GATHERING PACE

Infrastructure Opportunities in the Hydrogen Economy

RED PAPER

QIC

DECEMBER 2020

Contents

Important Information

Executive Summary

Ambitious decarbonisation targets are rapidly growing in focus across the globe. With the world hunting for a solution, hydrogen is increasingly being looked to as an enabler of the deep decarbonisation needed to move the dial.

But with the huge scale of investment required for a Hydrogen Economy over the coming decades, what's needed to make it a reality? And how do we get there?

Decarbonisation is no simple undertaking. While significant progress has been made globally to reduce carbon emissions from electricity generation, there has been very little progress in reducing carbon emissions from transport and heavy industrial uses. These sectors collectively account for over 40% of global greenhouse gas emissions.[1] Between 1990 to 2017, total emissions in the European Union reduced by more than 20%, but transport sector emissions actually increased by approximately 20%.[2]

These 'hard-to-decarbonise' sectors continue to rely on fossil fuels for heat, feedstock and for transport. And hydrogen is currently part of the problem. Hydrogen demand from industrial users has grown more than threefold since 1975,[3] but it is currently manufactured almost entirely from coal and natural gas. Production of hydrogen is currently responsible for around 830 million tonnes of CO2 emissions per year, which is equivalent to the carbon produced annually by the United Kingdom and Indonesia combined.[4]

The challenge is to transition to clean hydrogen, powered by low-cost, zero carbon sources and stored for use on demand. QIC expects that meeting this challenge will result in radical growth in adoption among industrial users and a broadening of hydrogen use into other 'hard-to-decarbonise' sectors such as long-haul and heavy transportation, building heating and long-term power storage.

The coming decade will be a period of enormous growth for the Hydrogen Economy, supported by a raft of global government policy announcements. The recent EU Green Deal states that hydrogen needs to become an intrinsic part of the integrated energy system by 2030, with at least 40GW of renewable hydrogen electrolysers to be installed.[5] This represents a huge gap in infrastructure to be filled – global installed electrolyser capacity was less than 1 MW in 2010 and only 25 MW in 2019.[6] In Australia, all State and Federal Governments are united in their support of the National Hydrogen Strategy, which also targets 2030 for the establishment of Australia as a leading global player in the production and export of renewable hydrogen.

1 International Energy Agency
2 Arregui, N & Jobst, A., "Seven Charts on Climate Policies for Key Sectors in the European Union". Published by the IMF: https://www.imf.org/en/News/Articles/2020/09/23/na092320-seven-charts-on-climate-policies-for-key-sectors-in-the-european-union
3 "The Future of Hydrogen". Accessed from IEA: https://www.iea.org/reports/the-future-of-hydrogen
4 "Hydrogen". Accessed from IEA: https://www.iea.org/fuels-and-technologies/hydrogen
5 "A hydrogen strategy for a climate-neutral Europe". Accessed from the European Union: https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf
6 "Hydrogen, June 2020". Accessed from IEA: https://www.iea.org/reports/hydrogen

Contacts

QIC also expects exponential improvement in the cost-competitiveness of hydrogen applications over the coming decade. This will occur through the economies of scale from increased electrolyser production and hydrogen storage facilities, as well as continued cost reductions in renewable energy. By 2030, we foresee the Hydrogen Economy to be well established but still growing rapidly, driving the next significant leap forward in decarbonisation.

The upcoming period of intensive investment in hydrogen-related infrastructure presents strong opportunity for institutional investors seeking real assets with stable long-term cash flows. Up to US$3 trillion of infrastructure investment may be needed by 2030 (and up to US$20 trillion by 2050) to develop the Hydrogen Economy.[7]

QIC is actively preparing for this opportunity. It is well positioned to deliver and actively manage hydrogen-related infrastructure, with strong established relationships with leading global hydrogen players and early learnings already developed from pilot and commercial projects within existing portfolio companies. Examples include a Hydrogen Demonstration Plant in remote Western Australia which will integrate a hydrogen fuel cell into a microgrid, as well as the roll out of multiple hydrogen-powered forklifts by our portfolio company Generate Capital in the US.

Hydrogen has enormous potential to reduce global carbon emissions through its versatility in production methods and uses, and its ability to be transported and stored for extended periods. And while realisation of a Hydrogen Economy will take some time, progress is accelerating rapidly, driven in part by 'green' stimulus packages supporting the global recovery from COVID-19.

QIC believes that targeted investment over the coming decade will see infrastructure investors well-prepared for transition to a hydrogen-powered future.

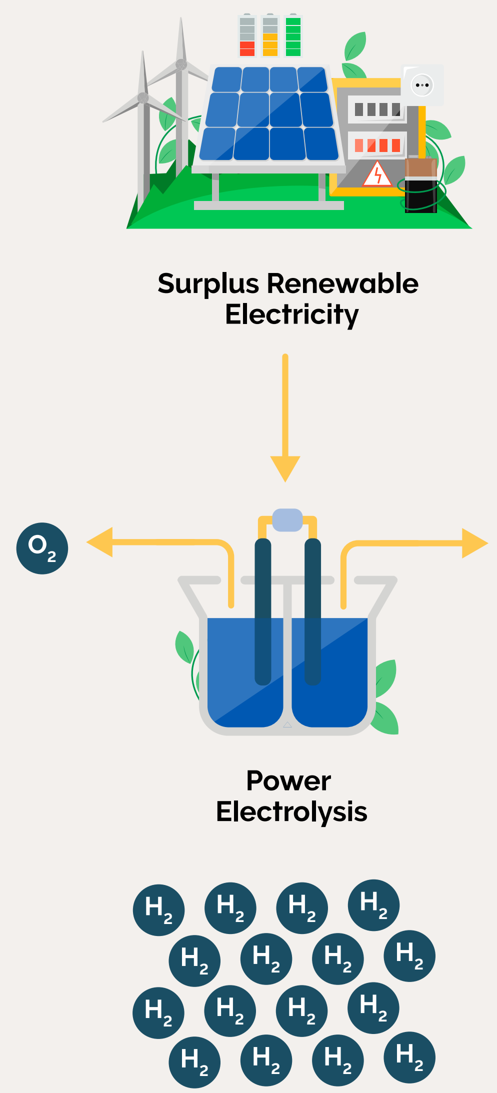
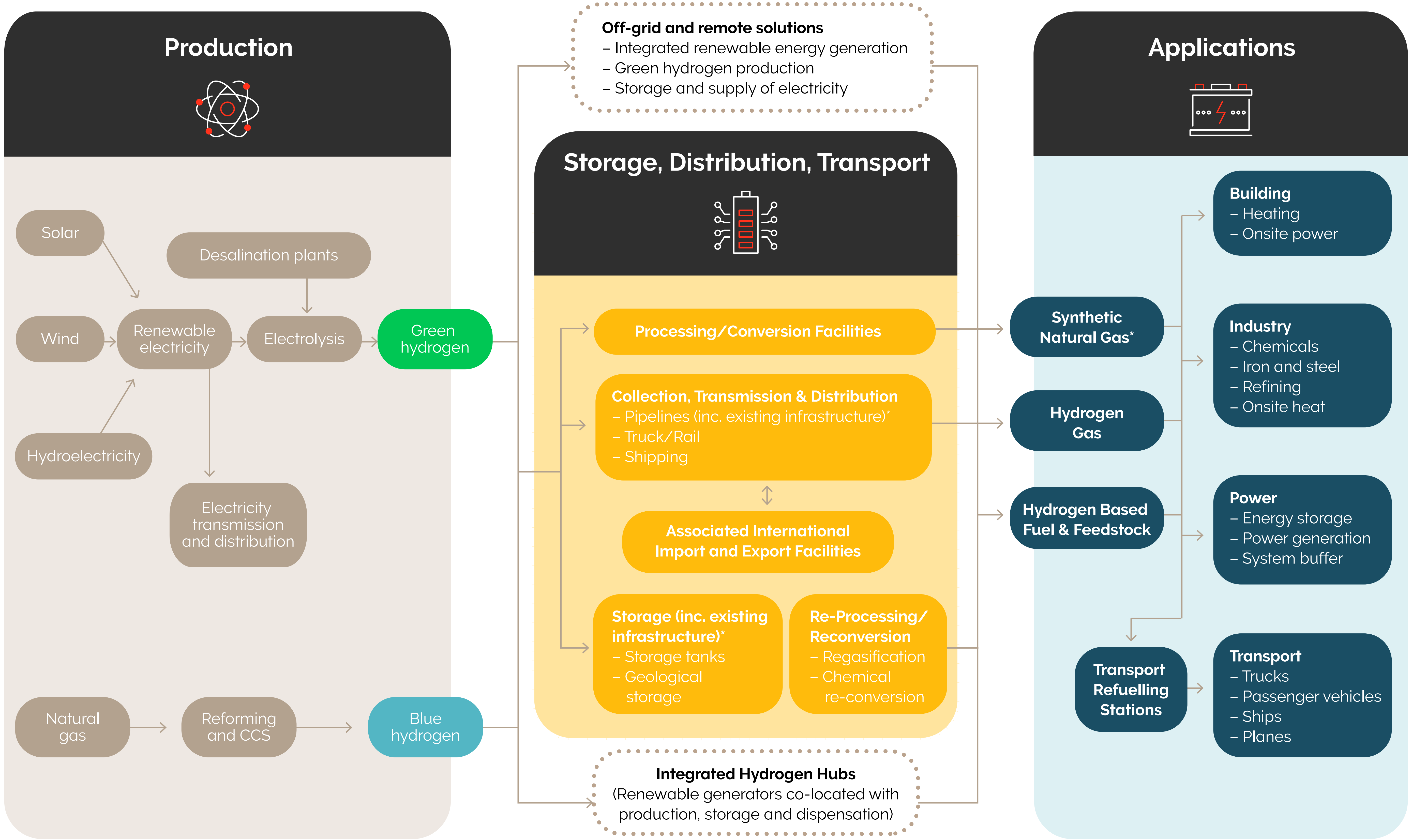


Figure 1: Producing 'green' hydrogen

7 Refer to section on: Assessing the potential scope of infrastructure investments for detailed cost estimates and sources

The Hydrogen Value Chain



*Hydrogen can be transported and stored using existing gas infrastructure, with limited adaptation required. Hydrogen can already be blended into existing gas infrastructure as a transition before potential longer-term conversion to 100% hydrogen. There is also optionality to convert hydrogen to synthetic natural gas by using captured carbon dioxide and a methanation reactor, which can provide additional flexibility in some contexts.

Figure 2: The Hydrogen Value Chain

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Gathering Pace:
Infrastructure Opportunities in the Hydrogen Economy

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The Hydrogen Economy

The Hydrogen Economy

"It is clear that the next significant transformation in the energy transition will be based on the Hydrogen Economy. For it to become mainstream, the Hydrogen Economy cannot be based on subsidies; sustainable markets must be created and getting cost right is one of the first boxes that must be checked."

– Dr. Armin Schnettler PhD, CEO of the New Energy Business at Siemens Energy[8]

The Hydrogen Economy is a collection of markets and technologies that together enable the utilisation of hydrogen in multiple energy uses.

It refers to the idea of transforming our existing hydrocarbon-based infrastructure – from static power generation to a full range of transportation applications – to be powered by hydrogen, in order to cut carbon and carbon dioxide emissions.

The potential of an expanded role for hydrogen is based on its versatility. As an agent of decarbonisation suitable across a range of market sectors, the roles of hydrogen in the emerging Hydrogen Economy are captured in Figure 3.

The Hydrogen Economy

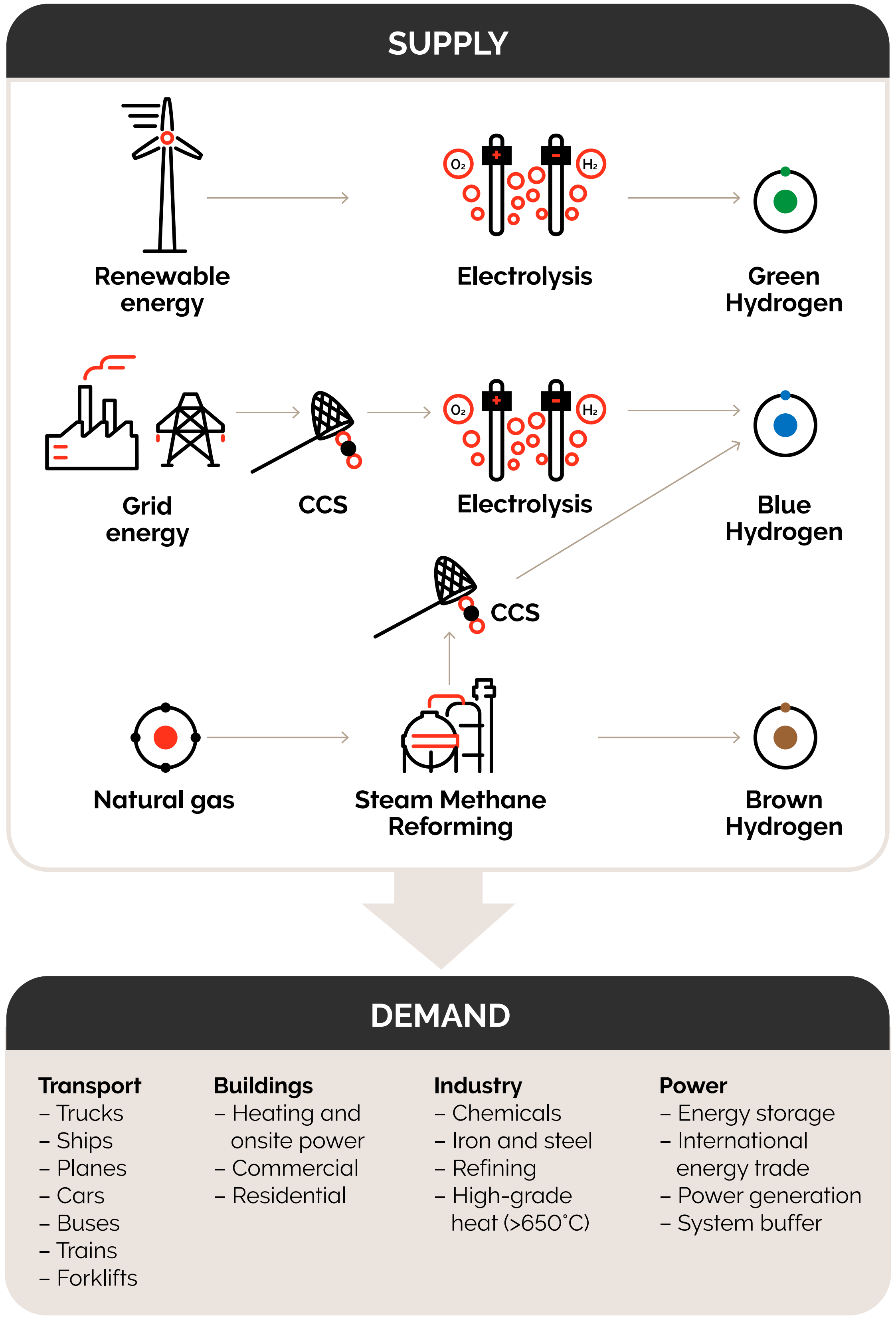


Figure 3: The Hydrogen Economy

Source: QIC, MIDC, Energy & Capital

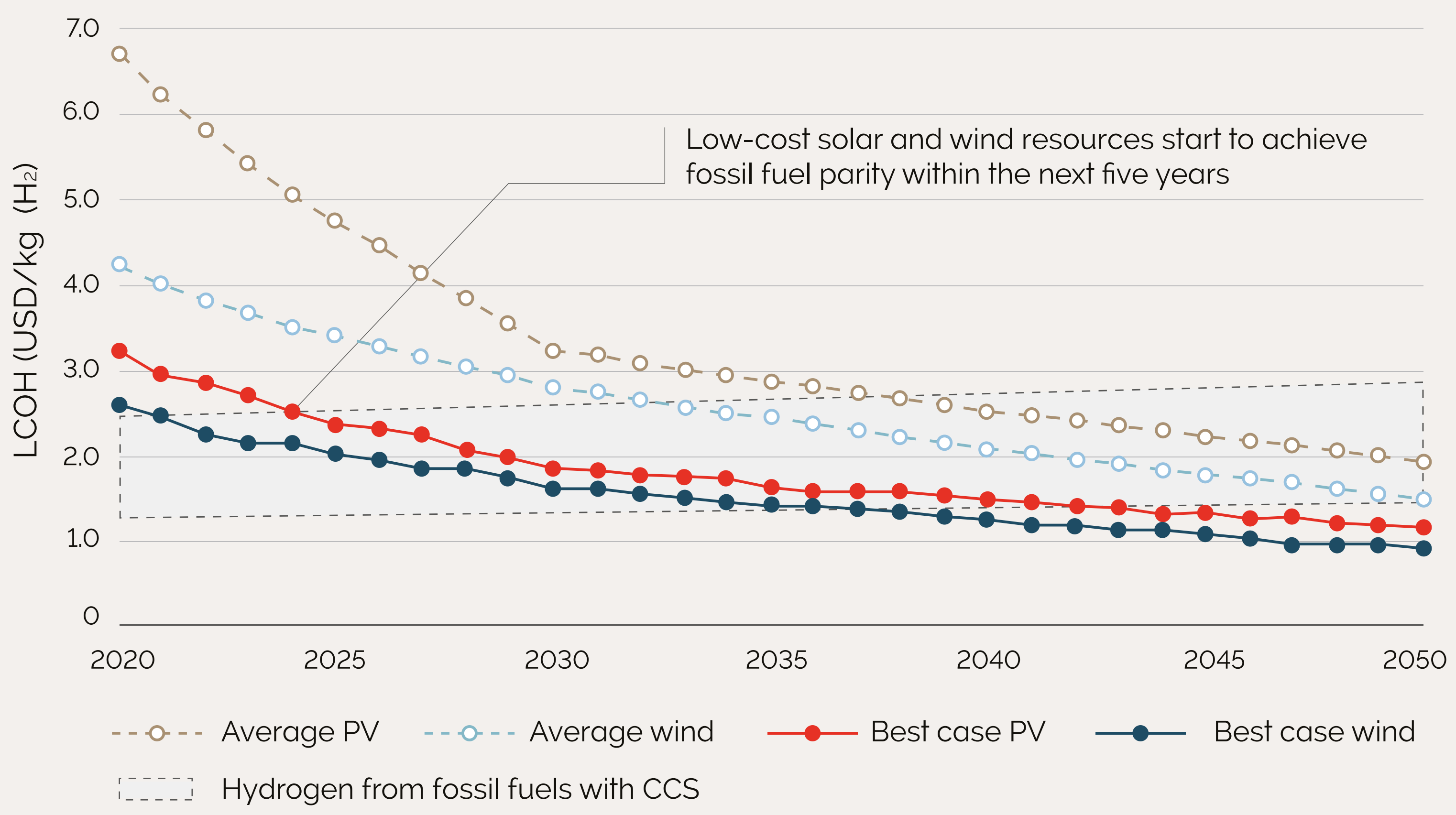
8 https://www.powermag.com/at-the-dawn-of-the-hydrogen-economy

The 'colours' of hydrogen

Most hydrogen (or H2) produced today comes from fossil fuels – referred to as 'brown' hydrogen.

There are however two primary options for producing hydrogen with lower carbon intensity: 'blue' hydrogen, produced via natural gas reforming and coal gasification with Carbon Capture and Storage (CCS)[9], and 'green' hydrogen, produced through electrolysis powered by renewable electricity such as wind, solar, etc. *(see Figure 3).*

Currently, the high production cost for 'green' hydrogen is hindering its adoption – for instance about US$6 per kg for renewable hydrogen from electrolysis. In total, less than 5% of hydrogen volume today comes from low-carbon sources. However, recent cost reductions in renewable energy generation (for renewable hydrogen from electrolysis) and development in CCS (with natural gas reforming) are now paving the way for a growing number of low-carbon hydrogen applications, and the cost reduction pathway is forecast to continue.



Note: Remaining CO2 emissions are from fossil fuel hydrogen production with CCS.
Electrolyser costs: USD 770/kW (2020), USD 540/kW (2030), USD 435/kW (2040) and USD 370/kW (2050).
CO2 prices: USD 50 per tonne (2030), USD 100 per tonne (2040) and USD 200 per tonne (2050). LCOH = levelised cost of hydrogen; CCS = carbon capture and storage.

Figure 4: Cost of 'green' H2 approaches blue H2 in 4-5yrs

Source: IRENA Global Renewables Outlook 2020; Other forecasters predict cost parity to be reached in approx. 10 years (BNEF)

9 CCS is the process of capturing CO2 and depositing it where it will not enter the atmosphere, normally an underground geological formation. Australia has a natural competitive advantage in CCS with known high-quality, stable geological depleted storage basins capable of injection at a rate of 300 million tonnes per annum for at least 100 years—the same basins that have previously safely and permanently held oil and gas in place for tens of millions of years (https://www.greencarcongress.com/2020/10/20201026-santos.html)

Hydrogen versatility

Hydrogen produced from low or zero carbon processes has the potential to reduce carbon emissions in many sectors.

On top of that, hydrogen is used in various industrial processes, such as ammonia and fertiliser production, as well as in the oil refining, metals and food processing sectors.

Hydrogen is currently considered to be the leading solution for decarbonising certain 'hard-to-decarbonise' sectors in the economy, including long-haul transport, industrial sectors (particularly steel and chemicals), heating, and long-term power storage (e.g. seasonal storage).

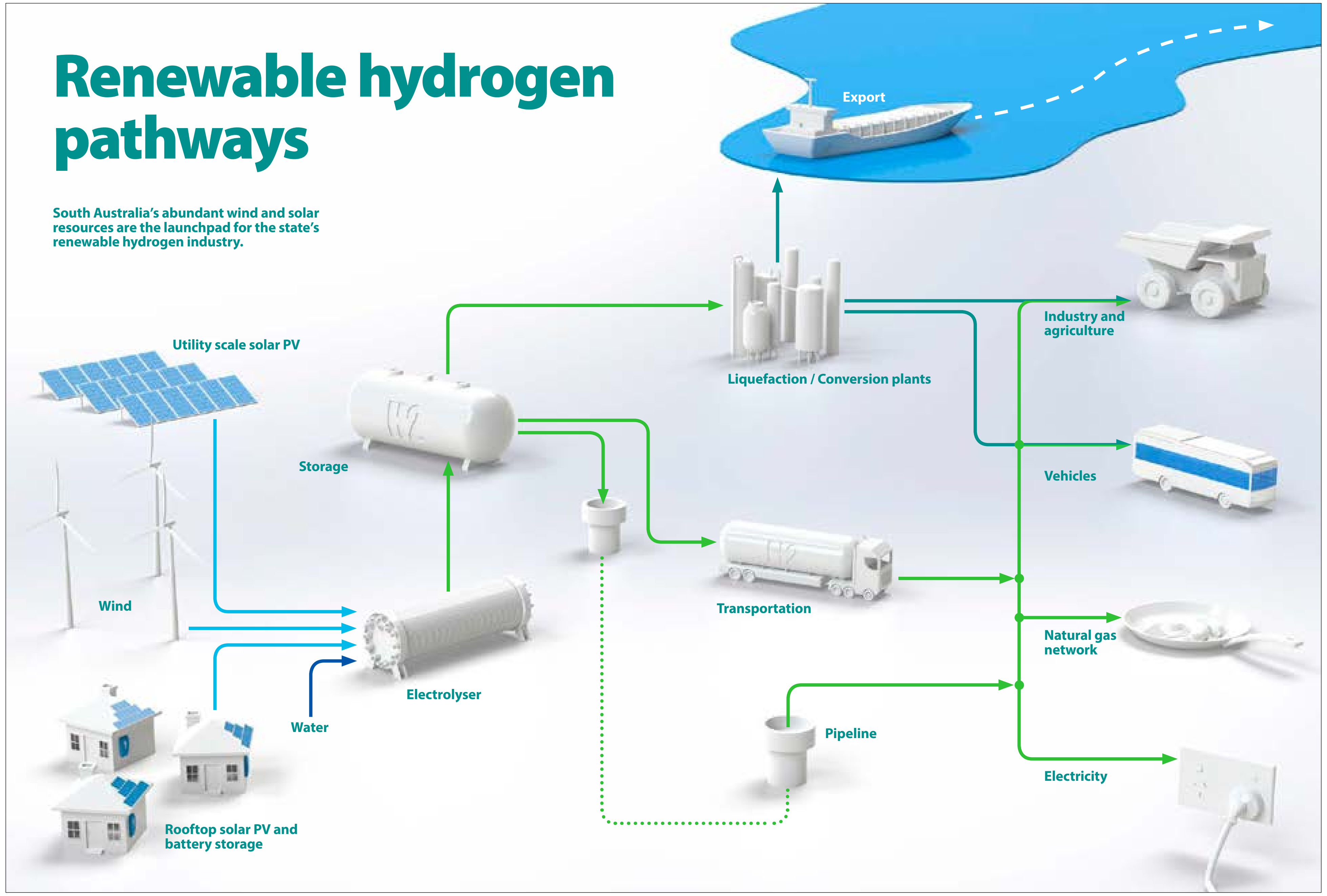


Figure 5: Visualisation of the Hydrogen Economy
Source: Government of South Australian Hydrogen Roadmap, September 2019

QIC has aggregated the technologies currently considered to be viable options for decarbonising various industries in the chart below:

	Hydrogen	Renewables	Carbon Capture and Storage	Electric Vehicles	Biofuels
Power (generation)	●	●	●		
Power (storage)	●			●	
Transport	●	●		●	●
Industry	●	●	●		
Buildings	●	●			

Figure 6: The five ‘decarbonisation’ technologies which offer solutions for several applications
Source: QIC, International Energy Agency

QIC is involved in the early exploration of some of these future applications through pilot and commercial projects, in its portfolio companies. We are currently, through Pacific Energy, delivering a Hydrogen Demonstration Plant to provide a reliable ‘green’ power solution for the remote town of Esperance in Western Australia, which will integrate a hydrogen fuel cell into a microgrid.

Case Study: Hydrogen Demonstration Plant - Pacific Energy (QIC)

Background

For a small community of circa 1,000 citizens located in Western Australia, tourism is central to the local economy and drives the main power load in the town.

QIC's client, the utility which provides power to the township, has a strategic goal to add no new diesel generation from 2025. To achieve this goal, investigation is underway for viable renewable solutions that can provide the necessary capacity to offset the requirement for diesel generation.

Solution

A Hydrogen Demonstration Plant is being piloted to provide base load green hydrogen power into a microgrid.

The Hydrogen Demonstration Plant will provide a minimum >1250 kWh/day, with a minimum agreed continuous output to the power station.

Output will be from the solar farm when available, with excess solar going to the electrolyser, so that the fuel cell can provide the power when solar is not available.

Key Outcomes

Prove the potential to integrate hydrogen fuel cell as a base green hydrogen power provider to a microgrid, providing reliable 'green' power for a remote community.

Proving the reliability of such a plant provides opportunity to implement this technology into other microgrids under management of our client.

Figure 7: Hydrogen Demonstration Plant – Pacific Energy (QIC)
Source: QIC

The Hydrogen Economy growth potential

A hydrogen economy has significant potential.

Hydrogen is being discussed as either a tool to meet ambitious decarbonisation goals or an opportunity for export, or both.

There is significant global interest in hydrogen, from high solar-resource hydrocarbon exporting countries in the Middle East, highly industrialised energy-importing countries in Asia and Europe, gas-rich countries like Russia, and coal-rich countries like Australia. Significant exporters of natural gas such as Russia are looking to produce hydrogen from natural gas, to become key suppliers to European and Asian markets.[10]

QIC has aggregated views from leading organisations on the forecast global hydrogen demand. The chart below represents a range of predictions as at key milestones.

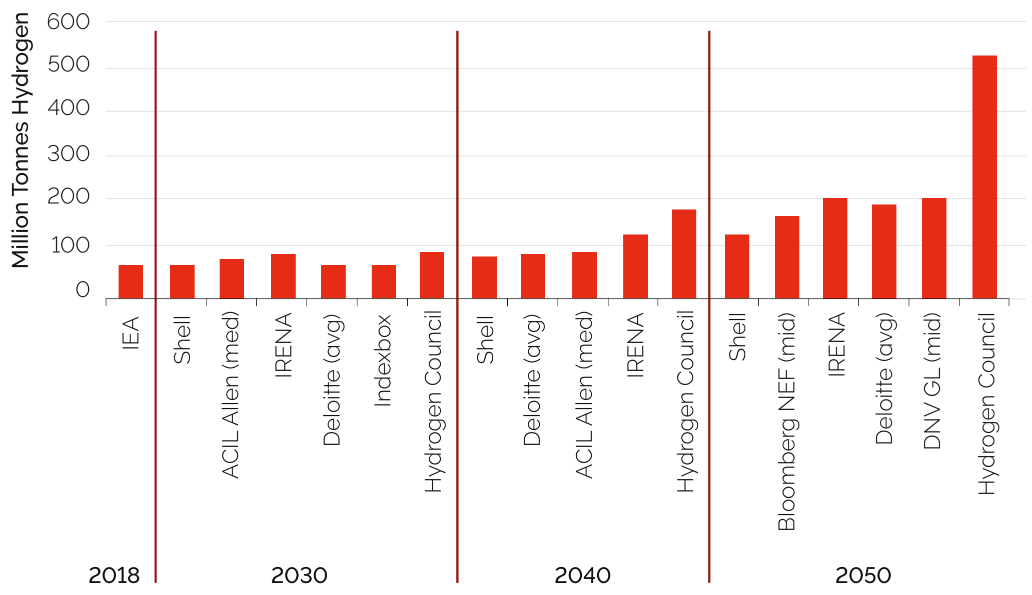


Figure 8: Forecast global hydrogen demand

Source: QIC, IEA, IRENA, ACIL Allen, Shell, Deloitte, DNV GL, Bloomberg NEF, Hydrogen Council
Note: ACIL Allen is medium scenario, Deloitte is average of Top 3 scenarios, Bloomberg NEF & DNV GL is mid-point of 2050 scenarios

Building on its flexibility, a major expansion of the Hydrogen Economy would be characterised by:

1. Rapid upscaling of 'green' hydrogen production by electrolysis, supported by the falling costs of renewables and technological progress in electrolyser production
2. Significant increases in hydrogen demand as a fuel, driven by the need to decarbonise key sectors including long-haul transport, industry, energy storage in power generation and heating in buildings.

10 "Russia's hydrogen bet sets up contest with Australian for Japanese market". Accessed from S&P Global: https://www.spglobal.com/en/research-insights/articles/russia-s-hydrogen-bet-sets-up-contest-with-australia-for-japanese-market

Contacts

Hydrogen take-up is driven by relative sector economics

There are three main economic drivers for adoption of hydrogen across a range of sectors:

1. **Cost reduction** for 'green' hydrogen relative to other low-carbon alternatives
2. **Cost competitiveness** for particular applications
3. **Carbon pricing** and its relative impact on market attractiveness of 'green' hydrogen applications

1 Cost reduction

While the levelised cost of 'green' hydrogen is currently uncompetitive with natural gas on an energy-equivalent basis, 'green' hydrogen cost is expected to significantly reduce over time, and is forecast to be produced in most parts of the world for US$0.7 to US$1.6/kg before 2050, making it competitive with natural gas in the long-term.

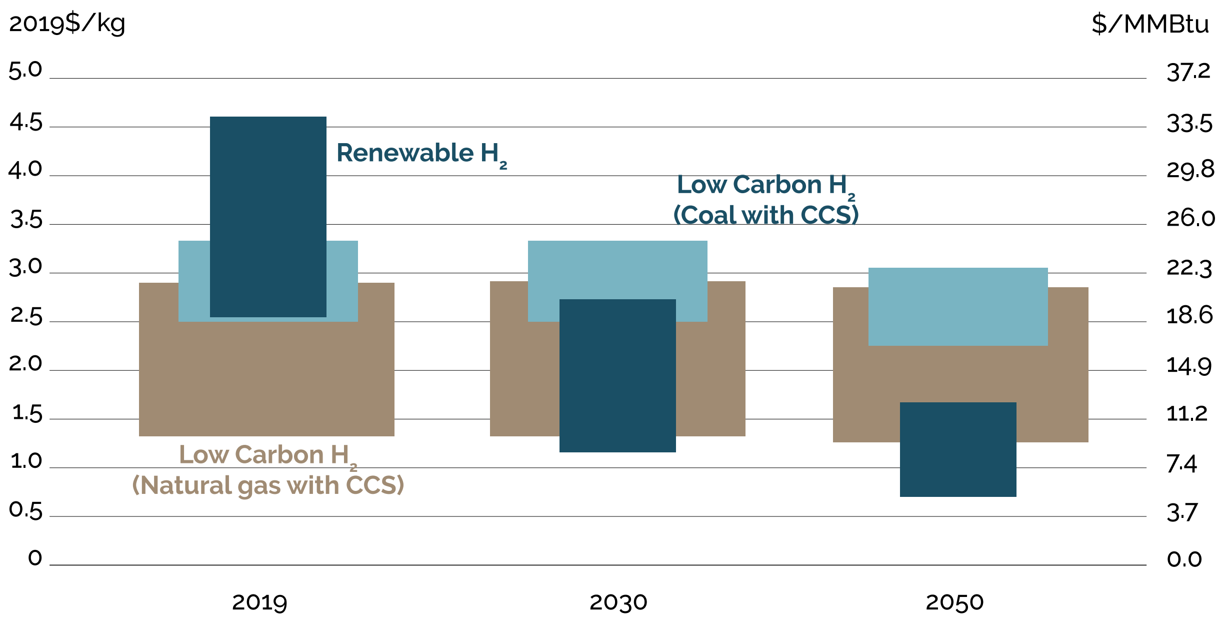


Figure 9: Forecast global range of levelised cost of hydrogen production from large projects
Source: BloombergNEF, 2020 Hydrogen Economy Outlook

2 Cost competitiveness

Hydrogen's role in different sectors is driven by its relative cost for various sectors and broad applications *(See Section 2 – Applications for Hydrogen Use)*.

As some renewable energy generation technologies become more cost-effective *(Figure 10)*, there is increased potential for hydrogen to play a role in power generation, initially as a blend with natural gas, and in the future combusted in turbines capable of 100% hydrogen combustion.

Levelised Cost of Energy Comparison (LCOE) – Unsubidised Analysis

Selected renewable energy gereration technologies are cost-competitive with conventional generation technologies under certain circumstances

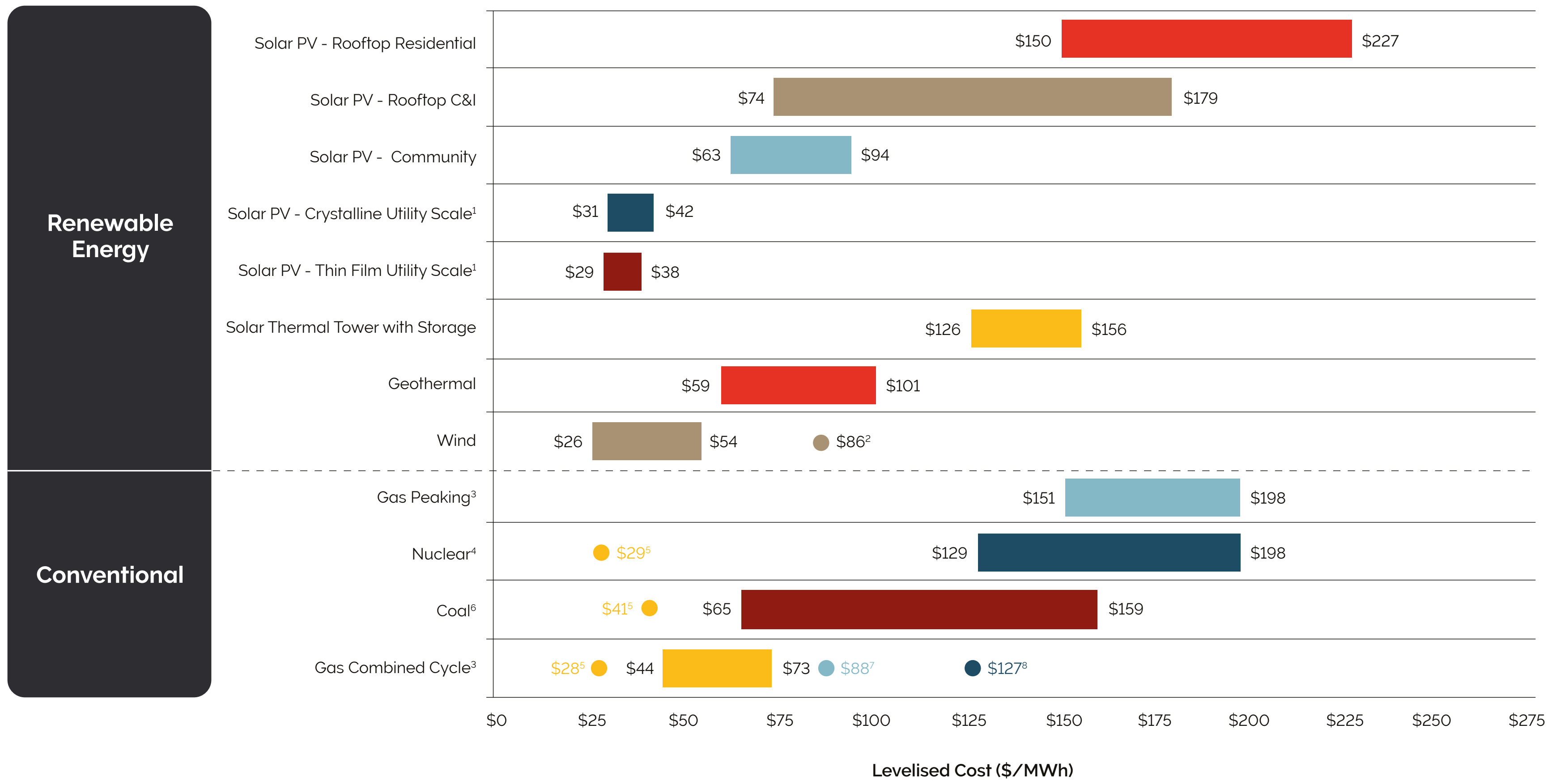


Figure 10: Levelised cost of energy comparison (LCOE) unsubsidised analysis

Source: Lazard levelised cost of energy version 14.0, October 2020

Note: Note: Unless otherwise indicated, the analysis assumes 60% debt at 8% interest rate and 40% equity at 12% cost. These results are not intended to represent any particular geography.

1 Unless otherwise indicated, the low case represents a single-axis tracking system and the high case represents a fixed-tilt system.

2 Represents the estimated implied midpoint of the LCOE of offshore wind, assuming a capital cost range of approximately $2,500- $3,675/kW.

3 The fuel cost assumption for Lazard's global, unsubsidized analysis for gas-fired generation resources is $3.45/MMBTU.

4 Unless otherwise indicated, the analysis does not reflect decommissioning costs, ongoing maintenance-related capital expenditures or the potential economic impacts of federal loan guarantees or other subsidies.

5 Represents the midpoint of the marginal cost of operating fully depreciated gas combined cycle, coal and nuclear facilities, inclusive of decommissioning costs for nuclear facilities. Analysist assumes that the salvage value for a decommissioned gas combined cycle or coal asset is equivalent to its decommissioning and site restoration costs. Inputs are derived from a benchmark of operating gas combined cycle, coal and nuclear assets across the U.S. Capacity factors, fuel, variable and fixed operating expenses are based on upper- and lower-quartile estimates derived from Lazard's research.

6 High end incorporates 90% carbon capture and storage. Does not include cost of transportation and storage.

7 Represents the LCOE of the observed high case gas combined cycle inputs using a 20% blend of "blue" hydrogen, (i.e. hydrogen produced from a steam-methane reformer, using natural gas as a feedstock and sequestering the resulting CO2 in a nearby saline aquifer). No plant modifications are assumed beyond a 2% adjustment to the plant's heat rate. The corresponding fuel cost is %.520/MMBTU.

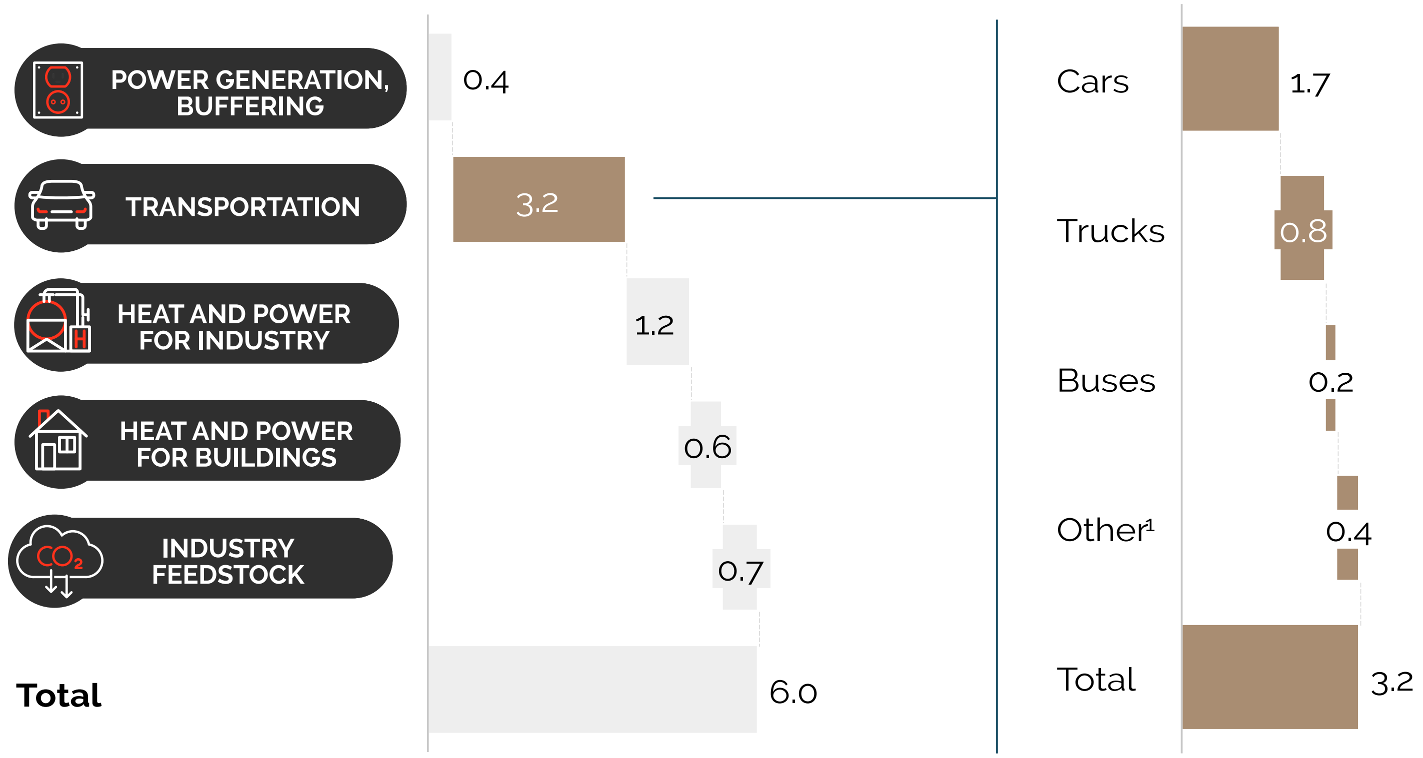
8 Represents the LCOE of the observed high case gas combined cycle inputs using a 20% blend of "Green" hydrogen, (i.e. hydrogen produced from an electrolyser powered by a mix of wind and solar generation and stored in a nearby salt cavern). No planned modifications are assumed beyond a 2% adjustment to the plant's heat rate. The corresponding fuel cost is $10.05/MMBTU.

Contacts

3 Carbon price dynamics

The legislation of carbon pricing is expected to further improve the cost-competitiveness of hydrogen as an alternative energy source. The resulting 'green' hydrogen applications are expected to significantly reduce annual CO2 emissions, with the Hydrogen Council estimating that emissions could be reduced by as much as 6Gt by 2050. This is equivalent to almost double the amount of annual emissions of the EU28 or the entire yearly emissions of the global industrial sector.[11]

C02 Avoidance Potential 2050, Gt



1 Other: aviation, shipping, rail, material handling

Figure 11: Forecast global range of levelised cost of hydrogen production from large projects
Source: Hydrogen Council

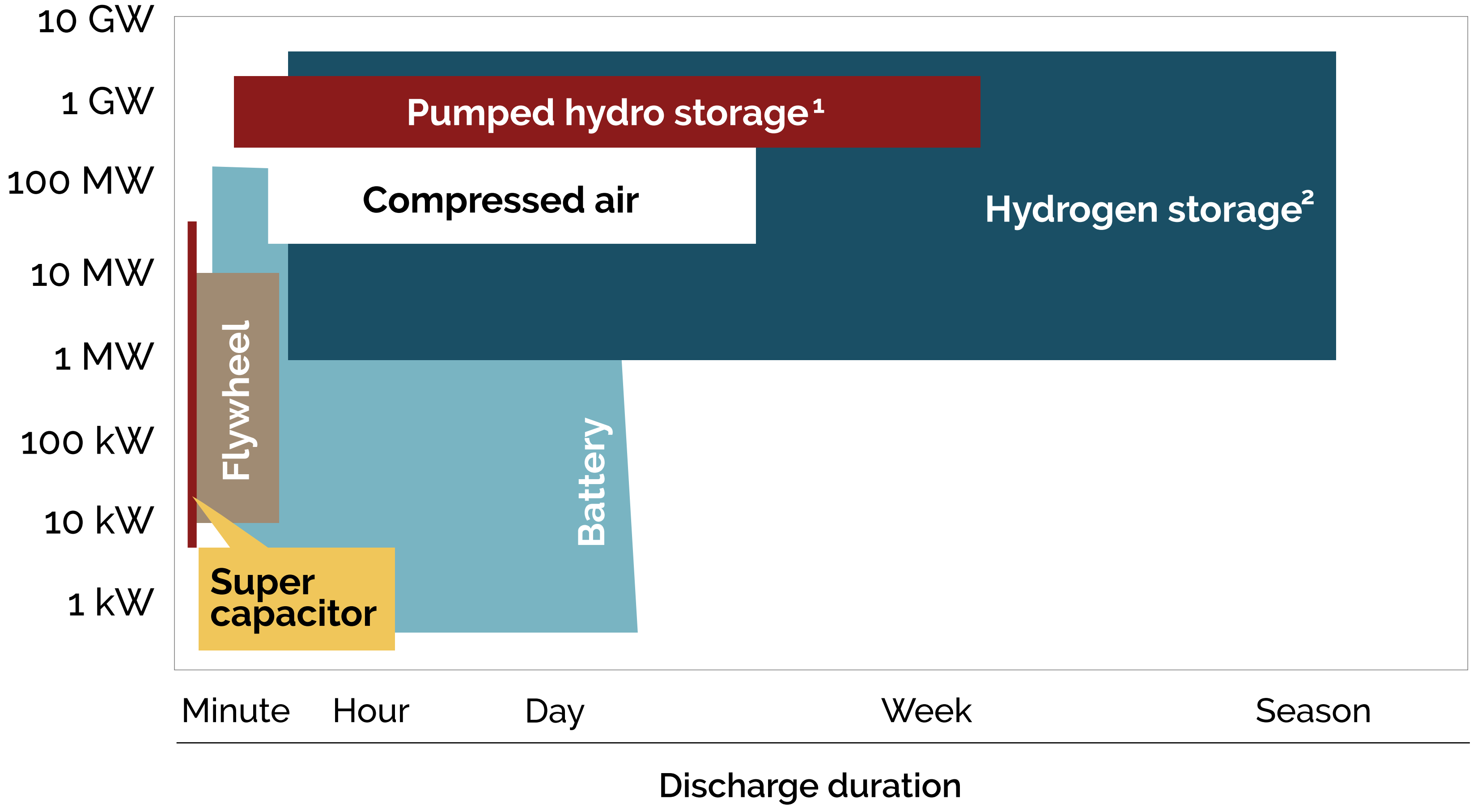
11 EDGAR database: https://edgar.jrc.ec.europa.eu/overview.php?v=booklet2020

Hydrogen is a very strong energy storage option

A significant advantage of hydrogen is that it can be produced from electricity generated by renewable energy, and can also be stored in large volumes for extended periods of time.

The increasing penetration of renewable energy generation across the world means that there is a growing need for cost-effective options to store large amounts of electricity over time. Hydrogen energy storage can play an important part in improved system integration and resilience, due to its flexibility in terms of the discharge duration.

Technology overview in power and time



1 Limited capacity (<1% of energy demand)
2 As hydrogen or SNG

Figure 12: Hydrogen can be stored for long periods compared to other power sources
Source: Hydrogen Europe

Contacts

Case Study: Hydrogen Forklifts - Generate Capital (QIC)

Background

Material handling in large distribution centres requires reliable and clean equipment, operating in heavy duty cycles

Fossil fuel-powered forklifts are increasingly being phased out due to concerns with their operation, including the air pollution and operational carbon intensity

Solution

Generate Capital (QIC entity) has supported multiple roll-outs of hydrogen powered forklifts, as well as hydrogen refuelling infrastructure deployed by major clients

The shift to hydrogen powered forklifts has been embraced by leading enterprises in the US including Amazon, FedEx, Walmart and many others

Key Outcomes

Fast adoption rates in the US, with close to 25,000 hydrogen fuel cell forklifts in operations to date and rapidly growing

Significant productivity gains due to:

- Reducton in fleet size - faster refuelling time for hydrogen compared to battery-powered forklifts.
- Fuel powered - unlike lead-acid batteries whose performance degradations are amplified in cold environments, fuel cells work just like a car. If the system has fuel, it has full power.
- Longer run time - forklifts powered by hydrogen fuel cells run up to twice as long as battery-powered units.

Figure 13: Hydrogen forklift major roll-out- by Generate Capital (QIC)
Source: QIC

Applications for Hydrogen Use

Applications for hydrogen considered to be a cost-competitive low-carbon solution

HEAT AND POWER FOR BUILDINGS

- Fuel cell-based combined heat and power (old hospital)
- *Hydrogen boilers (new-build house)**
- Hydrogen boilers (old hospital)
- Hydrogen boilers (old apartment city centre)
- *Hybrid heat pump and boiler**
- Blending of hydrogen in natural gas boilers
- *Fuel cell-based combined heating and power (new-build house)**
- *Fuel cell-based combined heating and power (old apartment city centre)**

* Not considered to be a cost-competitive low-carbon application

HEAT AND POWER FOR INDUSTRY

- Fuel cell-based backup generator
- *Simple cycle hydrogen turbine**
- Hydrogen furnace for high-grade heat
- Combined cycle hydrogen turbine
- Hydrogen furnace for medium-grade heat

INDUSTRY FEEDSTOCK

- Refining
- *Low-carbon ammonia production**
- Low-carbon steel
- Methanol production

TRANSPORTATION

- Mid-size vehicle with long range
- *Mid-size vehicle with short range**
- *Compact vehicle for urban transportation**
- Medium-duty truck for regional haul
- Heavy-duty truck for long-haul transportation
- *Lightweight truck/van for urban distribution**
- SUV for family usage
- Regional ferry
- *Large ferries for vehicle and people transport**
- Passenger train for regional transport
- Forklifts
- Large passenger vehicle for frequent usage
- Large passenger vehicle for commercial usage
- Bus for long-range urban transportation
- *Bus for short-distance urban transportation**
- Coaches for long-distance transportation

Figure 14: Applications for hydrogen considered to be a cost-competitive low-carbon solution
Source: Hydrogen Council, QIC

Applications for Hydrogen Use

"Hydrogen holds long-term promise in many sectors beyond existing industrial applications – particularly in transport, building and power sectors. Underlying this, the processes involved in developing and deploying hydrogen are complex, and carefully crafted policy support will be critical."

– Ross Israel, Head of Global Infrastructure at QIC

Hydrogen is expected to have a significant role to play as a clean energy vector in the future energy mix.

The Hydrogen Council outlined 22 applications for hydrogen which have potential to be a preferred green energy solution by 2030, accounting for up to 15% of total global energy consumption (17,500 TWh).[12]

Of the above applications (see Figure 14), QIC considers the following three areas to be the most promising in the short-term:

1. **For a range of transportation use cases, hydrogen will be cost-competitive against all alternatives, including conventional options.** This includes forklifts (already adopted in the US, with QIC portfolio company Generate Capital instrumental in this market growth), medium and heavy-duty trucks, buses and coaches, regional trains, and select sub-segments of passenger vehicles.

2. **Production of 'green' steel using 'green' hydrogen is becoming a reality,** with major adoption driven from the EU to occur by 2030. A 'green' steel pilot plant commenced in Sweden in 2020 (SSAB[13]), and Germany's largest steelmaker, Thyssenkrupp, is planning to augment its key plant in Duisburg (responsible for 2% of German GHG emissions) to produce 'green' steel. The plant will be completed by 2025 and have a capacity of 1.2 million Mt a year (10% of its total capacity).[14]

3. **Hydrogen power generation is already in-market**, with leading manufacturers including GE, Siemens, and Mitsubishi today offering Gas Combined Cycle Turbines (CGTs) able to combust up to a 20%[15] hydrogen blend, with a transition to 100% hydrogen-powered turbines expected by 2030.[16] A blend of 'blue' or 'green' hydrogen with natural gas is already considered to be within a "competitive range" for power generation, ahead of the forecast cost decline of 'green' hydrogen in this decade.

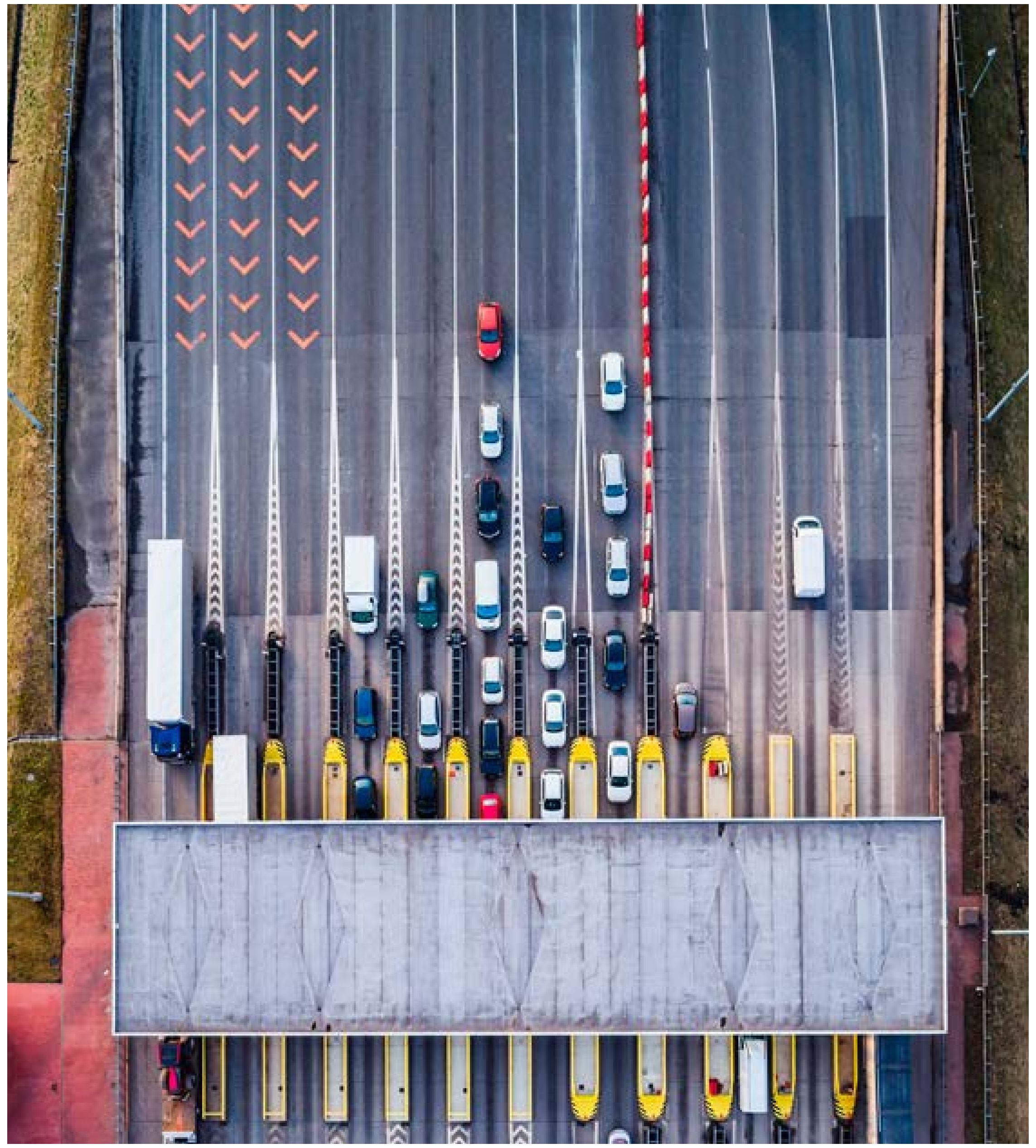
12 Hydrogen Council – Path to Hydrogen Competitiveness January 2020
13 "World-first fossil-free steel manufacturing plant completed in Sweden". Accessed from Renew Economy: https://reneweconomy.com.au/world-first-fossil-free-steel-manufacturing-plant-completed-in-sweden-36577
14 "Germany's Thyssenkrubb to build DRI plant run on hydrogen for green steel production". Accessed from S&P Global: https://www.spglobal.com/platts/en/market-insights/latest-news/metals/082820-germanys-thyssenkrupp-to-build-dri-plant-run-on-hydrogen-for-green-steel-production
15 "GE and partners adapt gas-fired plant to run on hydrogen". Accessed from PEi: https://www.powerengineeringint.com/gas-oil-fired/ge-and-partners-shifting-ohio-gas-fired-plant-to-hydrogen
16 "Siemens' Roadmap to 100% Hydrogen Gas Turbines". Accessed from PowerMag: https://www.powermag.com/siemens-roadmap-to-100-hydrogen-gas-turbines

Transport

The latest industry findings suggest hydrogen and fuel cell technologies are ideal for the decarbonisation of heavy-duty or long-range transport applications.

This will address the **8.3Gt** amount of annual emissions of these applications which represent approximately 25% of global carbon emissions.[17] These segments include use cases such as heavy-duty trucks, large passenger vehicles with long-ranges, and long-distance coaches. Heavy-duty trucks and coaches will likely achieve cost parity with battery-powered alternatives prior to 2025, particularly as the full battery alternative fails to meet commercial vehicle requirements due to the high cost and weight of batteries, and their long recharging times.[18]

Based on QIC's engagement with leading truck manufacturers globally, we expect substantial adoption of heavy-duty trucks powered by hydrogen from 2023 in Europe, and from 2025 globally. The largest global truck manufacturer, Daimler, committed to the launch of a 1,000km-range heavy-duty truck in Europe in 2023[19]. As expressed by Martin Daum, Chairman of the Board of Management of Daimler Truck AG and Member of the Board of Management of Daimler AG: *"For us at Daimler Truck AG and our intended partner, the Volvo Group, the hydrogen-based fuel cell is a key technology for enabling CO2-neutral transportation in the future."*[20]



17 "Transport sector CO2 emissions by mode in the Sustainable Development Scenario". Accessed from IEA: https://www.iea.org/data-and-statistics/charts/transport-sector-co2-emissions-by-mode-in-the-sustainable-development-scenario-2000-2030

18 IEA – The Future of Hydrogen June 2019

19 "Daimler plans H2 truck with 1,000km range". Accessed from electric.com: https://www.electrive.com/2020/09/16/daimler-reveals-plans-for-fuel-cell-truck-with-1000-km-range

20 "Daimler and Volve move forward with plans for hydrogen trucks". Sourced from h2-view: https://www.h2-view.com/story/daimler-and-volvo-move-forward-with-plans-for-hydrogen-trucks

Plans for phasing out internal combustion engines for transport are underway. Another tail wind for green hydrogen is that an increasing number of local and national governments in Europe have signalled their intention to phase out combustion engine-powered vehicles.

Half a dozen countries in Europe have set combustion-engine passenger car phase-out targets and dates in national strategies, plans, and programs, or have drafted or adopted such laws to mitigate climate change. Additionally, almost 30 cities have made plans or have pledged to prohibit combustion-engine cars in urban centres or entire metropolises with the main aim of improving local air quality.

Combustion-engine vehicle phase-out targets have added more pressure on car and truck manufacturers to adapt their product portfolios. Almost all car and trucks manufacturers have announced plans to steer their strategy away from combustion-engine vehicles over the next 10 years, with a number of truck manufacturers (Daimler, IVECO, Nikola Motors, Hyundai and Toyota) focusing on hydrogen.

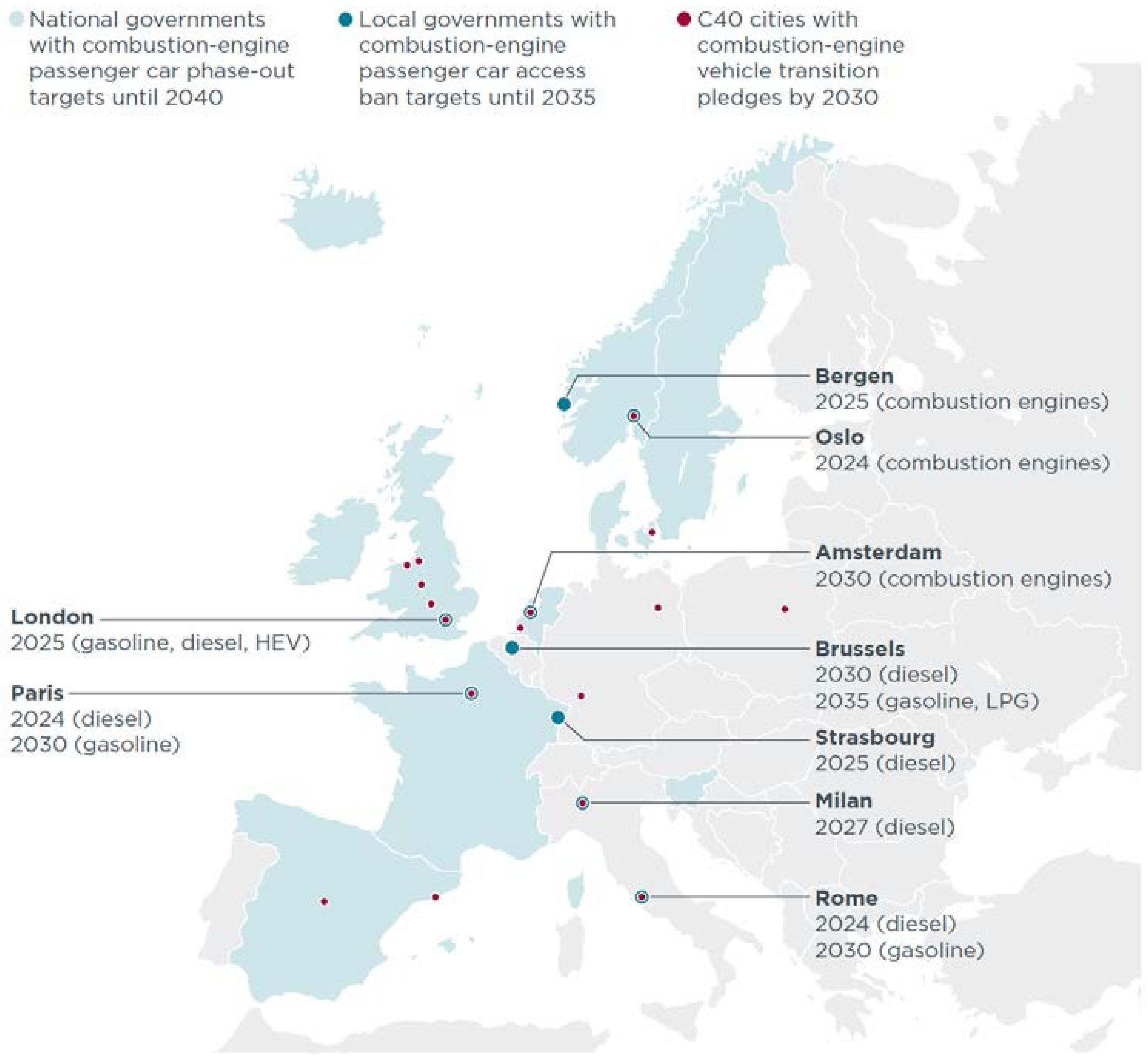


Figure 15: EU local governments targeting combustion engine car bans as at April 2020
Source: The International Council on Clean Transportation[21]

21 "The end of the road? An overview of combustion-engine car phase-out announcements across Europe". Accessed from the ICCT: https://theicct.org/publications/combustion-engine-car-phase-out-EU

The maritime sector is exploring several pathways to decarbonisation, to address its 855Mt of annual emissions (2018) which represent approximately 2.6% of global carbon emissions.[22]

The International Maritime Organization (IMO) has committed to reducing emissions by 50% or more by 2050, with options under consideration including replacement of current bunker fuels with LNG, replacing burning of marine fuel with liquid ammonia or hydrogen-based synfuels on larger ships, and hydrogen fuel cells in smaller ones.

The aviation sector is also looking at hydrogen fuel cells as a substitute for the conventional aircraft propulsion system. This sector produces 929Mt of annual emissions (2018), representing approximately 2.8% of Global carbon emissions.[23]

Figure 16: The aviation sector is considering hydrogen fuel cells as a substitute for conventional aircraft propulsion systems.

Image source: QIC

22 "Transport sector CO2 emissions by mode in the Sustainable Development Scenario, 2000-2030". Accessed from IEA: https://theicct.org/publications/combustion-engine-car-phase-out-EU

23 "Transport sector CO2 emissions by mode in the Sustainable Development Scenario, 2000-2030". Accessed from IEA: https://theicct.org/publications/combustion-engine-car-phase-out-EU

Sector coupling to unlock decarbonisation

Hydrogen has significant potential to enable deep decarbonisation of energy networks, due to its ability to effectively 'couple' with existing electricity and gas sectors.

To date, sector coupling has primarily referred to the electrification of end-use sectors like heating and transport, with the aim of increasing the share of renewable energy in these sectors. Recently however, the concept of sector coupling has broadened to include supply-side sector coupling, which focuses on integration of the power and gas sectors through technologies such as power-to-gas.

The broader notion of sector coupling provides a greater flexibility to the energy system so that decarbonisation can be achieved in a more cost-effective way.[24] Hydrogen provides additional coupling opportunities to facilitate increasingly renewable power generation, leading to substantial investment opportunity across the Hydrogen Economy. Increased use of hydrogen will also enable the continued use of gas infrastructure, as these networks are able to transport hydrogen with minimal adaptation required.

See Figure 17 *(over page)* for more on hydrogen-enabled sector coupling.

24 "Sector coupling: how can it be enhanced in the EU to foster grid stability and decarbonise?" Accessed from the EU: https://www.europarl.europa.eu/RegData/etudes/STUD/2018/626091/IPOL_STU(2018)626091_EN.pdf

Hydrogen Coupling

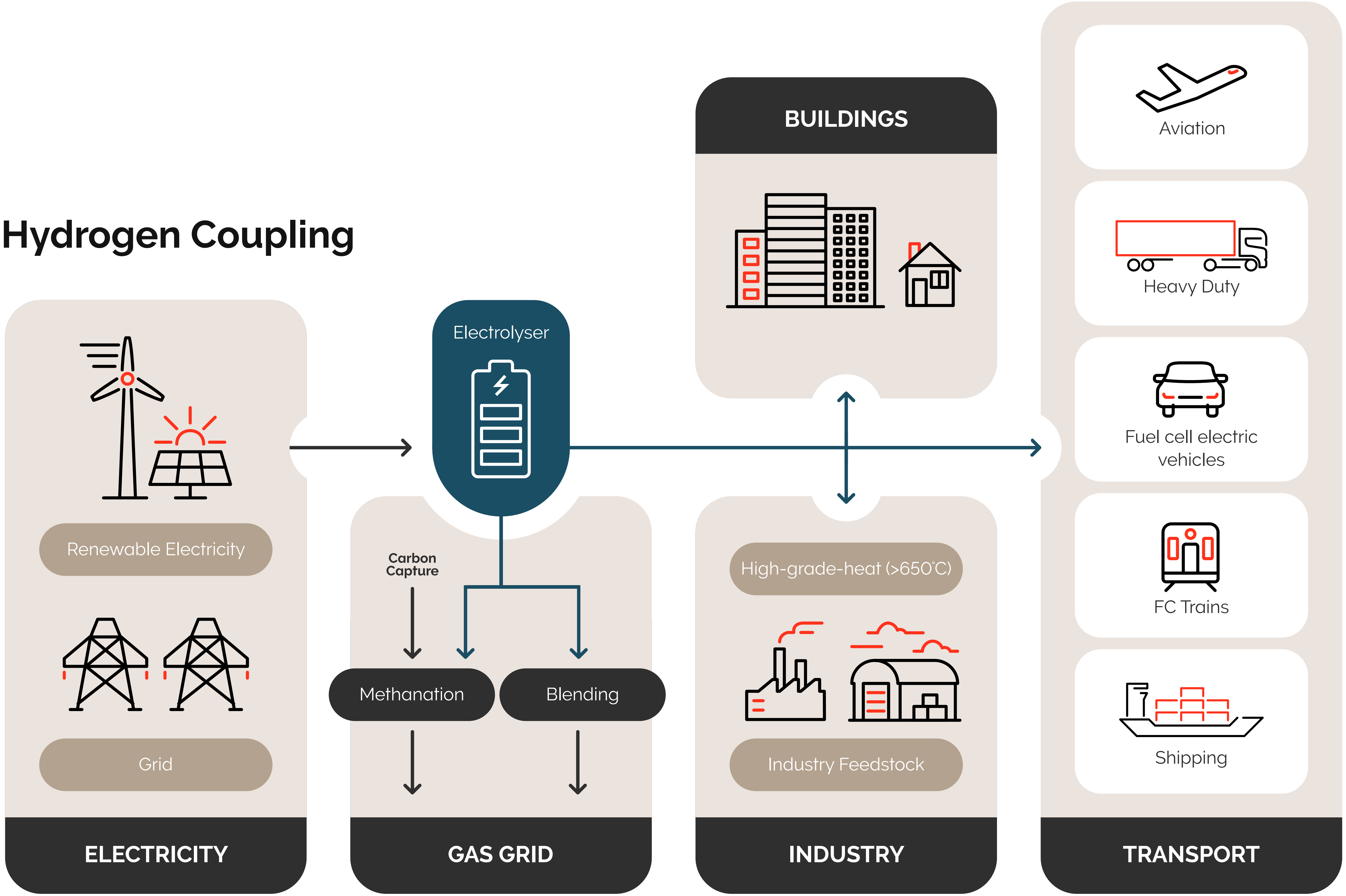


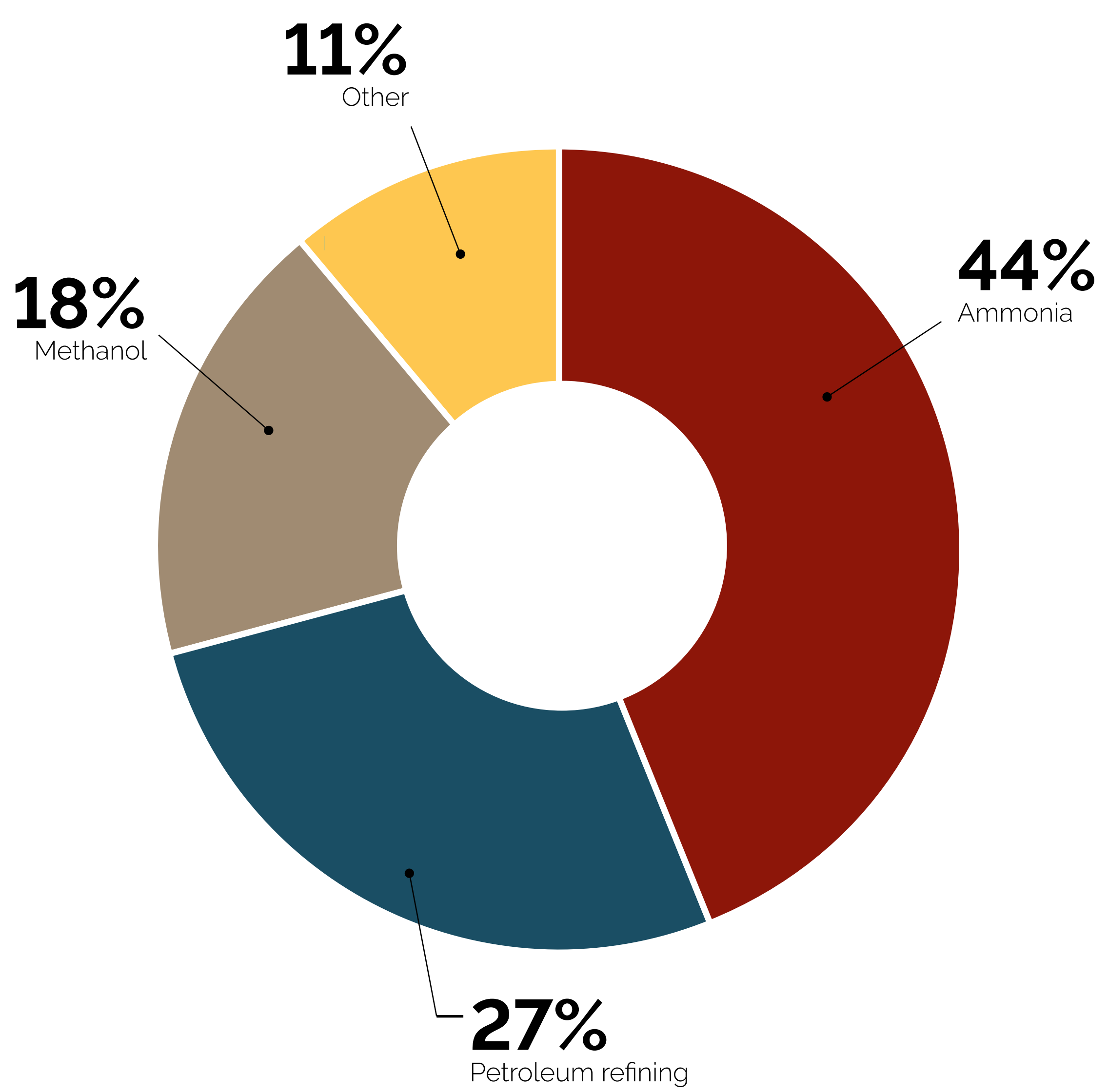
Figure 17: Coupling of energy system sectors
Source: QIC, IRENA

Industry feedstock

The significant existing industrial feedstock users can guarantee large-scale offtake and enable scale in the hydrogen production industry.

Over 90%[25] of the hydrogen consumed today is used as industrial feedstock (i.e. raw material in industrial processes to produce goods), with a large majority produced from fossil fuels. As key processes such as refining and the production of ammonia and methanol require hydrogen, the only way to decarbonise this process is to change the source of the hydrogen molecules to 'blue' or 'green'.

Hydrogen use today



Other: e.g. Hydrochloric acid, metals, fats and oils, electronics, etc.

Figure 18: Breakdown of hydrogen use today
Source: IHS Markit Chemical Economics Handbook 2017

25 Industrial Efficiency Technology Database. Accessed at: http://www.iipinetwork.org/wp-content/ietd/index.html

Industry feedstock – continued

For example, an ammonia plant that produces 1 Mt of ammonia per year consumes 200 kilotons of hydrogen. Producing this hydrogen would require 1.7 GW of electrolyser capacity, assuming a 50% utilisation factor.[26]

A plant of such scale would likely take up much of the short-term electrolyser manufacturing capacity in the Australian market today and could play a key role in the needed scale-up in production.

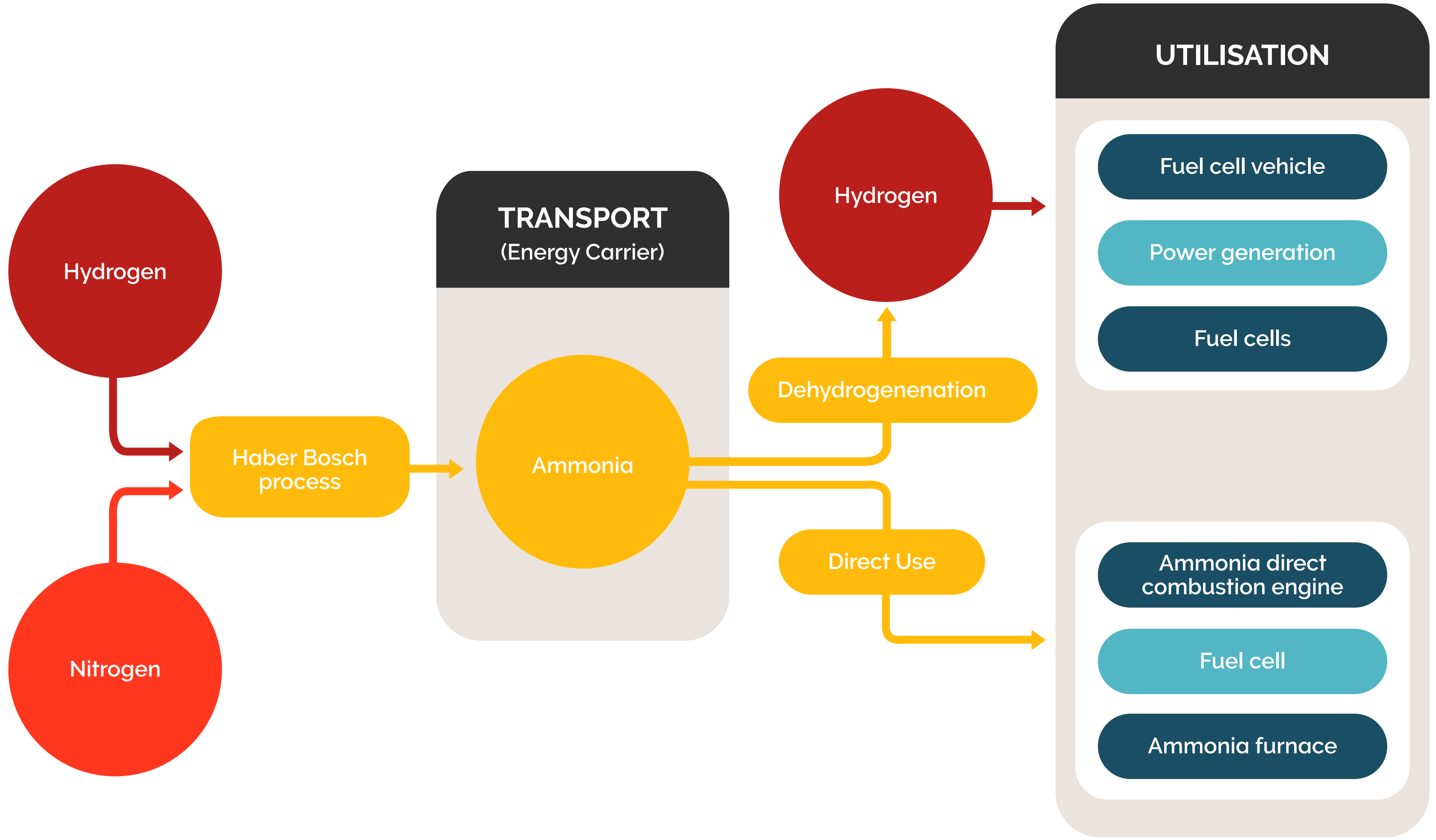


Figure 19: Ammonia as an energy carrier: Production of hydrogen for fuel cells and power generation
Source: The Royal Society: Options for Producing Low Carbon Hydrogen at Scale 2018

26 Hydrogen Council: Path to Hydrogen Competitiveness January 2020

Heating and power

Hydrogen solutions are among the most cost-effective and flexible ways to facilitate energy transition for heating and powering buildings – a sector which currently represents over a third of global energy demand and a quarter of global carbon emissions.[27]

The sector has proven difficult to decarbonise, particularly for heating where only a few low-carbon alternatives exist to compete with natural gas, the most common heating fuel used today.

The largest near-term opportunity for heating buildings is blending hydrogen into existing natural gas networks. By 2030, low concentration blending could supply up to 4 Mt of potential hydrogen use for heating buildings which, if sourced from low-carbon methods, could help to reduce emissions by around 1Gt of CO2 (3% of global CO2 emissions) assuming a 10% blending rate.[28] The potential is highest in multifamily and commercial buildings, particularly in dense cities, where conversion to heat pumps is a less viable alternative.

Longer-term prospects in heating could include the direct use of hydrogen in hydrogen boilers or fuel cells. In addition to hydrogen blending, pure hydrogen could heat and power about 1.5 million households globally. Together, this would require about 3.5 million tons of hydrogen production capacity. Producing this quantity of hydrogen would require significant investment- based on a balanced production mix, this is roughly equivalent to cumulative global investments of US$10 billion for hydrogen production, US$3 billion for infrastructure upgrades, and US$1.5 billion for the development of boilers and CHP units by 2030.[29]

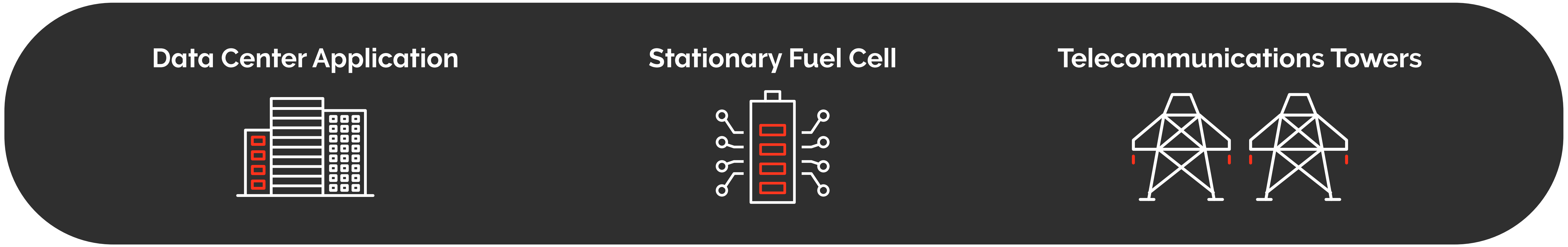


Figure 20: Hydrogen cells can be used to power data centres, and to back up heating/cooling and remote telecom towers

27 "Global Energy & CO2 Status Report 2019". Accessed from IEA: https://www.iea.org/reports/global-energy-co2-status-report-2019/emissions
28 IEA: The Future of Hydrogen June 2019
29 Hydrogen Council: Path to Hydrogen Competitiveness January 2020
Source: Hydrogen Tools

Why has Hydrogen Become an Important Investment Theme?

Why has hydrogen become an important investment theme?

The use of hydrogen will be critical if we are to meet current global climate objectives.

Governments are recognising hydrogen's ability to decarbonise sectors that are otherwise difficult to abate, such as logistics, industrial heating and industry feedstock. Industry leaders across the automotive, chemical, oil and gas, and heating sectors are looking to low-carbon and renewable hydrogen as a serious alternative to reach their increasingly robust sustainability objectives.

Examples of such objectives include the EU's Hydrogen Strategy which targets hydrogen to represent 13-14% of the region's energy mix by 2050, China's recent commitment to net zero carbon emissions by 2060, Spanish utility Iberdrola's plan to install 800MW of electrolyser capacity by 2030, and global shipping line AP Moller Maersk's target of a carbon neutral fleet by 2030.

In QIC's view, the growing interest in the hydrogen sector is underpinned by several long-term trends:

1. **Cost of renewables:** the significant decline in the cost of wind and solar photovoltaic (PV) generation in recent years has opened the prospect of large-scale production of 'green' hydrogen.
2. **Industrial decarbonisation:** there is fast-growing acknowledgement that there is a need for industry, heavy transport and other hard-to-abate sectors to examine and assess decarbonisation strategies in order to meet global carbon targets.
3. **Gas infrastructure decarbonisation:** hydrogen can be transported using existing gas infrastructure, with limited adaptation and costs required. While there are pipeline integrity issues to consider, hydrogen can be blended into existing gas infrastructure as a transition before potential longer-term conversion to 100% hydrogen. This has the potential to enhance hydrogen utilisation and protect asset valuations.
4. **Export opportunity:** there appears to be significant potential relating to the demand of hydrogen as a fuel source by economies such as China, Japan, and South Korea. This government-backed demand growth is driven by decarbonisation policies, energy security and reliability.

The increasing cost-competitiveness of renewables

The growing interest in hydrogen is closely linked to the recent sharp improvement in the key cost drivers of producing 'green' hydrogen.

Electrolysis fed with renewable electricity – the most common production method to produce renewable 'green' hydrogen – has become 60% more affordable as low-carbon and renewable electricity prices have dropped and electrolysis capex has fallen.[30] The cost of solar and wind power, the largest driver of renewable hydrogen production costs, has seen an 80% decrease over the past decade *(Figure 21).*

This downward cost trajectory for renewables is expected to continue, with 14 times more solar capacity projected to become available in 2030 than was previously estimated[31]. At the same time, electrolysis capacity has also started to accelerate, with at least 55 times more capacity expected by 2025 versus 2015 (Hydrogen Council), which will result in a similar cost drop in electrolysis capex.

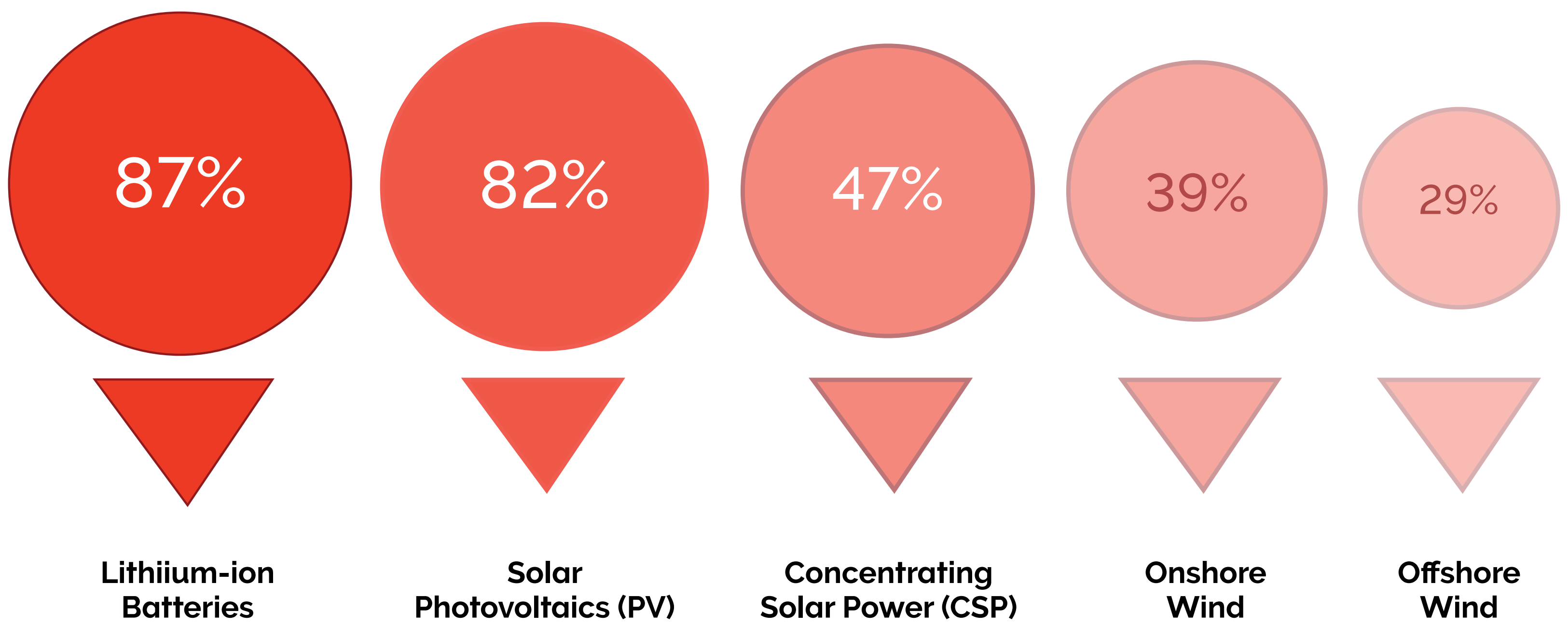


Figure 21: Renewable energy cost decline (2010-2019)
Source: IRENA

30 "Path to Hydrogen Competitiveness". Accessed from Hydrogen Council: https://hydrogencouncil.com/wp-content/uploads/2020/01/Path-to-Hydrogen-Competitiveness_Full-Study-1.pdf
31 "Future of Solar Photovaltaic". Accessed from IRENA: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Nov/IRENA_Future_of_Solar_PV_2019.pdf

Governments are setting ambitious decarbonisation targets

With governments and society becoming increasingly focused on environmental sustainability, hydrogen has notable potential to enhance global sustainability practices through facilitating low-carbon energy storage, transportation, and industrial processes.

It will also enable countries with lower renewable energy resources to decarbonise by enabling international trade in renewable energy.

The signs are positive – both Europe (via the EU Green Deal) and the US (via the US President-elect Joe Biden's new climate agenda) have announced ambitious investment plans in recent months *(see Figure 34)*. Other national governments have issued even more specific policies – Portugal and Germany both earmarking €7 billion in hydrogen-specific investments over the coming 1-2 decades.

At a company level the signs are also looking bright – a cross-industry group of over 40 businesses including Orsted, EDF, Equinor, and Siemens have written a letter to UK Chancellor Rishi Sunak urging the government to back a UK-wide hydrogen strategy, noting that they are ready to invest £1.5 billion into projects across the UK.[32]

The European Union's plans for hydrogen industry investment

	Investment (EU billions)	Details (to 2030)
Renewable Power	82	47GW solar, 14GW onshore wind, 9GW offshore wind
Electrolyser	13	40GW electrolyser capacity
Storage	55	500 salt caverns and hydrogen storage of 3 million tonnes
Pipelines	25	Natural gas pipeline conversion to hydrogen pipeline
Refuelling stations	10	3,700 refuelling stations and bunkering points
Fuel cell vehicles	40	3,700 million passenger cars, 500,000 light commercial vehicles, 45,000 heavy commercial vehicles, 570 trains
Building	37	Electricity and heating for equivalent of 8 million households
Total	**262**	

Figure 22: EU Hydrogen Industry Investment Plans
Source: Hydrogen Europe

32 "Businesses call on Chancellor to commit to UK-wide hydrogen strategy". Accessed from Fuel Cells Works: https://fuelcellsworks.com/news/businesses-call-on-chancellor-to-commit-to-uk-wide-hydrogen-strategy/

ESG is becoming a central consideration for astute investors

Another key motivator for interest in hydrogen is the growing investor focus on Environment, Social and Governance (ESG) factors.

We are seeing increasing momentum for fund flows toward ESG and sustainability themes, with both institutional and retail investors increasingly focused on environmentally-friendly investments and corporate accountability in their own approaches to addressing climate change and related themes.

In a recent polling of ESG investors, Morgan Stanley outlined the top six areas of investor interest and focus for their fund allocations related to the environment theme, with hydrogen featured alongside renewables, electric vehicles (EVs) and Carbon Capture and Storage (CCS).

Current environmental focus areas for investors

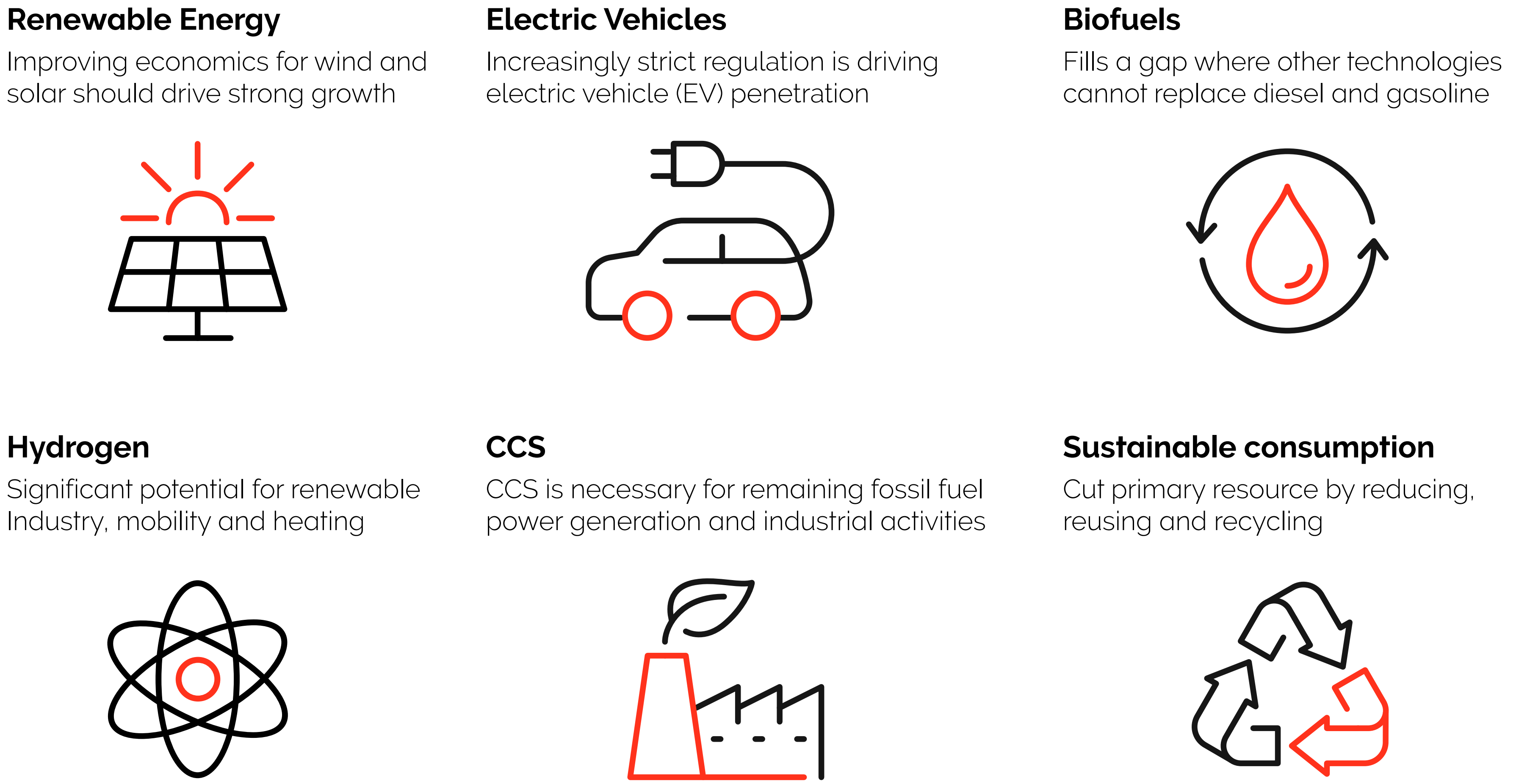


Figure 23: Current environmental focus areas for investors

Source: Morgan Stanley Research

Contacts

The Infrastructure Opportunities

The Infrastructure Opportunities

"The successful adoption and commercialisation of hydrogen as a decarbonisation tool relies on strategically integrated infrastructure. For many applications, especially mobility, infrastructure is considered as the main challenge. The most important elements of the hydrogen infrastructure are points of production, transmission and distribution systems and refuelling station networks."

– World Energy Council 2019[33]

Meeting ~25% of the total energy demand with hydrogen in a 2-degree scenario will require massive amounts of additional renewable electricity generation – creating major opportunity for infrastructure investment.[34]

If strong and comprehensive policy is in place, Bloomberg NEF estimates that 696MMT of hydrogen demand is possible – ahead of even the optimistic 2050 targets of the Hydrogen Council at 550MMT. Bloomberg NEF estimate this would require over US$11 trillion of investment in production, infrastructure and storage.[35]

In this scenario, around 31,320TWh of electricity would be needed to power electrolysers – this is more than is currently produced worldwide from all sources. Add to this the projected needs of the power sector, where renewables are also likely to expand significantly if deep emission targets are to be met, and total renewable energy generation excluding hydro would need to top 60,000TWh, compared to under 3,000TWh today.[36]

Another key investment requirement is the infrastructure needed to store hydrogen.

If hydrogen were to replace natural gas in the global economy today, 3-4 times more storage infrastructure would need to be built, at a cost of US$637 billion by 2050 to provide the same level of energy security.[37] While hydrogen is partially compatible with existing gas pipes and systems, to become as ubiquitous as natural gas, a huge coordinated program of infrastructure upgrades and construction would be needed.

Scenarios for hydrogen demand in 2050

	% Final Energy Demand 2050	Transport share	Industry Share	Power Share	Investment US$ trillion
Theoretical Max: 1370MMT	47%	38%	37%	32%	$21
Strong Policy: 696MMT	24%	43%	18%	31%	$11
Weak Policy 187MMT	7%	66%	20%	3%	$3

Figure 24: Scenarios for Hydrogen Demand, 2050
Source: QIC, BloombergNEF

33 "Innovation Insights Brief 2019". Accessed from World Energy Council: https://www.worldenergy.org/assets/downloads/WEInnovation-Insights-Brief-New-Hydrogen-Economy-Hype-or-Hope.pdf
34 Amount of hydrogen needed to reach net zero levels of energy-related CO2 emissions (approximately 9Gt) based on IEA's 2050 scenarios
35 BloombergNEF March 2020 Page 8
36 BloombergNEF March 2020 Page 8
37 Bloomberg NEF March 2020 Page 3

Contacts

Supporting the scale-up of hydrogen

The International Energy Agency has identified four near-term opportunities to boost hydrogen on the path toward its clean, widespread use:

1. **Make industrial ports the nerve centres for scaling up the use of clean hydrogen.** Today, much of the refining and chemicals production that uses hydrogen based on fossil fuels is already concentrated in coastal industrial zones around the world.

2. **Build on existing infrastructure, e.g. Natural gas pipelines.** Introducing clean hydrogen to replace just 5% of the volume of natural gas supplies would significantly boost demand for hydrogen and lower costs.

3. **Expand hydrogen in transport through fleets, freight and corridors.** Powering high-mileage cars, trucks and buses along popular routes can make fuel-cell vehicles more competitive.

4. **Launch the hydrogen trade's first international shipping routes.** Lessons from the successful growth of the global LNG market can be leveraged.

We note that almost all these recommendations involve a form of infrastructure investment, including ports, storage, pipelines, and refuelling stations.

Infrastructure potential for supporting the hydrogen economy

		Resource endowment			
	Group	Renewable energy resources	Renewable freshwater resource	Infrastructure potential	Example countries
1	Export champions with vast renewable energy and water resources, as well as high potential infrastructure	++	+	+	Australia, US, Morocco, Norway
2	Renewable-rich, but water-constrained nations with high infrastructure potential	++	---	+	Saudi Arabia, potentially China
3	Renewable-constrained nations with high infrastructure potential	–	+	+	Parts of EU, Japan, Korea
4	Renewable rich nations with high infrastructure potential	+	+	+	Turkey, Spain, Thailand
5	Renewable rich countries with low infrastructure potential	+	+/–	–	Most parts of South America

Legend
Abundant/very high (++)
Available/high (+)
Poorly available/constrained (–)
Scarce/highly constrained (---)

Figure 25: Infrastructure potential for supporting the Hydrogen Economy
Source: Belfer Center

Assessing the potential scope of infrastructure investments

With the Hydrogen Council forecasting that around 550 million tonnes of hydrogen required by 2050, the investment needed to support this level of hydrogen production could reach almost US$20 trillion *(see Figure 26 opposite).*

This would dwarf investment requirements for comparable industries including renewables, electric vehicles (EVs), biofuels and carbon capture and storage (CCS). Within this investment is approximately US$14 trillion of investment required for electricity, grid, and pipeline networks as well as storage of hydrogen.

Cumulative costs for adopting the decarbonisation technologies in alignment with Paris Agreement (2 degrees celcius scenario)

US$bn	2030	2040	2050
Hydrogen	$3,394	$6,940	$19,843
Renewables	$4,272	$8,845	$14,033
EVs	$1,852	$4,639	$10,990
Biofuels	$750	$936	$2,653
CCS	$583	$2,056	$2,538

Capital investment needed in Electrolyser, Electricity and Storage to meet 2050 targets

US$bn	2030	2040	2050
Hydrogen	$3,394	$6,940	$19,843
Electrolyser Capacity GW	822	1,644	4,579
Electrolyser Capex US$bn	$966	$1,932	$5,381
Incremental Renewable Power Capacity GW	1,995	3,991	11,117
Electricity Capex US$bn	$2,393	$4,785	$13,330
Storage Capex US$bn	$36	$224	$1,133

Figure 26: Proposed investment required to meet both 2030 and 2050 targets from Hydrogen Council
Source: Hydrogen Council, IEA, Global CCS Institute, Morgan Stanley Research

Assessing the landscape for scaling up

Scale-up of hydrogen to 2030 requires supportive regulation and funding of the economic gap. The Hydrogen Council has estimated the investment required to make hydrogen the most compelling renewable decarbonisation investment, and decarbonise the hydrogen supply chain, amounts to approximately US$73 billion between 2020 and 2030.[38]

A supportive regulatory environment for hydrogen-enabled decarbonisation is evident in multiple countries, and hydrogen roadmaps have been prepared by some leading countries and economic blocks including the EU and its members such as Germany and France, China, Japan, UK, Australia and South Korea.

The potential of Hydrogen Economy has also been recently imagined for the USA, prepared by a group of twenty organisations and companies. Scaling up hydrogen investment to meet the challenges of US decarbonisation would support hydrogen to meet close to 14% of the country's total energy demand across a range of sectors.[39]

As a growing number of pension funds, sovereign wealth funds, and banks tie climate ambitions and performance to their investment decisions, hydrogen offers businesses an opportunity to differentiate themselves in the race to decarbonise. Partnerships and technology sharing will be key, as will successfully navigating a landscape with shifting political winds and commodity prices.

In power generation and utilities, increasing hydrogen demand could drive renewables investment up to as much as US$160-170 billion per year between 2020 and 2050, in addition to the need for investments in grids[40]. There are also medium-to-long-term opportunities in creating new hydrogen-based value chains for existing sectors such as transportation, where investment in renewable generation can be coupled with hydrogen production, storage, handling and dispensation.

Requirements for scaling hydrogen for the USA

	Today	2022	2025	2030
	Immediate next steps	Early scale-up	Diversification	Broad rollout
H2 demand (metric tons)	11m	12m	13m	17m
Fuel Cell Electric Vehicles (FCEVs)	2,500	30,000	150,000	1,200,000
Material-handling FCEVs	25,000	50,000	125,000	300,000
Fuelling stations	63	165	1,000	4,300
Material handling fuelling stations	120	300	600	1,500
Annual investment		$1 bn	$2 bn	$8 bn
New jobs		+50,000	+100,000	+150,000

Figure 27: Scaling hydrogen for the USA: road map milestones
Source: Roadmap to a US Hydrogen Economy, McKinsey 2020

38 "Hydrogen Scaling Up: A sustainable pathway for the global energy transition", Hydrogen Council 2017
39 "Roadmap to a US Hydrogen Economy". Accessed from FCHEA: http://www.fchea.org/us-hydrogen-study
40 Morgan Stanley Research – Global Hydrogen: A US$2.5 trillion industry? (July 2018)

QIC

Gathering Pace:
Infrastructure Opportunities in the Hydrogen Economy

RED PAPER

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What is the Timeline for Realisation?

Contacts

What is the timeline for realisation?

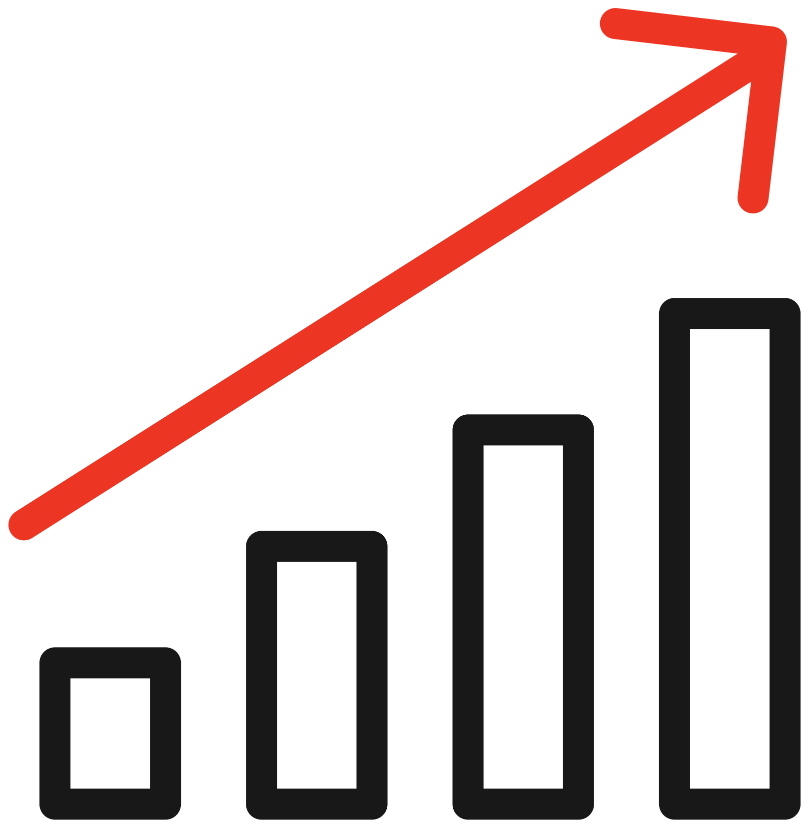
"Even with a multitude of challenges that await the nascent green hydrogen market, we firmly believe there will be some form of low-carbon Hydrogen Economy soon. Given the scale up we've seen so far, the 2020s is likely to be the decade of hydrogen."

– Wood Mackenzie, August 2020

While the timeline for the realisation of a Hydrogen Economy will not likely be overnight, there has been substantial recent acceleration.

This has been led by the European Union, select Asian countries (in particular South Korea), and Australia, with additional signs of potential acceleration from North America.

It is also important to note that as hydrogen has been in use in substantial quantities for decades, the "timeline for realisation" deals with a scale-up of the hydrogen industry, rather than the creation of a new industry.



Technology and innovation advances for scaling-up

As a rapidly growing technology, there are significant advances being made across all areas of hydrogen production to support its scaled up trajectory.

Key areas to watch include:

- **Production:** the technology to support moving from production of 'brown' to 'green' hydrogen is well understood, and its scale-up is expected to see "green" hydrogen cost-competitiveness from about 2030.
- **Storage:** substantial innovation is taking place in storage, complimenting well-understood and long-adopted storage methods such as compression and cooling. In addition to physical storage methods, advances are being made in material-based storage methods such as metal hydrides and organic liquid carriers *(Figure 29)*. Salt domes are also being considered for storage at scale. The Advanced Clean Energy Storage project in Utah, USA, is aiming to build the world's largest storage facility for 1,000 megawatts of clean power, partly by storing hydrogen in underground salt caverns.[41]
- **Liquification:** inter-continental transportation will likely require liquification, and the lead player in the international gas transportation (MISC Berhad in partnership with Samsung Heavy Industries) have this technology ready for delivery.[42] Kawasaki Heavy Industries also recently launch the world's first liquefied hydrogen carrier the Suiso Frontier.[43]
- **Transport:** This area requires the most development, with the first cryogenic tankers with small capacity first launched in Japan in December 2019.[44] Hyundai also recently announced that it has secured class and flag approvals for a large-capacity cryogenic hydrogen carrier design.[45] Other intercontinental transportation options include Liquid Organic Hydrogen Carrier (LOHC) options which can use existing liquid fuel transportation infrastructure. Key innovators in this area include Chiyoda which demonstrated the end-to-end supply chain[46] using LOHC and Hydrogenious which developed an alternative transport solution for hydrogen in a LOHC similar to diesel propulsion.[47]
- **Distribution:** While limited blending of hydrogen (ranging from several percent up to 20%) is allowed and has commenced in a number of countries, detailed studies are required to establish technical and commercial parameters for each pipeline.

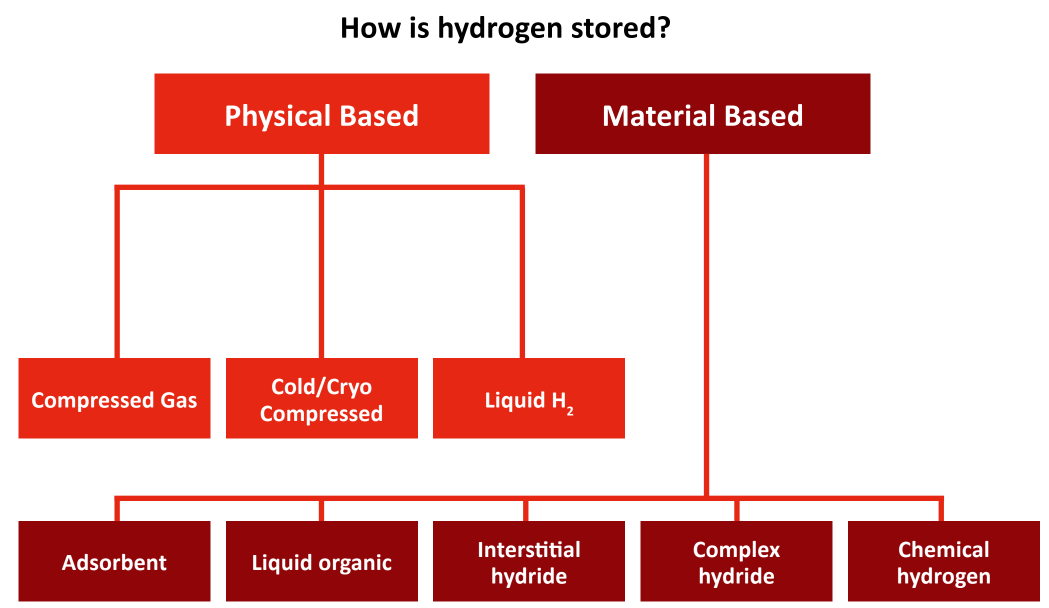


Figure 29: Hydrogen storage options
Source: Hydrogen Europe

41 "'World's largest' renewable energy storage project to launch in Utah from MHPS". Accessed from Energy Storage News: https://www.energy-storage.news/news/mhps-to-launch-worlds-largest-renewable-energy-storage-project-in-utah
42 "Samsung's ammonia-fueled tanker design gets LR AIP". Accessed from Marine Link: https://www.marinelink.com/news/samsungs-ammoniafueled-tanker-design-gets-481956
43 "World's first liquefied hydrogen carrier SUISO FRONTIER launches building an international hydrogen energy supply chain aimed a carbon-free society". Accessed from Kawasaki: https://global.kawasaki.com/en/corp/newsroom/news/detail/?f=20191211_3487
44 "World's first liquid hydrogen carrier ship launches in Japan". Accessed from Nikkei Asia: https://asia.nikkei.com/Business/Energy/World-s-first-liquid-hydrogen-carrier-ship-launches-in-Japan
45 "South Korea touts world's first large liquefied hydrogen carrier design". Accessed from Lloyd's List Maritime Intelligence: https://lloydslist.maritimeintelligence.informa.com/LL1134370/South-Korea-touts-worlds-first-large-liquefied-hydrogen-carrier-design
46 "Japan aims to set up commercial hydrogen fuel supply chain by 2030". Accessed from Reuters: https://www.reuters.com/article/us-japan-energy-hydrogen-idUSKBN2700PM
47 "Hyundai invests in startup aiming to transport hydrogen in oil". Accessed from Green Car Reports: https://www.greencarreports.com/news/1129846_hyundai-invests-in-startup-aiming-to-transport-hydrogen-in-oil

Timelines to adoption

Scale-up of hydrogen across its many application areas will be driven by several key considerations:

- **Cost parity with fossil fuels:** this is the most important determinant, driven by the cost-competitiveness of hydrogen against other low-carbon alternatives.
- **Technology readiness:** while there is no technology dependency for substitution of 'green' hydrogen for areas of large current hydrogen use, certain applications such as hydrogen fuel-cell powered trucks require integration of significant new technologies.
- **Scale up for international energy export:** new technologies are currently emerging to enable large scale exportation of hydrogen in cryogenic or organic liquid carrier form, such as tankers.

The transportation sector represents the biggest opportunity in the short-to-medium-term. Comparison of technology readiness of hydrogen vs. other low-carbon solutions, is captured at right *(Figure 30)*.

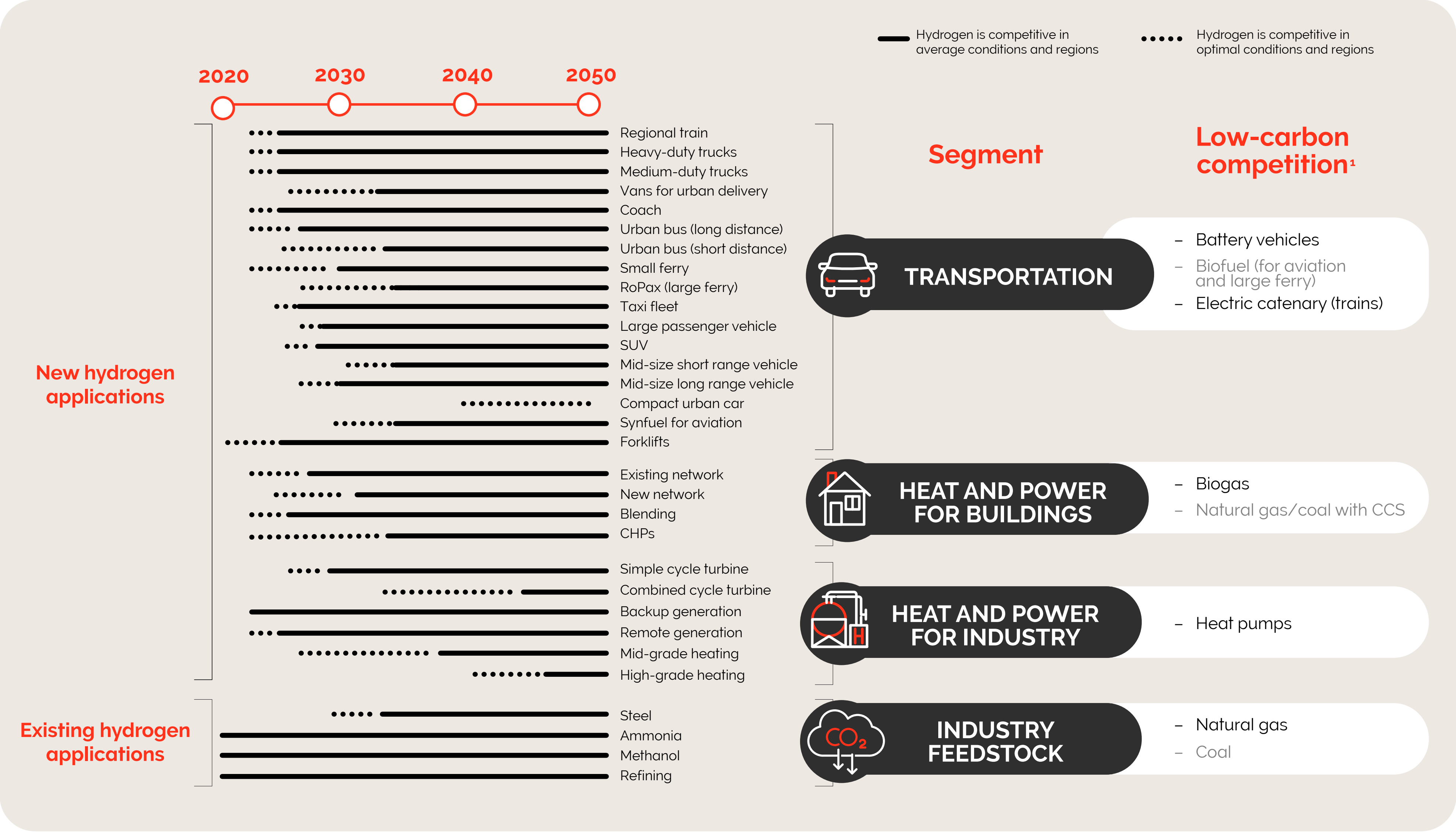


Figure 30: Hydrogen investments/realisation of opportunities: timeline for cost-competitiveness

Source: Hydrogen Council: Path to Hydrogen Competitiveness (2020)

1 In some cases hydrogen may be the only realistic alternative, e.g. for long-range heavy-duty transport and industrial zones without access to CCS

COVID-19 may prove a helpful accelerator

We are immensely encouraged by the progress in just the past 2-3 years to accelerate and incentivise the move toward the practical realisation of a hydrogen economy.

In fact, many industry players and hydrogen start-ups have indicated they are actually optimistic that the sector is likely to emerge as a winner from COVID-19.

Despite the ongoing disruption of the pandemic, on the 8th of July 2020, the European Commission adopted the proposed EU hydrogen strategy.[48] This was a particularly important development for hydrogen, as the plan facilitates substantial scale-up of the commitment to investment to green hydrogen production in the European Union.

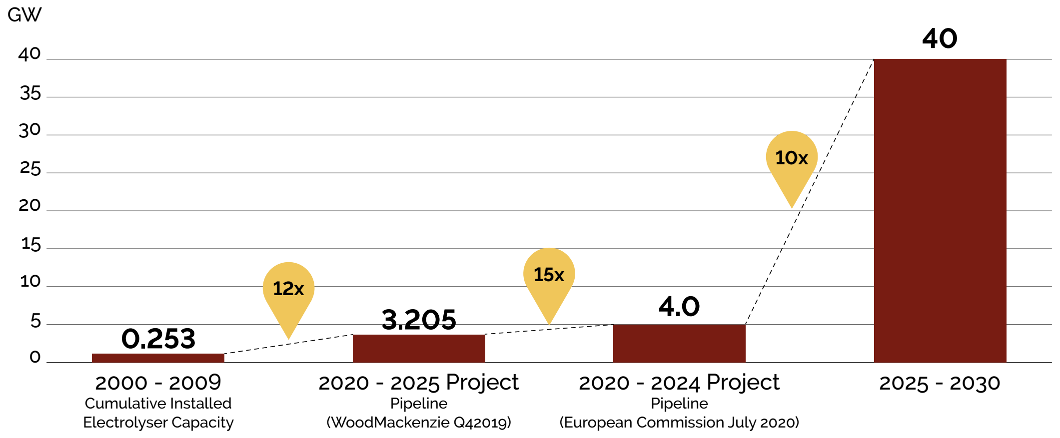


Figure 31: 'Green' hydrogen production pipeline: cumulative installed capacity vs. future project pipeline [49]

Source: energylivenews.com

48 "Adoption of EU Hydrogen Strategy". Accessed from EU: https://ec.europa.eu/info/news/adoption-eu-hydrogen-strategy-2020-jul-08_en

49 "A hydrogen strategy for a climate-neutral Europe". Accessed from EU: https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf

50 "H2IQ Hour May 27: Leveraging hydrogen and fuel cell tech to help coronavirus relief efforts". Accessed from US Office of Energy Efficiency and Renewable Energy: https://www.energy.gov/eere/fuelcells/articles/h2iq-hour-may-27-leveraging-hydrogen-and-fuel-cell-tech-help-coronavirus

51 "Air pollution and COVID-19: The role of particulate matter in the spread and increase of COVID-19's morbidity and mortality". Accessed from US National Library of Medicine: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7345938/

Hydrogen is also playing a direct role in the fight against COVID-19, with the level of R&D effort seeing a number of hydrogen start-ups utilising hydrogen to jump-start improvements to the design and manufacturing of health care devices, protective equipment, and hand sanitizers.[50]

For instance, renewable hydrogen production technology is being used by US vodka producer Air Co. to produce ethanol, which is then distilled to make 80% ethanol-based hand sanitizers for New York City hospitals. Another start-up, E-Spin Technologies is using its expertise in nanofibers, originally developed for use in hydrogen fuel cell membranes, to manufacture state-of-the-art surgical masks.

The impacts of COVID-19 have accelerated calls for a 'green-led' COVID recovery and policy support for the hydrogen sector.

With most governments already acknowledging the need to tackle climate change is more urgent now than ever before, we expect increased global calls to address urban air quality in line with recent studies which have demonstrated a link between COVID-19 mortality rates and long-term exposure to particulate matter above 2.5 microns.[51] There is an increased push to include renewables as part of any stimulus package announced globally, and hydrogen remains a critical decarbonization tool in almost all of these discussions.

Contacts

Accelerating research and development

Given the substantial investment commitment implicit in plans from the EU and a number of other countries including Japan, Korea, China and Australia, the hydrogen-related R&D effort has stepped up substantially.

Several examples of important hydrogen-related technology developments are underway in Australia. The University of New South Wales (UNSW), the pioneer of solar PV technology globally, is leading the way with low pressure storage solutions using organic metal frameworks. These modular, cost-effective and scalable storage using metal hydrides will enable other new products, such as integration of residential solar PV with onsite hydrogen generation and storage, enabling several days of energy storage for an average Australian house *(Figure 32)*.

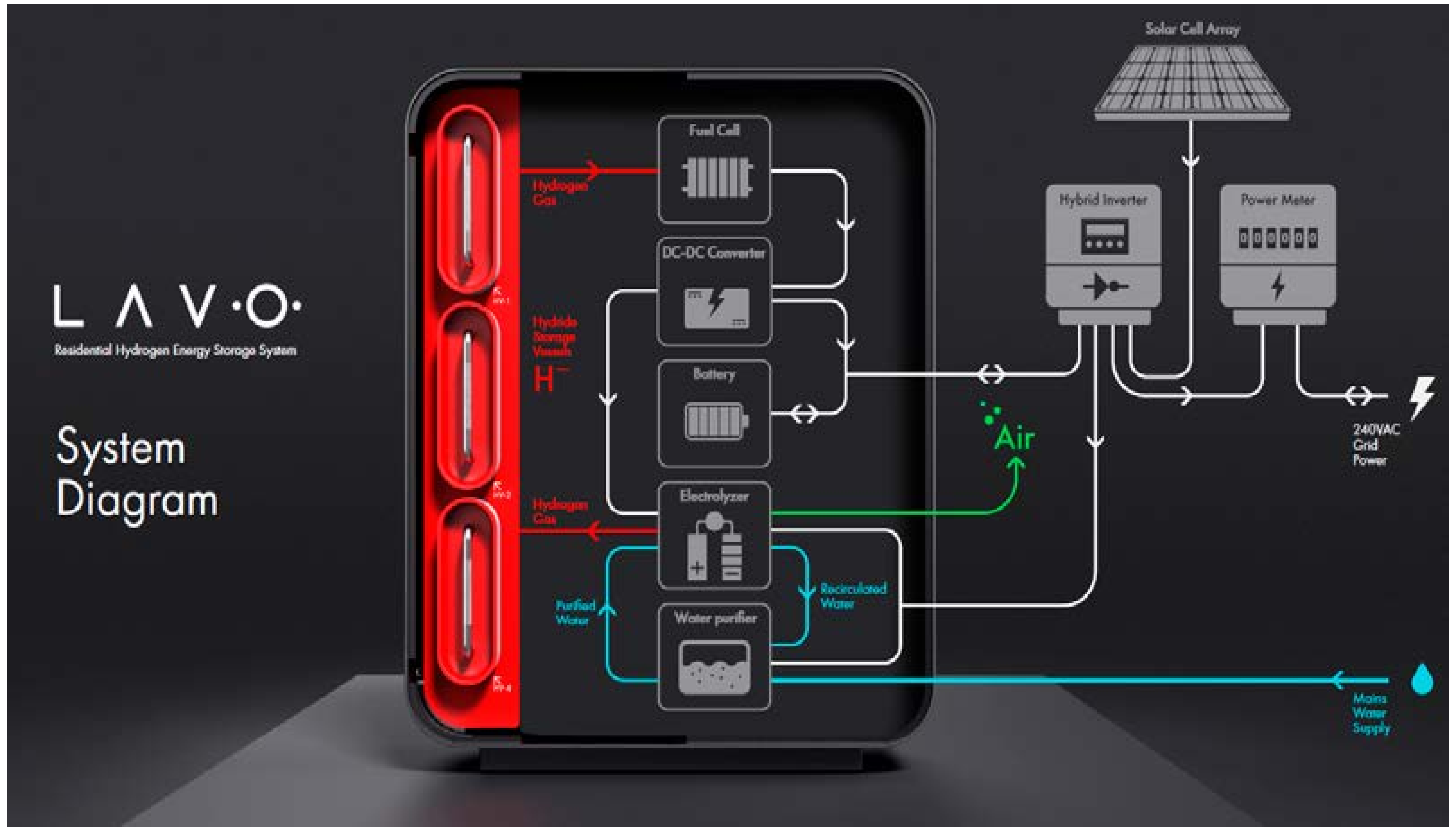


Figure 32: The first integrated hydrogen energy storage system
Source: Hydrogen Energy Research Centre, UNSW, September 2020

Contacts

Conclusion

Hydrogen is already scaling up and considerable investments are being made globally.

It will provide an important low-carbon option across a wide range of sectors. However, hydrogen's development still requires suitable enabling infrastructure, as well as financial and policy support to allow it to achieve a wide deployment and scale-up through commercial projects. Given the urgency of the global decarbonisation challenge, society must capitalise on hydrogen's advantages now.

Hydrogen has experienced a hype cycle before, and there is currently still limited policy to support investment and scale up of a clean hydrogen industry. But with a growing number of countries elevating decarbonisation, policy announcements in this area are being supported by Governments (see Appendix).

We expect the coming decade to 2030 will be an intensive period of investment in hydrogen-related infrastructure.

QIC is actively preparing for this opportunity and is well-positioned to capitalise through its existing portfolio companies and new investments.

QIC has identified several key signposts to watch for, with the following events expected to be key indicators of progress and help determine the pace at which a Hydrogen Economy is emerging:

Signpost	Implications
Net-zero climate targets are legislated	Provides clarity that 'hard-to-abate' sectors will need to decarbonise
Standards governing hydrogen use are harmonised and regulatory barriers removed	Clears or minimises obstructions to hydrogen projects optimises capital spend
Targets are introduced within investment mechanisms	Provides a revenue stream for producers, increases competition, builds capacity and experience, and gives equipment manufacturers confidence to invest in plant
Stringent heavy transport emissions standards are set	Provides an incentive for manufacturers to produce, and users to buy, hydrogen fuel-cell trucks and ammonia-powered ships
Mandates and markets for low-emission products are formed	Provides an incentive for manufacturers to produce low-emission goods (e.g. steel, fertilisers, cement, plastics) that will often require the use of hydrogen
Industrial decarbonisation policies and incentives are put in place	Helps coordinate infrastructure investment and scale efficient accelerated use of hydrogen
Hydrogen-ready equipment becomes commonplace	Enables and reduces the cost of fuel switching to hydrogen

Source: QIC, BloombergNEF

Contacts

Appendix: National Government Policy Announcements

For any country seeking to develop a Hydrogen Economy, a major consideration is the level of investment required for new infrastructure for manufacturing, distributing and storing hydrogen fuels.

The announced project pipeline for 'green' hydrogen has quadrupled from 3.5 GW to just over 15 GW in the year to July 2020 (with more to be added via the EU Hydrogen Strategy's 40GW target), and Wood Mackenzie says volumes will be large enough and stable enough for the nascent market to scale.[52]

We are immensely encouraged by the amount of progress that has already occurred in just the past 2-3 years to accelerate and incentivise the move toward the practical realisation of a Hydrogen Economy.

Overall, there are still relatively few explicit and effective national government policies for incentivising significant investment in hydrogen and hydrogen related technologies – but that is changing. We are seeing an uptick in announcements, proposals and commitments to R&D efforts by many countries, so the outlook is positive.

The below table outlines key global energy policy announcements which relate to hydrogen.

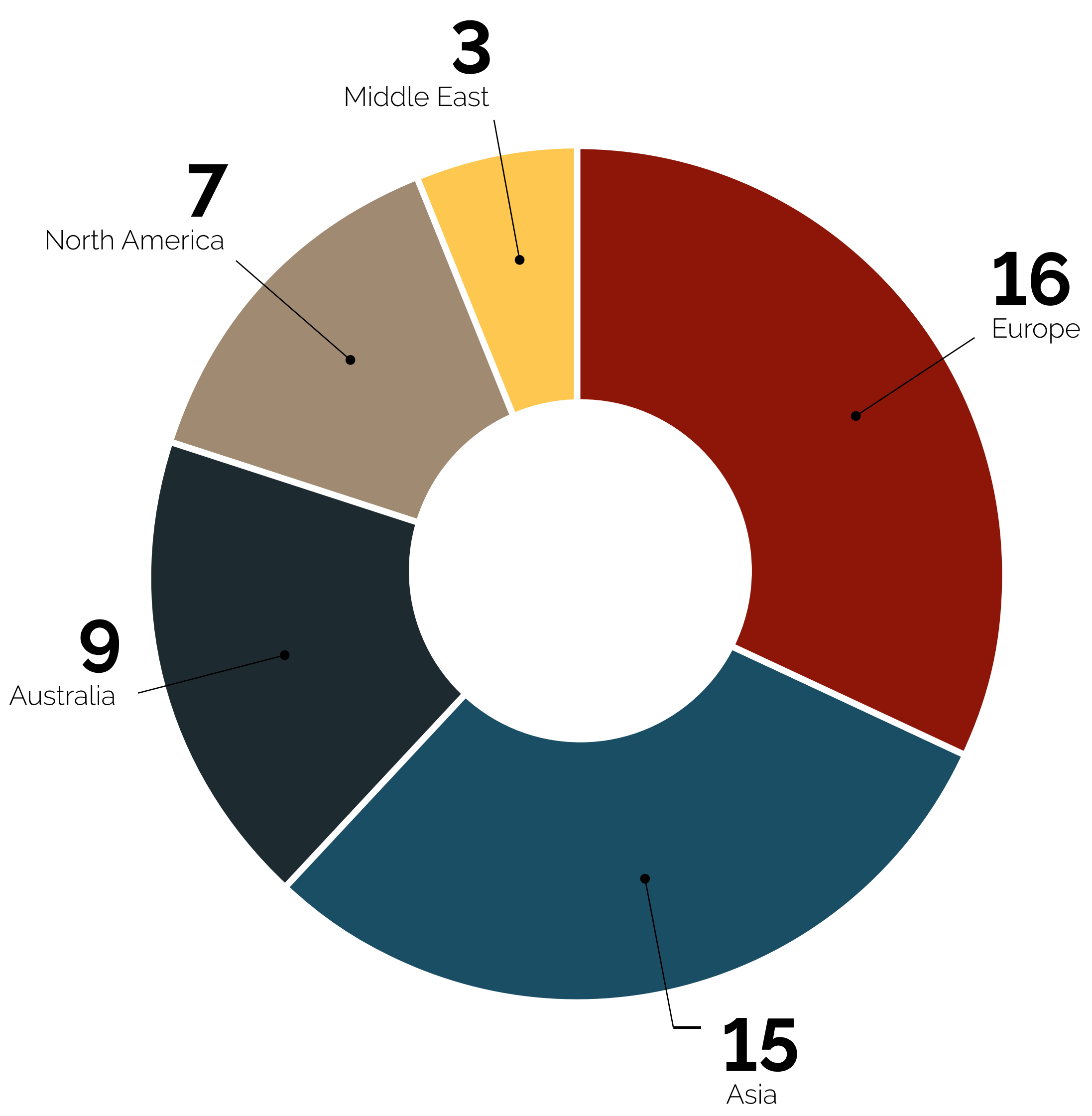


Figure 33: Large Scale Global Hydrogen Projects by Region
Source: Institute for Energy Economics and Financial Analysis (IEEFA)[53]

52 "Green hydrogen costs to fall by up to 64% by 2040". Sourced from Wood Mackenzie: https://www.woodmac.com/press-releases/green-hydrogen-costs-to-fall-by-up-to-64-by-2040

53 "Great Expectations; Asia, Australian and Europe leading emerging green hydrogen economy, but project delays likely". Accessed from IEEFA: https://ieefa.org/wp-content/uploads/2020/08/Asia_Australia_Europe-Lead-Green-Hydrogen-Economy_August-2020.pdf

Figure 34 – Recent announcements of hydrogen-related energy policy

Country/Region	Latest announcements
Europe	
Austria[54]	The hydrogen strategy for Austria is to be presented in Autumn 2020. The government's mandate to develop the strategy was given at the end of 2018, and broad goals announced involved targeting Austria to be the "number 1 hydrogen country". This government policy entails specific plans to start greening Austria's natural gas with hydrogen and biogas and aims to have 5TWh more renewable gas by 2030 as well as demonstrate a 1.5% yearly increase of renewable district heating. Although there is no completely finalised strategy in place for hydrogen, the programme also begins to outline a hydrogen strategy, elevating hydrogen as a flexible option for renewable electricity.
Belgium[55]	In January 2020 announced a new hydrogen plant to be constructed on the North Sea coast. The project in the Port of Ostend will only use wind power that is not absorbed by Belgium's electricity grid, fuelling a hydrogen-producing electrolyser exclusively with renewable energy. A 50MW demo electrolyser is due for completion in 2022, before a full-scale plant is ramped up in 2025. The final stage of the project aims to reduce CO2 levels by between 500,000 and one million tonnes of CO2 per year.
European Union[56]	On July 8, 2020, Europe announced the EU Hydrogen Strategy; a key priority of Europe's green recovery from Covid-19. The European Commission has targeted 40 GW of renewable hydrogen capacity by 2030. Europe will prioritise renewable hydrogen, produced using mainly wind and solar energy. The Commission suggests that this will open up 80-120 GW worth of investment opportunities in wind and solar projects today. To put this in perspective, it would increase wind and solar capacity by 25-40% in Europe. The European Commission suggests that cumulative investments in renewable hydrogen in Europe could be up to €180-470 billion by 2050, and in the range of €3-18 billion for low-carbon fossil-based hydrogen. Within this, by 2030, investments in electrolysers could range between €24 and €42 billion, while €220-340 billion would be required to scale up and connect 80-120 GW of solar and wind energy production capacity to the electrolysers. Investments in carbon capture and storage are estimated by the European Commission at around €11 billion, while €65 billion will be needed for hydrogen transport, distribution, storage, and refuelling.
France[57]	Government ministers Barbara Pompili and Bruno Le Maire unveiled on September 10, 2020 a national strategy for carbon-free hydrogen to the French Association for hydrogen and fuel cells and other major players in the state's Hydrogen Economy. The French government wants 6.5 GW of hydrogen generation capacity by 2030 under the France Relance Covid recovery plan. The hydrogen strategy has been allocated €7.2 billion to 2030 under the France Relance plan, including €3.4 billion allocated to hydrogen up to 2023 will be split 54% towards decarbonization, 27% to public transport and goods and 19% for R&D, innovation and training.
Germany[58]	The Government announced its National Hydrogen Strategy in June 2020. The strategy lists existing government programmes supporting hydrogen technologies, however it adds: "In addition to this, the stimulus package agreed on 3 June 2020 provides for a further €7 billion euros to be made available for the market ramp-up of hydrogen technologies in Germany and a further €2 billion for international partnerships." The paper states that Germany will use its EU presidency to push the topic of hydrogen.

54 https://www.klimafonds.gv.at/wp-content/uploads/sites/6/MI_2020_v8b_EN.pdf
55 https://www.euractiv.com/section/energy/news/belgium-hopes-to-lead-world-with-new-hydrogen-project
56 https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf
57 https://www.electrive.com/2020/09/14/france-presents-national-hydrogen-strategy
58 https://www.dw.com/en/germany-and-hydrogen-9-billion-to-spend-as-strategy-is-revealed/a-53719746

Contacts

Figure 34 – Recent announcements of hydrogen-related energy policy – continued

Country/Region	Latest announcements
Europe	
The Netherlands[59]	The government announced it initial strategy for Hydrogen within its national Climate Agreement in April 2020. To boost demand for 'green' hydrogen, the Netherlands suggest mandating an obligatory mix of hydrogen in gas networks of 2%, which could gradually be increased to 10-20%. The basic conditions for the growth of hydrogen will be shaped in the period leading up to 2025. 'Green' hydrogen production in particular will be supported by a new financial instrument of €35 million per year through 2030. In order to support the targets, set out in the National Climate Agreement (50 refuelling stations, 15,000 fuel cell vehicles and 3,000 heavy-duty vehicles by 2025; 300,000 fuel cell vehicles by 2030), a cooperation agreement with stakeholders will be signed in 2020.
Norway[60]	In the crisis package presented to Parliament in May 2020, the government announced an increased focus on hydrogen-related research and technology development as a way of meeting these challenges. Emissions pricing, through taxes and the Emissions Trading System, is designed to promote low emission solutions. A more stringent emissions trading market, combined with the increase in the CO2 tax announced by the government, will make emission-intensive solutions more expensive. In the Granavold political platform, it was announced that the government will increase the flat CO2 tax by 5% every year for all sectors until 2025. The government proposes granting NOK 120 million to the Research Council of Norway's ENERGIX programme and NOK 20 million to zero/low emission passenger ferries including hydrogen powered vehicles. This funding will go to innovation projects with a commercial focus, in order to maintain the level of research activity and stimulate Norwegian businesses' green transition projects. Hydrogen-related technologies and solutions will hold a key place in this initiative.
Portugal[61]	Portugal's government recently approved (May 2020) the national strategy for hydrogen, which foresees investments of €7 billion by 2030 leading to a reduction in natural gas imports of €300-600 million. The 'National Hydrogen Strategy' (EN-H2) includes a large project in Sines (at a cost of €400-450 million) out of the €7billion, with the remainder divided into smaller units of which 85% is expected to be private investment. The short-term actions focus on finance – namely, the implementation of mechanisms that support investment in hydrogen projects, with a budget of US$40 million.
Spain[62]	Spain is stepping up its efforts to enter the race to build a hydrogen industry, putting it on par with France and Germany in seeking a greener fuel for heavy industry. The government in Madrid announced on October 6 a roadmap to build 4 gigawatts of 'green' hydrogen capacity by 2030. The program would require an investment of €8.9 billion (US$10.5 billion) within the next decade. Spain's plan includes 60 measures that will help establish a hydrogen supply chain, according to a government document seen by Bloomberg. The roadmap targets manufacturing plants with a capacity to make 300 to 600 megawatts of hydrogen from renewables by 2024 and 4 gigawatts by 2030. That would represent 10% of the EU's target.
United Kingdom[63]	The U.K. government's official climate change advisory body "Committee on Climate Change's (CCC)" announced in June 2020 it is calling for fast-tracking investment in early-stage hydrogen infrastructure, as well as prioritizing carbon capture and storage and EV charging infrastructure, as immediate responses to the coronavirus outbreak. It urges the development of a comprehensive national hydrogen strategy within the next 12 months to map out progress for the next decade. According to an article in Recharge, June 20, 2020, a cross- industry group of over 40 businesses including Orsted, EDF, Equinor, and Siemens have written a letter to Chancellor Rishi Sunak urging the government to back a UK-wide hydrogen strategy, noting that they are ready to invest £1.5 billion into hydrogen projects across the country.

59 https://www.government.nl/documents/publications/2020/04/06/government-strategy-on-hydrogen
60 https://www.regjeringen.no/en/aktuelt/the-norwegian-hydrogen-strategy/id2704774
61 https://jornaleconomico.sapo.pt/en/news/five-central-points-in-the-hydrogen-strategy-for-portugal-619971
62 https://www.euractiv.com/section/energy/news/spain-approves-hydrogen-strategy-to-spur-low-carbon-economy
63 https://www.theccc.org.uk/publication/reducing-uk-emissions-2020-progress-report-to-parliament

Figure 34 – Recent announcements of hydrogen-related energy policy – continued

Country/Region	Latest announcements
Asia-Pacific	
Australia[64]	In recent months Commonwealth and State Governments have announced a number of funding and policy developments dedicated to "energising" Australia's position in the global Hydrogen Economy. Of significance is the Clean Energy Finance Corporation's (CEFC) A$300 million Advancing Hydrogen Fund (announced May 2020) one of the largest commitments made to the hydrogen sector by any government in the world. On 20 July 2020, the Australian Renewable Energy Agency (ARENA) announced that seven companies (including BHP Billiton and Woodside Petroleum) have been shortlisted and invited to submit a full application for the next stage of the Agency's A$70m 'green' hydrogen funding round. Final go-ahead for construction of Infinite Blue Energy's A$350 million Arrowsmith project in WA is scheduled for early next year. The first stage would produce 25 tonnes a day of hydrogen through the electrolysis of water powered by solar and wind energy. A second phase would see it expanded to 120 tonnes a day to support the export of liquid hydrogen to Asia.
China[65]	In early September 2020 the Chinese Government announced it will roll out a new package of policies to support hydrogen FCEVs (primarily in long distance heavy vehicles), including a focus on helping companies with R&D on new technologies. This announcement was followed in late September by President Xi Jinping announcing China would target carbon neutrality by 2060 during a speech to a virtual meeting of the United Nations General Assembly. China is the world's largest hydrogen producer, with more than 20mt of the gas produced each year, accounting for about one-third of the world's production volumes. Its current target is to produce over 30mt of hydrogen (>50% of which is green) by 2030. According to its 2019 whitepaper, hydrogen fuel is expected to account for some 10% of the Chinese energy system by 2050, by which time demand for hydrogen fuel is anticipated to grow to nearly 60mt and its annual economic output is expected to surpass 10 trillion yuan (approx. US $1.4T).
India[66]	The use of hydrogen as an automotive fuel has gained momentum in India. India's transport ministry has announced approval in late September 2020 for blending of hydrogen (18% mix) with CNG which should further support the reduction in India's carbon footprint. As of February 2020, India's Ministry of Renewable Energy has partnered with NTPC Ltd., an Indian energy conglomerate, to propose the launch of a pilot fuel cell bus project. The potential scale of hydrogen use in India is huge and can increase in a range between 3 times and 10 times by 2050, facilitating the transition to a carbon neutral economy, according to The Energy and Resources Institute (TERI).
Japan[67]	In March 2020, the 10MW solar-powered Fukushima Hydrogen Energy Research Field (FH2R) project was completed. The FH2R project can apparently produce as much as 1,200 Nm3 of hydrogen per hour and is powered by a 20MW solar farm and some power from the grid. The federal government-backed project includes plans for 11 solar farms and 10 wind farms with a total capacity of 600MW, scheduled for completion by March 2024. The Fukushima government has said it expects the new renewables hub to provide 13-14% of Japan's national energy mix by 2030. In the 2019-2020 budget request for the Ministry of Economy, Trade and Industry as approved by cabinet, JPY 16.3 billion (USD 150 million) was approved to establish a hydrogen supply chain utilising untapped energy resources and JPY 10 billion (USD 91.7 million) was approved to offer subsidies toward public hydrogen station development for fuel-cell vehicles.
New Zealand[68]	For New Zealand to reach the coalition government's goal of having 100% renewable electricity by 2035, an over-capacity of renewable energy (hydro, geothermal, wind, solar and biomass) needs to be built. While the government has indicated 'green' hydrogen will play a role in this roadmap, there has to date not been any firm targets set. In August 2020, the Infrastructure Reference Group has provisionally approved NZ$20 million for Hiringa Energy to establish New Zealand's first nationwide network of hydrogen fuelling stations. The initiative will involve the installation of eight hydrogen refuelling stations located in Waikato, Bay of Plenty, Taranaki, Manawatu, Auckland, Taupō, Wellington and Christchurch. These stations will provide refuelling for zero emissions heavy FCEVs (hydrogen-powered fuel cell electric vehicles) such as trucks and buses. This initial network will provide coverage for about 95% of heavy freight routes in the North Island and 82% of the South Island.

64 https://www.industry.gov.au/news/national-hydrogen-strategy-priorities-and-delivery
65 https://climateactiontracker.org/countries/china/ and http://www.h2cn.org/en/publication.html
66 https://www.livemint.com/news/india/govt-specifies-hydrogen-enriched-cng-as-automobile-fuel-11601267630446.html
67 https://www.meti.go.jp/english/press/2017/pdf/1226_003a.pdf
68 https://www.mbie.govt.nz/building-and-energy/energy-and-natural-resources/energy-strategies-for-new-zealand/

Figure 34 – Recent announcements of hydrogen-related energy policy – continued

Country/Region	Latest announcements
Asia-Pacific - continued	
South Korea[69]	The government announced three key strategies to accelerate the development of its car industry into the future and four specific action plans to achieve these goals. The action plans included seeking to become a leading player in the green car industry which had a specific aim to build a total of 660 hydrogen refuelling stations by 2030 and 15,000 electric recharging stations by 2025. Further to the October 2019 announcement regarding the plan to build three hydrogen-powered cities, the government announced the three cities will be Ansan, Ulsan and Jeonju/Wanju. Samcheok was also selected to be a city focusing on hydrogen R&D.
Africa	
South Africa[70]	South Africa's Department of Science and Innovation has invited South African hydrogen fuel cell specialist Bambili Energy and other companies to participate in the South African Hydrogen Society Roadmap development process that commenced in June 2020 for a period of 6-12 months. Meanwhile DSI is implementing the Cabinet-approved Hydrogen South Africa (HySA) strategy through the 15-year research, development and innovation HySA program, which is aimed at developing hydrogen and fuel cell technologies, with a focus on benefitting South Africa's platinum group metals (PGMs) resource base.
North America	
United States	The United States has long been a leader in global energy innovation and has led the world in the production and distribution of gaseous and liquid hydrogen. The US is among the leading countries in moving towards broad commercialisation of fuel cells and hydrogen energy. With over 7,600 fuel cell electric vehicles (FCEVs) currently on the road – more than any other country – the US is home to more than half of the global FCEV stock. In addition, the US is a global leader in the development of fuel cell applications that compete with incumbent technologies. For example, more than 25,000 fuel cell–powered material handling products, such as forklifts, are operating in warehouses and distribution facilities across the country. There are over 8,000 small-scale fuel cell systems operating across 40 states, primarily for cell phone towers and remote communications networks. In total, there are over 550 MW of installed or planned fuel cells for large-scale stationary power for backup power, critical loads and combined heating and power applications.[71] While hydrogen has a strong technical foundation, positioning it as the energy carrier of choice and creating a vibrant, competitive Hydrogen Economy will also require a foundation of financial and policy support. In the US, abundant low-cost renewable resources make domestic 'green' hydrogen production some of the most competitive globally. At the same time, the US represents one of the largest addressable markets for fossil fuel displacement at ~20% of global oil demand (China is the next biggest at ~15%).[72] Oil majors Chevron and Exxon have experience in the production, use and distribution of hydrogen, making them well suited to participate in the development and adoption of this new market over time. However, cheap 'green' hydrogen also presents a material risk to their core business: an emissions free alternative to fossil fuels, and one that can compete in traditionally hard to displace end markets including industrial activity and transport. In March, a coalition of major US oil and gas, power, automotive, fuel cell, and hydrogen companies developed a "Road Map to a US Hydrogen Economy"[73] which augurs with the time horizons outlined by both the financial markets and industry groups like the Hydrogen Council. Due to great variation among national and state policies, infrastructure needs, and community interests, the report notes that each state and region of the US will likely have its own specific policies and road maps for implementing hydrogen infrastructure. Nonetheless, the report outlines the successful rollout of the Hydrogen Economy in the US could yield ~US$750 billion in revenues by 2050, creating 3.4 million jobs.

69 https://docs.wixstatic.com/ugd/45185a_fc2f37727595437590891a3c7ca0d025.pdf
70 https://fuelcellsworks.com/news/south-africas-hydrogen-economy-takes-off-bambili-energy-invited-to-join-government-hydrogen-strategy/
71 www.ushydrogenstudy.org
72 IEA 2019
73 Roadmap to a US Hydrogen Economy: www.fchea.org/us-hydrogen-study
Source: National Government websites

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