2$ from being released into the atmosphere: $CO_2$ is separated from the waste stream of a polluting source, compressed and transported to the site of suitable underground rock formations, and then injected underground, usually at a depth of more than one kilometre, for long-term storage (Global CCS Institute 2018). The production of hydrogen through CCS integration with SMR is also called the ‘blue hydrogen’ pathway.

Carbon capture and storage technology is not 100% effective: some $CO_2$ will escape into the atmosphere, and additional $CO_2$ is emitted due to the extra power needed to compress, transport and store $CO_2$. Capture efficiencies are expected to reach 80–90% (Muradov 2017), but current projects have reported much lower capture rates, as low as 31% (IRENA 2019). Additionally, there are currently no international standards for compulsory monitoring to ensure that the captured $CO_2$ is not released at a later date. Currently, most CCS plants use the captured $CO_2$ in enhanced oil recovery, which can result in significant amounts of $CO_2$ escaping back to the atmosphere (IRENA 2019): one study demonstrated that different enhanced oil recovery projects had very different $CO_2$ leakage rates, varying between 4% and 72% (Olea 2015).

Hydrogen production via SMR and coal gasification are good candidates for CCS, as the $CO_2$ is released in a concentrated stream, making it easy to capture. However, as of 2019, there are only two dedicated SMR-based hydrogen production plants that have demonstrated successful CCS integration, namely, Air Products’ SMR in Port Arthur, Texas, and Quest in Alberta, Canada. Several more CCS-integrated low-carbon hydrogen production projects are at the planning and feasibility stages. These include the Hydrogen 2 Magnum (H2M) in the Netherlands, H21 North of England, Hynet North West, Ervia Cork CCS and HyDeploy in the UK and the Hydrogen Energy Supply Chain (HESC) in Australia (Global CCS Institute 2018).

Integrating CCS to SMR increases the cost of hydrogen production. The International Energy Agency (IEA) estimates roughly a 50% increase in capex (capital expenditure), an additional 10% for fuel and doubling of opex (operational expenditure) due to $CO_2$ storage and transport costs (IEA 2019d).

Methane cracking (MC) could be a low-emission alternative to the SMR–CCS technology. In the MC process, methane ($CH_4$) from natural gas is subjected to a thermal treatment at high temperatures in the absence of air, producing solid carbon and pure hydrogen. If the required heat is provided by burning the hydrogen produced in the process, or through a renewable source, then the process can (theoretically) be made emissions free. Methane cracking for production of hydrogen has been demonstrated at a commercial scale; however, the process has a relatively low efficiency and high cost compared to SMR. New reactor/process designs have demonstrated higher energy conversion efficiency on a laboratory scale (Geißler et al. 2016) but scalability of this technology is yet to be demonstrated (Weger et al. 2017).

Low-emissions technologies relying on fossil fuels for hydrogen production have been proposed as an important stepping stone towards a fully renewable hydrogen economy, supporting the development of global hydrogen supply chains. However, it is not yet clear if these technologies can scale up sufficiently rapidly. There is a risk that fossil-fuel-based production will ramp up much faster than the required CCS facilities, resulting in significant $CO_2$ emissions. The International Renewable Energy Agency (IRENA) has also expressed some concern that investment in CCS could divert limited capital away from the renewable energy technologies towards fossil fuels, ultimately slowing the transition to a decarbonised energy system (IRENA 2019). Additionally, these technologies do not mitigate the fugitive GHG emissions that occur during the extraction of fossil fuels, which can be significant.

#### *8.2.1.3 Zero-Carbon Hydrogen*

Electrolysers driven by renewable electricity are likely to be the main production technology for zero-carbon hydrogen in the near term. Electrolysis is the process of splitting water into hydrogen and oxygen using electricity. Although only a few per cent of hydrogen is currently produced this way, it is a mature technology. Hydrogen generation with electrolysis does not produce any $CO_2$ emissions, and has the potential to be a truly 'zero-carbon' technology if the electricity used in the process is itself generated from renewable sources. Hydrogen produced this way is referred to interchangeably as 'green' or 'renewable' hydrogen. It should be noted that significant emissions are released if the electrolysers are powered using the electricity generated with fossil fuels; the IEA calculated average emissions at 26 kg $CO_2$/kg $H_2$ for grid-connected electrolysers, assuming a 'world average electricity mix' (IEA 2019d: 53); while the Australian National Hydrogen Strategy have estimated emissions to be 40.5 kg $CO_2$/kg $H_2$ for electrolysers connected to the Australian electricity grid (COAG Energy Council Hydrogen Working Group 2019).

The most common commercial electrolysers employ two electrodes separated by a thin membrane in an alkaline electrolyte. The membrane allows the ions in the electrolyte to conduct electricity between the electrodes, but keeps the product gases separate so that pure hydrogen and oxygen can be collected independently. Current electrolyser technologies run at 60–80 °C and are around 65% efficient, with incremental efficiency enhancements up to roughly 80% expected over the next decade (Schmidt et al. 2017).

Alkaline electrolysers currently dominate the market and have the lowest capital costs; however, proton exchange or polymer electrolyte membrane (PEM) technologies are becoming competitive (Buttler and Spliethoff 2018). The term 'PEM' refers to technologies that employ a solid electrolyte to conduct ions and separate product gases. Such technologies have the advantage of running at higher current densities and can react more quickly to changes in the electricity supply, which may be particularly relevant for systems powered by variable renewable electricity (Schmidt et al. 2017). Another alternative is high-temperature electrolysers, called solid-oxide electrolyser cells (SOECs). These are still in demonstration phase, but could offer significant electricity-to-hydrogen efficiency enhancements over standard electrolysers by running at 650–1100 °C (Hauch et al. 2008). They require a heat source to generate steam, which could be provided from renewable sources such as solar thermal, or from waste heat from industrial process.

In general, standard electrolysers require roughly 54 kWh (kilowatt-hours) of electrical energy and 9 litres of water to produce 1 kg of hydrogen. They also need a range of supporting systems, known as the balance of plant, including pumps, compressors, heat exchangers and gas lines. Additionally, most electrolysers include a water treatment system to remove impurities found in potable water that could otherwise affect the reaction and contaminate the evolved gases. Electrolysers are highly modular and are generally sold in standard-sized units rated by their maximum power input (typically in the 100 kW–1 MW range).

Producing hydrogen with renewable energy and electrolysis is still significantly more expensive than hydrogen produced with SMR. However, recent analysis from IRENA has suggested that 'lowest-cost wind and solar projects can provide hydrogen at a cost comparable to that of hydrogen produced from fossil fuels' with integrated CCS (IRENA 2019). Predictably, costs for renewable hydrogen are sensitively dependent on electricity prices and the cost of electrolyser systems. However, running electrolyser systems at high capacity factors[3] is also critical to keep costs low (Bruce et al. 2018). It is likely that the cost of electrolysers will fall as the industry scales up, with estimated experience rates of 18% (Schmidt et al. 2017).

#### *8.2.1.4 Water Use*

Water is used as a feedstock for almost all hydrogen production technologies, with the notable exception of MC. Producing 1 kg of hydrogen requires 7–9 litres of water, depending on the production pathway (see Figure 8.1) (IEA 2019d). To put this into perspective: the fuel cycle of conventional natural gas consumes less than a third of a litre per kilogram of gas produced, and roughly 1 L/kg for shale gas.[4]

Large-scale hydrogen production could result in an undesirable burden on fresh water supplies in the future. For example, the Australian National Hydrogen Strategy estimated that 'Under strong hydrogen growth settings, water consumption in Australia may be the equivalent of about one-third of the water now used by the mining industry' (COAG Energy Council Hydrogen Working Group 2019). To avoid this, desalination plants could be co-located with hydrogen production in coastal areas. Desalination would necessarily add to overall system costs, but the additional energy requirements are negligible. The energy required for desalination with reverse osmosis is 4 Wh/L (Caldera et al. 2017) or 36 Wh/kg $H_2$ – less than a thousandth of the energy needed to generate 1 kg of hydrogen with electrolysis.

#### *8.2.1.5 Emerging Technologies*

There are several hydrogen production technologies under active development that have the potential to disrupt the hydrogen value chain in the future.

A range of different technologies aim to split water into hydrogen and oxygen directly using the power of the sun. Concentrated solar thermal hydrogen production uses the heat of concentrated sunlight (at 500–2000 °C) to run a thermochemical reaction to split water. This technology has the potential to have higher solar-to-hydrogen efficiencies than solar-power-driven electrolysers. Photoelectrochemical (PEC) systems use solar-cell-like

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[3] The capacity factor is defined as the actual hydrogen output divided by the maximum possible hydrogen output of a given system over a period of time.

[4] Estimated from data in Meldrum et al. (2013).

components made of semiconductors to provide the current and voltage needed for water electrolysis using only sunlight. These systems could potentially be cheaper than renewable-energy-driven electrolysis; however, questions remain over how much the cost of hydrogen can be reduced, as they could require more complex balance of plant (Shaner et al. 2016). Photocatalytic hydrogen production takes advantage of materials that can absorb sunlight and generate high-energy electrons, which can initiate the water splitting reaction and release oxygen and hydrogen without any additional power, external wiring, membranes or additional components. Photocatalyst systems have very low solar-to-hydrogen conversion efficiencies but are attractive as the materials have the potential to be very cheap and scalable. However, it is not yet clear if this low materials cost will translate into a lower production cost, as additional gas separation systems will be needed to collect and store pure hydrogen.

Another class of technologies aim to leverage microbial processes for hydrogen generation. These include photobiological processes, where waste water is combined with microorganisms and sunlight; and microbial electrolysis, where an electric current is used to drive the reaction instead of sunlight (Feng et al. 2015). Alternatively, microbes can be used in a fermentation process called microbial biomass conversion, which breaks down organic matter to produce hydrogen without any additional energy input. These systems are interesting as they do not use potable water sources.

### *8.2.2 Transport and Storage*

The low volumetric density of hydrogen makes it challenging to economically store and transport large quantities of hydrogen fuel. For comparison, one litre of hydrogen gas at atmospheric pressures and ambient temperatures contains roughly one-third of the energy of the same volume of natural gas. Developing safe, low-cost and scalable techniques to increase the amount of hydrogen that can be stored in a given volume is a key challenge to realising a future global hydrogen economy.

#### *8.2.2.1 Mature Storage and Transport Technologies*

As hydrogen has been used as an industrial feedstock for many decades, there are well established processes for safe handling and storage. However, the current hydrogen supply chain is much simpler and on a smaller scale than that envisioned for the hydrogen economy. The majority of hydrogen is currently consumed at the point of production and only about 15% is distributed off-site (IEA 2019d).

Small volumes of hydrogen gas can be mechanically compressed and stored in pressurised vessels. Under high pressure, the energy density is improved but specialised high-pressure tanks are needed, and a large amount of energy is required to compress the gas, making it costly for large volumes. To further improve energy densities, hydrogen can be converted to a cryogenic liquid. This is also a mature technology but is highly energy intensive and requires complex storage vessels. Compressed or liquefied hydrogen can be transported in tanks by rail or truck.

Very large volumes of hydrogen gas can be pumped underground and stored in suitable geological features, like salt caverns and depleted natural gas reservoirs. Similar structures are already used for long-term storage of natural gas. Geological storage is very promising, as it has a very high efficiency (i.e. most of the gas pumped in can be recovered successfully), good economies of scale and low operational costs, although it is limited to areas with storage capacity. Several successful pilot projects have already been demonstrated, most notably hydrogen storage in salt caverns at Teeside in England by Imperial Chemical Industries (Foh et al. 1979).

Compressed or liquefied hydrogen can also be stored and distributed in pipelines. While 100% hydrogen pipelines are already used in industry, the extent of these networks is very limited (IEA 2019d). Unfortunately, there are several key differences between natural gas and hydrogen which mean that existing natural gas pipelines and distribution networks cannot be directly used for pure hydrogen (Melaina et al. 2013). Hydrogen is a very small molecule that can diffuse easily, requiring specialised components such as valves and seals to contain it securely. Diffusion also causes the phenomenon of *metal embrittlement*, which occurs when steel and certain other alloys commonly used in industry are exposed to hydrogen. Absorption of hydrogen by the metal can lead to sudden and unpredictable cracking and fracturing of components, and the risks increase if the gas is stored at high pressures. Scaling up hydrogen distribution networks would be costly due to the specialised components required.

#### *8.2.2.2 Large-Scale Transport of Hydrogen*

Technologies and supply chains for the large-scale and long-distance transport of hydrogen will need to be developed. It is instructive to consider the natural gas industry, which is already adept at trading large quantities of gaseous fuel across large distances. The global supply chain for liquefied natural gas (LNG) includes liquefaction, pipelines, large-scale storage, port infrastructure and shipping tankers. The hydrogen economy will require a similar supply chain; however, there are specific challenges related to handling liquid hydrogen (LH2) that will make it unlikely that existing infrastructure can be used as-is. As well as the dangers of hydrogen embrittlement, and the need for specialised plant components, hydrogen has a much lower boiling point (–253 °C compared to –163 °C for LNG) meaning that more energy is needed to liquefy the gas – between 25% and 40% of the energy embedded in the hydrogen (assuming the low heating value of hydrogen) (IEA 2019d). Maintaining this low temperature also requires much more complex and expensive storage tanks and insulation. In addition, LH2 has only 40% the energy density of LNG – meaning that bigger tanks are needed to carry the equivalent amount of fuel. While the technology for handling LH2 already exists, the stringent requirements for hydrogen and the lower density will mean that the costs are likely to be significantly higher than for LNG.

Chemical storage offers another route for increasing the density of hydrogen fuel, while simultaneously making it easier to store and transport. Ammonia is the most mature hydrogen carrier and is produced by reacting hydrogen with nitrogen in the Haber–Bosch process. Aqueous ammonia is 1.5 times denser than LH2 and can be stored and transported at ambient conditions, although it is usually pressurised and transported in large tanks. Once again, there is a significant energy penalty in converting hydrogen to ammonia – between 7% and 18% of the total energy contained in the hydrogen (IEA 2019d). Reconverting ammonia back to hydrogen is a less mature process and incurs an additional energy penalty of less than 20%. Ammonia is also highly toxic, flammable and corrosive, and careful handling is needed to ensure safety. While ammonia production is an extensive industry in its own right, with applications in fertilisers, refrigerants, pharmaceuticals and textiles, very large-scale and widespread distribution as needed in the hydrogen economy may introduce challenges.

Liquid organic hydrogen carriers (LOHCs) are another promising option for liquid-phase hydrogen storage and transport. These material systems consist of organic compounds that reversibly react with hydrogen by catalytic hydrogenation and dehydrogenation. The result is a hydrogen-rich liquid that can be stored at ambient temperatures and pressures, and is compatible with existing liquid fuel infrastructure such as oil pipelines. Unlike ammonia, the materials themselves are not used up in the process of releasing the hydrogen, and need to be returned to place of origin for reuse. The most advanced LOHC is methylcyclohexane (MCH), and is currently being trialled by several organisations developing hydrogen supply chains (IEA 2019c). Methylcyclohexane uses toluene as a carrier molecule, which is a low-cost chemical already widely used as a solvent in paints, lacquers and leather processing, among other applications. Unfortunately, toluene is toxic, and while safe handling procedures have been developed for its current commercial use, it may cause difficulties in scaling up MCH for large-scale hydrogen storage. A range of non-toxic LOHCs are under development. The main challenges are to reduce material costs and the amount of energy needed to bind and release the hydrogen, while maintaining high-capacity hydrogen storage (Preuster et al. 2017).

Other potential carrier material systems are under active research and development. Solid-phase metal hydrides can chemically bond with hydrogen (chemisorption), releasing heat (He et al. 2016). The hydrogen can be recovered by a heating step. Hydrogen can also be physically adsorbed (physisorption) onto the surface of porous media like carbon-based nanomaterials, metal–organic frameworks and polymers (Dalebrook et al. 2013).

### *8.2.3 Applications of Hydrogen*

#### *8.2.3.1 Existing Uses of Hydrogen in Industry*

The vast majority of the hydrogen produced today is used in the industrial sector. One-third of existing capacity is used by the petroleum industry where it serves two purposes – first, catalytic cracking and hydrogenation (hydrocracking) of heavy hydrocarbons to produce gasoline and diesel and, second, to upgrade low-quality crude oil by removing impurities. Nearly one-third of the remaining hydrogen is used for the production of ammonia, which in turn finds application in the manufacture of fertilisers, a range of nitrogenous compounds and, directly, as a cleaning agent, refrigerant and anti-microbial agent.

Hydrogen is also used to produce methanol, an important organic solvent, fuel additive and additive for polymer/resin production. Additionally, hydrogen is used in the iron and steel industry for annealing, as a blanketing gas and as forming gas (a mixture of nitrogen and hydrogen). Hydrogen also finds some general industrial uses, albeit in smaller quantities, such as propellant fuel, semiconductors, glass production, hydrogenation of fats and as a cooling agent.

#### *8.2.3.2 New Applications of Hydrogen in Industry*

As well as decarbonising existing applications, zero- or low-carbon embedded hydrogen could be used to replace fossil fuels in a range of industry applications that cannot be easily electrified, including metallurgical extraction and the production of high-temperature heat.

The steel industry accounts for roughly 7–8% of the total global GHG emissions from fossil fuels use. Producing steel from iron ore is energy intensive and has a significant carbon footprint due to the use of coke as both a fuel and a reductant. New steelmaking routes using hydrogen as a reducing agent (H2-DRI) have the potential to completely eliminate the GHG emissions from steelmaking, if renewable hydrogen is used (Vogl et al. 2018).

Industrial high-temperature heat ($>400$ °C) is responsible for 3% of global energy sector emissions and is required in a range of industrial applications such as calcination, annealing, forging and rolling. Most of these processes burn fossil fuels to provide the heat, although some specific applications employ electric resistance furnaces or microwave technology. Electrifying these processes is likely to be challenging and, instead, hydrogen, or derivatives of hydrogen, could be combusted to provide high-temperature heat with no carbon emissions. Unfortunately, converting from fossil fuel combustion to hydrogen is also not straightforward and will require changes in equipment, as well as fuel handling procedures.

Renewable hydrogen can also be combined with $CO_2$ to produce syngas, which can be further processed to produce a variety of synthetic fuels, including gasoline, diesel and methanol, via a range of commercial synthesis processes. This is particularly interesting as it offers a way of converting renewable electricity to ‘drop-in’ fuels that can be used in place of standard fossil fuels. Synthetic fuels contain carbon and will release $CO_2$ again when combusted. However, if the $CO_2$ used for the process is sourced from a waste stream the process can be considered to have low life-cycle emissions. It should be noted that biomass-derived synthetic liquid fuels[5] is a competing technology for ‘drop-in’ fuels, with a lower emissions profile (National Academies of Sciences Engineering and Medicine 2016).

#### *8.2.3.3 Decarbonising Transport*

Hydrogen could play a role in decarbonising a range of transportation systems in two ways: by direct use of hydrogen in fuel cells, and by using hydrogen-based fuels in modified internal combustion engines.

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[5] Biomass-based synthetic fuels also emit $CO_2$, but this carbon is biogenic, having been extracted from the atmosphere by plants. It can be considered carbon neutral if the associated land-use change impacts are negligible.

Fuel cell electric vehicles (FCEVs) are a type of electric drivetrain vehicle that uses hydrogen as on-board energy storage rather than relying on batteries. Fuels cells are essentially reverse electrolysers: hydrogen is reacted with oxygen from the air to produce electricity in an electrochemical cell. The most mature technology is PEM, which uses a solid polymer between the electrodes in place of a liquid electrolyte.

Fuel cell electric vehicles have two main advantages over battery electric vehicles (BEVs), due to the fact that energy is stored chemically (in the bonds of hydrogen), instead of electrochemically (in batteries). Unlike batteries that require long charging times (from 30 minutes, for super charging, to hours), refuelling with hydrogen can be done in a matter of minutes. Additionally, the specific energy of hydrogen is much greater than that of batteries, meaning that FCEVs can store more fuel on board and have a longer range than BEVs.

However, it is important to note that FCEVs fuelled by renewable hydrogen will always be less efficient than BEVs run directly on renewable energy. In an FCEV, electricity is first converted to hydrogen in an electrolyser, then converted back into electricity in the on-board fuel cell, with a significant energy loss associated with each conversion process. In comparison, a BEV is only limited by the efficiency of the battery. By one analysis, FCEVs powered by renewable energy have overall electricity-to-wheel efficiencies of 41%, compared to 86% for BEVs (Committee on Climate Change 2018). FCEVs also require specialised infrastructure and refuelling stations, and are a less mature technology. For this reason, FCEVs should be considered a complementary technology to BEVs, for applications not well suited to battery technologies. Fuel cell electric vehicles are most promising for vehicles that need long ranges or high energy intensity per kilometre (i.e. heavy vehicles), and for vehicles that are heavily used – making the long charging times required for batteries unsuitable. In particular, vehicles such as forklifts, buses, trains, ferries and trucks that have predesignated routes and predictable refuelling needs are particularly suited to hydrogen fuel cells.

Hydrogen-based fuels could enable the decarbonisation of the maritime and aviation sectors, which are both very energy intensive and require very long ranges and are not well suited to electrification. Synthetic ‘drop-in’ fuels could be used directly, or ammonia can be burnt in modified internal combustion engines (National Academies of Sciences Engineering and Medicine 2016).

#### *8.2.3.4 Replacing the Use of Natural Gas for Domestic Use and Commercial Buildings*

Hydrogen gas can be combusted for space heating and cooking, and could replace the use of gas in urban settings. However, it is much more energy efficient to use the electricity directly, using modern technologies such as heat pumps and induction cookers, rather than using the electricity to generate, store and transport hydrogen for these applications (Committee on Climate Change 2018).

Coupling hydrogen production with the natural gas networks could, however, prove useful during the transition to the hydrogen economy. Hydrogen gas can be blended into existing natural gas networks with concentrations of up to 10–20% by volume without having to modify the network infrastructure or appliances at the point of use (Melaina et al. 2013). This could provide a relatively large market for the nascent renewable hydrogen industry, as well as providing built-in distribution and storage. However, due to the low volumetric energy density of hydrogen compared to methane, blending up to 20% hydrogen into the gas network would only reduce carbon emissions from domestic gas use by up to 7%.[6]

Due to the material properties of hydrogen, it is unlikely that existing natural gas networks could be used for the distribution of higher concentrations of hydrogen without substantial upgrades (Melaina et al. 2013). In addition to embrittlement issues and the need for specialised components, differences in gas density, ignition temperature and flame velocity mean that gas meters and end-use appliances may also need modification. Widespread use of pure hydrogen in domestic and urban settings would also pose specific safety challenges: for example, hydrogen is odourless and burns with a clear flame, making difficult to detect leaks and fires.

## Box 8.1 **System Integration**

One of the advantages of hydrogen as an energy carrier is that it is very versatile: it can be generated, converted and used in a range of ways in the electricity, industry and transport sectors.

Figure 8.2 demonstrates some of the ways that the technologies in the hydrogen value chain could be integrated into the energy network during the transition to a zero-carbon economy.

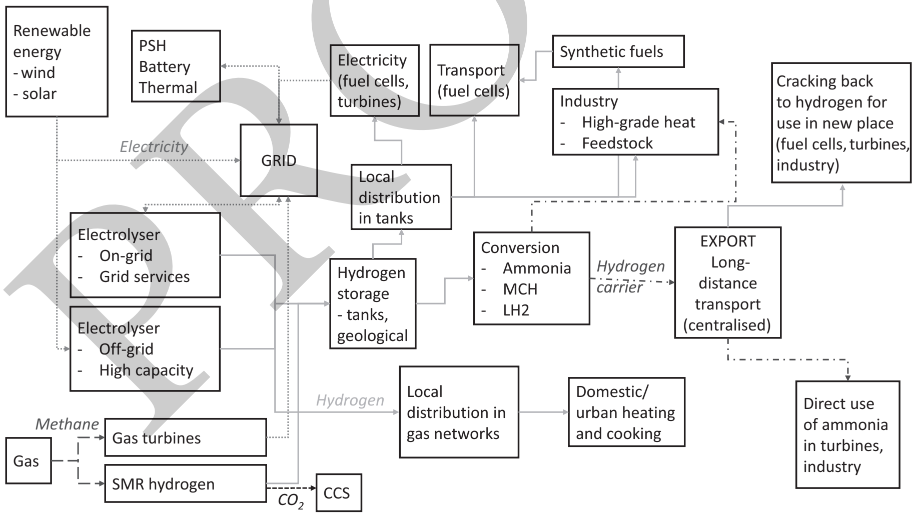

Figure 8.2 Schematic showing the possible ways that hydrogen technologies could be integrated into the larger energy system.

*Source*: Authors' summary. For a colour version of this figure, please see the colour plate section.

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[6] Calculation by Associate Professor Matthew Stocks at The Australian National University.

It is important to consider that each conversion, transport and storage process will incur an energy and concomitant cost penalty. This means that although the flexibility of hydrogen as an energy carrier allows multiple pathways from production to use, not all of these routes will be cost-effective.

#### *8.2.3.5 Renewable Electricity Generation and Storage*

Hydrogen can be used to generate electricity in two ways: in fuel cells or by combustion in a gas turbine. Like electrolysers, fuel cells for stationary electricity applications are highly modular, ranging from kilowatt to megawatt scales. For very large applications (>100 MW), gas turbines can be used, analogous to standard natural gas electricity production; however, pure hydrogen gas and ammonia turbines are still at the demonstration phase. Hydrogen can also be blended into natural gas up to concentrations of 20% and co-fired in existing gas turbines. This could be used during the transition to a hydrogen economy as another source of hydrogen demand and to reduce emissions from gas-fired electricity generation, although as mentioned above, this is likely to provide only modest $CO_2$ emissions reductions.

Converting renewable electricity into hydrogen and back into electricity incurs a significant energy penalty, and the round-trip efficiency for storing electricity as hydrogen is very low, at only 35–40%. It is unlikely that hydrogen electrolysers and fuel cells will be able to compete with more established storage technologies – like batteries or pumped storage hydro (PSH) –for small- to medium-capacity electricity storage, as the fuel cells, hydrogen storage and electrolysers needed are still too expensive. However, hydrogen has the potential to be used for high-capacity electricity storage, employing underground geological sites to store large quantities of hydrogen in order to mitigate the effects of seasonal variation in renewable resources. Seasonal hydrogen storage would be beneficial for high penetration of renewables on the grid, and could be economically viable in Northern Europe even with a relatively low round-trip efficiency of 45% (DNV-GL 2018; IRENA 2019). The potential for international trade is discussed in Section 8.4.1.

## 8.3 Challenges and Policy Responses

The IEA (IEA 2019d) lists three major challenges to overcome if a hydrogen economy is to emerge. These are: the complexity of supply chains and infrastructure; uncertainty regarding policy and technology; and the need to establish regulations, standards and acceptance. These are discussed below. To establish a hydrogen economy, governments will have an important role in overcoming these challenges, which could be addressed through policy and engagement multilaterally, bilaterally, nationally or subnationally.

The hydrogen opportunity is likely to be different from country to country. Some countries will have comparative advantages in particular areas, such as access to a surplus of low-cost renewable electricity that can be used for electrolysis or existing manufacturing demand, that will shape their hydrogen industry in a particular direction. An important role for governments is to identify these areas of comparative advantage, and their most viable hydrogen pathways, and use these as the basis for scaling up the industry. One way governments can do this is by developing a hydrogen strategy or plan. As of mid-2019, nine of the G20 countries and the EU had a hydrogen plan in place (IEA 2019b). Determining and leveraging countries' areas of competitive advantage is a major focus of these plans (Kosturjak et al. 2019). Establishing and adhering to a national plan can reduce policy uncertainty for businesses looking to invest in hydrogen infrastructure or applications.

### *8.3.1 Economic Challenges*

Market failures could prevent a hydrogen economy from emerging or scaling up efficiently. Most pertinent is that hydrogen will have to compete against fuels that produce carbon emissions, such as oil and natural gas. As of 2018, 87% of global GHG emissions were not subject to any form of carbon pricing, while less than 1% are subject to a carbon price equivalent to the social cost of carbon (Jenkins 2019). All else being equal, this will result in a continued overuse of fossil fuels, and an underuse of green hydrogen.

As discussed above, while there are established technologies to produce hydrogen, the industry needs to take risks and innovate to learn how to produce, transport and deploy hydrogen at scale. Knowledge is often thought of as a public good as it is available for all to benefit from. Companies can undervalue the activities required to do this, as they take on all the associated risk while the benefits are available to all companies in the industry (Gillingham and Sweeney 2011; Carbon Pricing Leadership Coalition 2017). This could result in the rate of innovation in hydrogen being below what is required to scale up the industry efficiently. This is a problem that exists in all new industries and is often used as a justification for government research and development (R&D) support.

A hydrogen economy will require investment in complementary infrastructure across the supply chain. These investments will need to be synchronised in time, scale and technology pathway. A failure to coordinate can lead to a suboptimal rate or type of investment (Rodrik 2004; Bento 2008; Gillingham and Sweeney 2011). For example, some jurisdictions may adopt an ammonia-based supply chain, while others prefer LOHCs, severely limiting the efficiency of hydrogen trade. For firms investing in hydrogen production, demand uncertainty is a major risk that will affect decisions about the scale of their investments, while potential hydrogen users face similar risks from the supply side uncertainty about whether sufficient hydrogen will be available. At the extreme end, coordination failures can prevent investment altogether, although they can be overcome with inter-industry collaboration.

Investment in hydrogen infrastructure is likely to have high capital costs. Innovative projects can struggle to secure the necessary capital (or secure it at too high a cost) as lenders do not have access to sufficient information to adequately assess the risk of the project (Carbon Pricing Leadership Coalition 2017). This will be a barrier to market entry for new projects, although it should be noted that this challenge is not specific to hydrogen and is common across new industries, particularly in energy systems.

Governments can implement a range of policy measures to address these market failures. Carbon pricing can help to ensure hydrogen's emissions reduction potential is adequately valued in the market. However, the carbon price required to make hydrogen competitive with alternative fuels is likely to be unfeasibly high, at least in the short term. At the same time, carbon pricing alone is unlikely to be enough to establish a hydrogen industry due to the presence of multiple market failures (Bataille et al. 2018). Government support for R&D, knowledge sharing and, particularly, early pilot and demonstration projects can improve the local stock of knowledge, addressing an undersupply of innovation. If coordination failures are not resolved within the industry, governments can overcome these by making sure the necessary investments are made across the supply chain. This could be done while addressing credit constraints, such as through providing grants or guarantees to hydrogen projects to 'de-risk' them, or by providing finance with a higher risk tolerance or at concessional rates. State-owned investment banks, such as Germany's KfW or Australia's Clean Energy Finance Corporation (CEFC), would be well placed to provide this. Governments could also reduce the risk of coordination failures by establishing dedicated hydrogen 'clusters' with shared infrastructure (IEA 2019d), or by facilitating cooperation between businesses.

Ensuring there is reliable demand for hydrogen will require more than just putting the infrastructure in place. Many new hydrogen applications are not yet cost-competitive with alternative technologies. Deploying targeted subsidies or tax breaks in the short term could bring down the costs of these applications (IRENA 2018). During the transition to a hydrogen economy, governments could also use mandated targets to set a base level of demand to provide certainty to investors in hydrogen production or supply chains. This could include mandating hydrogen be blended in domestic natural gas supply (up to local technical limits) or targeting a percentage of existing industrial hydrogen use to come from low emissions sources.

### *8.3.2 Safety, Social License and Acceptance Challenges*

Like all chemical fuels, hydrogen has specific handling requirements and safety considerations. Hydrogen is non-toxic, but it is highly flammable, prone to leakage and can cause the embrittlement of metals. It therefore requires specialised infrastructure for safe distribution and storage. Both ammonia and toluene used in hydrogen carriers are toxic. As discussed above, hydrogen and synthetic fuels based on hydrogen have been in use by industry and the energy sector for decades. Safe handling procedures and some standards already exist. However, international trade, and widespread use of hydrogen in urban settings, will bring with them new health and safety challenges. These challenges posed by hydrogen, while real and unique, are not more severe than the risks associated with other fuels that have broad use and acceptance today, such as oil and natural gas (IEA 2019d).

Nevertheless, the public will have to accept these risks for hydrogen use to become widespread in people's vehicles or homes, or for it to be produced, stored or transported near population centres. Incidents such as the explosion of one of Norway's three hydrogen refuelling stations in June 2019, caused by escaped hydrogen which ignited (Huang 2019), highlights the reality of these risks.

Studies conducted to date suggest that most people do not have predisposed attitudes towards hydrogen, either positive or negative. The vast majority of respondents to an Australian study conducted in 2018 (81%) gave a neutral response when asked their perceptions of hydrogen. At the same time, only 3% of respondents had positive perceptions of hydrogen, while 13% made negative associations, such as to the hydrogen bomb or the Hindenburg airship (Lambert and Ashworth 2018). This is consistent with other studies, conducted in Europe and Asia, which have also found mostly neutral associations with hydrogen (Hickson et al. 2007; Zimmer and Welke 2012; Schmidt and Donsbach 2016; Itaoka et al. 2017). The Australian study also found that respondents had limited overall awareness of hydrogen's properties or its uses (Lambert and Ashworth 2018).

A hydrogen industry can earn a social license to operate by building a strong safety record. Governments will also be essential in establishing public trust that these risks are well managed. Through public awareness campaigns that assume no prior knowledge, governments can build on the public's limited existing awareness and lack of preconceived notions to establish a positive public perception of hydrogen. Governments should expect industry to contribute to building awareness and acceptance for hydrogen, and a coordination approach that brings together governments, industry and academics is likely to increase the chance of success (Lambert and Ashworth 2018).

The public also expects governments to ensure the safety of hydrogen by implementing the right standards and safety regulations (Lambert and Ashworth 2018). This can also increase acceptance, as the belief that domestic hydrogen applications conform to international standards can itself be an important factor in building public trust (Chen et al. 2016; Lambert and Ashworth 2018).

### *8.3.3 Regulatory Challenges*

At present, countries' regulatory regimes could be a barrier to hydrogen uptake in new applications. This is because hydrogen was not considered when regulations were drafted for sectors such as gas infrastructure, transportation and power generation. This means that in most jurisdictions there are likely to be gaps where required regulations or standards do not exist, as well as regulations that could actively restrict the use of hydrogen in certain applications. The types of regulation needed to support a hydrogen industry fall under three categories: the functional use of hydrogen, the safety of hydrogen use and commercial frameworks for hydrogen business activities (Bruce et al. 2018).

In Europe, the HyLAW project has reviewed the legislation and regulations relevant to hydrogen production and applications across 23 European countries to determine the legal barriers to its uptake. For functional use and safety, the project found major structural barriers preventing the injection of hydrogen into existing gas networks, stemming from the fact the regulations governing gas networks were written to account for the physical properties of natural gas (Floristean et al. 2018). The project also found commercial barriers of varying severity that could affect hydrogen use for electricity generation or in buildings, while FCEVs were relatively unaffected (Floristean et al. 2018).

To ensure the right standards are in place, governments should first review their own regulatory settings to identify any relevant gaps or barriers. Following this, governments should look to global standards as the basis for hydrogen-specific regulations before considering country-specific requirements. This is important to ensure aspects such as safety and technical compatibility are the same across jurisdictions. The current state of international standards, and further work required on this, are discussed in the following section.

## 8.4 International Trade and Governance

### *8.4.1 International Trade*

Hydrogen has the potential to be a major new globally traded commodity; however, there are significant variations in estimates of its share of future global energy use. At the high end, the Hydrogen Council envisions hydrogen accounting for 18% of final global energy demand in 2050 (Hydrogen Council 2017). Modelling exercises have predicted that hydrogen has the potential to account for 3% by 2050 (Chapman et al. 2019).

In the short term, government policy and especially targets are likely to be the strongest factors in determining the size of the global hydrogen market. As of late 2019, several jurisdictions have announced hydrogen targets for the decade from 2020 to 2030 and beyond, the majority of which are for deployment numbers of FCEVs or the associated infrastructure (i.e. number of fuel stations). The hydrogen roadmaps of Japan and South Korea are major drivers behind hydrogen's global momentum (IEA 2019d). Both countries rely on imported fossil fuels for the majority of their energy needs, have poor renewable energy potential and large manufacturing bases. As a result, both countries view hydrogen as a promising route to decarbonise their economies. Both countries have targets for hydrogen use in their roadmaps and both acknowledge that a large proportion of this will have to be imported.

Although ambitious, these targets are well below the scale of the hydrogen economy envisioned by the Hydrogen Council and are likely to be insufficient to draw in significant investment. For example, Japan envisions a hydrogen supply chain of 300 000 tonnes by 2030, with a long-term target of up to 10 million tonnes (METI 2017). This, however, is a fraction of existing industrial demand for hydrogen (70 million tonnes in 2018) (IEA 2019d). In the long term, the size of a global hydrogen trade will depend on a number of factors, including the cost-competitiveness of production and storage with existing fuels, whether global interest translates into infrastructure investment and geopolitical concerns such as energy security.

Countries with high renewable energy potential could establish hydrogen production capability to take advantage of this new export opportunity. This includes countries in regions such as North Africa and the Middle East, as well as Australia, Chile, New Zealand and Norway (IEA 2019d). The ability to produce large quantities of hydrogen at low cost will be one factor in determining which countries are able to become major exporters. Other important factors will include proximity to markets, existing trading relationships and infrastructure.

### *8.4.2 Energy Security*

The IEA defines energy security as the uninterrupted availability of energy sources at an affordable price (IEA 2019a). Other conceptions of energy security take a broader view to encompass factors such as environmental sustainability and energy efficiency (Ang et al. 2015). Energy security has different implications over different time frames. Short-term energy security concerns are focused on managing sudden changes in the supply–demand balance, while long-term concerns deal with ensuring timely investments to supply energy in line with economic developments and environmental needs (IEA 2019a).

The development of the hydrogen economy has important implications for global energy security, particularly over the long term. These implications are largely positive. For example, hydrogen provides an opportunity to diversify global energy supply chains. Traditionally, fossil fuel industries have relied on a limited number of actors, and continuity of energy supply depended on a range of volatile political, economic and ecological factors (Sheffield and Sheffield 2007). Comparatively, hydrogen is more flexible as it can be produced in a range of ways from different fuel sources by a much wider variety of country actors. Hydrogen could also enhance global energy security through its wide application across emissions sectors. As an energy vector, renewable hydrogen provides a form of energy storage similar to fossil fuel sources like LNG, but without supply limitations or an emissions footprint. If renewable and low-carbon hydrogen can overcome the high production and storage costs which exist at present, they have a range of energy security advantages over fossil fuels.

Renewable hydrogen has energy security advantages over other vectors for international renewable energy trade, such as high-voltage direct current (HVDC) cables. For example, renewable hydrogen offers more flexibility in terms of its transport and storage than HVDC transmission of renewable energy. It circumvents many of the geopolitical complexities with regulating energy trade across multiple national electricity markets that have resulted in slow development of transnational HVDC networks (IEA 2019d). It can be stored and shipped anywhere in the world, particularly when converted to ammonia (European Commission 2003). While the transmission efficiency of HVDC cables transporting renewable energy is higher than renewable hydrogen production at present, there is little analysis directly comparing costs between these technologies.

### *8.4.3 International Governance to Facilitate Trade of Green Hydrogen*

A complex array of international organisations is engaged in the development of the hydrogen economy. This is symptomatic of international energy governance more broadly, but also a reflection of the diverse range of end uses for renewable hydrogen. Existing international governance actors perform a variety of functions. These include information-sharing and capacity-building, the coordination of research, development and demonstration funding, international financing and setting international standards for hydrogen production, storage and transport. The following sections provide an overview of existing international governance relevant to the development of a hydrogen economy. This list is not exhaustive; it does not detail, for example, energy subgroups within multilateral organisations like the G20 or ASEAN (the Association of Southeast Asian Nations). However, it provides an overview of the key public multilateral institutions facilitating the development of the hydrogen economy at present.

#### *8.4.3.1 Information-Sharing and Capacity-Building*

A number of international organisations perform knowledge-sharing and capacity-building functions related to the development of the hydrogen economy. These include the International Energy Agency (IEA), the International Renewable Energy Agency (IRENA) and the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE).

The IEA is an autonomous body within the Organisation for Economic Cooperation and Development (OECD) framework, founded in 1974 in the wake of the 1973 oil crisis. It undertakes analysis across all energy sectors (although historically it has focused more on fossil fuel sectors), develops global scenarios and advocates policies to enhance the reliability, affordability and sustainability of energy for its 30 member countries and beyond. Since 1977, the IEA has coordinated a Hydrogen Technology Collaboration Program (TCP) to accelerate hydrogen implementation and utilisation.

Recently, the IEA has increased its analytical focus on the development of hydrogen technologies and their potential to create a more sustainable and secure global energy supply (IEA 2019a). For example, in 2019 the G20, through its Japan Presidency, commissioned the IEA to undertake analysis on the current state of the hydrogen industry as well as recommendations for its future development (IEA 2019b). The report carried a broad analysis across all hydrogen production routes and uses, and made a range of recommendations seeking to assist in future growth of a green hydrogen economy (IEA 2019d). In May 2019, the IEA also began coordinating a new hydrogen partnership though the Clean Energy Ministerial to drive international collaboration on policies, programmes and projects to accelerate the commercial deployment of hydrogen and fuel cell technologies across all sectors of the economy (Clean Energy Ministerial 2019).

The IPHE was established in 2003 to facilitate the development of the hydrogen economy through information-sharing and capacity-building among its members. It consists of 19 member countries and the European Commission. It currently has two working groups: one focused on education and outreach and another on regulations, codes, standards and safety (IPHE 2019).

Lastly, as the only multilateral institution focused solely on renewable energy, IRENA also has an interest in undertaking analysis and building capacity to facilitate the development of a hydrogen economy. Founded in 2009, IRENA is a relatively new organisation with 160 member countries and another 23 states in accession (IRENA 2019). IRENA is seeking to provide policy-makers with analysis around the technology outlook for renewable hydrogen (IRENA 2018). For example, a recent report focused on the role of hydrogen in the energy transition, hydrogen supply economics and the existing challenges that restricted hydrogen production (IRENA 2019).

#### *8.4.3.2 Research and Development Funding*

Although funding for research, development and demonstration (R&D&D) has traditionally been the domain of national governments, in 2015 a multilateral R&D&D initiative, Mission Innovation, was launched on the eve of the Paris Agreement. It is a global initiative of 24 countries and the EU, which seeks to accelerate the pace of clean energy innovation to achieve performance breakthroughs and cost reductions, to provide widely affordable and reliable clean energy solutions (Mission Innovation 2019b). Together, Mission Innovation members account for approximately 80% of global government funding for R&D&D research. Mission Innovation has a number of innovation challenges designed to facilitate global collaborations and innovation in key technology areas. In 2018, it announced the creation of a new innovation challenge focused on renewable and clean hydrogen. Its objective is to accelerate the development of a global hydrogen market by identifying and overcoming key technology barriers to the production, distribution, storage, and use of hydrogen at gigawatt scale (Mission Innovation 2019a).

#### *8.4.3.3 International Financing*

Like most emerging energy sectors, the development of the hydrogen economy will require large capital investments and the establishment of new global value chains that span numerous countries (IEA 2019d). A range of international financing tools will be needed to assist in the development of the hydrogen economy. For example, multilateral development banks can facilitate finance flows to assist in commercialising renewable hydrogen projects and assisting in the development of the hydrogen economy. Many countries also have export finance agencies to facilitate international trade and mitigate export risks.

#### *8.4.3.4 International Standards*

Widely adopted international codes and standards are vital to establishing the hydrogen economy and for lowering regulatory barriers to trade (IEA 2019d). International standards are mainly developed through the International Organization for Standardization (ISO); an independent, non-governmental international organisation with a membership of 164 national standards bodies. The ISO develops voluntary consensus-based, international standards, including a number related to hydrogen production, storage and transportation through the ISO Technical Committee 197 (International Standards Organization 2019). At present, there are 21 hydrogen standards that have either been published or are under development through the ISO. These include standards on safety of hydrogen systems (ISO/TR 15916:2015), gaseous hydrogen fuelling station standards (ISO 19880-3:2018, ISO 19880-5:2019, ISO/FDIS 19880-1) and industrial, commercial and residential application of hydrogen generators using water electrolysis (ISO 22734:2019).

The International Electrotechnical Commission (IEC), a sister organisation of the ISO, has also developed some standards relating to hydrogen fuel cell technologies. However, there are some existing gaps in international standards on hydrogen, particularly around utilisation of gas networks. As mentioned above, the IPHE is also seeking to coordinate global standards for hydrogen internationally, with the support of member countries, particularly Japan.

#### *8.4.3.5 Sectoral Organisations*

One of the benefits of renewable hydrogen is its potential to be used in sectors where other renewable fuels are not suitable, such as transport and heavy industry. The International Maritime Organization (IMO) and the International Civil Aviation Authority (ICAO) are both engaged in the development of the hydrogen economy in their respective sectors to meet emissions reductions commitments. For example, the IMO has committed to reduce emissions by 50% from 2008 levels by 2050. To achieve this target, alternative fuels for shipping will need to be developed. Using hydrogen with marine fuel cells is one promising technology being explored, although capital and fuel costs remain prohibitively high (Balcombe et al. 2019). Like the IMO, the ICAO recognises the potential of renewable hydrogen as an alternative fuel which provides abatement opportunities to replace bunker fuel use in the aviation sector with a sustainable alternative.

#### *8.4.3.6 International Certification and Other Measures for Renewable and Low-Carbon Hydrogen*

Using hydrogen does not produce GHG emissions; however, only the use of green hydrogen will ensure the supply chain is zero emissions. The international certification of green and low-carbon hydrogen can assist in the development of the hydrogen economy by providing assurance to consumers on how and where a product was produced. By guaranteeing the provenance of renewable hydrogen, international certification will create a market where there is demand for zero- or low-emissions hydrogen. Research has shown that consumers care about the emissions intensity of hydrogen and are far more supportive of renewable hydrogen production as opposed to hydrogen using CCS (Lambert and Ashworth 2018).

International certification could take the form of a ‘guarantee of origin’ scheme such as that provided by the EU’s CertifHy scheme (CertifHy 2015). The CertifHy scheme is managed and operated from a central registry, which issues, transfers and cancels guarantees of origin for green and low-carbon hydrogen. This is similar to other national and private registries for emissions units. There is a need for a global guarantee of origin scheme for green and low-carbon hydrogen, as the CertifHy scheme has only recently completed its pilot phase and only operates in the EU. A global scheme could potentially be linked to international standards for hydrogen production developed through the ISO and other international standards organisations. It could also possibly be utilised through

Article 6 of the Paris Agreement, depending on how rules for carbon markets are implemented through this agreement.

In the absence of the development of a guarantee of origin scheme, there is scope to facilitate trade of renewable hydrogen bilaterally, plurilaterally or multilaterally through development or modification of free trade agreements.

## 8.5 Conclusion

While the hydrogen economy is not a new concept, there are promising signs that the development of renewable hydrogen energy production may be about to scale up substantially. Globally, there is an urgent need to find carbon-free forms of energy that can be produced cheaply, used across multiple emissions sectors and stored to balance energy grid intermittency. While renewable and low-carbon hydrogen is still significantly more expensive than other zero or low-carbon energy sources, hydrogen's versatility in terms of end use, and capacity to be converted into other chemicals like ammonia for transportation and storage, mean that it has unique advantages as an energy fuel and vector. Renewable and low-carbon hydrogen also provides the opportunity to improve global energy security through diversification of energy supply and other co-benefits such as improved air quality. This is not to say it is a silver bullet. Producing, transporting and storing hydrogen has significant safety considerations and its conversion to chemical form results in significant efficiency losses. However, in a global energy landscape searching for opportunities to decarbonise rapidly, development of the hydrogen economy offers a significant opportunity.

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