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Hydrogen Energy

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by Lenny Roth and Tom Gotsis

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by

Lenny Roth and Tom Gotsis

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Lenny Roth (BCom, LLB) Acting Senior Manager, Law	(02) 9230 2768
Daniel Montoya (BEnvSc (Hons), PhD) Senior Research Officer, Environment/Planning	(02) 9230 2003
Talina Drabsch (BA, LLB (Hons)) Senior Research Officer, Law	(02) 9230 2484
Tom Gotsis (BA, LLB, Dip Ed, Grad Dip Soc Sci) Research Officer, Law	(02) 9230 3085
Rowena Johns (BA (Hons), LLB) Research Officer, Law	(02) 9230 2484
Eline Saleuesile (BA, GradCert PLPP) Research Officer, Social Policy	(02) 9230 3019

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Abbreviations

ACT – Australian Capital Territory
AE – Alkaline electrolysers
AEM – Anion Exchange Membrane electrolyser
AEMO – Australian Energy Market Operator
ARENA – Australian Renewable Energy Agency
ATR – Autothermal Reforming
AUD – Australian Dollar
BEVs – Battery Electric Vehicles
°**C –** Degrees Celsius
CCS – Carbon Capture Storage
CCUS – Carbon Capture Utilisation and Storage
CEFC – Clean Energy Finance Corporation
CH_4 – Methane
CMB – Compagnie Maritime Belge
CO – Carbon Monoxide
CO_2 – Carbon Dioxide
COAG – Council of Australian Governments
CSIRO – Commonwealth Scientific and Industrial Research Organisation
CNR – Catalytic Naphtha Reforming
e - Electron
EV – Electric Vehicle
FCEVs – Fuel Cell Electric Vehicles
FCHEA – Fuel Cell and Hydrogen Energy Association
GDP – Gross Domestic Product
GW – Gigawatt
H – Hydrogen
H_2 – Hydrogen gas
H_2O – Water
HESC – Hydrogen Energy Supply Chain
IEA – International Energy Agency
IRENA – International Renewable Energy Agency
kg – Kilogram
$kgCO_2$ – Kilogram of Carbon Dioxide
kgH_2 – Kilogram of Hydrogen gas
kg/m^3 – Kilogram per cubic metre
Km Kilometre

kWh – Kilowatt hour
kWh/kg – Kilowatt hour per kilogram
LCOH – Levelised Cost of Hydrogen
LH$_2$ – Liquid Hydrogen
LNG – Liquefied Natural Gas
MJ/L – Megajoules per Litre
Mt – Megatonne
MW – Megawatt
MWh - Megawatt Hour
NASA – National Aeronautics and Space Administration
NEM – National Electricity Market
NH$_3$ – Ammonia
NO – Nitric Oxide
NO$_2$ – Nitrogen Dioxide
NO$_X$ – Nitrogen Oxides
NSW – New South Wales
O$_2$ – Oxygen molecule
PES – Planned Energy Scenario
POX – Partial Oxidation
PEM – Proton Exchange Membrane electrolyser
Pty Ltd – Proprietary Limited
PV – Photovoltaic
QLD – Queensland
R&D – Research and Development
RAPS – Remote Areas Power Systems
SA – South Australia
SAP – Special Activation Precinct
SDS – Sustainable Development Scenario
SMR – Steam Methane Reforming
TES – Transforming Energy Scenario
tkmH$_2$ – tonne-kilometre Hydrogen gas
tkmNH$_3$ – tonne-kilometre Ammonia
USD – United States Dollar
VIC – Victoria
WA – Western Australia
\$/tkmH$_2$ – dollar per tonne-kilometre Hydrogen gas
\$/tkm NH$_3$ – dollar per tonne-kilometre Ammonia

SUMMARY

This paper was produced to assist the Legislative Council's Standing Committee on State Development with its current inquiry into the Development of a hydrogen industry in New South Wales.

What is hydrogen and what can it be used for?

Hydrogen is the most abundant element in the universe, with the simplest atomic structure of any element (a single negatively charged electron circling a single positively charged proton). The most abundant source of hydrogen on Earth is water, the compound H_2O. Hydrogen can also form hydrogen gas (H_2); a colourless, odourless, non-toxic, flammable gas that is present in the Earth's atmosphere in amounts less than 1 part per million by volume. Below -252.87°C, hydrogen gas forms Liquid Hydrogen (LH_2). **[2.1]**

Hydrogen can be used to generate two forms of energy: heat and electricity. Heat energy is generated when hydrogen undergoes combustion in the presence of oxygen. The output from the combustion of hydrogen in the presence of pure oxygen is heat energy and water. No carbon dioxide (CO_2) or other greenhouse gas is emitted. However, if hydrogen is burned in the presence of air, harmful nitrogen oxides (NO_x) can be formed. Electrical energy is generated when electrochemical processes in a fuel cell strip hydrogen atoms of their electrons and the electrons flow through a circuit. The only by-products are heat energy and water. **[2.1]**

Hydrogen can be used in the natural gas network for home heating, cooking and water heating. It could replace up to 13% of the natural gas distributed by the network without any modification of appliances, existing pipeline infrastructure and gas meters. High-temperature industrial processes that currently rely on natural gas can convert to hydrogen with minimal retrofitting of existing equipment. **[2.2]**, **[2.3]**

Hydrogen is used as a fuel in electric vehicles equipped with hydrogen fuel cells. In Europe, hydrogen trains are being used to decarbonise parts of rail networks that have not been electrified. Hydrogen trucks have also been purchased for commercial use. Hydrogen buses, ships and aeroplanes are in various stages of development. The use of hydrogen as a transport fuel could improve Australia's domestic fuel security. **[2.2]**, **[2.4]**

Electricity generation in NSW is moving away from coal and towards renewable energy. Renewable energy can be intermittent; which can affect the security and reliability of the National Electricity Market (NEM). Similar to batteries and pumped hydro, hydrogen can provide security and reliability to the NEM. Surplus renewable energy can be used to generate hydrogen using electrolysis, which can be stored and used at times where renewable energy output is not able to meet energy demand. **[2.5]**

Hydrogen has a range of existing industrial uses. For instance, it is used to refine petrochemicals and manufacture ammonia, glass, metals and electronics. Most hydrogen currently used by industry is produced using fossil fuels. Renewably sourced hydrogen could power industrial processes that require high

temperatures; thereby contributing, for example, to the production of “green steel” and “green aluminium”. **[2.2], [2.6]**

How is hydrogen produced, stored and transported?

Most current hydrogen production (95%) is based on thermochemical processes involving fossil fuels; such as Steam Methane Reforming (SMR) and coal gasification. Globally, the use of fossil fuels to produce hydrogen creates 830 Mt of carbon dioxide emissions annually. **[3.1]**

Hydrogen produced from coal is referred to as “brown”. If hydrogen is produced from natural gas, it is referred to as “grey”. Hydrogen produced from natural gas with Carbon Capture and Storage (CCS) is referred to as “blue”. CCS involves capturing carbon dioxide emissions at the point of production and permanently storing them in underground reservoirs or under the sea bed. Proponents of CCS argue that it is an effective means of producing low-cost and low-emission hydrogen. Opponents of CCS argue that it is an expensive and unproven technology that fortifies the use of polluting fossil fuels**.** One site in the USA and one site in Canada provide CCS for hydrogen produced using SMR. **[3.1]-[3.3]**

A small proportion of hydrogen (5%) is produced using electrolysis. Electrolysis can be powered by nuclear energy, in which case the hydrogen produced is referred to as “pink”. If the electrolysis is powered by renewable energy, the hydrogen is referred to as “green”. **[3.1], [3.4]**

Producing hydrogen using fossil fuels emits up to 0.76 $kgCO_2$ per kgH_2; while producing hydrogen with electrolysis and renewable energy has zero emissions. **[3.5]** In 2018, producing hydrogen with electrolysis cost up to $7.43 per kg; while producing hydrogen with fossil fuels cost as low as $2.27 per kg. **[3.6]**

The main ways to store hydrogen include: compressing it in tanks, pipelines or underground reservoirs; liquefying it at temperatures below -252.87°C; and converting it into another chemical (such as ammonia). The CSIRO expects that, by 2025, compressing hydrogen in tanks will cost approximately $0.3 per kg. In contrast, liquefying hydrogen is expected to cost $1.59-$1.94/kg. Hydrogen produced with ammonia as the product is expected to cost $1.10-$1.33kg but additional costs will be incurred in converting ammonia into hydrogen at the point of use. **[3.7]**

Hydrogen can be transported by truck, rail or ship in compressed gas or liquid forms. Hydrogen can also be transported in pipelines as a compressed gas**.** Pipelines are capital intensive but enable cost-effective transport over large distances. Transporting hydrogen on ships, trucks and trains using diesel engines creates emissions and pollution; whereas transporting hydrogen on ships, trains and trucks powered by hydrogen does not create emissions or pollution. **[3.8]**

Due to the larger cargo capacity of ships, the increased density of liquids and the greater distances travelled, shipping liquefied hydrogen offers the lowest transportation cost per tonne-kilometre ($0.09/$tkmH_2$). Shipping ammonia offers even lower costs ($0.03/tkm NH_3). **[3.8]**

What is the current state and potential of hydrogen globally?

Clean and low-carbon hydrogen is being supported by governments of most of the world's largest economies: e.g. Japan, European Union, United States. A 2021 report estimated that globally governments have pledged more than USD 70 billion to support the hydrogen industry. It also estimated there were USD 80 billion of mature investments in hydrogen projects until 2030. The report identified 228 hydrogen projects around the world. Europe had the largest number of projects (128), followed by Asia (46), and Oceania (24). The most common applications were large-scale industrial usage (90) and transport (53). **[4.1]**

A 2020 report by the International Energy Agency analysed technology options to examine what would need to happen for the world to reach net zero emissions by around 2070. It found that low-carbon hydrogen would be an important part of the energy mix. In this scenario, global hydrogen production grows by a factor of seven to reach 520 million tonnes in 2070. Hydrogen use expands to all sectors and reaches a share of 13% in final energy demand in 2070. Hydrogen becomes important for the decarbonisation of heavy trucks, aviation and shipping as well as for the production of chemicals and steel. **[4.2]**

The International Renewable Energy Agency (IRENA) identified several barriers to the uptake of green hydrogen including high production costs, a lack of dedicated infrastructure, and energy losses at each stage of the value chain. IRENA recommended that a policy approach to green hydrogen should have four pillars: (1) national hydrogen strategies; (2) policy priority setting; (3) a guarantee of origin scheme; and (4) governance system and enabling policies. With respect to policy priority setting, it noted that hydrogen is just one of several possible decarbonisation alternatives that should be carefully considered. **[4.3]**

What is the potential of hydrogen in Australia?

A 2018 briefing paper by the Hydrogen Strategy Group identified three key opportunities that clean and low-carbon hydrogen offers for Australia: (1) export; (2) domestic economy; and (3) energy system resilience. In terms of hydrogen exports, Japan and South Korea are seen as key markets. A 2020 report by KPMG stated that the development of a hydrogen industry is a significant long-term opportunity for NSW. **[5.1]** Australia has vast physical resources that could support a large-scale hydrogen industry. **[5.2]**

A 2019 report by Deloitte modelled the economic impacts of a clean and low-carbon hydrogen industry in Australia under three scenarios. Compared to the business as usual scenario (where global demand expands gradually), under the targeted deployment scenario, by 2050 the Australian hydrogen industry is worth $11 billion more in GDP and there are an additional 7,600 jobs. Under the Energy of the Future scenario, by 2050 GDP is projected to be around $26 billion higher; and employment is estimated to be 16,700 jobs higher. **[5.3]**

The 2019 Deloitte report identified three key challenges for market activation: (1) the cost-effectiveness of hydrogen compared to other technologies and processes; (2) policy and technology uncertainty; and (3) regulations, standards and acceptance. **[5.4]** The CSIRO's 2018 National Hydrogen Roadmap provided a blueprint for the development of the industry. The 2020 KPMG report made three strategic recommendations to develop the industry in NSW. **[5.5]**

How are Australian governments supporting hydrogen and what is the current state of the industry?

In November 2019, the COAG Energy Council adopted *Australia's National Hydrogen Strategy*. The Commonwealth Government also announced that it would reserve $370 million from existing Clean Energy Finance Corporation and Australian Renewable Energy Agency funding to back new hydrogen projects. The Government's September 2020 *Technology Investment Roadmap: First Low Emissions Technology Statement 2020* includes clean hydrogen as one of five priority low emissions technologies. In April 2021, the Government announced $276 million in funding to accelerate the development of four clean hydrogen hubs in regional Australia and implement a clean hydrogen certification scheme. **[6.1]**

The NSW Government is currently developing a hydrogen strategy. One of the priorities of its March 2020 *Net Zero Plan Stage 1: 2020–2030* is to invest in the next wave of emissions reduction innovation, and a key focus of this is low-emissions hydrogen. The Plan set a target of up to 10% hydrogen in the NSW gas network by 2030. In March 2021, the NSW Government announced a $750 million funding program to help achieve the *Net Zero Plan Stage 1*. There will be investments in green hydrogen initiatives across the Program's three focus areas; and it is expected to contribute $70 million to support the establishment of hydrogen hubs in the Hunter and Illawarra. **[6.2]**

All other States and the Northern Territory have developed a hydrogen strategy or action plan; and most States have committed significant funding to the development of a hydrogen industry. The Victorian Government has committed over $70 million in funding to the hydrogen industry, and the Queensland Government has committed over $60 million. **[6.3]**

As at early May 2021, there were 61 clean and low-carbon hydrogen-related projects in Australia. Over 60% of hydrogen projects (37 out of 61) were in Western Australia and Queensland; five projects were in NSW. Of the 23 projects that were in operation, under construction or in advanced development, eight were in Western Australia, five in Queensland, four in Victoria, and three were in NSW. The most advanced NSW hydrogen project is the $15 million Western Sydney Green Gas Project, which is under construction. **[6.4]**

1. INTRODUCTION

In a June 2019 report, the International Energy Agency (IEA) stated that interest in hydrogen is "enjoying unprecedented momentum around the world and could finally be set on a path to fulfil its longstanding potential as a clean energy solution".[1] It noted that there had been previous waves of interest in hydrogen but what was new this time was "both the breadth of possibilities for hydrogen use being discussed and the depth of political enthusiasm for those possibilities around the world".[2] The IEA explained that hydrogen can be used without direct emissions of air pollutants or greenhouse gases; and it can be made from a range of low-carbon energy sources: e.g. from fossil fuels with carbon capture and storage (low emissions), or renewable electricity (zero emissions).[3]

In November 2019, the COAG Energy Council adopted *Australia's National Hydrogen Strategy*, which stated:

> Australia has the resources, and the experience, to take advantage of increasing global momentum for clean hydrogen and make it our next energy export. There is potential for thousands of new jobs, many in regional areas – and billions of dollars in economic growth between now and 2050. We can integrate more low-cost renewable generation, reduce dependence on imported fuels, and help reduce carbon emissions in Australia and around the world.[4]

In December 2020, the Legislative Council's Standing Committee on State Development commenced an inquiry into the Development of a hydrogen industry in New South Wales, following a reference by the NSW Minister for Energy and Environment, Matt Kean. In summary, the terms of reference for the inquiry include:

- The size of the economic and employment opportunity created by the development of a hydrogen industry in NSW;
- The State's existing hydrogen capabilities;
- The capacity of and barriers to NSW becoming a major production, storage and export hub for hydrogen;
- The economics of hydrogen's use in different sectors of the economy;
- The infrastructure, technology, skills, and workforce capabilities needed to realise the economic opportunities of hydrogen; and
- The actions needed of the public and private sectors to support the development of a hydrogen industry in NSW.[5]

The Committee Chair asked the Parliamentary Research Service to prepare a

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[1] IEA, *The Future of Hydrogen: Seizing today's opportunities*, June 2019, p 3.

[2] Ibid, p 18-19.

[3] Ibid, p 17.

[4] COAG Energy Council, *Australia's National Hydrogen Strategy*, November 2019, p vii.

[5] The full terms of reference can be viewed on the Committee's website.

briefing paper on hydrogen to assist the inquiry.[6] The Research Service prepared the paper by conducting independent desktop-based research into relevant literature. The Research Service did not access submissions to the inquiry, which closed on 26 February 2021. The paper aims to provide an introduction to the topic by answering five questions:

1. What is hydrogen and what can it be used for?
2. How is hydrogen produced, stored and transported?
3. What is the current state and potential of hydrogen internationally and what are the challenges?
4. What is the current state and potential of hydrogen in Australia and NSW and what are the challenges?
5. What are Australian governments doing to support a hydrogen industry?

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[6] The Hon Sam Farraway MLC replaced the Hon Taylor Martin MLC as Chair of the committee on 17 February 2021. The Hon Catherine Cusack MLC replaced the Hon Sam Farraway MLC as Chair of the committee on 15 March 2021.

2. WHAT IS HYDROGEN AND WHAT CAN IT BE USED FOR?

2.1 What is hydrogen?

Hydrogen is the most abundant element in the universe.[7] It is also the most abundant element in our Sun, making it the major source of the solar energy that supports all life on Earth.[8] Represented by the chemical symbol H, hydrogen is the first element on the Periodic Table of the Elements. It has the simplest atomic structure of all elements (a single negatively charged electron circling a single positively charged proton).[9]

On Earth, hydrogen typically does not exist in its elemental form. The density of a hydrogen atom is so low it cannot be held by the Earth's gravity, and it floats into space.[10] Instead, hydrogen is typically found on Earth in the form of compounds and molecules.[11] The most abundant source of hydrogen on Earth is water, the compound H_20.[12] Hydrogen is also present in the complex carbon compounds found in all living matter and in fossil fuels.[13]

Hydrogen can also form the molecule hydrogen gas (H_2); a colourless, odourless, non-toxic, flammable gas that is present in the Earth's atmosphere in amounts less than 1 part per million.[14] Hydrogen can become the gas H_2 at temperatures above its boiling point of -252.87°C.[15] Below its boiling point of-252.87°C and above its melting point of -259.16°C, it becomes Liquid Hydrogen (LH_2).[16]

Hydrogen can be used to generate two forms of energy: heat and electricity.[17] The only input required to generate heat or electrical energy from hydrogen is oxygen, and the only output produced is water (as a vapour or as condensation):

> From an energy perspective, hydrogen has two outstanding properties. First, it is an excellent carrier of energy, with each kilogram of hydrogen containing about 2.4 times as much energy as natural gas. This energy can be released as heat through combustion, or as electricity using a fuel cell. In both cases the only other input needed is oxygen, and the only by-product is water.
>
> The chemical reaction is: $2H_2 + O_2 \rightarrow 2H_2O$ + energy.
>
> Second, hydrogen is a carbon-free energy carrier, with reactions such as that shown above producing no CO_2 or any other greenhouse gas.[18]

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[7] Royal Society of Chemistry, Hydrogen, 2021, [website-accessed 10 February 2021].

[8] By number of atoms, the Sun is made of 91.0% hydrogen. By mass, the Sun is about 70.6% hydrogen: NASA, Our Sun [website-accessed 12 February 2021].

[9] Hydrogen Strategy Group, *Hydrogen for Australia's future: A briefing paper for the COAG Energy Council*, August 2018, p 5.

[10] *What is Hydrogen?* Hydroville [website-accessed 16 February 2021].

[11] Hydrogen Strategy Group, *Hydrogen for Australia's future: A briefing paper for the COAG Energy Council*, August 2018, p 5.

[12] Royal Society of Chemistry, Hydrogen, 2021, [website-accessed 10 February 2021].

[13] William LJ, Hydrogen, Britannica and *Coal*, Geoscience Australia, [websites-accessed 11 February 2021].

[14] Royal Society of Chemistry, Hydrogen, 2021, [website-accessed 10 February 2021].

[15] At atmospheric pressure. Ibid.

[16] At atmospheric pressure. Ibid.

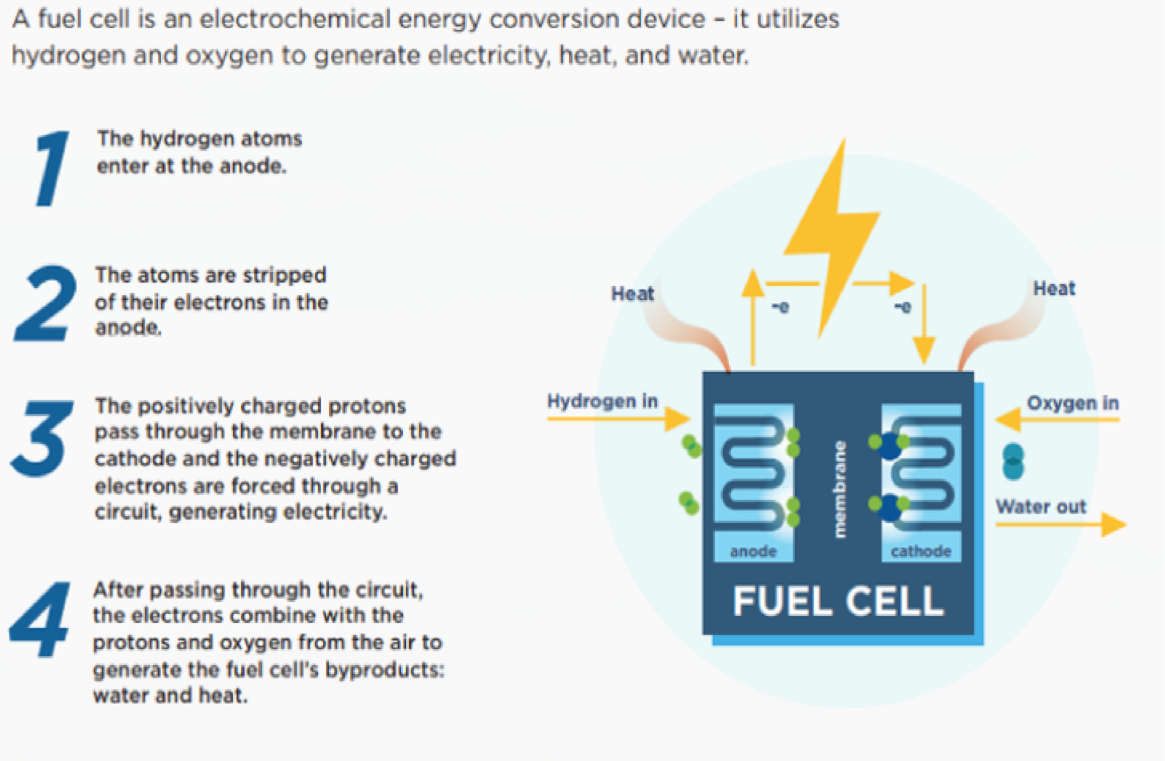
[17] Hydrogen Strategy Group, *Hydrogen for Australia's future: A briefing paper for the COAG Energy Council*, August 2018, p 5.

[18] Ibid, p 5 (footnotes omitted).

Heat energy is generated when hydrogen undergoes combustion in the presence of oxygen. Combustion is an exothermic process that produces heat irrespective of the fuel being burned.[19] Unlike the combustion of fossil fuels, which produces heat energy and carbon dioxide, the output from the combustion of hydrogen in the presence of pure oxygen is heat energy and water. No carbon dioxide (CO_2) or other greenhouse gas is emitted. However, if hydrogen is burned in the presence of air, which is composed of 78% nitrogen,[20] nitrogen oxides (NO_x) can be formed.[21] Nitrogen oxides, which include nitric oxide (NO) and nitrogen dioxide (NO_2), are harmful to human health and the environment.[22]

Electrical energy is generated when electrochemical processes in a fuel cell strip hydrogen atoms of their electrons and the electrons flow through a circuit (Figure 1). The fuel cell is essentially an “electrochemical conversion device” that uses hydrogen and oxygen to generate electricity, heat and water.[23]

Figure 1: How electricity is created from hydrogen in a fuel cell[24]



A fuel cell is an electrochemical energy conversion device - it utilizes hydrogen and oxygen to generate electricity, heat, and water.

1. The hydrogen atoms enter at the anode.
2. The atoms are stripped of their electrons in the anode.
3. The positively charged protons pass through the membrane to the cathode and the negatively charged electrons are forced through a circuit, generating electricity.
4. After passing through the circuit, the electrons combine with the protons and oxygen from the air to generate the fuel cell's byproducts: water and heat.

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[19] Schmidt-Rohr K, Why Combustions Are Always Exothermic, Yielding About 418 kj per Mole of O_2, *Journal of Chemical Education*, 1 September 2015, p 2094-2099. For a discussion of hydrogen internal combustion engines for motor vehicles, see: Hosseini SE and Butler B, An overview of development and challenges in hydrogen powered vehicles, *International Journal of Green Energy*, Volume 17(1), 2020, p 13-17.

[20] Helmenstine AM, The Chemical Composition of Air, *ThoughCo*, 7 July 2019.

[21] *Burning hydrogen for heating*, ICAX [website- accessed 16 February 2021]. Menzies M, Hydrogen: The Burning Question, *The Chemical Engineer*, 23 September 2019.

[22] *Nitrogen oxides*, Queensland Government, 27 September 2016.

[23] FCHEA, Fuel Cell & Hydrogen Energy Association, *Fuel Cell Basics* [website-accessed 12 February 2021].

[24] Ibid. See also: See also: US Department of Energy, Office of Energy Efficiency and Renewable Energy, *Fuel Cells* [website accessed – 12 February 2021]

2.2 Uses overview

Hydrogen has a range of existing industrial uses. For instance, it is used to refine petrochemicals and manufacture ammonia, glass, metals and electronics.[25] It is also used as a fuel in electric vehicles equipped with hydrogen fuel cells[26] and has even been used as rocket fuel for space ships.[27]

Hydrogen can be used in the domestic economy for heating, electricity generation and energy storage. It can also be used as a fuel for trucks, trains and shipping; and its suitability for use as an aviation fuel is under active investigation. Hydrogen can also power industrial processes that require high temperatures, such as steel and aluminium production.

The ability to transport hydrogen overseas in liquid or compressed gas forms provides the opportunity to develop a new export industry that will enable other nations to benefit from hydrogen's potential uses. As discussed at 3.1, most hydrogen currently used by industry is produced using fossil fuels; although it is possible to use hydrogen in industrial processes that is produced using nuclear energy or renewable energy.

2.3 Heating

In Australia, energy for heating comes from either the direct combustion of fossil fuels, particularly natural gas, or from the generation of electricity.[28] It has been proposed that hydrogen can replace the use of natural gas for low temperature heating applications, such as home heating, cooking and water heating.[29] This can occur on a partial basis (up to 13%) without any modification of appliances, existing pipeline infrastructure and gas meters.[30] Beyond a 13% replacement, modification of natural gas appliances and pipeline infrastructure will be required.[31] Gas meters would not need to be changed for small injections of hydrogen but would need to be changed for the use of 100% hydrogen.[32]

High-temperature industrial processes that currently rely on natural gas can convert to hydrogen with minimal retrofitting of existing equipment.[33] As discussed below (2.6), such industrial uses include the production of alumina and steel.[34]

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[25] COAG Energy Council, *Australia's National Hydrogen Strategy*, 2019, p 5

[26] Nicholson T, Everything you need to know about hydrogen cars, *RoyalAuto*, 6 October 2020.

[27] Huang Z, Hydrogen fuels rockets, but what about power for daily life? We're getting closer, *The Conversation*, 11 March 2019. See also: NASA, Space Applications of Hydrogen and Fuel Cells, [website-accessed 11 March 2021]

[28] Hydrogen Strategy Group, *Hydrogen for Australia's future: A briefing paper for the COAG Energy Council*, August 2018, p 28.

[29] Ibid, p 29. Indeed, from the early 19th Century, Australia relied on burning "town gas" for heat. Town gas is a mixture of carbon monoxide and hydrogen obtained from coal. It was replaced with natural gas in the 1960s, after large reserves of domestic natural gas were discovered.

[30] Ibid, p 29.

[31] Ibid, p 29 (footnotes omitted).

[32] Ibid, p 29 (footnotes omitted).

[33] Ibid, p 29 (footnotes omitted).

[34] See, for instance: Wood T, *Green steel is no longer a fantasy*, Grattan Institute, 11 May 2020.

Whether existing pipelines that transport natural gas from production to storage facilities can carry Hydrogen depends on such factors as:

- the condition of the pipe and its welds;
- the grade of steel used;
- the type of steel used;
- the operating pressure for which the pipeline was designed; and
- the proximity of storage facilities to sites of Hydrogen production.[35]

Much of the cast iron or steel pipeline infrastructure that transports natural gas from storage facilities to end users has already been replaced with polyethylene or nylon pipes, making it compatible with 100% hydrogen distribution.[36]

Upgraded infrastructure should be designed to manage the heightened safety risks posed by hydrogen, compared to natural gas. In particular, the higher pressures under which compressed hydrogen gas is stored increases the risk of explosion; while the smaller size of H_2 molecules increases the potential for leakages.[37] Additionally, the pale blue hydrogen flame is nearly invisible in daylight and has relatively low radiant heat.[38]

2.4 Transport

Hydrogen can be used in many facets of transportation; from light passenger vehicles, buses, trucks, trains, ships, aircraft and even spacecraft.[39] In most cases, hydrogen is used to produce electricity in fuel cells that power electric motors. Trials are also being conducted as to whether hydrogen can be combusted instead of fossil fuels in internal combustion engines.[40] Hydrogen can also be used to improve Australia's fuel security.

Hydrogen powered passenger vehicles

Battery electric vehicles (BEVs) and hydrogen fuel cell electric vehicles (FCEVs) both use electricity stored in batteries to power their electric motors. FCEVs charge their batteries from the electricity generated when hydrogen passes through a fuel cell.[41] The hydrogen is typically stored in a fuel tank as highly compressed gas (H_2).[42] BEVs do not use hydrogen. Instead, they charge their batteries directly from the electricity network.

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[35] Hydrogen Strategy Group, *Hydrogen for Australia's future: A briefing paper for the COAG Energy Council*, August 2018, p 30.

[36] Ibid, p 30.

[37] *Burning hydrogen for heating*, ICAX, [website-accessed 16 February 2021].

[38] *Hydrogen flames*, Hydrogen Tools, [website-accessed 16 February 2021]. See also: *Burning hydrogen for heating*, ICAX, [website-accessed 16 February 2021].

[39] NASA, *Liquid Hydrogen – the Fuel of Choice for Space Exploration*, 29 July 2010 [website accessed 13 February 2021]. For a detailed economic analysis of the use of hydrogen in the transport sector, see: Advisian, *Australian hydrogen market study*, May 2021, p 45 ff.

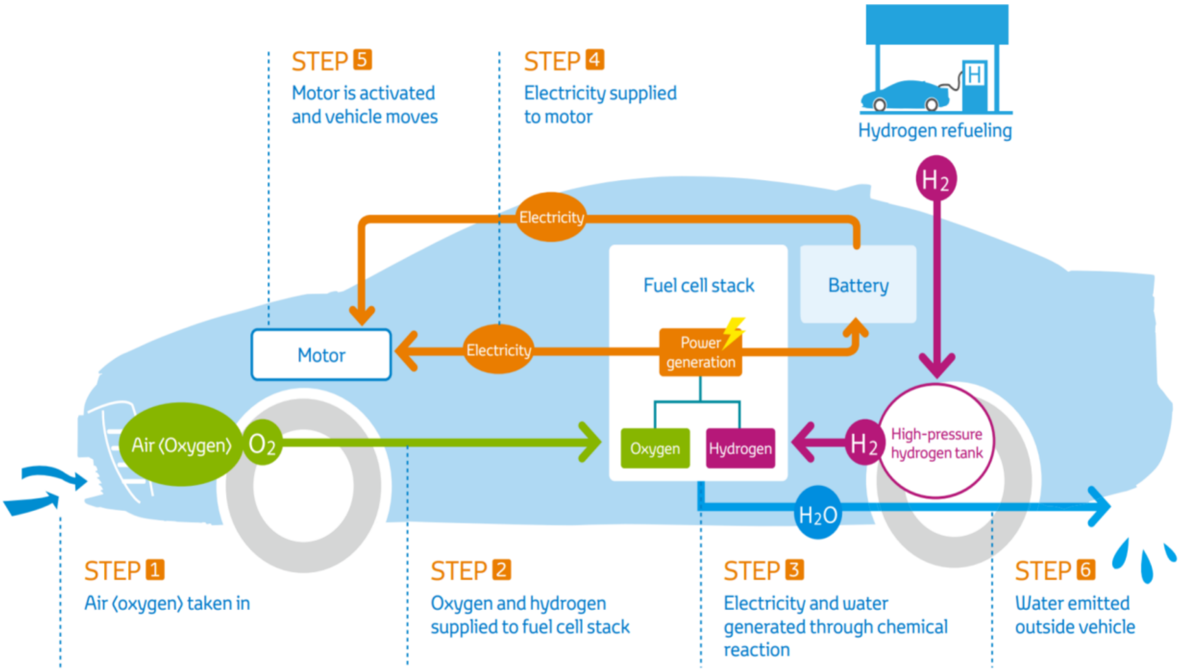
[40] Airbus, Hydrogen combustion, explained: How hydrogen's unique properties are ideal for engine combustion, 26 November 2020.

[41] For a discussion of Battery, Plug-in Hybrid and Hydrogen Electric Vehicles, see: Gotsis T, *Electric vehicles in NSW*, NSW Parliamentary Research Service, May 2018.

[42] Roberts D, This company may have solved one of the hardest problems in clean energy, *Vox*, 16 February 2018.

BEVs produce zero tail pipe emissions and zero indirect tailpipe emissions if charged with renewably generated electricity. FCEVs produce zero direct tailpipe emissions and zero indirect tailpipe emissions if they are fuelled with hydrogen that was produced from renewable energy.[43] The operation of a FCEV is illustrated in Figure 2.

Figure 2: The operation of a FCEV (the Toyota Mirai)[44]



To ensure safety, the fuel tanks that contain the compressed hydrogen gas are made of high-strength substances, such as carbon fibre, and are designed to prevent leakage in the event of an accident.[45] The passenger cabin is also isolated from the fuel tank and, in the event of any leakage, the tanks are designed to harmlessly vent the hydrogen gas into the atmosphere; while sensors shut down the fuel system and the vehicle.[46] Being the lightest of all atoms, hydrogen disperses quickly into the atmosphere; rather than accumulating dangerously at ground level, like petrol.[47] In the event of an abnormal temperature increase caused by fire, pressure relief valves gradually release the hydrogen in order to prevent an explosion.[48]

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[43] Gotsis T, *Electric vehicles in NSW*, NSW Parliamentary Research Service, May 2018, p 2, 3-4, 7 and 8.

[44] Toyota, Outline of the Mirai [website-accessed 13 February 2021]. The vehicle depicted in the Toyota Mirai

[45] Williams B, How safe are hydrogen vehicles in a crash? *Hydrogen Fuel News,* 1 May 2020. See also: Toyota, *Hydrogen? Is that safe?* 5 August 2015 [website-accessed 15 February 2021]; and Toyota, New Mirai: Press Information 2020 [website-accessed 15 February 2021].

[46] Toyota, *Hydrogen? Is that safe?* 5 August 2015 [website-accessed 15 February 2021]. See also: Toyota, New Mirai: Press Information 2020 [website-accessed 15 February 2021].

[47] Ibid.

[48] Ibid.

Presently, there is only one permanent hydrogen refuelling station in Australia, located in Sydney at Hyundai's Macquarie Park Showroom.[49] The ACT and Queensland Governments are in the process of developing hydrogen refuelling stations that will fuel new government fleet hydrogen vehicles (20 in the ACT and five in Queensland).[50] A hydrogen refuelling station is also planned for Victoria[51] and West Australia.[52]

Hydrogen trucks

FCEVs have relatively long driving ranges and fast refuelling times, which makes them "particularly well-suited"[53] to low emission, long-distance heavy transport, where the size and weight of the battery required by a BEV truck becomes "impractical".[54] These relative differences in driving range and refuelling times are illustrated in the following comparison of FCEV, BEV and petrol passenger vehicles:

> Hyundai's Nexo can drive for 666 kilometres before needing to be refuelled, while the Toyota Mirai's range is 550 kilometres. Typically, petrol cars have a driving range of 400 to 600 kilometres on a tank of fuel. The driving range of battery electric vehicles varies depending on the battery size. The Nissan Leaf, for example, can travel 270 kilometres on a full charge while the Tesla Model S Long Range can reach 610 kilometres.
>
> Recharging an EV battery takes anywhere between 30 minutes or 12 hours depending on the speed of the charging point and battery size. Refuelling a hydrogen-powered passenger car takes just three to five minutes at a refuelling station.[55]

Switzerland has already purchased ten of the world's first hydrogen trucks, known as the "XCIENT Fuel Cell". Manufacturer Hyundai has committed to building 1,600 of the hydrogen trucks by 2025.[56]

The NSW Government has approved $500,000 in funding for Coregas, an Australian industrial gases company, to acquire two hydrogen trucks and build a hydrogen refuelling facility at its Port Kembla plant.[57]

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[49] *Hydrogen Vehicle Refuelling Deal Could Be Green Light for Australian Fuel Cell Electric Vehicles*, Jemena, 10 August 2020. [website-accessed 15 February 2021].

[50] Mazengard M, ACT Government's 20-vehicle hydrogen fleet grounded due to Covid difficulties, *The* Driven, 6 August 2020. Caldwell F, Hydrogen cars to be added to government's fleet in net step to phasing out petrol, *Brisbane Times*, 27 August 2019.

[51] Australian Renewable Energy Agency (ARENA), Melbourne's first hydrogen refuelling station takes shape, *ARENAWIRE*, 2 November 2020. See also: Dowling J, Hyundai Nexo: first hydrogen car certified for Australia, now for the refuelling stations, *Car Advice*, 27 August 2020.

[52] Western Australia Government, *$22 million investment to accelerate renewable hydrogen future*, 17 August 2020.

[53] Hydrogen Strategy Group, *Hydrogen for Australia's future: A briefing paper for the COAG Energy Council*, August 2018, p 31.

[54] Ibid, p 31.

[55] Nicholson T, Everything you need to know about hydrogen cars, *Royal Auto*, 6 October 2020. See also: Graham R, Hydrogen fuell cell vs electric cars, *Euronews*, 14 February 2002; and Gotsis T, *Electric vehicles in NSW*, NSW Parliamentary Research Service, May 2018, p 9.

[56] Hyundai, World's first fuel cell heavy-duty truck, XCIENT Fuel Cell, heads to Europe for commercial use, 6 July 2020 [website-accessed 15 February 2021].

[57] Fernandez T, Australia's first hydrogen trucks to come to Port Kembla after landmark project gets green light, *ABC News*, 19 March 2021.

Figure 3: Hyundai's XCIENT Fuel Cell Hydrogen truck[58]

Hydrogen buses

FCEVs have effectively performed the role of public buses in overseas demonstrations:

> There have been a number of hydrogen bus fleet demonstrations … that show FCEVs can meet the performance requirements of public transport. There is strong competition, however, from BEV buses being made in rapidly increasing numbers …[59]

Foton Mobility Pty Ltd is a new company that, commencing in 2021, will introduce hydrogen buses into the Australian market.[60] Its Chief Executive Officer, Neil Wang, argues that the long driving ranges and fast refuelling times of hydrogen vehicles makes them well-suited for use as public transportation:

> A few key benefits are that Hydrogen buses only need 12-15 mins to refuel which is in line with current diesel fuelling time and just one hydrogen fuel station deployed onsite can refuel around 160 buses. Compared to battery electric, recharging 160 electric city buses would need installation of 160 charging stations. Importantly, we can make hydrogen in regional areas which will promote jobs and stimulate local economies.[61]

Foton Mobility Pty Ltd plans to manufacture its hydrogen buses in Moss Vale, NSW, by the second quarter of 2022.[62]

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[58] Hyundai, World's first fuel cell heavy-duty truck, XCIENT Fuel Cell, heads to Europe for commercial use, 6 July 2020 [website-accessed 15 February 2021].

[59] Hydrogen Strategy Group, *Hydrogen for Australia's future: A briefing paper for the COAG Energy Council*, August 2018, p 32.

[60] Cotter F, Foton Bus Australia Powers with Truegreen, *Australian Bus & Coach*, 15 January 2021.

[61] Matich B, Hydrogen buses are on their way to Australia, *PV magazine*, 19 January 2021.

[62] Ibid.

Figure 4: A Hydrogen bus[63]

Hydrogen trains

Only approximately 10% of Australia's rail network is currently electrified.[64] Hydrogen trains could be a cost effective means by which to decarbonise the remaining rail network.[65] The world's first hydrogen train to be powered by a hydrogen fuel cell, the Coradia iLint, has completed more than 180,000 kilometres of testing in Germany and will be in regular passenger service from 2022.[66] The Coradia iLint has been designed specifically for use on non-electrified lines, enabling an emission-free alternative to diesel train operations.[67] The Coradia iLint has also been successfully tested in the Netherlands, which has "approximatively 1,000 kilometres of non-electrified line on which around 100 diesel trains currently operate daily."[68]

Figure 5: The Coradia iLint hydrogen train[69]

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[63] Ibid.

[64] Hydrogen Strategy Group, *Hydrogen for Australia's future: A briefing paper for the COAG Energy Council*, August 2018, p 33.

[65] Ibid, p 33.

[66] Alstom, *World's first hydrogen train Coradia iLint honoured*, press release, 22 January 2021.

[67] Ibid.

[68] Alstom, *Alstom's hydrogen train Coradia iLint completes successful tests in the Netherland*, press release, 6 March 2020.

[69] Ibid.

Hydrogen ships

In 2018, the International Maritime Organisation decided that emissions from global shipping "should peak as soon as possible and then fall by at least 50% by 2050 compared with 2008 levels".[70] In an effort to reduce carbon emissions, some shipping companies are attempting to develop hydrogen powered ships.[71] Different technologies are being investigated.

Battery powered ships are technically possible but practical limits arise for powering large ships over vast distances, as they "would simply need too many batteries to run on these alone".[72] The use of hydrogen in internal combustion diesel engines in ships is being explored and currently used by the Hydroville.[73] This use of hydrogen generates power without carbon dioxide emissions, or the particulate matter and sulphur dioxides associated with the burning of conventional shipping fuels.[74] However, the combustion of hydrogen in the presence of air, rather than in the presence of pure oxygen, can produce pollution in the form of nitrogen oxides.[75]

The Norwegian shipping firm Wilhelmsen plans to develop a prototype ship that is powered by liquid hydrogen (LH_2).[76] The prototype will convert the LH_2 into electricity using a 3MW hydrogen fuel cell and this energy source will be supported by a 1MWh battery pack charged by renewable electricity from the Norwegian grid.[77] The only emission that would be produced is water.

One challenge that LH_2 poses for long-distance shipping is the need to store it at -252.87°C or below.[78] Another challenge is the need to provide additional storage, as LH_2 takes up around eight times more space to store than the amount of marine gas oil needed to give the same amount of energy.[79] Installing enough hydrogen fuel cells to power a ship is also expensive.[80] It remains to be seen whether these ships can operate profitably in the current market.

The Australian firm Global Energy Ventures is developing the world's first compressed hydrogen fuel cell ship (Figure 6).[81] The ship is designed to use compressed hydrogen gas (H_2) in its fuel cells and transport compressed hydrogen gas to the Asian market.[82]

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[70] Turner J, HySHIP: Inside Europe's flagship hydrogen ship demonstrator project, *Ship Technology*, 22 December 2020.

[71] Timperley J, The Fuel that could transform shipping, *BBC*, 30 November 2020.

[72] Ibid.

[73] *Hydroville*, CMB, [website- accessed 16 February 2021].

[74] Ibid.

[75] Timperley J, The Fuel that could transform shipping, *BBC*, 30 November 2020.

[76] Turner J, HySHIP: Inside Europe's flagship hydrogen ship demonstrator project, *Ship Technology*, 22 December 2020.

[77] Ibid. See also: Radowitz B, World's first liquid hydrogen fuel cell cruise ship planned for Norway's fjords, *Recharge*, 3 February 2020.

[78] Timperley J, The Fuel that could transform shipping, *BBC*, 30 November 2020.

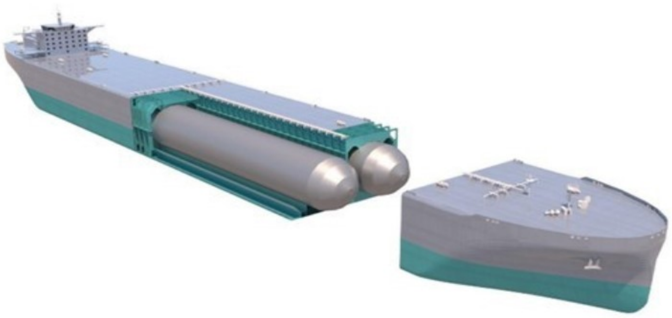
[79] Ibid.

[80] Ibid.

[81] Ovcina J, Design unveiled for world's 1st compressed hydrogen ship, *Offshore Energy*, 14 October 2020.

[82] Global Energy Ventures Signs MOU with Pacific Hydro for Export of Green Hydrogen, *Fuel Cell*

Figure 6: Artist rendering of Global Energy Ventures compressed H2 ship[83]



Hydrogen aeroplanes

The first aeroplane to fly on electricity generated from hydrogen fuel cells was built by Boeing in 2008.[84] It was a single-person plane that used power from lithium ion batteries to supplement its hydrogen power during take-off and landing. However, considerable challenges remain for hydrogen aviation; particularly in relation to commercial viability and ensuring hydrogen aeroplane safety standards matches those of existing conventional aeroplanes.[85] The weight required for fuel storage is one of the most significant challenges to hydrogen-powered aviation.[86] In the case of liquid hydrogen (LH2), the storage tanks must be light-weight and able to keep the fuel at a temperature below -252.87°C.[87] In the case of compressed gas, the fuel tanks must be light-weight but be able to withstand high pressures (250-350 bar).[88] Industry stakeholders suggest that, if they ultimately prove to be viable, hydrogen aeroplanes will remain in development at least until 2030.[89]

Transport fuel security

Due to a 23% decline in Australia's crude oil production in the decade to 2016, Australia became reliant on imports for 91% of oil used for transport.[90] In response to concerns that the reliance on imports and low fuel reserves were compromising Australia's fuel security, the Australian Government recently introduced a suite of reforms[91] and entered into a fuel security deal with the United States.[92] Under the deal, the Australian Government has purchased a

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Works, 21 January 2021. See also: MOU signed with Pacific Hydro for Export of Green Hydrogen, Global Energy Ventures, ASX Announcement, 20 January 2021.

[83] Ovcina J, Ballard, GEV join forces on developing fuel-cell powered ship, *Offshore Energy*, 4 February 2021 and Offshore Energy, CNW Group/Ballard Power Systems Inc.

[84] Kramer D, Hydrogen-powered aircraft may be getting a lift, *Physics Today*, 2020, 73(12) p 27.

[85] Ibid.

[86] Ibid.

[87] Kramer D, Hydrogen-powered aircraft may be getting a lift, *Physics Today*, 2020, 73(12) p 27.

[88] Ibid.

[89] Ibid.

[90] Hydrogen Strategy Group, *Hydrogen for Australia's future: A briefing paper for the COAG Energy Council*, August 2018, p 39.

[91] Australian Government, *Australia's fuel security package*, [website-accessed 2 March 2021].

[92] Taylor A, *Australia to boost fuel security and establish national oil reserve*, media release, 22 April 2020.

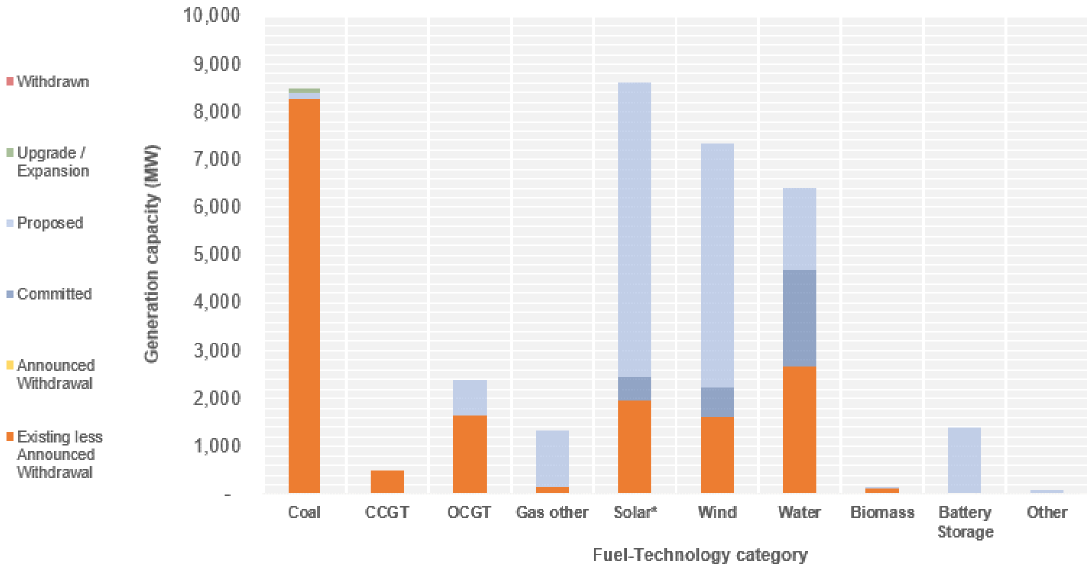
portion of the United States’ Strategic Petroleum Reserve.[93] The United States Government will store the Australian Government owned crude oil in its Strategic Petroleum Reserve.[94]

The Hydrogen Strategy Group has advised that hydrogen fuel cell vehicles “could play an important role in diversifying fuel types and reducing our reliance on imported liquid fuels for transport.”[95]

2.5 Electricity generation

Figure 7 illustrates the shift towards renewable electricity generation occurring in NSW.[96] Committed solar (473 MW), wind (609 MW) and water (2,040 MW) renewable energy projects will add 3,122 MW of generation capacity; while proposed solar (6,159 MW), wind (5,086 MW) and water (1,700 MW) will add 12,945 MW. Together, committed and proposed solar, wind and water renewable energy projects will add 16,067 MW of electricity generation capacity in NSW; more than the combined 10,554 MW currently provided by coal (8,255 MW) and the three types of gas generation (2,299 MW).[97] This shift towards renewable energy is also occurring across the National Electricity Market (NEM).[98]

Figure 7: Electricity generation capacity (MW) in NSW, January 2021[99]



* Excludes rooftop solar. CCGT: Combined-cycle gas turbine. OCGT: Open-cycle gas turbine. Source: AEMO

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[93] Ibid.

[94] Ibid.

[95] Hydrogen Strategy Group, *Hydrogen for Australia’s future: A briefing paper for the COAG Energy Council*, August 2018, p 39.

[96] See also: Foley M and Toscano N, Coal plant closures loom large as NSW backs hydrogen for the Hunter, *Sydney Morning Herald*, 12 March 2021.

[97] AEMO, *NEM Generation Information as at 29 January 2021* and excel spreadsheet [website-accessed 17 February 2021].

[98] Ibid. For the latest announcement of a coal power plant closure, see: Whittaker J, Energy Australia to close Yallourn power station early and build 350 megawatt battery, *ABC News*, 10 March 2021.

[99] AEMO, *NEM Generation Information as at 29 January 2021* and excel spreadsheet [website-accessed 17 February 2021].

In NSW, the shift towards renewable energy is occurring in the context of all five operating coal-fired power stations being scheduled for retirement between 2022 and 2043 (based on an assumed 50-year technical life); beginning with the Liddell Power Station in April 2023, followed by Vales Point B in 2029, Eraring in 2031, Bayswater in 2035 and Mount Piper in 2043.[100]

Being dependent on prevailing weather conditions, the generation of solar and wind energy can be intermittent; producing too much electricity when it is not needed and too little when it is needed.[101] This variability can affect the security and reliability of the NEM. Security is achieved when the NEM operates within set technical parameters; whereas reliability is achieved when the NEM can meet electricity demand with a high degree of confidence.[102]

Hydrogen can promote NEM reliability and security because it is a "flexible load" and provides dispatchable generation (Figure 8).[103] Hydrogen can act as a flexible load because electrolysers can increase hydrogen production when renewable energy output rises (and electricity costs falls). The hydrogen can be used immediately or stored for later use. As discussed below at 3.3, electrolysers produce hydrogen through the chemical process of electrolysis. Electrolysis involves using electricity to split water into hydrogen gas and oxygen gas.[104] Electrolysers can be powered by renewable energy generators, nuclear energy or fossil fuels.[105]

The dispatchability of a generator refers to whether it is reliable and responsive in meeting a load target.[106] For that reason, dispatchable generation can be contrasted with the intermittent nature of renewable energy generation.[107]

Stored hydrogen can be used for dispatchable electricity generation in times of low renewable energy supply or high electricity demand. The generation of electricity from hydrogen can occur either in a fuel cell or from hydrogen combustion powering a gas turbine.[108] The gas turbine option requires further development and, unlike the fuel cell option, generates nitrogen oxide pollution due to the burning of oxygen at high temperatures:

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[100] NSW Government, *NSW Electricity Strategy*, p 14.

[101] Hydrogen Strategy Group, *Hydrogen for Australia's future: A briefing paper for the COAG Energy Council*, August 2018, p 36.

[102] Gotsis T, Angus C, Montoya D, Roth L, Johns R, Dobson M, *Uranium Mining and Nuclear Energy in New South Wales*, NSW Parliamentary Research Service, September 2019, p 16.

[103] Hydrogen Strategy Group, *Hydrogen for Australia's future: A briefing paper for the COAG Energy Council*, August 2018, p 36. See also: Advisian, *Australian hydrogen market study*, May 2021, p 71 ff.

[104] US Department of Energy, Office of Energy Efficiency and Renewable Energy, *Hydrogen Production: Electrolysis* [website-accessed 17 February 2021]. See also: *Shell Hydrogen study: Energy of the Future? Sustainable Mobility through Fuel Cells and H_2*, Shell, 2017, p 14.

[105] US Department of Energy, Office of Energy Efficiency and Renewable Energy, *Hydrogen Production: Electrolysis* [website-accessed 17 February 2021].

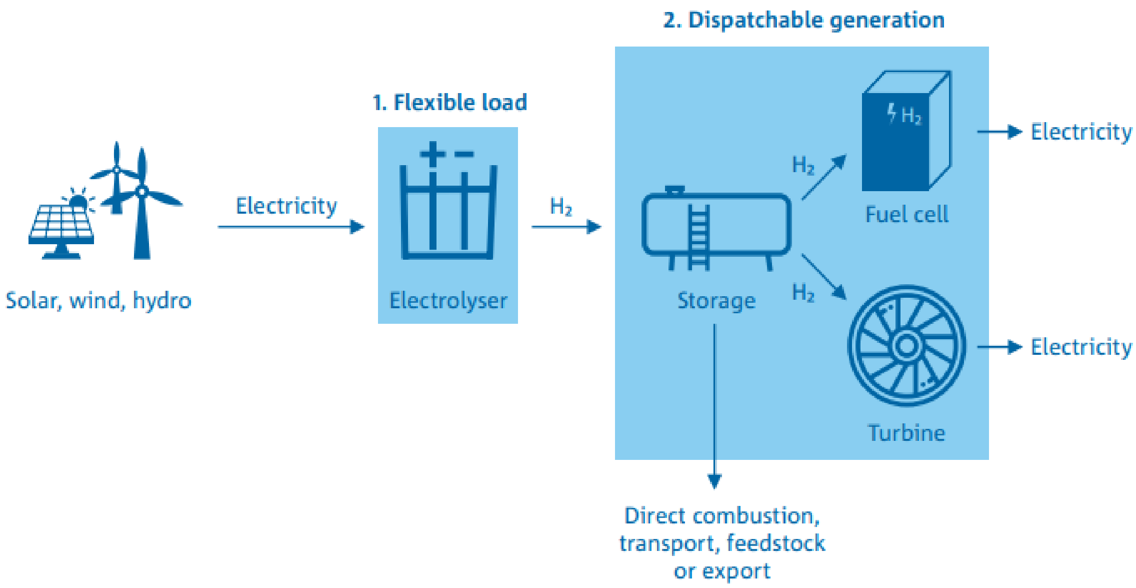
[106] Gotsis T, Angus C, Montoya D, Roth L, Johns R, Dobson M, *Uranium Mining and Nuclear Energy in New South Wales*, NSW Parliamentary Research Service, September 2019, p 19.

[107] See, for instance, Ibid, p 27.

[108] Hydrogen Strategy Group, *Hydrogen for Australia's future: A briefing paper for the COAG Energy Council*, August 2018, p 36.

> Although gas mixtures with a high proportion of hydrogen have been demonstrated, the high operating temperatures required for high efficiency lead to unwanted nitrogen oxide emissions. If the challenges can be overcome, hydrogen (or ammonia) turbines have excellent potential for large-scale systems (>100 MW). There is the potential to repurpose existing gas turbines, which would reduce capital costs.[109]

Figure 8: Flexible load and dispatchable generation functions of hydrogen[110]



Electricity generated from renewable sources can also be stored; in batteries and in pumped hydro systems (after renewable energy has been used to pump the water up an incline for later release). As is the case with stored hydrogen, the electricity stored in batteries and pumped hydro can be used to promote the security and reliability of the NEM. However, stored hydrogen, batteries and pumped hydro have different costs and characteristics that determine their suitability in particular circumstances.[111]

Hydrogen and pumped hydro are viable at larger sizes and better suited to applications requiring longer-term storage; energy generation at peak output that lasts for days (in the case of pumped hydro) or weeks (in the case of hydrogen). In comparison, batteries are viable at smaller sizes and are better suited to short-term storage (energy generation at peak output that lasts for hours) that is highly utilised or requires a fast response.[112]

A residential hydrogen Energy Storage system, costing $34,750, has been developed by an Australian-led venture involving researchers from the University of New South Wales.[113] The Lavo Green Energy Storage System uses excess

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[109] Ibid, p 37 (footnotes omitted).

[110] Ibid, p 36.

[111] Ibid, p 37.

[112] Ibid, Table 2, p 38.

[113] Blain L, World-first home hydrogen battery stores 3x the energy of a Powerwall 2, *New Atlas*,

rooftop solar energy and household water to produce hydrogen from electrolysis. The hydrogen is stored and passed through a fuel cell to create electricity when needed.

Hydrogen could also potentially reduce emissions from natural gas power plants if it is blended with natural gas and used as a combustible fuel source.[114]

2.6 Industrial uses

Presently, 90% of industrial hydrogen use is by the chemical industry and approximately 50% of that hydrogen is used to manufacture ammonia (NH_3).[115] Ammonia, in turn, has many industrial applications; including as an ingredient of fertilisers, plastics, textiles, dyes and cleaning products. It is also used in glass making and in the refining of petrochemicals. Existing hydrogen use could be replaced with renewably-sourced hydrogen, lowering greenhouse gas emissions from the production of chemicals, glass and synthetic fuels.[116]

Renewably sourced hydrogen could also replace the use of fossil fuels in energy intensive manufacturing processes; and, for instance, lead to the production of what has been referred to as “green steel” and “green aluminium”.[117] If electricity produced from hydrogen leads to lower energy costs, as well as lower emissions, it can also lead to reduced costs of production.[118]

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22 January 2021. See also: Mazengarb M, Australian-led venture takes next step towards residential solar hydrogen storage system, *Renew Economy*, 13 July 2020.

[114] Fernandez T and Drewitt-Smith A, Australia’s first net-zero hybrid station gets the green light, *ABC News*, 4 May 2021. See also: Morton A, The Coalition is backing a gas plant that also runs on hydrogen. Is this the future or a folly?, *The Guardian*, 8 May 2021.

[115] Hydrogen Strategy Group, *Hydrogen for Australia’s future: A briefing paper for the COAG Energy Council*, August 2018, p 34-35.

[116] KPMG, *NSW: A Clean Energy Superpower: Industry Opportunities Enabled by Cheap, Clean and Reliable Electricity*, 23 September 2020, p 38-54. See also: Advisian, *Australian hydrogen market study*, May 2021, p 74 ff.

[117] Ibid, ch 4 and 5.

[118] KPMG, *NSW: A Clean Energy Superpower: Industry Opportunities Enabled by Cheap, Clean and Reliable Electricity*, 23 September 2020, p 22-37.

3. HOW IS HYDROGEN PRODUCED, STORED AND TRANSPORTED?

3.1 Production overview

Most current hydrogen production (95%) is based on thermochemical processes involving fossil fuels; in particular, gas (68%), oil (16%) and coal (11%).[119]

Of the thermochemical processes involving fossil fuels, steam reforming is currently the most commonly used. Other thermochemical processes include partial oxidation, autothermal reforming and gasification of solid fuels.[120]

The International Energy Agency (IEA) notes that the use of fossil fuels to produce hydrogen accounts for 6% of global natural gas use and 2% of global coal consumption, and is responsible for 830 Mt of annual CO_2 emissions.[121]

The Hydrogen Strategy Group has said that some form of carbon capture and storage (CCS) is "essential if hydrogen from fossil fuels is to deliver decarbonisation benefits."[122]

A small proportion of hydrogen (5%) is produced using electrolysis.[123] Electrolysis may be powered with renewable energy, fossil fuels or nuclear energy. It may also be possible to produce hydrogen from biomass and biochemical processes using algae.[124]

Methane pyrolysis is a process that, pending further development, may enable hydrogen to be produced from natural gas with solid carbon as the by-product.[125]

An overview of the hydrogen production processes is shown in Figure 9. This paper focuses on the most common and technologically mature forms of hydrogen production: reforming and gasification using fossil fuels, and electrolysis.[126]

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[119] *Shell Hydrogen study: Energy of the Future? Sustainable Mobility through Fuel Cells and H_2*, Shell, 2017, p 11.

[120] Ibid.

[121] International Energy Agency, *Hydrogen*, 28 August 2020 [website-accessed 24 February 2020].

[122] Hydrogen Strategy Group, *Hydrogen for Australia's future: A briefing paper for the COAG Energy Council*, August 2018, p 15.

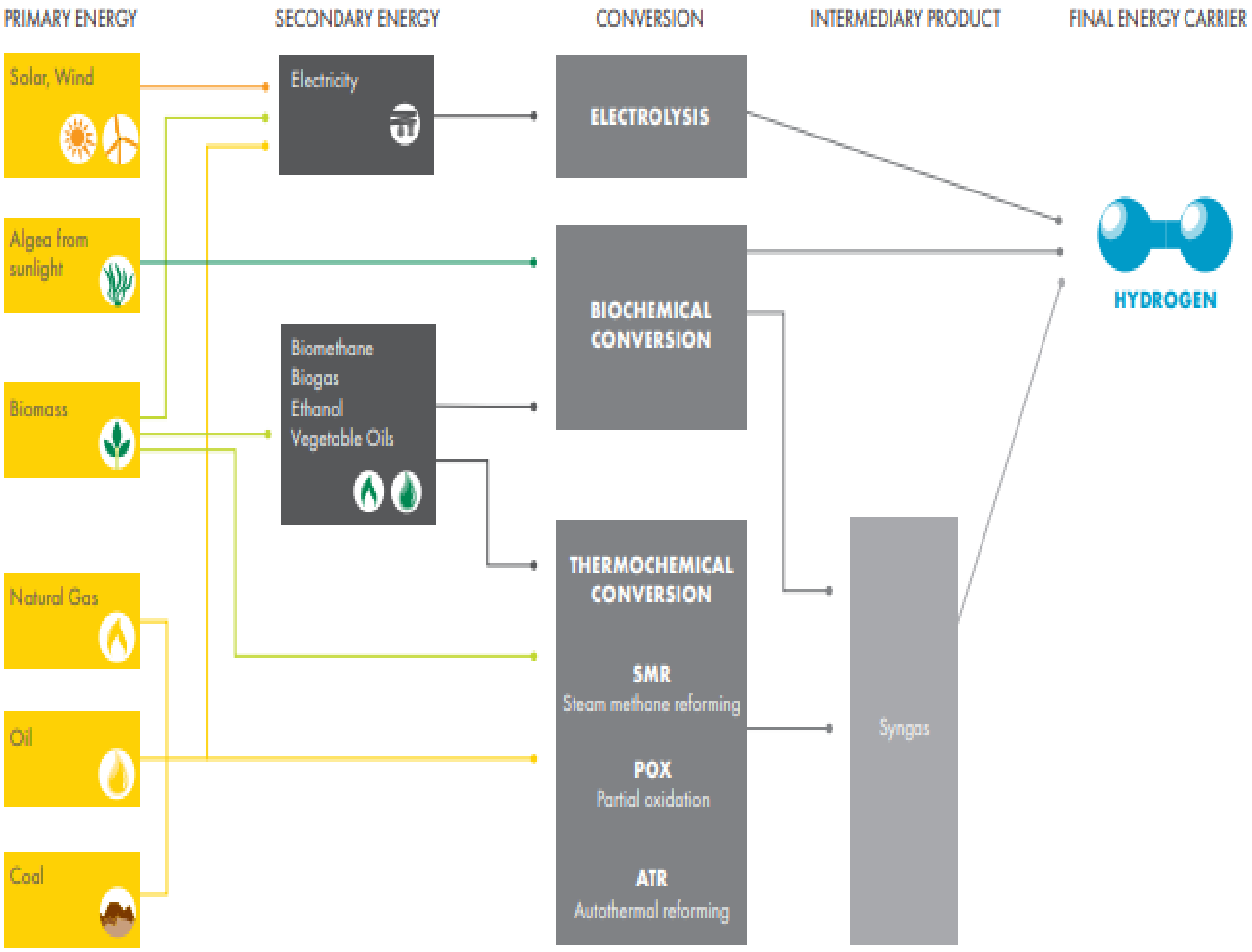
[123] *Shell Hydrogen study: Energy of the Future? Sustainable Mobility through Fuel Cells and H_2, Shell*, 2017, p 11.

[124] Ibid, p 11.

[125] Schneider S, Bajohr S, Graf F and Kolb T, State of the Art of Hydrogen Production via Pyrolysis of Natural Gas, *ChemBioEng Reviews*, 12 August 2020.

[126] For information on other forms of hydrogen production, see: Bruce S, Temminghoff M, Hayward J, Schmidt E, Munnings C, Palfreyman D, Hartley P, *National Hydrogen Roadmap*, CSIRO, 2018, p 67-6.

Figure 9: Overview of hydrogen production processes*[127]



*Electricity for electrolysis also can be provided by nuclear energy. The experimental thermochemical conversion process of methane pyrolysis is not depicted.

The different hydrogen production processes result in varying amounts of greenhouse gas emissions. In each case, the hydrogen produced remains colourless. Nevertheless, as a way of distinguishing between the emissions produced by the various production process, an informal categorisation of hydrogen by colour has developed (Table 1). Each colour represents the means of production and associated level of greenhouse gas emissions.

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[127] *Shell Hydrogen study: Energy of the Future? Sustainable Mobility through Fuel Cells and H_2*, Shell, 2017, p 12.

Table 1: Hydrogen colour categories[128]

Brown	Hydrogen produced from coal with emissions released into the atmosphere
Grey	Hydrogen produced from natural gas with emissions released into the atmosphere
Blue	Hydrogen produced from natural gas, with emissions subject to carbon capture and storage
Turquoise	Hydrogen produced using the process of methane pyrolysis, which produces solid carbon as a by-product (zero direct emissions)
Pink	Hydrogen produced from electrolysis using nuclear energy (zero direct emissions)
Green	Hydrogen produced from electrolysis using renewable energy (zero direct emissions)

Additionally, the colour white is sometimes used to refer to naturally occurring Hydrogen gas (H_2). Yellow is sometimes used to refer to hydrogen produced from electrolysis using a mix of renewable and non-renewable electricity. However, yellow can also refer to hydrogen produced from electrolysis using only solar energy.

The current international discussion about hydrogen's potential focuses on the production of blue and green hydrogen.

3.2 Production using fossil fuels

There are two main thermochemical processes for producing hydrogen from fossil fuels: reforming and gasificaton.

Reforming is "by far the most widespread method of hydrogen production".[129] It is a thermochemical process that requires high temperatures, a fuel (fossil fuels or biomass) an oxidant and a catalyst.[130] During the reforming process, the fuel is converted into hydrogen and the following by-products: water vapour, carbon monoxide and carbon dioxide.[131] There are three basic types of reforming processes: Steam Methane Reforming (SMR), Partial Oxidation (POX) and Autothermal Reforming (ATR).[132]

In SMR**,** methane (CH_4) (the largest component of natural gas)[133] and water (H_20)

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[128] Van Puyvelde D, Shades of hydrogen – What's in a colour?, *2020 Energy Insider*, Energy Networks Australia, 24 September 2020 and Giovannini S, *50 shades of (grey and blue and green) hydrogen*, Energy Cities: The European association of cities in energy transition, 13 November 2020.

[129] *Shell Hydrogen study: Energy of the Future? Sustainable Mobility through Fuel Cells and H_2*, Shell, 2017, p 12.

[130] Ibid, p 12.

[131] Ibid, p 12.

[132] *Shell Hydrogen study: Energy of the Future? Sustainable Mobility through Fuel Cells and H_2*, Shell, 2017, p 12.

[133] US Energy Information Administration, *Natural gas explained*, 9 December 2020 [website-

are initially converted into synthesis gas (or "syngas"). Synthesis gas is comprised of hydrogen (H_2), carbon monoxide (CO), carbon dioxide (CO_2), water vapour and residual hydrocarbons.[134] The carbon monoxide and water undergo a subsequent reaction that produces more hydrogen and carbon dioxide.[135]

POX converts mainly heavy hydrocarbons (such as fuel oil or coal) into hydrogen using oxygen (rather than water vapour) as the oxidant, and a partial combustion process.[136] ATR uses a partial oxidation process to convert methane into hydrogen.[137] POX and ATR have higher carbon dioxide emissions than SMR.[138]

Gasification provides an alternative method of converting solid carbon carriers such as coal into synthesis gas.[139]

The CSIRO notes that SMR and coal gasification sites need to be situated near fuel resources and suitable carbon storage reservoirs:

> For SMR, the North West shelf of Australia contains extensive natural gas reserves (if made available) as well as a number of potential CO2 storage reservoirs in the form of nearby depleted gas fields.
>
> CO2 storage from coal gasification is less straightforward. While black coal may provide a preferred gasification feedstock, it is concentrated in New South Wales and Queensland where storage reservoirs are either not well characterised or situated onshore and therefore face a greater social licence risk.[140]

Hydrogen is also produced as a by-product of other industrial processes, such as the catalytic reforming of naphtha (a crude oil product) that occurs in refineries.[141]

3.3 Carbon Capture and Storage

Carbon Capture and Storage (CCS) essentially involves capturing carbon dioxide gas that is generated from the burning of fossil fuels, concentrating it, transporting it, and storing it permanently in underground reservoirs.[142] Typically, the underground reservoirs may have held fossil fuels or salty water (subterranean

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accessed 23 February 2020.

[134] *Shell Hydrogen study: Energy of the Future? Sustainable Mobility through Fuel Cells and H_2,* Shell, 2017, p 12.

[135] Ibid, p 12.

[136] Ibid, p 13.

[137] Ibid, p 13.

[138] Hydrogen Strategy Group, *Hydrogen for Australia's future: A briefing paper for the COAG Energy Council*, August 2018, p

[139] *Gasification Introduction*, US Department of Energy, National Energy Technology Laboratory, [website-accessed 24 February 2021].

[140] Bruce S, Temminghoff M, Hayward J, Schmidt E, Munnings C, Palfreyman D, Hartley P, *National Hydrogen Roadmap*, CSIRO, 2018, p 22.

[141] *Shell Hydrogen study: Energy of the Future? Sustainable Mobility through Fuel Cells and H_2*, Shell, 2017, p 29.

[142] For a detailed discussion of CCS, including modelling of the risk of CO_2 leakage over time, see: International Panel on Climate Change, *Carbon Dioxide Capture and Storage*, 2005.

brine).[143] Carbon Capture Utilisation and Storage (CCUS) is similar to CCS, except that the carbon is either used as an input in other industrial processes or permanently stored.[144]

In 1996, the Sleipner project in Norway became the first CCS project with dedicated CO_2 storage and monitoring.[145] It was designed to capture carbon dioxide at a natural gas production facility and inject it into a reservoir 800-1,100 metres under the seabed.[146] As at July 2019, more than 20 million tonnes of CO_2 have been stored at the Sleipner facility.[147]

In 2020, the global capacity of CCS facilities to provide permanent CO_2 storage was almost 40 million tonnes per annum.[148] This capacity was provided by 26 operating CCS facilities.[149] The Air Products Steam Methane Reformer facility in Texas, USA, and the Quest facility in Alberta, Canada, provide CCS for CO_2 generated from the production of hydrogen using SMR:

> **Air Products Steam Methane Reformer facility** captures CO2 from two steam methane reformers located in the Valero Energy refinery at Port Arthur, Texas. It produces 500 tonnes of clean hydrogen per day. In April 2020, …the facility had cumulatively captured and stored over six [Million tonnes] of CO2.
>
> **Quest CCS facility** captures CO2 from three steam methane reformers at the Scotford Upgrader in Alberta, Canada. It produces 900 tonnes of clean hydrogen per day. In July 2020, the facility reached five [Million tonnes] of CO2 safely and permanently stored in dedicated geological storage.[150]

The International Energy Agency (IEA) views (CCS) as an important part of efforts to combat climate change in a timely manner; the "potential 'sleeping giant' that needs to be awakened to respond to the increased ambition of the Paris Agreement".[151]

The Australian Government views large-scale deployment of CCS as having the potential to underpin new low emission industries, including hydrogen production

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[143] Flude S and Alcade J, Carbon capture and storage has stalled needlessly – three reasons why the fears of CO_2 leakage are overblown, *The Conversation*, 4 March 2020.

[144] International Energy Agency, *Carbon Capture, Utilisation and Storage*, 5 November 2020 [website-accessed 8 March 2021].

[145] International Energy Agency, *20 Years of Carbon Capture and Storage: Accelerating future deployment*, 2016, p 9. Other pre-existing projects inject the captured CO_2 into the ground for the purpose of Enhanced Oil Recovery (EOR), rather than permanent storage. For an overview of EOR, see: US Department of Energy, Office of Fossil Energy, *Enhanced Oil Recovery* [website-accessed 8 March 2021].

[146] International Energy Agency, *20 Years of Carbon Capture and Storage: Accelerating future deployment*, 2016, p 9.

[147] ExxonMobil, Sleipner: Pioneering Carbon storage under the sea, *Energy Factor: Europe*, 9 July 2019.

[148] Global CCS Institute, *Global Status of CCS 2020*, 2020, p 19.

[149] Ibid, p 19.

[150] Ibid, p 21.

[151] International Energy Agency, *20 Years of Carbon Capture and Storage: Accelerating future deployment*, 2016, p 9.

using reforming and gasificaton.[152] On 1 March 2021, the Australian Government's $50 million Carbon Capture, Use and Storage (CCUS) Development Fund opened to applications.[153]

In 2018 the NSW Government stated that potential CSS storage reservoirs in NSW were "relatively unexplored".[154] Accordingly, it was "a priority for NSW to identify potential storage sites suitable for storing greenhouse gases."[155] The NSW CO_2 Storage Assessment Program was developed to identify deep geological storage sites throughout NSW "suitable for the safe and secure storage of carbon dioxide".[156] The NSW CO_2 Storage Assessment Program states that a prospective site has been identified in the Pondie Range Trough in the northern half of the Darling Basin.[157] A Stage 2 exploration program is being planned of the Pondie Range Trough.[158]

Opponents of CCS argue that its ability to effectively capture and permanently store carbon dioxide emissions underground is unproven.[159] They further argue that the technology is expensive and fortifies the use of uncompetitive and polluting fossil fuels.[160] For instance, the Australian Greens argue that, since 1999, Australian governments have committed more than $4 billion to CCS research for no material gain, and those resources could have been more effectively directed towards developing renewable energy industries.[161] For these reasons, the Climate Council has argued that producing hydrogen from fossil fuels with CCS should not be classified as "clean".[162]

3.4 Production using electrolysis

Electrolysis is a chemical process that uses electricity to split water molecules (H_2O) into hydrogen and oxygen gases.[163] As indicated in Table 1, if the electricity used to power the electrolysis process is sourced from renewable energy (green hydrogen) or nuclear energy (pink hydrogen), no direct greenhouse gas emissions are produced. According to the petrochemical and energy company

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[152] Australian Government, *Technology Investment Roadmap-First Low Emissions Technology Statement-2020*, 2020, p 21.

[153] Australian Government, *New fund to support capture, use and storage projects*, 1 March 2021 [website-accessed 8 March 2021]

[154] NSW Government, *Carbon Capture and Storage*, February 2018.

[155] Ibid.

[156] Ibid.

[157] NSW Government, Coal Innovation NSW, NSW CO2 Storage Assessment Project [website-accessed 9 March 2021].

[158] Ibid.

[159] Nick O'Malley, What is carbon capture and storage (and does it work)? *Sydney Morning Herald*, 24 January 2021. See also: Climate Council, What is carbon capture and storage?, 15 January 2021 [website-accessed 8 March 2021]. See also:

[160] Ibid. See also: Longden T et al, 'Clean' Hydrogen? An analysis of the emissions and costs of fossil fuel based versus renewable electricity based hydrogen, March 2021, CCEP Working Paper, Australian National University.

[161] Nick O'Malley, What is carbon capture and storage (and does it work)? *Sydney Morning Herald*, 24 January 2021.

[162] Climate Council, *Unpacking the 'Tech Roadmap'*, 22 September 2020 [website-accessed 9 March 2021].

[163] US Department of Energy, Office of Energy Efficiency and Renewable Energy, *Hydrogen Production: Electrolysis* [website-accessed 24 February 2021].

Shell, hydrogen production from electrolysis “will rise significantly if (surplus) electricity from renewable energies becomes increasingly available.”[164]

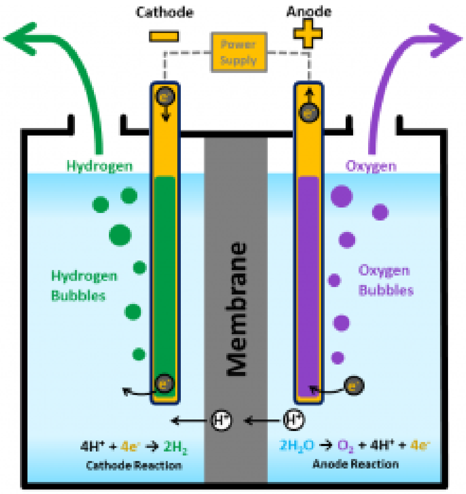
The electrolysis process occurs in a device called an electrolyser. Electrolysers are scalable and can range in size from small units to large units directly linked to electricity generation facilities.[165] Electrolysers are comprised of a positive electrode (anode) and a negative electrode (cathode). The cathodes are separated by an electrolyte or a membrane.[166]

Electrolysers are classified on the basis of the electrolyte material used and the temperature at which they operate.[167] Presently, the two types of electrolysers with the broadest commercial application are Alkaline electrolysers (AE) and Proton Exchange Membrane (PEM) electrolysers.[168] Anion Exchange Membrane (AEM) electrolysers are also commercially available.[169] Solid Oxide electrolysers are in the process of development.[170]

Figure 10 shows electrolysis occurring in an Alkaline electrolyser, which involves the following steps:

Figure 10: Electrolysis in a PEM electrolyser[171]

- Water reacts at the anode to form oxygen and positively charged hydrogen ions (protons).
- The electrons flow through an external circuit and the hydrogen ions selectively move across the PEM to the cathode.
- At the cathode, hydrogen ions combine with electrons from the external circuit to form hydrogen gas.
- Anode Reaction: $2H_2O \rightarrow O_2 + 4H^+ + 4e^-$
- Cathode Reaction: $4H^+ + 4e^- \rightarrow 2H2$



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[164] *Shell Hydrogen study: Energy of the Future? Sustainable Mobility through Fuel Cells and H_2*, Shell, 2017, p 11.

[165] US Department of Energy, Office of Energy Efficiency and Renewable Energy, *Hydrogen Production: Electrolysis* [website-accessed 24 February 2021].

[166] Hydrogen Strategy Group, *Hydrogen for Australia’s future: A briefing paper for the COAG Energy Council*, August 2018, p 16.

[167] *Shell Hydrogen study: Energy of the Future? Sustainable Mobility through Fuel Cells and H_2*, Shell, 2017, p 14.

[168] Hydrogen Strategy Group, *Hydrogen for Australia’s future: A briefing paper for the COAG Energy Council*, August 2018, p 16.

[169] Enapter, AEM water electrolysis: how it works, 20 October 2020 [website – accessed 24 February 2021].

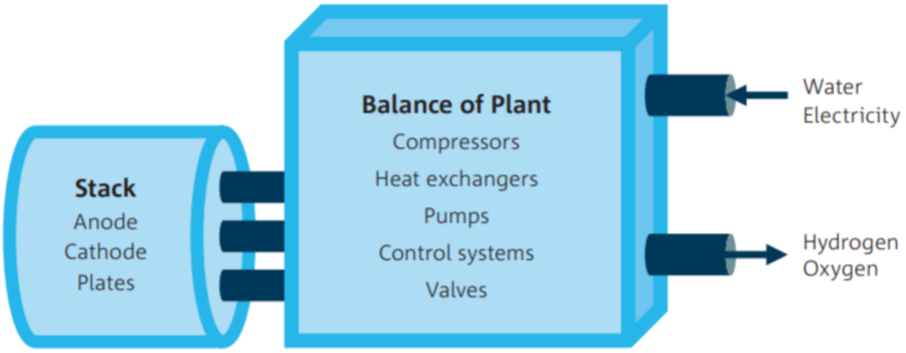
[170] For a discussion of developments, see: Hauch A et al, Recent advances in solid oxide cell technology for electrolysis, 370, 6513, *Science*, 9 October 2020 (abstract) and Harrison SB, CSIRO exclusive: Solid oxide electrolysis growing on an industrial scale, *Gasworld*, 4 May 2020.

[171] US Department of Energy, Office of Energy Efficiency and Renewable Energy, *Hydrogen*

A continuous supply of purified water is required for electrolysis (9 kg for every 1 kg of hydrogen produced).[172] The water needs of large-scale hydrogen production were considered by the Hydrogen Strategy Group. It found that less than 2.5% of Australia's annual water consumption was required to produce enough hydrogen to match the energy content of Australia's 2019 Liquefied Natural Gas (LNG) exports.[173]

Electrolysers can be scaled-up for industrial purposes into a "stack", with the other equipment required for production referred to as the Balance of Plant:

Figure 11: Electrolyser stack and balance of plant[174]



3.5 Production emissions

The CSIRO compared the operation of hydrogen production technologies in terms of lifecycle emissions.[175] It found that producing hydrogen using SMR and coal gasification creates the highest amounts of CO_2 lifecycle emissions; whereas producing hydrogen using electrolysis and renewable electricity creates no lifecycle emissions:

- **SMR with CCS** produced the highest level of emissions (0.76 $kgCO_2$ per kgH_2).
- **Coal gasification with CCS** produces 0.71 $kgCO_2$ per kgH_2.[176]
- **Alkaline electrolysis** and **PEM electrolysis** using renewable energy both produced 0 $kgCO_2$ per kgH_2.[177]

Production: Electrolysis [website-accessed 24 February 2021].

[172] Hydrogen Strategy Group, Hydrogen for Australia's future: A briefing paper for the COAG Energy Council, August 2018, p 16.

[173] Ibid, p 16.

[174] Bruce S, Temminghoff M, Hayward J, Schmidt E, Munnings C, Palfreyman D, Hartley P, National Hydrogen Roadmap, CSIRO, 2018, p 12. See also: Borello E and Birch, Green hydrogen electrolysers to be built in regional Australia with government backing, *ABC News*, 5 May 2021.

[175] In this context, lifecycle emission includes the direct and indirect emissions associated with the use of natural gas, coal and renewable energy.

[176] Bruce S, Temminghoff M, Hayward J, Schmidt E, Munnings C, Palfreyman D, Hartley P, National Hydrogen Roadmap, CSIRO, 2018, p 67.

[177] Ibid, p 67.

Based on those figures, producing 1,000 tonnes of hydrogen using SMR would create 760 tonnes of carbon dioxide emissions; while producing 1,000 tonnes of hydrogen using coal gasification would create 710 tonnes of carbon dioxide emissions. No emissions would be created by using electrolysers powered by renewable energy to produce 1,000 tonnes of hydrogen.[178]

3.6 Production costs

The Commonwealth Government's *Technology Investment Roadmap* states that, at $2 per kilogram or below ("H_2 under 2"), hydrogen becomes competitive as an industrial feedstock, transport fuel and in electricity generation.[179]

The CSIRO calculated the 2018 levelised cost of hydrogen (LCOH) as:

- **Alkaline electrolysis**: $4.78-$5.84 per kilogram (kg),
- **PEM electrolysis**: $6.08-$7.43 per kg,
- **SMR (with CCS)**: $2.27-$2.77 per kg,
- **Black coal gasification (with CCS)**: $2.57-$3.14 per kg.[180]

The LCOH produced by Alkaline and PEM electrolysis includes the "option for grid connected electrolysis where electricity pricing is reflective of current premiums paid for renewable energy".[181]

PEM electrolysis LCOH sensitivity

The CSIRO identified five material cost drivers for PEM electrolysis: electricity price, capacity factor, plant size, capital cost and plant efficiency:

> **1. Electricity price:** Accessibility to cheaper low emissions electricity pricing can have a material impact on LCOH.
>
> **2. Capacity factor:** The more the electrolyser is used, the greater the potential to derive revenue and pay back the capital investment.
>
> **3. Plant size:** Increasing the size of the stack and number of stacks in a plant decreases capital costs and enables greater utilisation of [Balance of Plant] which can improve system efficiencies.
>
> **4. Capital cost:** Capital costs can be improved by increasing the plant size as well through increases in production economies of scale.
>
> **5. Efficiency:** Efficiency increases with the size of the plant but improvements can also be achieved via [research and development] and operation optimisation …[182]

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[178] See: Longden T et al, 'Clean' Hydrogen? An analysis of the emissions and costs of fossil fuel based versus renewable electricity based hydrogen, March 2021, CCEP Working Paper, ANU.

[179] Australian Government, *Technology Investment Roadmap: First Low Emissions Technology Statement-2020*, 2020, p 18.

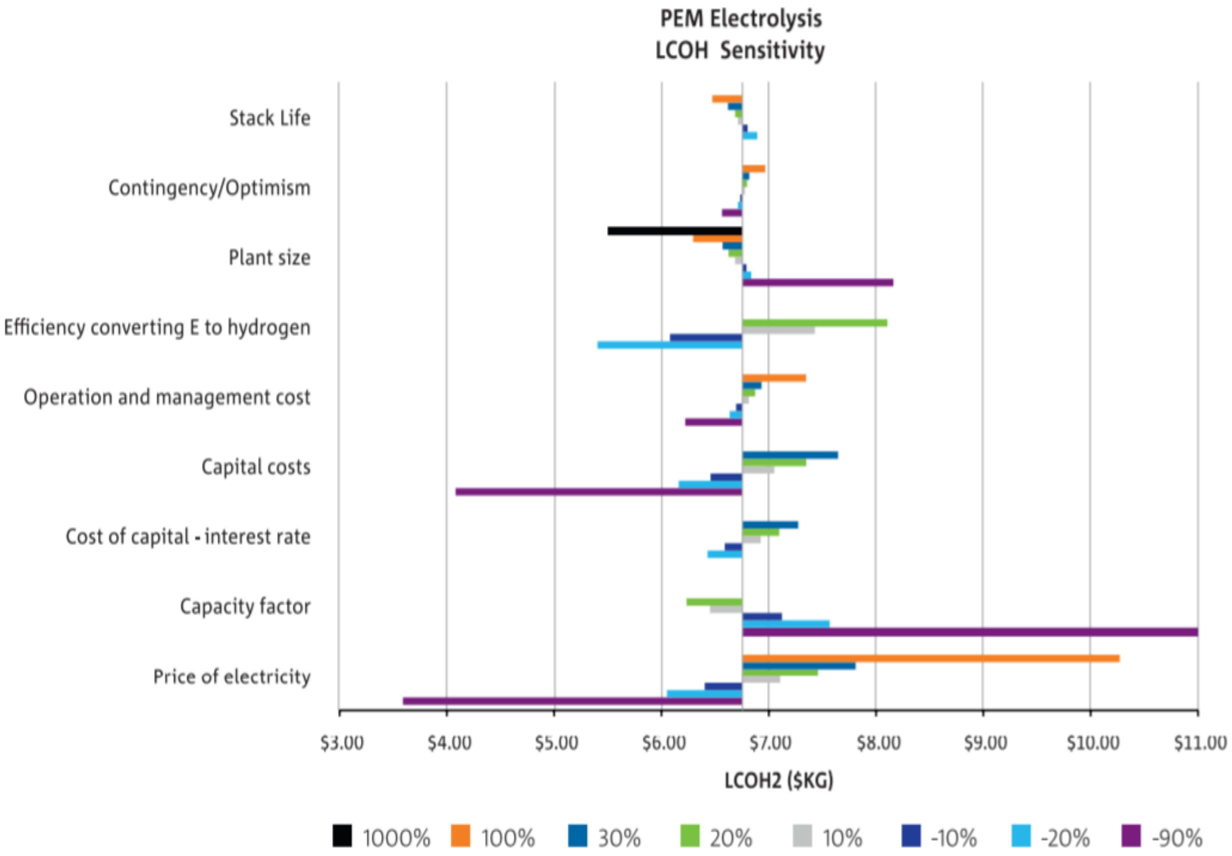
[180] Bruce S, Temminghoff M, Hayward J, Schmidt E, Munnings C, Palfreyman D, Hartley P, *National Hydrogen Roadmap*, CSIRO, 2018, p 13 and 20. See also: Advisian, *Australian hydrogen market study*, May 2021, p 9-11.

[181] Ibid, p 13.

[182] Ibid, p 14.

The CSIRO's LCOH sensitivity analysis for hydrogen produced with PEM electrolysis is set out in Figure 12.

Figure 12: PEM electrolysis, LCOH sensitivity[183]



SMR LCOH sensitivity

Figure 13 presents the CSIRO's LCOH sensitivity analysis for hydrogen produced using SMR. For SMR with carbon capture and storage, the factor that exerts the greatest downward influence on the price of hydrogen is a decrease in the cost of gas. A 90% decrease in the price of gas would see the price of hydrogen produced by SMR fall below $1.50 per kg. The CSIRO noted that CCS has a relatively low impact on the LCOH:

> This is primarily due to the fact that capture of CO2, typically the most expensive CCS component, is embedded in the hydrogen extraction and purification process. This scenario assumes that the production and storage plants are reasonably proximate and therefore the CO2 transport costs are absorbed into the overall storage cost of $10-40/t.[184]

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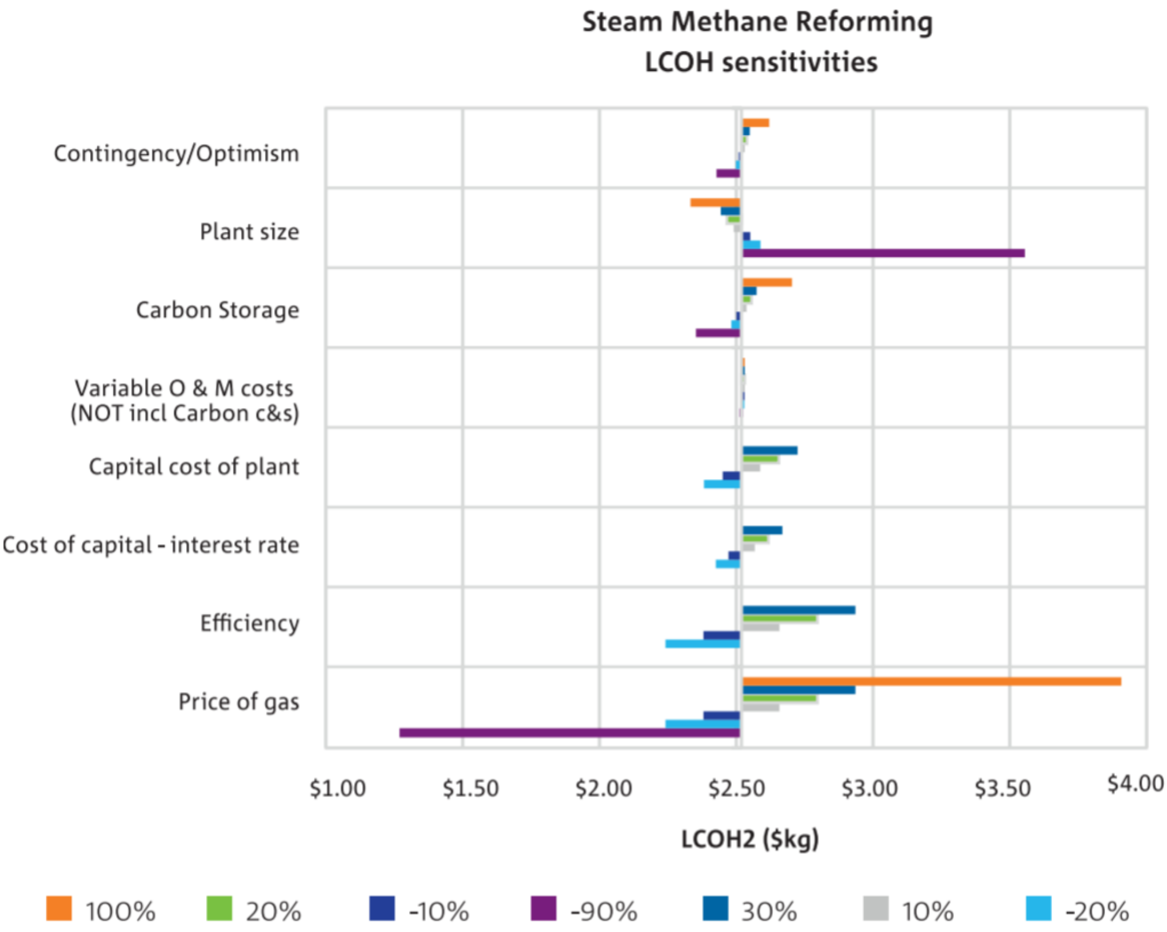
[183] Ibid, p 14.

[184] Ibid, p 20.

Figure 13: SMR LCOH sensitivities[185]



3.7 Storing hydrogen

Hydrogen gas has a low physical density (mass divided by volume) of 0.09 kg/m^3.[186] By way of comparison, air has a density of 1.3 kg/m^3.[187] Consequently, the energy carried by hydrogen by volume (volumetric energy density) is relatively low, at just 0.01 Megajoules per litre (MJ/L) under ambient conditions.[188]

The physical and volumetric energy density of hydrogen has to be increased in order for its storage and transportation to become both practical and economical. An increase in density can be achieved by:

- compressing hydrogen gas at high pressures in tanks, pipelines or underground;

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[185] Ibid, p 21.

[186] Evans P, *Density of Gases*, The Engineering Mindset, 26 July 2015.

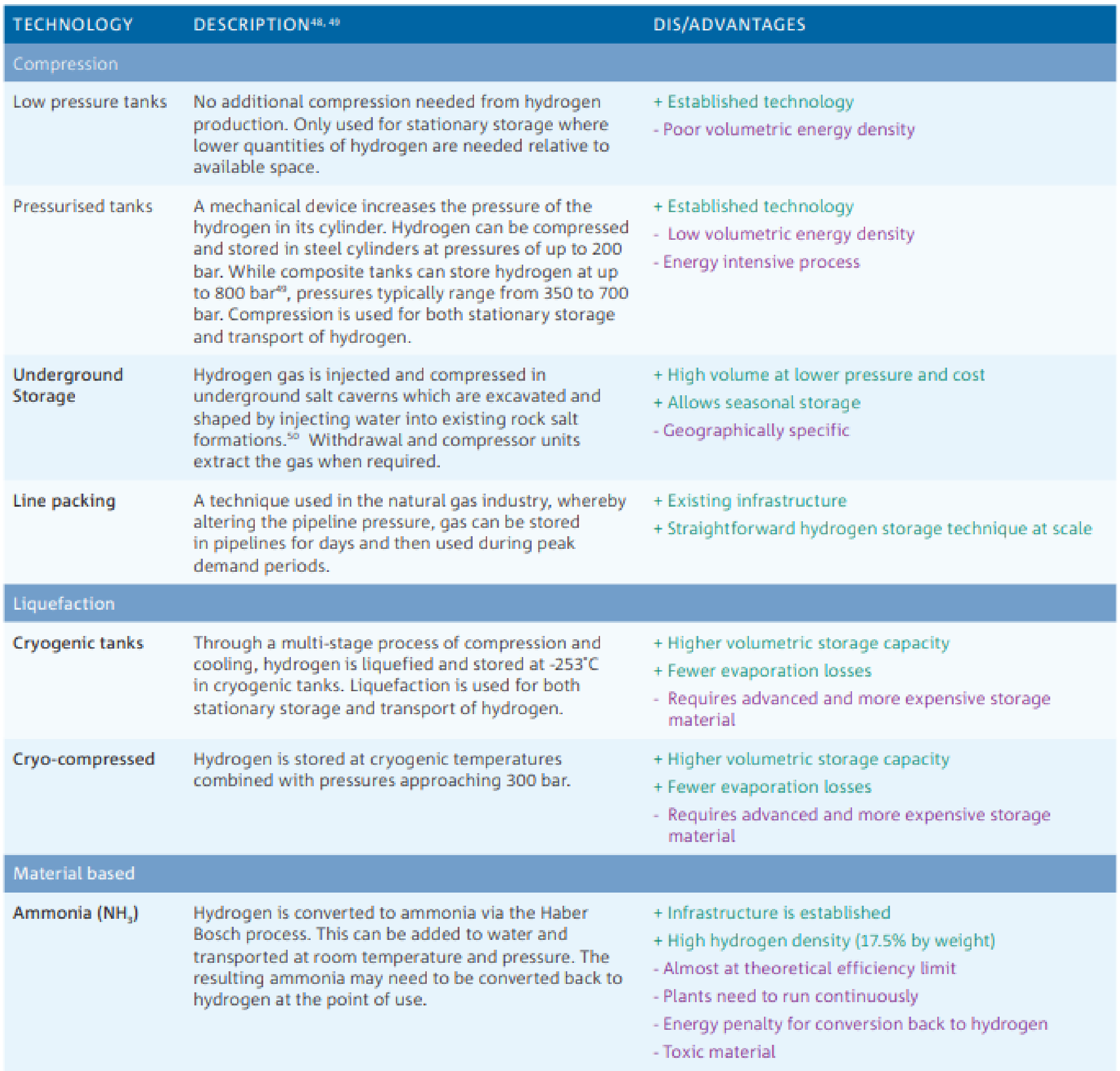
[187] Ibid.

[188] *Shell Hydrogen study: Energy of the Future? Sustainable Mobility through Fuel Cells and H_2*, Shell, 2017, p 21. See also: US Department of Energy, Office of Energy and Renewable Energy, *Hydrogen Storage* [website-accessed 26 February 2021]. In contrast, hydrogen carries a relatively high amount of energy by mass (Gravimetric energy density), at 120.1 MJ/kg.

- liquefying hydrogen through cryogenic processes;
- converting hydrogen into another chemical that contains hydrogen (such as Ammonia, NH_3); or
- attaching hydrogen to a solid substrate.[189]

Table 2 provides an overview of hydrogen storage technologies (excluding solid substrates).[190]

Table 2: Mature hydrogen storage technologies[191]



TECHNOLOGY	DESCRIPTION[48, 49]	DIS/ADVANTAGES
Compression		
Low pressure tanks	No additional compression needed from hydrogen production. Only used for stationary storage where lower quantities of hydrogen are needed relative to available space.	+ Established technology - Poor volumetric energy density
Pressurised tanks	A mechanical device increases the pressure of the hydrogen in its cylinder. Hydrogen can be compressed and stored in steel cylinders at pressures of up to 200 bar. While composite tanks can store hydrogen at up to 800 bar[49], pressures typically range from 350 to 700 bar. Compression is used for both stationary storage and transport of hydrogen.	+ Established technology - Low volumetric energy density - Energy intensive process
Underground Storage	Hydrogen gas is injected and compressed in underground salt caverns which are excavated and shaped by injecting water into existing rock salt formations.[50] Withdrawal and compressor units extract the gas when required.	+ High volume at lower pressure and cost + Allows seasonal storage - Geographically specific
Line packing	A technique used in the natural gas industry, whereby altering the pipeline pressure, gas can be stored in pipelines for days and then used during peak demand periods.	+ Existing infrastructure + Straightforward hydrogen storage technique at scale
Liquefaction		
Cryogenic tanks	Through a multi-stage process of compression and cooling, hydrogen is liquefied and stored at -253°C in cryogenic tanks. Liquefaction is used for both stationary storage and transport of hydrogen.	+ Higher volumetric storage capacity + Fewer evaporation losses - Requires advanced and more expensive storage material
Cryo-compressed	Hydrogen is stored at cryogenic temperatures combined with pressures approaching 300 bar.	+ Higher volumetric storage capacity + Fewer evaporation losses - Requires advanced and more expensive storage material
Material based		
Ammonia (NH_3)	Hydrogen is converted to ammonia via the Haber Bosch process. This can be added to water and transported at room temperature and pressure. The resulting ammonia may need to be converted back to hydrogen at the point of use.	+ Infrastructure is established + High hydrogen density (17.5% by weight) - Almost at theoretical efficiency limit - Plants need to run continuously - Energy penalty for conversion back to hydrogen - Toxic material

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[189] Hydrogen Strategy Group, Hydrogen for Australia's future: A briefing paper for the COAG Energy Council, August 2018, p 19.

[190] The use of solid substrates has more limited applications and is not considered further in this paper. See: Ibid, p 21.

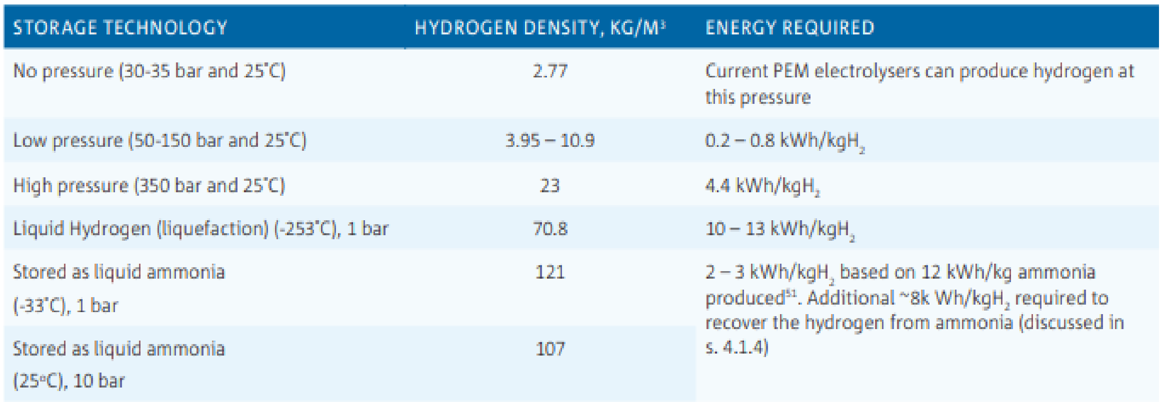
[191] Bruce S, Temminghoff M, Hayward J, Schmidt E, Munnings C, Palfreyman D, Hartley P, National Hydrogen Roadmap, CSIRO, 2018, p 27 (footnotes omitted).

The CSIRO stated that underground storage and line packing provide the most cost effective compression storage methods, but may not always be available options:

> Where large volumes of hydrogen storage are required (e.g. in the order of 210,000kg/day for 30 days), underground storage such as salt caverns (if available) are likely to be the most cost effective at approximately $0.20/kg (with pressure at 45 bar). Line packing also becomes more relevant at scale, particularly if hydrogen is already being distributed by pipe.[192]

As detailed in Table 3, converting hydrogen into a liquid is the most energy-intensive method of storage.[193]

Table 3: Hydrogen density and energy requirements[194]



STORAGE TECHNOLOGY	HYDROGEN DENSITY, KG/M³	ENERGY REQUIRED
No pressure (30-35 bar and 25˚C)	2.77	Current PEM electrolysers can produce hydrogen at this pressure
Low pressure (50-150 bar and 25˚C)	3.95 – 10.9	0.2 – 0.8 kWh/kgH_2
High pressure (350 bar and 25˚C)	23	4.4 kWh/kgH_2
Liquid Hydrogen (liquefaction) (-253˚C), 1 bar	70.8	10 – 13 kWh/kgH_2
Stored as liquid ammonia (-33˚C), 1 bar	121	2 – 3 kWh/kgH_2 based on 12 kWh/kg ammonia produced[51]. Additional ~8k Wh/kgH_2 required to recover the hydrogen from ammonia (discussed in s. 4.1.4)
Stored as liquid ammonia (25ºC), 10 bar	107	

The CSIRO expects that, by 2025, compressing hydrogen in tanks will cost approximately $0.3 per kg.[195] In contrast, liquefying hydrogen is expected to cost $1.59-1.94/kg".[196] In part, this reflects the greater energy expenditure required for liquefying hydrogen.[197] Hydrogen produced with ammonia as the product could be expected to cost $1.10-1.33kg by 2025.[198] Additional costs will be incurred in converting ammonia into hydrogen at the point of use.

3.8 Transporting hydrogen

Hydrogen can be transported by truck, rail or ship in either compressed gas or liquid forms.[199] Hydrogen can also be transported in pipelines as a compressed gas.[200] The CSIRO provides the following overview of hydrogen transportation methods:

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[192] Ibid, p 29.

[193] Ibid, p 28.

[194] Ibid, p 28.

[195] Ibid, p 29.

[196] Ibid, p 29.

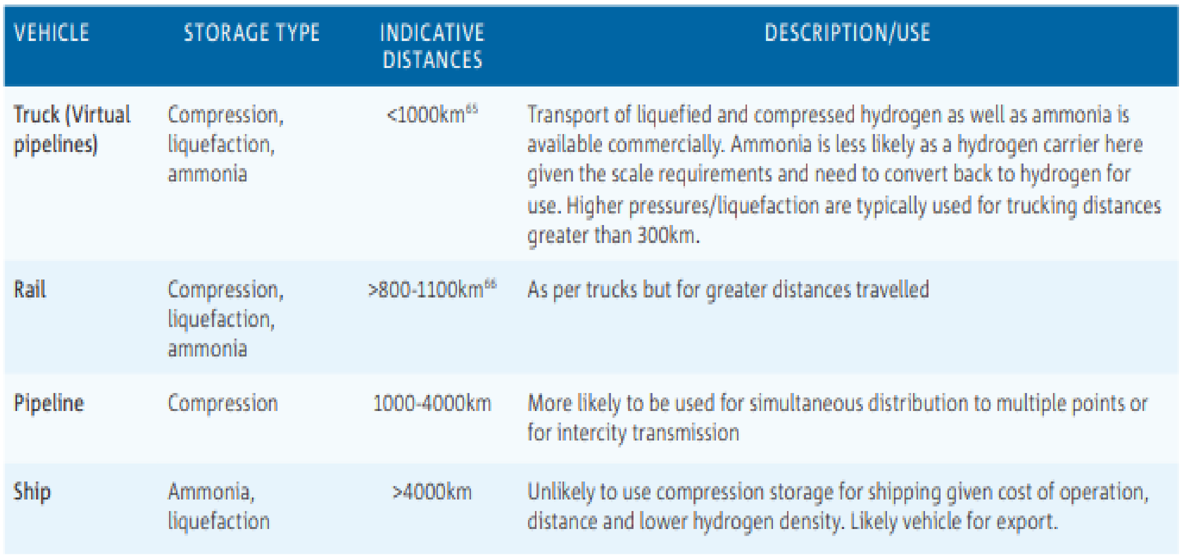
[197] Ibid, p 28. Liquefying hydrogen (-253°C at 1 bar) requires 10-13 kWh of energy per kg of hydrogen gas stored; whereas high pressure compression (350 bar and 25°C) requires 4.4 kWh of electricity per kg of hydrogen gas stored.

[198] Ibid, p 31.

[199] Ibid, p 31.

[200] US Department of Energy, Office of Energy Efficiency and Renewable Energy, _Hydrogen Pipelines_ [website-accessed 1 March 2021].

Table 4: Hydrogen transportation methods[201]



VEHICLE	STORAGE TYPE	INDICATIVE DISTANCES	DESCRIPTION/USE
Truck (Virtual pipelines)	Compression, liquefaction, ammonia	<1000km[65]	Transport of liquefied and compressed hydrogen as well as ammonia is available commercially. Ammonia is less likely as a hydrogen carrier here given the scale requirements and need to convert back to hydrogen for use. Higher pressures/liquefaction are typically used for trucking distances greater than 300km.
Rail	Compression, liquefaction, ammonia	>800-1100km[66]	As per trucks but for greater distances travelled
Pipeline	Compression	1000-4000km	More likely to be used for simultaneous distribution to multiple points or for intercity transmission
Ship	Ammonia, liquefaction	>4000km	Unlikely to use compression storage for shipping given cost of operation, distance and lower hydrogen density. Likely vehicle for export.

Pipelines

Hydrogen transportation by pipeline requires large initial capital expenditure. The pipelines extend across large distances and the materials used must cope with high operating pressures and the risk of embrittlement.[202] Once infrastructure has been developed, "[t]ransporting gaseous hydrogen via existing pipelines is a low-cost option for delivering large volumes of hydrogen."[203]

In February 2021, plans for Australia's first 100% hydrogen transmission pipeline were announced:

> Energy infrastructure business APA Group yesterday (23rd Feb) said it hopes to convert 43-kilometers of Parmelia Gas Pipeline in Western Australia into hydrogen-ready transmission pipeline…Valued at $3m, the project will consist of three phases, including: research and testing of the material for embrittlement in the laboratory, development of safe operation guidelines and full-scale testing on-site.[204]

By way of comparison, in 2016 there were more than 4,500 km of hydrogen pipelines worldwide.[205] The United States had most hydrogen pipelines (2,608 km), followed by Belgium (613 km), Germany 376 km and France (303 km).[206]

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[201] Bruce S, Temminghoff M, Hayward J, Schmidt E, Munnings C, Palfreyman D, Hartley P, National Hydrogen Roadmap, CSIRO, 2018, p 32.

[202] Ibid, p 33.

[203] US Department of Energy, Office of Energy Efficiency and Renewable Energy, Hydrogen Pipelines [website-accessed 1 March 2021].

[204] Burgess M, Australia's first 100% hydrogen pipeline could be a near-term reality, *H2 View*, 24 February 2021.

[205] Shell Hydrogen study: Energy of the Future? Sustainable Mobility through Fuel Cells and H_2, Shell, 2017, p 25.

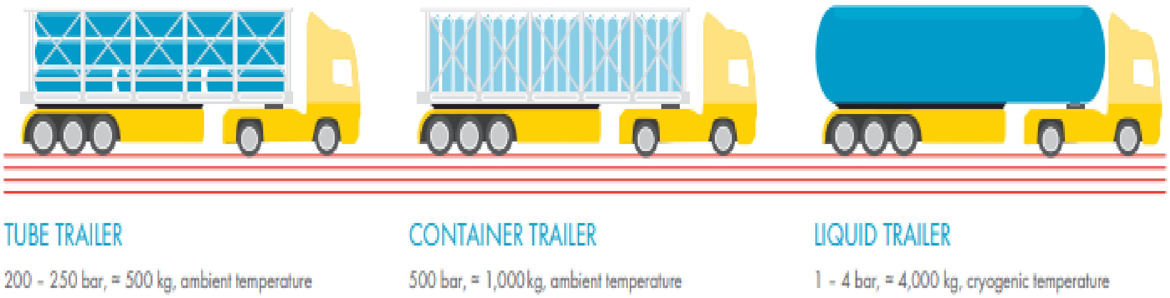
[206] Ibid, p 26.

Trucks, rail and ships

Trucks, rail and ships can transport compressed hydrogen gas or liquid hydrogen. As is the case with other cargo, distance and cargo quantity are the two factors that will determine the mode of hydrogen transport. Trucks will likely be used for short distances and smaller cargo quantities; rail for intermediate distances and intermediate cargo quantities; and shipping for large distances and large quantities of hydrogen.

Cargo quantity is also relevant to whether hydrogen is transported as a compressed gas or as a liquid. For instance, as Figure 14 indicates, at least four times more hydrogen can be transported by truck as a liquid (4,000 kg) compared to a relatively highly compressed gas (1,00kg).[207]

Figure 14: Hydrogen road transport capacities[208]



Emissions and costs from transportation

Some modes of hydrogen transportation, such as diesel ship engines, produce high direct emissions. In contrast, trucks or trains powered by fuel cells produce no direct emissions. The mode of transportation can therefore affect the total emissions produced from the use of hydrogen.

In December 2019 it was announced that a Japanese ship, the *Suiso Frontier*, had been built to carry liquid hydrogen from Victoria, Australia, to Kobe, Japan.[209] Initially, three tonnes of hydrogen gas will be trucked 150 km from the La Trobe Valley to the port of Hastings, and transported to Japan using the *Suiso Frontier*'s diesel-electric motors.[210] It has been suggested in the media that such commercial arrangements essentially outsources emissions to Australia, while enabling the use of low-emission fuel in Japan.[211]

As set out in Table 5, due to the larger cargo capacity of ships, the increased density of liquids and the greater distances travelled, shipping liquefied hydrogen offers the lowest hydrogen transportation cost per tonne-kilometre

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[207] Ibid, p 25.

[208] Ibid, p 25.

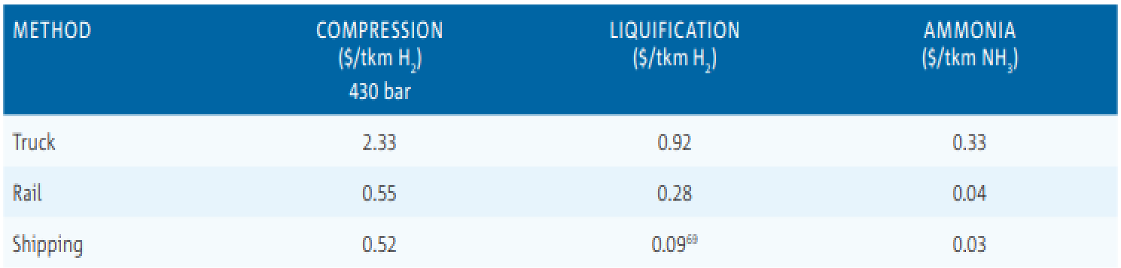
[209] Blain L, Kawasaki launches the world's first liquid hydrogen transport ship, *New Atlas*, 15 December 2019. The *Suiso Frontier* is a 116 metre long ship that will be fitted with a vacuum-insulated double-shelled tank capable of holding 1,250 cubic metres of liquid hydrogen at a temperature of -253°C.

[210] Ibid.

[211] Ibid.

(\$0.09/tkmH_2).[212] Shipping ammonia offers even lower costs (\$0.03/tkm NH_3) but an additional cost arises from the need convert the ammonia into hydrogen at the point of use.[213]

Table 5 Transport costs[214]



METHOD	COMPRESSION (\$/tkm H_2) 430 bar	LIQUIFICATION (\$/tkm H_2)	AMMONIA (\$/tkm NH_3)
Truck	2.33	0.92	0.33
Rail	0.55	0.28	0.04
Shipping	0.52	0.09[69]	0.03

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[212] Bruce S, Temminghoff M, Hayward J, Schmidt E, Munnings C, Palfreyman D, Hartley P, *National Hydrogen Roadmap*, CSIRO, 2018, p 32. A tonne-kilometre (tkm) represents the “transport of one tonne of goods (including packaging and tare weights of intermodal transport units) by a given transport mode … over a distance of one kilometre.”: *Eurostat*, Glossary: Tonne-kilometre (tkm), 14 June 2013 [website-accessed 1 March 2021].

[213] Ibid, p 30 and 32.

[214] Ibid, p 32.

4. WHAT IS THE CURRENT STATE AND POTENTIAL OF HYDROGEN GLOBALLY?

4.1 Interest and state of industry

In its June 2019 report, the International Energy Agency (IEA) noted that hydrogen has seen several waves of interest in recent history – none of which fully translated into rising, sustainable investment.[215] The report identified four reasons why this time might be different:

1. Greater attention to the deep emissions reductions that hydrogen can help deliver, especially in hard-to-abate sectors including shipping, steel production, chemicals manufacture, and long-distance transport;

2. Hydrogen is seen as able to contribute to a wider range of policy objectives including energy security, local air pollution, economic development and energy access;

3. Hydrogen can help with the matching of variable energy supply and demand alongside alternatives such as pumped-storage hydropower, batteries and grid upgrades; and

4. Hydrogen can benefit from positive experiences of developing other clean energy technologies that have benefited from government support systems and policies: e.g. solar PV and wind turbines.[216]

The IEA stated that hydrogen was supported by various industry sectors "and the governments of most of the world's largest economies".[217] It observed:

> The number of countries with polices that directly support investment in hydrogen technologies is increasing, along with the number of sectors they target. By mid-2019 the total number of targets, mandates and policy incentives in place globally to directly support hydrogen was around 50. Those that are sector-specific cover six main areas, with transport being by far the largest. Among the Group of Twenty (G20) and the European Union, 11 have such policies in place and 9 have national roadmaps for hydrogen energy...Over the past few years, global spending on hydrogen energy research, development and demonstration (RD&D) by national governments has risen, although it remains lower than the 2008 peak. [218]

Examples of countries that have developed a hydrogen strategy are Japan (2017), European Union (2020), United States (2020), and Canada (2020).[219]

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[215] IEA, The Future of Hydrogen: Seizing today's opportunities, June 2019, p 19.

[216] Ibid, p 23-27.

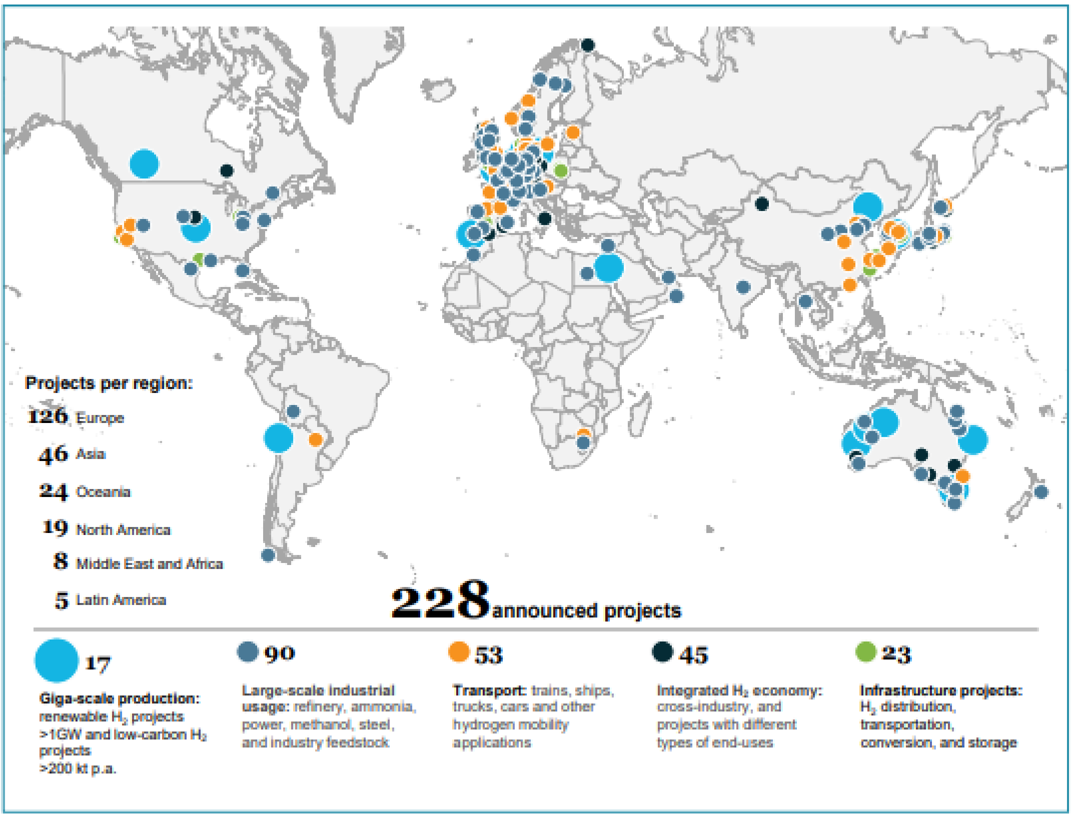
[217] Ibid, p 19 (see also p 20-22).

[218] Ibid, p 20.

[219] Japan Ministerial Council on Renewable Energy, Basic Hydrogen Strategy, December 2017; European Commission, A hydrogen strategy for a climate-neutral Europe, July 2020; US Department of Energy, National Hydrogen Strategy, July 2020; Government of Canada, Hydrogen Strategy for Canada, December 2020. For other countries, see IRENA, Green

A 2021 report by the Hydrogen Council estimated that globally governments have pledged more than USD 70 billion to support the hydrogen industry.[220] It also estimated there were USD 80 billion of “mature” investments in hydrogen projects until 2030.[221] The report identified 228 hydrogen projects around the world (Figure 15).[222] Europe had the largest number of projects (128), followed by Asia (46), and Oceania (24). The most common applications were large-scale industrial usage (90), followed by transport (53). There were also 17 Gigawatt-scale production projects with the biggest in Europe, Australia, the Middle East and Chile.[223]

Figure 15: Global hydrogen projects across the value chain[224]



4.2 Potential hydrogen demand

The IEA’s report *Energy Technology Perspectives 2020* analysed technology options to examine what would need to happen for the world to reach net zero emissions by around 2070 (the Sustainable Development Scenario, (SDS)).[225] It

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Hydrogen: A Guide to Policy Making, 2020, p 22 (Fig 2.2).

[220] Hydrogen Council, Hydrogen Insights: A perspective on hydrogen investment, market development and cost competitiveness - February 2021, January 2021, p iv.

[221] Ibid, p iv. Mature means investment is in the planning stage, has passed a final investment decision, or relates to a project under construction, already commissioned or operational.

[222] Ibid, p iv.

[223] Ibid, p 6. Gigawatt scale means more than 1 GW for renewable hydrogen and over 200,000 tons a year for low-carbon hydrogen.

[224] Ibid, p 6.

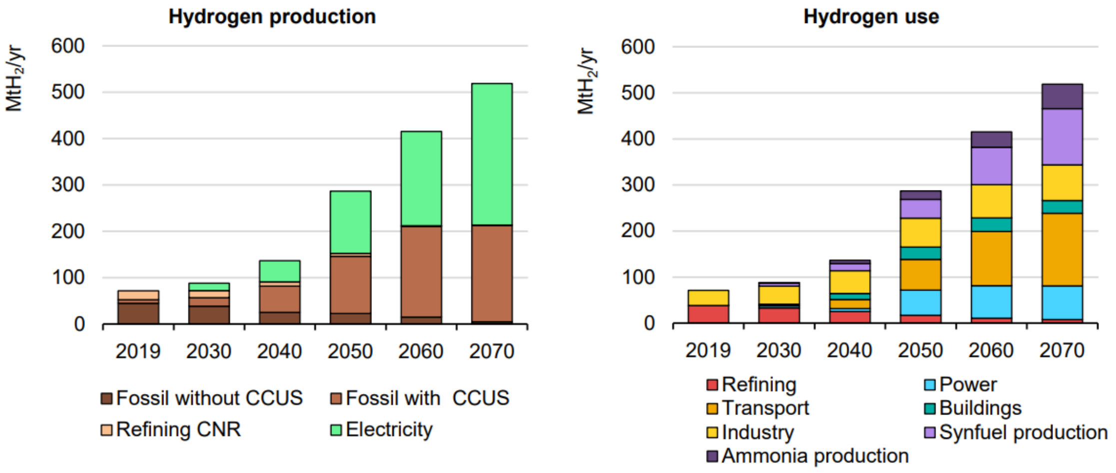
[225] IEA, Energy Technology Perspectives 2020, 2020.

found that low-carbon hydrogen (hydrogen produced from fossil fuels in combination with carbon capture and storage, or through water electrolysis from low-carbon electricity) would be an important part of the energy mix:

> Global hydrogen production grows by a factor of seven to 520 Mt in 2070. Hydrogen use expands to all sectors and reaches a share of 13% in final energy demand in 2070. The development of technologies at the demonstration and prototype stage today leads to hydrogen and hydrogen-based fuels becoming important for the decarbonisation of heavy trucks, aviation and shipping as well as for the production of chemicals and steel.[226]

The report presented the following charts on potential hydrogen production by fuel type, and hydrogen demand by sector, up to 2070.

Figure 16: Global hydrogen production by fuel and hydrogen demand by sector in the Sustainable Development Scenario, 2019-70[227]



IEA 2020. All rights reserved

Notes: CCUS = carbon capture, utilisation and storage. *Refining CNR* refers to the production of hydrogen as a by-product of catalytic naphtha reforming in refineries. *Ammonia production* refers to the fuel production for the shipping sector. Hydrogen use for industrial ammonia production is included within the industry use.

The report also outlined a Faster Innovation Case, which explored the technology implications of reaching net-zero emissions by 2050. The IEA found that demand for hydrogen, including for hydrogen-derived synthetic fuels such as ammonia, would increase by around 55% in the Faster Innovation Case in 2050, relative to the SDS. Around 60% of the 2050 demand for hydrogen would come from the transport and industry sectors.[228] More than 95% of the hydrogen production in the Faster Innovation Case in 2050 would be through electrolysis or would be linked to carbon, capture and storage.[229]

The International Renewable Energy Agency's (IRENA's) 2020 report *Global Renewables Outlook: Energy Transformation 2050* explored a Transforming

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[226] Ibid, p 66.

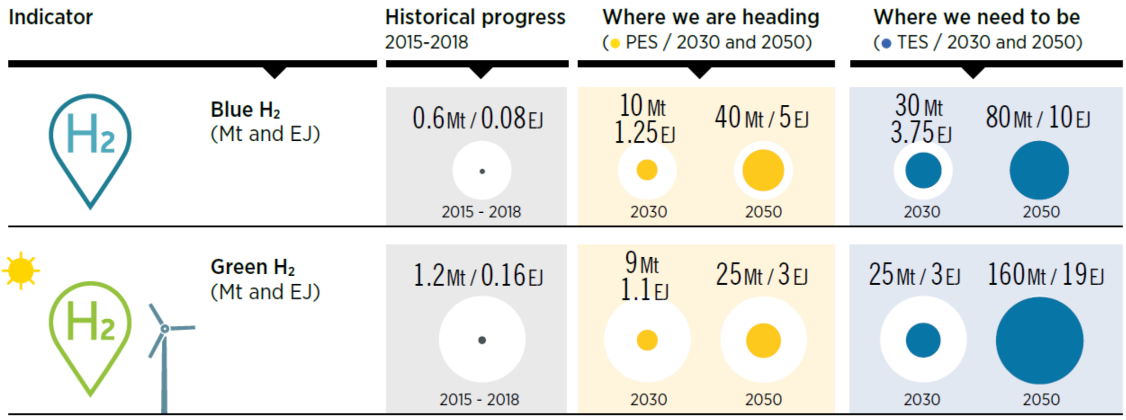
[227] Ibid, p 110 (Fig. 2.15).

[228] Ibid, p 351.

[229] See also IEA, Net Zero by 2050: A Roadmap for the Global Energy Sector, 2021, Ch 2.5.5.

Energy Scenario (TES), in which energy-related CO_2 emissions would fall by 70% by 2050, keeping the temperature rise well below 2^0C in line with the Paris Agreement.[230] Clean and low-carbon hydrogen would be a significant part of the energy mix by 2050. As shown in Figure 17, there would be 240 Mt of clean and low-carbon hydrogen produced annually by 2050 (including 160 Mt of green hydrogen).[231] Clean and low-carbon hydrogen would provide around 7-8% of global final energy.[232] Clean and low-carbon hydrogen could play an even larger role in a scenario of net zero emissions by 2050-2060 (Deeper Decarbonisation Perspective) – specifically in the industry, transport and building sectors.[233]

Figure 17: Clean hydrogen production scenarios in 2030 and 2050[234]



4.3 Barriers and policy recommendations

IRENA's 2020 *Green Hydrogen: A guide to policy making* identified five key barriers for the uptake of green hydrogen:

1. *High production costs* – Green hydrogen produced using electricity from an average variable renewable energy plant in 2019 would be two to three times more expensive than grey hydrogen. In addition, adopting green hydrogen technologies for end uses can be expensive. Vehicles with fuel cells and hydrogen tanks cost at least 1.5 to 2 times more than their fossil fuel counterparts.

2. *Lack of dedicated infrastructure* – To date, hydrogen has been produced close to where it is used, with limited dedicated transport infrastructure. There are only about 5,000 kilometres of hydrogen transmission pipelines around the world, compared with more than 3 million for natural gas. There are 470 hydrogen refuelling stations globally compared with more than

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[230] IRENA, Global Renewables Outlook: Energy Transformation 2050, 2020.

[231] Ibid, p 31.

[232] Ibid, p 182.

[233] Ibid, p 182. The report did not state how much hydrogen would be produced under this scenario.

[234] PES = Planned Energy Scenario (based on governments' current energy plans and other planned targets and policies (as of 2019).

200,000 petrol and diesel refuelling stations in the US and EU.

3. *Energy losses at each stage of the value chain* – green hydrogen incurs significant energy losses at each stage of the value chain. About 30-35% of the energy used to produce hydrogen through electrolysis is lost. In addition, the conversion of hydrogen to other carriers (such as ammonia) can result in 23-25% energy loss. The higher the energy losses, the more renewable electricity is needed to produce green hydrogen.

4. *Lack of value recognition* – There is no green hydrogen market, no green steel, no green shipping fuel and no valuation of the lower carbon emissions that green hydrogen can deliver. There are no internationally recognised ways of differentiating green from grey hydrogen.

5. *Need to ensure sustainability* – Electricity can be supplied from a renewable energy plant directly connected to the electrolyser, from the grid, or from a mix of the two. Grid-connected electrolysers can produce for more hours, reducing the cost of hydrogen. However, they may include electricity produced from fossil fuel plants, so any CO_2 emissions will have to be considered in evaluating the sustainability of hydrogen.[235]

IRENA's policy guide suggested that a policy approach should have four pillars:

1. National hydrogen strategies;
2. Policy priority setting;
3. A guarantee of origin scheme; and
4. Governance system and enabling policies.

With respect to policy priority setting, the policy guide noted that hydrogen is not a full substitute for fossil fuels:

> Despite the great promise of green hydrogen and its suitability to replace fossil gases, it is not a complete substitute for fossil fuels. Instead, it is just one of several possible decarbonisation alternatives that should be carefully weighed when setting priorities.[236]

In addition, it stressed the need for policy-makers to identify the highest value applications of green hydrogen:

> Policy makers should identify the highest-value applications for a given amount of green hydrogen, in order to focus their policy efforts where they could provide the most immediate advantages and enable economies of scale.[237]

With respect to a guarantee of origin scheme, the policy guide stated that a certification system is needed that allows end users and governments to know the origin and quality of the hydrogen.[238]

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[235] IRENA, Green Hydrogen: A Guide to Policy Making, 2020, p 13.

[236] Ibid, p 26.

[237] Ibid, p 27.

[238] Ibid, p 29.

Some of the general enabling policy suggestions in relation to pillar 4 included:

- Implementing measures to maintain industrial competitiveness and create export opportunities;
- Identifying economic growth and job creation opportunities;
- Building or repurposing infrastructure;
- Ensuring access to finance;
- Setting research priorities; and
- Implementing carbon pricing.[239]

The guide also made policy recommendations in relation to certain elements of the hydrogen value chain including electrolysis, infrastructure, and the industry, aviation, and shipping sectors.[240] For example, setting targets for electrolyser capacity as has been done in the European Union.[241]

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[239] Ibid, p 31-33.

[240] Ibid, Ch 3.

[241] Ibid, p 37. For further discussion of barriers and policy ideas, see IEA, *The Future of Hydrogen: Seizing today's opportunities*, June 2019.

5. WHAT IS THE POTENTIAL OF HYDROGEN IN AUSTRALIA?

5.1 Opportunities

A 2018 briefing paper by the Hydrogen Strategy Group identified three key opportunities that clean and low-carbon hydrogen offers for Australia:

1. Hydrogen for export – due to its potential for decarbonising energy systems, many countries around the world are investing to develop hydrogen energy value chains;

2. Hydrogen for the domestic economy – this could include replacing natural gas, using hydrogen for high-temperature industrial processes such as making alumina, and using it for transport; and

3. Hydrogen for energy system resilience – an industry producing clean hydrogen for export and domestic use can support electricity grid security and reliability.[242]

In terms of exports, the briefing paper stated:

> Access to the Japanese energy market is the prize for the nations now bidding to be global hydrogen suppliers. Japan, the world's third-largest economy by GDP, currently imports 94% of its energy as coal, oil and natural gas. Japan does not have domestic access to low emissions resources at the scale required to replace these, and so its comprehensive multi-decade plan to transition to hydrogen spans both the take-up of hydrogen for domestic use and outreach to international partners as hydrogen producers and potential hydrogen technology customers. Similarly, South Korea imports 81% of its energy and has signalled its strong commitment to the uptake of hydrogen.[243]

A 2020 KPMG report discussed the opportunities for NSW:

> The development of a hydrogen industry is a significant long-term opportunity for NSW. In addition to the economic benefits of new industry formation, it has the potential to enable many downstream industry applications, including transport, agriculture and advanced manufacturing. However, the production, transport and storage infrastructure required for green hydrogen to be scalable and cost competitive is not expected until at least the medium term.[244]

5.2 Competitive advantages

Australia is seen to have significant competitive advantages for developing a substantial hydrogen export industry.[245] It has the natural resources needed to make clean and low-carbon hydrogen, a track record in building large-scale

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[242] Hydrogen Strategy Group, *Hydrogen for Australia's future: A briefing paper for the COAG Energy Council*, August 2018, p 6-7.

[243] Ibid, p 2.

[244] KPMG, *A Clean Energy Superpower: Industry Opportunities Enabled by Cheap, Clean and Reliable Electricity*, 23 September 2020, Executive Summary.

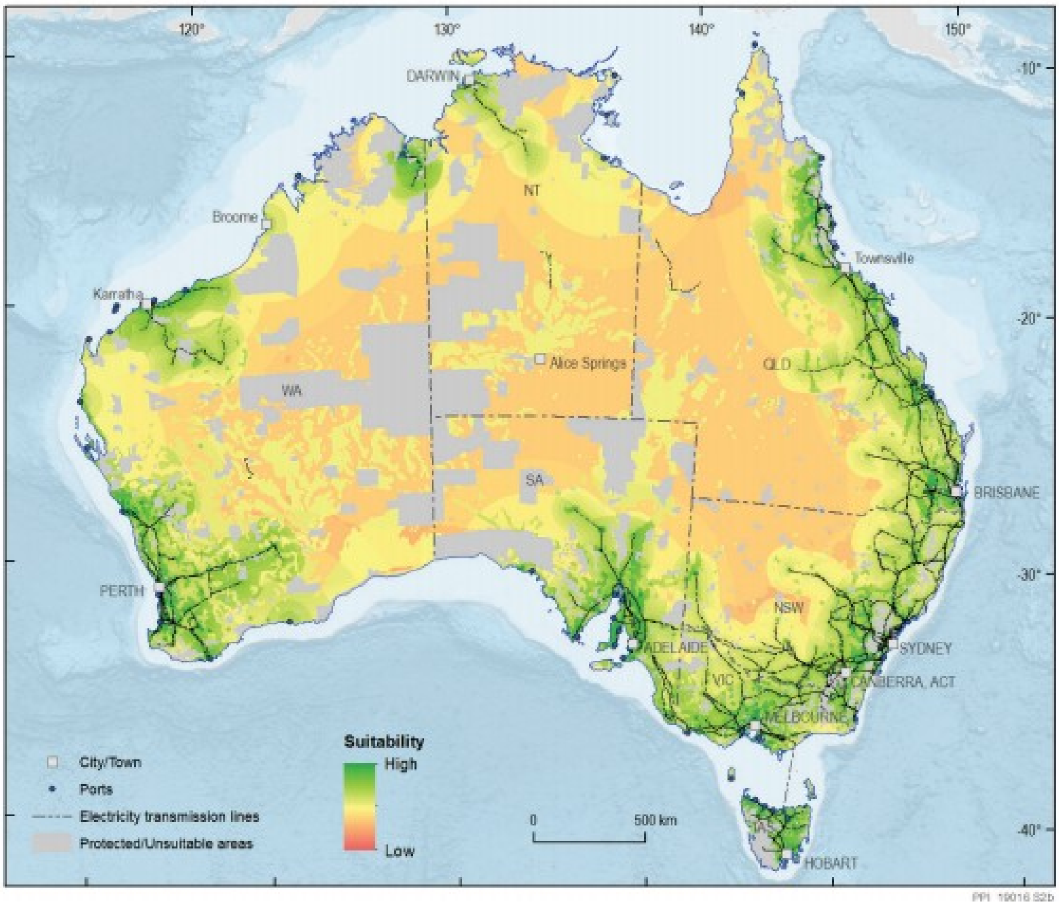
[245] COAG Energy Council, *Australia's National Hydrogen Strategy*, November 2019, p 9.

energy industries, and an established reputation as a trusted energy supplier to Asia.[246]

A 2019 report by GeoScience Australia found that “Australia has vast physical resources that could support a large-scale hydrogen industry”.[247] It noted that most coastal areas are favourable for hydrogen production from electrolysis.[248] This is because of “the unlimited supply of desalinated seawater and the availability of electrical and port infrastructure”. The report also stated that Australia “has extensive fossil fuel resources that can be used with [carbon capture and storage] to produce hydrogen with low carbon emissions”.

The report presented maps showing potential for hydrogen production based on access to resources and infrastructure. Five scenarios were modelled: three for renewable hydrogen and two for fossil fuel-produced hydrogen with carbon capture and storage. For example, the map below is for Scenario 2: Renewable hydrogen – coastal production, constrained by existing infrastructure.

Figure 18: Heat map for scenario 2: Renewable hydrogen – Coastal production, constrained by existing infrastructure[249]



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[246] Ibid, p 9.

[247] GeoScience Australia, *Prospective hydrogen production regions of Australia*, 2019, p vii.

[248] Ibid, p vii.

[249] Ibid, p 8. As outlined on p 4 of the report, this scenario requires that renewable power sources for future hydrogen production are located close to a connected grid, which can power hydrogen

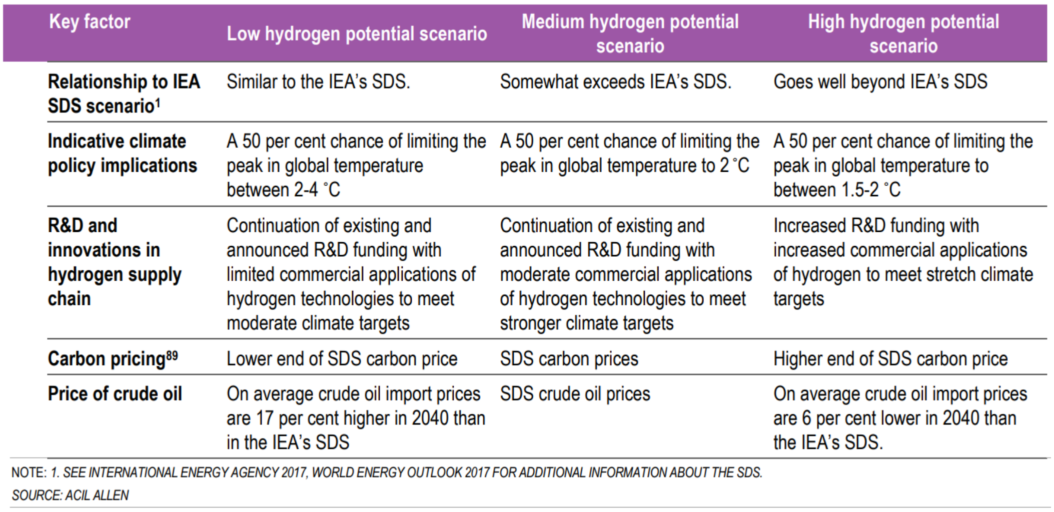
The 2020 KPMG report stated that "NSW is well placed to leverage several strengths in supporting the potential for a new local hydrogen industry and meet expected growing domestic and international demand".[250] It identified the following four strengths and competitive advantages:

1. NSW is abundant with renewable energy sources, such as wind and solar, and is one of the largest investors nationally in renewable energy;
2. Hydrogen can be blended into existing natural gas networks at 5-15 per cent concentrations;
3. Current ports and transport links can be leveraged as part of a future hydrogen fuel transport network; and
4. Many universities in NSW have research and development programs focusing on hydrogen production, storage and utilisation technologies.

5.3 Economic benefits

A 2018 report by ACIL Allen estimated the economic contribution (direct and indirect impacts) of Australian clean hydrogen production for export under three international demand scenarios (Table 6).[251] The scenarios were based around the Sustainable Development Scenario (SDS) in the International Energy Agency's *World Energy Outlook 2017*.[252] The scenarios reflect different assumptions about climate change, adoption of hydrogen technologies, and alternative fuel prices in sectors where hydrogen might enter the market.[253]

Table 6: International hydrogen demand scenarios



Key factor	Low hydrogen potential scenario	Medium hydrogen potential scenario	High hydrogen potential scenario
Relationship to IEA SDS scenario[1]	Similar to the IEA's SDS.	Somewhat exceeds IEA's SDS.	Goes well beyond IEA's SDS
Indicative climate policy implications	A 50 per cent chance of limiting the peak in global temperature between 2-4 °C	A 50 per cent chance of limiting the peak in global temperature to 2 °C	A 50 per cent chance of limiting the peak in global temperature to between 1.5-2 °C
R&D and innovations in hydrogen supply chain	Continuation of existing and announced R&D funding with limited commercial applications of hydrogen technologies to meet moderate climate targets	Continuation of existing and announced R&D funding with moderate commercial applications of hydrogen technologies to meet stronger climate targets	Increased R&D funding with increased commercial applications of hydrogen to meet stretch climate targets
Carbon pricing[89]	Lower end of SDS carbon price	SDS carbon prices	Higher end of SDS carbon price
Price of crude oil	On average crude oil import prices are 17 per cent higher in 2040 than in the IEA's SDS	SDS crude oil prices	On average crude oil import prices are 6 per cent lower in 2040 than the IEA's SDS.

NOTE: 1. *SEE INTERNATIONAL ENERGY AGENCY 2017, WORLD ENERGY OUTLOOK 2017 FOR ADDITIONAL INFORMATION ABOUT THE SDS.*

SOURCE: *ACIL ALLEN*

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production at the coast. Water availability is not considered a constraint provided hydrogen production is in proximity to the coast.

[250] KPMG, A Clean Energy Superpower Industry Opportunities Enabled by Cheap, Clean and Reliable Electricity, 23 September 2020, Ch 3, p 11.

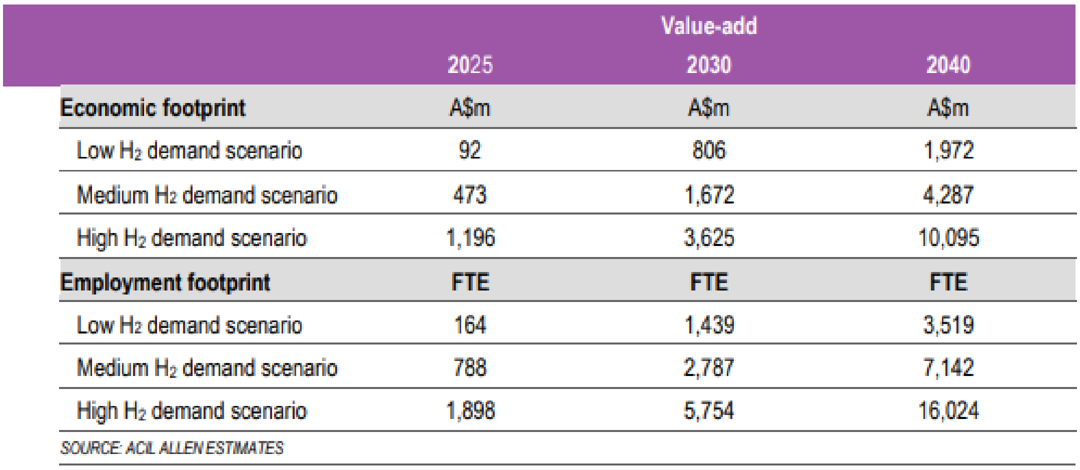
[251] ACIL Allen, Opportunities for Australia from Hydrogen Exports, August 2018. 'Clean' hydrogen is defined in the report to includes zero emissions hydrogen produced from renewable energy via electrolysis, and low emissions hydrogen produced from fossil fuels, such as through steam methane reforming or coal gasification, in conjunction with carbon capture and storage.

[252] International Energy Agency, *World Energy Outlook 2017,* 2017.

[253] ACIL Allen, Opportunities for Australia from Hydrogen Exports, August 2018, p ii.

The results of the economic analysis are shown in Table 7. In the medium hydrogen demand scenario, the report estimated that by 2030 clean hydrogen exports would contribute $1.7 billion to the Australian economy and create 2,787 jobs; and that, by 2040, clean hydrogen exports would contribute $4.3 billion to the Australian economy and generate 7,142 jobs.

Table 7: Total Economic Contribution of Hydrogen Production for Export[254]



	Value-add		
	2025	2030	2040
Economic footprint	A$m	A$m	A$m
Low H_2 demand scenario	92	806	1,972
Medium H_2 demand scenario	473	1,672	4,287
High H_2 demand scenario	1,196	3,625	10,095
Employment footprint	**FTE**	**FTE**	**FTE**
Low H_2 demand scenario	164	1,439	3,519
Medium H_2 demand scenario	788	2,787	7,142
High H_2 demand scenario	1,898	5,754	16,024

SOURCE: ACIL ALLEN ESTIMATES

Key estimates of international hydrogen demand and Australia's hydrogen exports that underpinned the economic analysis were as follows.[255] In the low hydrogen demand scenario, by 2040 international hydrogen demand is 15.8 Mt, and Australia's hydrogen exports are 0.6 Mt. In the medium demand scenario, by 2040 international demand is 34.8 Mt, and Australia's exports are 1.4 Mt. In the high demand scenario, by 2040 international demand was 82.1 Mt, and Australian's exports are 3.2 Mt.

A November 2019 report by Deloitte modelled the economic impacts of a clean hydrogen industry in Australia under three international demand scenarios:

1) Business as usual – global market for hydrogen expands gradually;
2) Targeted deployment of hydrogen – countries adopt a targeted approach which aims to maximise economic value and benefits for effort in the deployment of hydrogen; and
3) Hydrogen as the energy of the future – rapid expansion in international demand.[256]

In the economic analysis, the targeted deployment and hydrogen of the future scenarios were compared with the business as usual scenario. The results are shown in the **charts** below. Under the targeted deployment scenario, by 2050, the Australian hydrogen industry is worth $11 billion more in Gross Domestic

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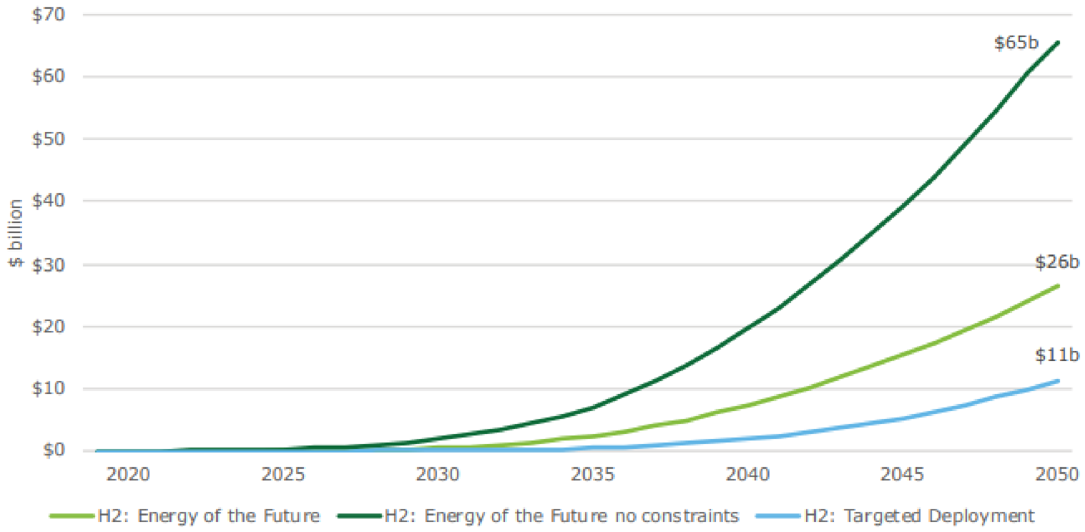
[254] Ibid, p 53 (Table 5.4).

[255] Ibid, p 27 (Table 3.3), and p 49 (Table 4.11).

[256] Deloitte, *Australian and Global Hydrogen Demand Growth Scenario Analysis*, November 2019. Clean hydrogen is defined in the report to include zero emissions hydrogen produced from renewable energy and low emissions hydrogen produced from fossil fuels.

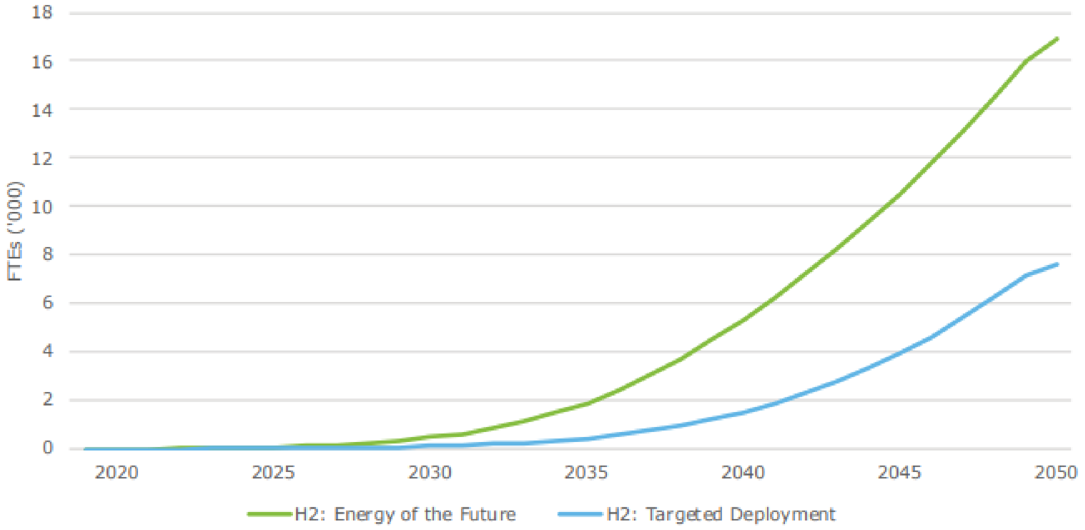
Product (GDP) and there are an additional 7,600 jobs. Under the Energy of the Future scenario, GDP is projected to be around $26 billion higher by 2050; and employment is estimated to be 16,700 jobs higher. Note that the modelling did not consider a fourth scenario identified in the report, where there is rapid technological development in electrification leading to much lower demand for hydrogen than the business as usual scenario.

Figure 19 – Projected deviation in Australian GDP from Business as usual scenario, selected policy scenarios[257]



Source: DAE-RGEM

Figure 20 - Projected deviation in employment from Business as usual scenario, selected policy scenarios[258]



Source: DAE-RGEM

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[257] Ibid, p 88 (Figure 6.35). The report noted that "Relaxing capital and labour constraints in the Energy of the future (without constraints) scenario is an extreme assumption" (p 87).

[258] Ibid, p 92 (Figure 6.39).

Key estimates of international hydrogen demand and Australian production that underpinned the analysis were as follows.[259] In the Targeted Deployment scenario, by 2050 global demand is around 150 Mt, and Australian production is around 8 Mt. In the Energy of the Future scenario, by 2050 global hydrogen demand is 304 Mt and Australian hydrogen production is around 20 Mt.

5.4 Barriers

The 2019 Deloitte report identified three key challenges for market activation:

- The ability of hydrogen to replace other technologies and processes will be dependent on its cost effectiveness;
- Policy and technology uncertainty is another challenge and requires government and policy support; and
- Regulations, standards and acceptance will also be a hurdle for the industry as they are generally currently in their infancy.[260]

The 2020 KPMG report outlined several significant long-term barriers to "reaching end-users to adopt hydrogen as a source of energy or feedstock at scale".[261] These included:

- Without more abundant and cheaper renewable energy, clean hydrogen may continue to be too expensive for end-users to adopt;
- Hydrogen production through electrolysis is water intensive, placing additional demand on water supply;
- Hydrogen production, storage, transportation and use will require the development of a range of specialty equipment, processes and skills;
- Hydrogen production has a high marginal cost, discouraging its accelerated uptake and industry specific compatible technologies;
- Existing fuel transport infrastructure will require retrofitting or upgrades to equipment to ensure compatibility and safe use with hydrogen;
- The significant costs to liquefy or convert hydrogen it to a carrier, such as ammonia, in order to export it; and
- The cost of upgrading or obtaining new hydrogen fuel compatible appliances, technology or machinery.[262]

5.5 Policy recommendations

The CSIRO's 2018 *National Hydrogen Roadmap* provided a blueprint for the development of the industry, as summarised in the Table 8.

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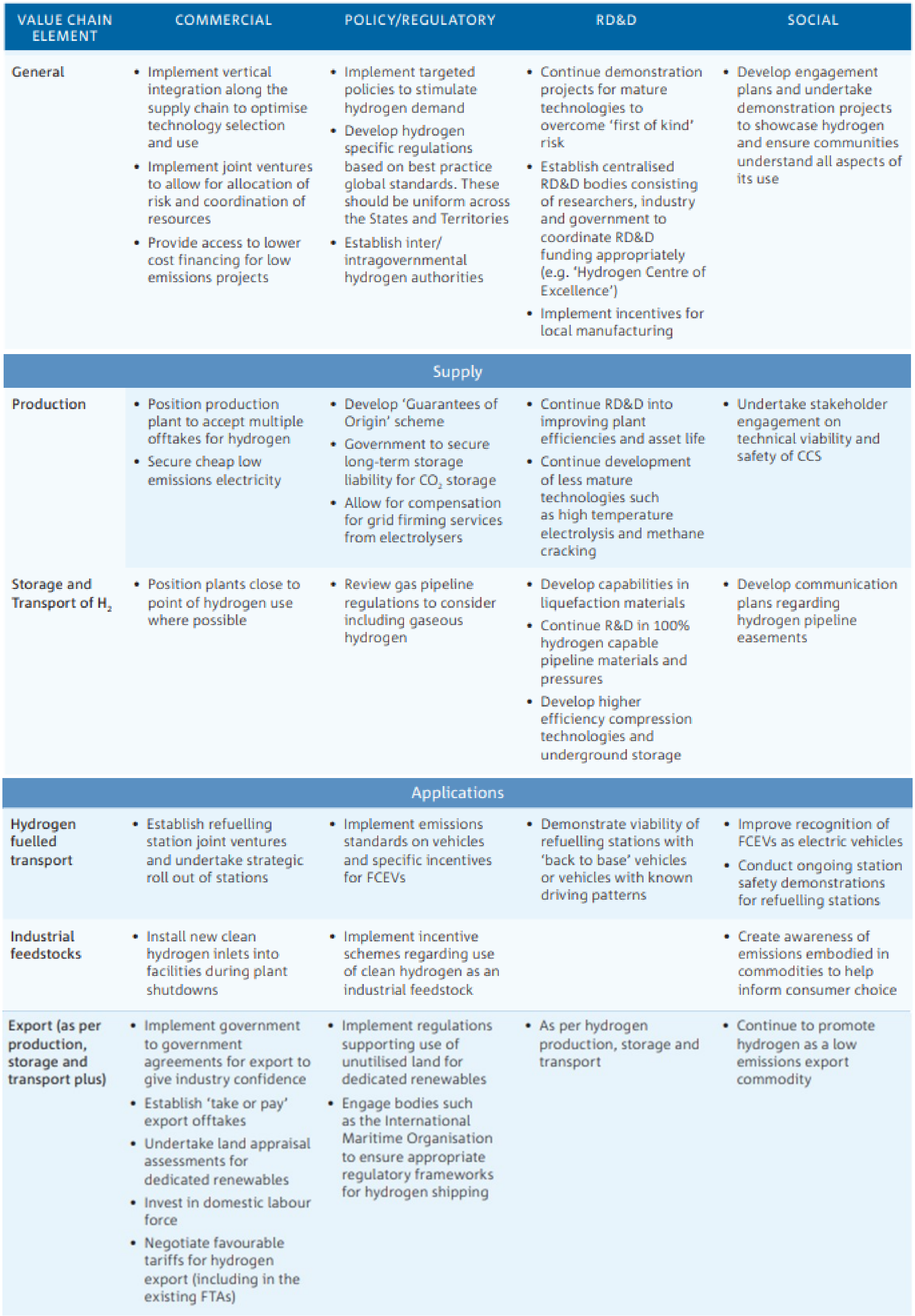
[259] Ibid, p 69, (Figure 6.1), p 78 (Figure 6.18).

[260] Ibid, p 34-35.

[261] KPMG, *A Clean Energy Superpower: Industry Opportunities Enabled by Cheap, Clean and Reliable Electricity*, 23 September 2020, p 12.

[262] Ibid, p 12-13.

Table 8: CSIRO National Hydrogen Roadmap priorities[263]



VALUE CHAIN ELEMENT	COMMERCIAL	POLICY/REGULATORY	RD&D	SOCIAL
General	• Implement vertical integration along the supply chain to optimise technology selection and use • Implement joint ventures to allow for allocation of risk and coordination of resources • Provide access to lower cost financing for low emissions projects	• Implement targeted policies to stimulate hydrogen demand • Develop hydrogen specific regulations based on best practice global standards. These should be uniform across the States and Territories • Establish inter/intragovernmental hydrogen authorities	• Continue demonstration projects for mature technologies to overcome 'first of kind' risk • Establish centralised RD&D bodies consisting of researchers, industry and government to coordinate RD&D funding appropriately (e.g. 'Hydrogen Centre of Excellence') • Implement incentives for local manufacturing	• Develop engagement plans and undertake demonstration projects to showcase hydrogen and ensure communities understand all aspects of its use
		Supply		
Production	• Position production plant to accept multiple offtakes for hydrogen • Secure cheap low emissions electricity	• Develop 'Guarantees of Origin' scheme • Government to secure long-term storage liability for CO_2 storage • Allow for compensation for grid firming services from electrolysers	• Continue RD&D into improving plant efficiencies and asset life • Continue development of less mature technologies such as high temperature electrolysis and methane cracking	• Undertake stakeholder engagement on technical viability and safety of CCS
Storage and Transport of H_2	• Position plants close to point of hydrogen use where possible	• Review gas pipeline regulations to consider including gaseous hydrogen	• Develop capabilities in liquefaction materials • Continue R&D in 100% hydrogen capable pipeline materials and pressures • Develop higher efficiency compression technologies and underground storage	• Develop communication plans regarding hydrogen pipeline easements
		Applications		
Hydrogen fuelled transport	• Establish refuelling station joint ventures and undertake strategic roll out of stations	• Implement emissions standards on vehicles and specific incentives for FCEVs	• Demonstrate viability of refuelling stations with 'back to base' vehicles or vehicles with known driving patterns	• Improve recognition of FCEVs as electric vehicles • Conduct ongoing station safety demonstrations for refuelling stations
Industrial feedstocks	• Install new clean hydrogen inlets into facilities during plant shutdowns	• Implement incentive schemes regarding use of clean hydrogen as an industrial feedstock		• Create awareness of emissions embodied in commodities to help inform consumer choice
Export (as per production, storage and transport plus)	• Implement government to government agreements for export to give industry confidence • Establish 'take or pay' export offtakes • Undertake land appraisal assessments for dedicated renewables • Invest in domestic labour force • Negotiate favourable tariffs for hydrogen export (including in the existing FTAs)	• Implement regulations supporting use of unutilised land for dedicated renewables • Engage bodies such as the International Maritime Organisation to ensure appropriate regulatory frameworks for hydrogen shipping	• As per hydrogen production, storage and transport	• Continue to promote hydrogen as a low emissions export commodity

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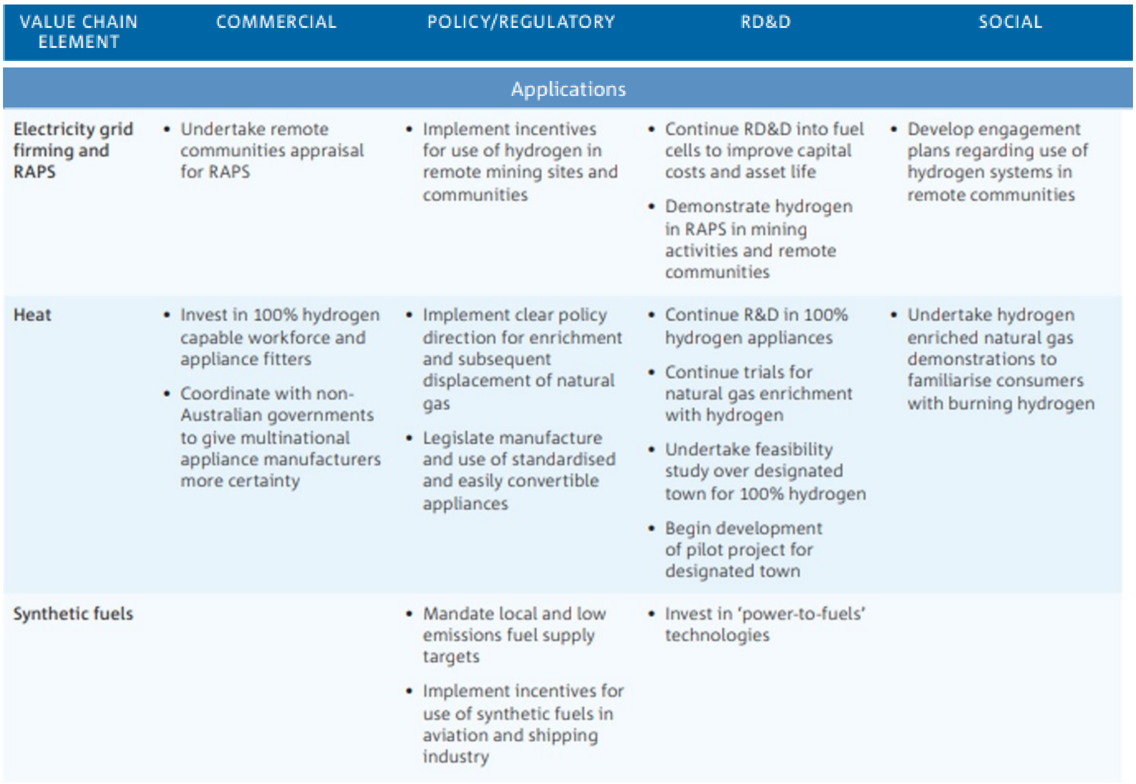
[263] CSIRO, *National Hydrogen Roadmap*, August 2018, p xx – xxi.



VALUE CHAIN ELEMENT	COMMERCIAL	POLICY/REGULATORY	RD&D	SOCIAL
Applications				
Electricity grid firming and RAPS	• Undertake remote communities appraisal for RAPS	• Implement incentives for use of hydrogen in remote mining sites and communities	• Continue RD&D into fuel cells to improve capital costs and asset life • Demonstrate hydrogen in RAPS in mining activities and remote communities	• Develop engagement plans regarding use of hydrogen systems in remote communities
Heat	• Invest in 100% hydrogen capable workforce and appliance fitters • Coordinate with non-Australian governments to give multinational appliance manufacturers more certainty	• Implement clear policy direction for enrichment and subsequent displacement of natural gas • Legislate manufacture and use of standardised and easily convertible appliances	• Continue R&D in 100% hydrogen appliances • Continue trials for natural gas enrichment with hydrogen • Undertake feasibility study over designated town for 100% hydrogen • Begin development of pilot project for designated town	• Undertake hydrogen enriched natural gas demonstrations to familiarise consumers with burning hydrogen
Synthetic fuels		• Mandate local and low emissions fuel supply targets • Implement incentives for use of synthetic fuels in aviation and shipping industry	• Invest in 'power-to-fuels' technologies	

In order to develop a hydrogen industry in NSW, the 2020 KPMG report recommended that the NSW Government:

1. In partnership with industry and other governments, continue driving the acceleration of the hydrogen pathway, including through the upcoming NSW Hydrogen Strategy;

2. Build on this Strategy by identifying and prioritising specific pilots and initiatives, research and development, and other programs and incentives to support and accelerate industry development; and

3. Strengthen collaboration to consider and align the safety and regulatory implications of increased hydrogen production, transport, storage and use with several current and future applications and locations.[264]

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[264] KPMG, A Clean Energy Superpower: Industry Opportunities Enabled by Cheap, Clean and Reliable Electricity, 23 September 2020, Executive Summary.

6. HOW ARE AUSTRALIAN GOVERNMENTS SUPPORTING HYDROGEN AND WHAT IS THE CURRENT STATE OF THE INDUSTRY?

6.1 National level policy

In November 2019, the COAG Energy Council adopted *Australia's National Hydrogen Strategy*. The Strategy was developed by the Council's Hydrogen Strategy Working Group, which was chaired by Australia's Chief Scientist, Dr Alan Finkel. The Strategy lists 57 actions for Australian governments that relate to seven themes:

1. National coordination;
2. Developing production capacity, supported by local demand;
3. Responsive regulation;
4. International engagement;
5. Innovation and Research & Development;
6. Skills and workforce; and
7. Community confidence.

The Strategy states that a key element of Australia's approach to achieve scale and become a globally competitive supplier will be creating hydrogen hubs – regions where users of hydrogen are co-located – in metropolitan, regional and remote areas.[265] These hubs would help the hydrogen industry in the early stages of development. They would make infrastructure more economic, allow for efficiencies from scale, foster innovation, facilitate the sharing of expertise and services and promote sector coupling.

The Strategy lists 15 measures of success around three themes:

1. A clean, innovative, safe and competitive industry;
2. Benefits all Australians; and
3. A major global player.[266]

At the time of releasing the National Strategy, the Commonwealth Government announced that it would reserve $370 million from existing Clean Energy Finance Corporation (CEFC) and Australian Renewable Energy Agency (ARENA) funding to back new hydrogen projects.[267] The two funds that were created were the $300 million CEFC Advancing Hydrogen Fund; and the $70 million ARENA Hydrogen Deployment Funding Round (which was later increased to $100 million).[268]

Some actions taken in 2020 in relation to the National Strategy included:

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[265] COAG Energy Council, *Australia's National Hydrogen Strategy*, November 2019, p 31.

[266] Ibid, p 70-71.

[267] Canavan M, *Australia to be a world leader in hydrogen*, Media Release, 23 November 2019.

[268] See CEFC, *Advancing Hydrogen Fund*; and ARENA, *Renewable Hydrogen Deployment Funding Round*, [websites – accessed 17 February 2021]. See also ARENA, *Over $100 million to build Australia's first large-scale hydrogen plants*, Media Release, 5 May 2021.

- The Department conducted an initial consultation with industry on a hydrogen certification scheme;
- The Government engaged with governments in several other countries including Japan, South Korea, Singapore and Germany (e.g. in January 2020, Australia and Japan signed the Joint Statement on Cooperation on Hydrogen and Fuel Cells); and
- The COAG Hydrogen Project Team is coordinating a review of State, Territory and Commonwealth regulations relevant to hydrogen safety and industry development; and leading a review of activities to support the use of hydrogen in Australian gas networks.[269]

In September 2020, the Commonwealth Government released its *Technology Investment Roadmap: First Low Emissions Technology Statement 2020*.[270] The Statement includes clean hydrogen as one of five priority low emissions technologies. The Statement sets economic stretch goals for each of the five priority technologies, including achieving under AUD$2 per kilogram for clean hydrogen at the site of production. The Statement was accompanied by a $1.9 billion funding package including $1.6 billion for ARENA to invest; $75 million for a Future Fuels Fund; and $70 million to set up a hydrogen export hub.[271]

In February 2021, the Commonwealth Government published a *Future Fuels Strategy Discussion Paper*.[272] It sets out the government's direction and practical actions that will enable the private sector to commercially deploy low emissions road transport technologies at scale. Also in February 2021, National Energy Resources Australia announced a $1.9 million investment in 13 regional hydrogen technology clusters across Australia.[273]

On 21 April 2021, the Commonwealth Government announced $276 million in funding to accelerate the development of four clean hydrogen hubs in regional Australia and implement a clean hydrogen certification scheme.[274] The May 2021 Budget also included $25 million over three years to assist new gas generators to become hydrogen ready; and up to $30 million for early works on the proposed dual-fuel (gas and green hydrogen) power station at Port Kembla.[275]

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[269] Department of Industry, Science, Energy and Resources, *National Hydrogen Strategy priorities and delivery*, News, 11 September 2020.

[270] Department of Industry, Science, Energy and Resources, *Technology Investment Roadmap: First Low Emissions Technology Statement 2020*, September 2020.

[271] Morrison S, *Investment in New Energy Technologies*, Media Release, 17 September 2020.

[272] See Department of Industry, Science, Energy and Resources, *Future Fuels Strategy Discussion Paper – Powering choice*, February 2021.

[273] NERA, *Regional hydrogen technology clusters launched across Australia*, 1 February 2021.

[274] Morrison S, *Jobs Boost From New Emissions Reduction Projects*, Media Release, 21 April 2021.

[275] Taylor A, *Investing in reliable affordable energy and reducing emissions to secure Australia's recovery*, Media Release, 11 May 2021.

6.2 NSW Government policy

The NSW Government is currently developing a hydrogen strategy.[276]

The 2019 National Hydrogen Strategy contains a jurisdictional showcase that identifies four priorities for NSW:

- Develop the supporting infrastructure and capabilities;
- Planning approval and infrastructure development;
- Regulatory oversight; and
- Support for business and R&D.[277]

With respect to planning approval and infrastructure development, it noted “the system of Special Activation Precincts (SAP) in NSW offers a mechanism that can align with the development of hydrogen hubs in regional areas”.[278]

The NSW Government has set a goal of net zero emissions by 2050 and in March 2020, it released the *Net Zero Plan Stage 1: 2020–2030.* One of the Plan’s four priorities is to invest in the next wave of emissions reduction innovation, and a key focus of this is low-emissions hydrogen. The Plan states:

> To boost the commercialisation of low-emissions hydrogen production and applications, the NSW Government will establish a **Hydrogen Program** that will help the scale-up of hydrogen as an energy source and feedstock. The NSW Government will set an aspirational **target of up to 10% hydrogen in the gas network by 2030**. This could have benefits for the transport, energy storage, ammonia, glass, metal and electronics production industries. This will also develop NSW's potential as a competitive hydrogen exporter to a growing international market.[279] (*Original emphasis)*

The Plan noted that the Hydrogen Program will offer competitively-based grants for demonstration, research and development and commercialisation projects. The Plan did not indicate the size of the program or when it would commence.

The NSW Government’s November 2020 *NSW Electricity Infrastructure Roadmap* has several aims including creating Renewable Energy Zones, delivering energy storage infrastructure, and harnessing opportunities for industry from the supply of cheap, reliable and low emissions electricity. One of these opportunities is the creation of a hydrogen industry.[280] The *Electricity Infrastructure Investment Act 2020* gives effect to this Roadmap.

When the *Electricity Infrastructure Investment Bill* was being considered by the

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[276] See NSW Legislative Council, *Legislative Council Questions and Answers No. 313*, 7 August 2020, p 2825.

[277] COAG Energy Council, *Australia’s National Hydrogen Strategy*, November 2019, p xviii.

[278] For further information on SAPs, see NSW Department of Planning, Industry and Environment, *Special Activation Precincts* [website – accessed 17 February 2021].

[279] NSW Department of Planning, Industry and Environment, *Net Zero Plan Stage 1: 2020–2030*, p 30.

[280] NSW Department of Planning, Industry and Environment, *NSW Electricity Infrastructure Roadmap*, November 2020, p 38.

Legislative Assembly, Greens MP, Jamie Parker, successfully moved an amendment to commit $50 million from the Climate Change Fund between 2021 and 2030 to develop the green hydrogen sector, including: (i) the production of hydrogen energy using renewable energy, and (ii) the supply, use and export of hydrogen energy produced using renewable energy.[281]

On 8 March 2021, the NSW Government announced a $750 million *Net Zero Industry and Innovation Program* to help achieve the *Net Zero Plan Stage 1: 2020-2030*.[282] The Program has three focus areas: (1) Clean Technology Innovation; (2) New Low Carbon Industry Foundations; and (3) High Emitting Industries. There "will be important investments in green hydrogen initiatives" across all three areas; and "these will meet the legislative commitment to invest $50 million before 2030 to develop the green hydrogen sector".[283] The Program is "expected to contribute at least $70 million to support the establishment of hydrogen hubs in the Hunter and Illawarra".[284]

In May 2021, the NSW Government announced an $83 million funding agreement with Energy Australia for a proposed dual fuel gas/hydrogen power plant in the Illawarra (Tallawara B project).[285] Energy Australia will offer to buy enough green hydrogen equivalent to over five per cent of the plant's fuel use from 2025, and it will invest in engineering studies on the potential to upgrade the plant so it can use more green hydrogen in its fuel mix in the future.[286] The NSW Government committed $78 million to this project, with the Commonwealth Government providing $5 million to make it hydrogen-ready.[287]

6.3 Other State and Territory governments

All other States and the Northern Territory have developed a hydrogen strategy or action plan; and most States have committed significant funding to the development of a hydrogen industry. This is summarised in Table 9.

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[281] See *Energy and Utilities Administration Act 1987*, s 34H(D1); and Parker J, *NSW Hansard (LA)*, 17 November 2020, p 92 (Proof).

[282] NSW Department of Planning, Industry and Environment, *NSW to drive clean industrial revolution*, Media Release, 8 March 2021.

[283] NSW Department of Planning, Industry and Environment, *Net Zero Industry and Innovation Program*, March 2021, p 10.

[284] Ibid, p 13. See also Kean M, *Hunter hydrogen hub to drive jobs, investment and a net zero future*, Media Release, 12 March 2021.

[285] Barilaro J, *Australia's first green hydrogen and gas power plant*, Media Release, 3 May 2021.

[286] Ibid. See also Morton A, The Coalition is backing a gas plant that also runs on hydrogen. Is this the future or a folly?, *The Guardian*, 8 May 2021.

[287] Taylor A, *Tallawarra B power station to be built*, Media Release, 4 May 2021.

Table 9 State and Territory hydrogen strategies and funding[288]

State	Strategy	Funding commitments	($m)
Queensland	Queensland Hydrogen Industry Strategy 2019–2024 (May 2019)	**Total**[289]	**62**
		Hydrogen Industry Development Fund	25
		Hydrogen workforce training facilities	33
		Other initiatives	4
Western Australia	Western Australian Renewable Hydrogen Strategy (July 2019) and Roadmap (November 2020)	**Total**[290]	**32**
		Renewable Hydrogen Fund	15
		Other initiatives and projects	17
South Australia	South Australia's Hydrogen Action Plan (September 2019)	**Total**[291]	**43**
		Study to identify optimal locations	1
		Grants for four projects	17
		Loans for four projects	25
Tasmania	Tasmanian Renewable Hydrogen Action Plan (March 2020)	**Total**[292]	**50**
		Renewable Hydrogen Fund	20
		Concessional loans	20
		Other initiatives	10
Northern Territory	Northern Territory Renewable Hydrogen Strategy (July 2020)	**Total**[293]	**1**
		Remote Hydrogen Program	1
Victoria	Victorian Renewable Hydrogen Development Plan (Feb 2021)	**Total**[294]	**72**
		Hydrogen Investment Program	2

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[288] The funding figures are based on government media releases and may not be comprehensive. The figures are restricted to hydrogen-specific funding programs and projects. Hydrogen projects may be eligible for funding under climate change or renewable energy funding programs. See also HyResource, A Short Report on Hydrogen Industry Policy Initiatives and the Status of Hydrogen Projects in Australia, May 2021, p 9 (Table 2).

[289] Palaszczuk A, Queensland positioned to power the hydrogen highway, Media Release, 30 May 2019, 19 May 2020; and Palaszczuk A, Palaszczuk Government to pump $10 million into hydrogen pipeline, Media Release, 1 December 2020.

[290] MacTiernan A, Course set for WA's renewable hydrogen future, Media Release, 18 July 2019; and Western Australian Government, $22 million investment to accelerate renewable hydrogen future, News, 17 August 2020.

[291] Marshall S, SA Government releases Hydrogen Action Plan to international experts, Media Release, 14 September 2019; and SA Renewables, Hydrogen Projects in SA, [website – accessed 17 February 2021].

[292] Gutwein P, Building Tasmania's hydrogen energy industry, Media Release, 2 March 2020.

[293] Lawler E, Budget 2021: Affordable, Clean and Reliable Energy for Territorians, Media Release, 3 May 2021.

[294] Andrews D, New Program To Drive Investment In Hydrogen Energy, Media Release, 18 December 2018; Cash M, Local jobs and a new energy industry for the LaTrobe valley, Media Release, 12 April 2018; Andrews D, Hydrogen Hub Cements Victoria As Clean Energy Leader, Media Release, 7 February 2021; and Victoria Government, Victorian Renewable Hydrogen Development Plan, February 2021, p 1.

State	Strategy	Funding commitments	($m)
		Hydrogen Energy Supply Chain project	50
		Victorian Hydrogen Hub project	10
		Accelerating Victoria's Hydrogen Industry Program	10
Australian Capital Territory	No hydrogen-specific strategy was identified.	No media releases were identified with funding commitments specifically for hydrogen.	-

6.4 State of industry

As at early May 2021, there were 61 clean and low-carbon hydrogen-related projects in Australia listed in HyResource.[295] Five of these projects were in operation, nine under construction, nine in advanced development, and 38 in development. Over 60% of hydrogen projects (37 out of 61) were in Western Australia and Queensland; five projects were in NSW. As noted above, Western Australia and Queensland were the first States to publish hydrogen strategies.

Of the 23 projects that were in operation, under construction or in advanced development, eight were in Western Australia, five in Queensland, four in Victoria, three in NSW, two in the ACT, and one in South Australia. These projects are focused on hydrogen in gas networks, hydrogen mobility (i.e. transport) and hydrogen in power use, with many projects designed with multiple applications in mind.[296] Table 10 lists these projects and some of their key features.

Table 10: Hydrogen projects operating, in construction, or in advanced development[297]

Project name / location	Status	Start date	Main end-uses	Cost ($m)
Sir Samuel Griffith Centre (QLD)	Operating	2013	Microgrid – power use	-
Hydrogen Test Facility – ACT Gas Network (ACT)	Operating	2018	Hydrogen in gas networks	0.3
Clean Energy Innovation Hub (WA)	Operating	2019	Natural gas blending, power use	3.5
Hydrogen Energy Supply Chain – Pilot Project (VIC)	Operating	2021	Export – liquid hydrogen	500
Renewable Hydrogen Refuelling Pilot (ACT)	Operating	2021	Hydrogen mobility	-

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[295] HyResource, *A Short Report on Hydrogen Industry Policy Initiatives and the Status of Hydrogen Projects in Australia*, May 2021, p 11.

[296] Ibid, p 13.

[297] Adapted from Appendix A, p 17.

Project name / location	Status	Start date	Main end-uses	Cost ($m)
Hydrogen Park South Australia (SA)	Construction	2021	Hydrogen in gas networks, mobility	11.4
Toyota Hydrogen Centre (VIC)	Construction	2021	Power use, hydrogen mobility	7.4
Western Sydney Green Gas Project (NSW)	Construction	2021	Hydrogen in gas networks, power, mobility	15
Hydrogen Refueller Station Project (WA)	Construction	2021	Hydrogen mobility	-
Renewable Hydrogen Production and Refuelling Project (QLD)	Construction	2021	Industrial gas and mobility	4.2
Hazer Commercial Demonstration Plant (WA)	Construction	2021	Hydrogen mobility, power and industrial uses	17
Christmas Creek Renewable Hydrogen Mobility Project (SA)	Construction	2022	Hydrogen mobility	32
Denham Hydrogen Demonstration Plant (WA)	Construction	2022	Microgrid – power use	8.9
APA Renewable Methane Demonstration Project (QLD)	Construction	2022	Hydrogen in gas networks	2.3
Port Kembla Hydrogen Refuelling Facility	Advanced development	2022	Hydrogen mobility	-
Manilla Solar and Renewable Energy Storage Project	Advanced development	2022	Microgrid – power use	7.3
Swinburne University of Technology Victorian Hydrogen Hub – CSIRO Refuelling Station (VIC)	Advanced development	2022	Hydrogen mobility	-
Arrowsmith Hydrogen Project – Stage 1 (WA)	Advanced development	2022	Hydrogen mobility, power use	-
Hydrogen Park Gladstone (QLD)	Advanced development	2022	Hydrogen in gas networks	4.2
Spicers Retreats Ecotourism Demonstration (QLD)	Advanced development	-	Microgrid – power use	-
Yara-ENGIE Fertiliser Renewable Ammonia (WA)	Advanced development	2023	Ammonia production	70
Hydrogen Park Murray Valley (VIC)	Advanced development	-	Hydrogen in gas networks	-

Project name / location	Status	Start date	Main end-uses	Cost ($m)
Clean Energy Innovation Park (WA)	Advanced development	2023	Hydrogen in gas networks	-

Brief descriptions are provided below for the most advanced NSW project (the $15 million Western Sydney Green Gas Project)[298] and the largest project in Australia (the $500 million Hydrogen Energy Supply Chain Project in Victoria).[299]

Western Sydney Green Gas Project (NSW)

This renewable gas five-year trial project will convert solar and wind power into hydrogen gas, via electrolysis, which will then be stored for use in the gas network. A 500kW electrolyser will be able to generate enough hydrogen to power approximately 250 homes. The project could also support refuelling for hydrogen vehicles. The project received planning approval in August 2020. The NSW Energy Minister, Matt Kean, said that this project "will help to position NSW as a nation-leader in green gas supply and storage projects". This project is in construction and is due to be operational in 2021.

Hydrogen Energy Supply Chain Project (Victoria)

This project aims to produce and transport hydrogen from the Latrobe Valley in Victoria to Japan. Hydrogen will be produced from coal gasification with gas-refining carbon offsets purchased to mitigate emissions. If the project proceeds to a commercial phase, it will use carbon capture and storage. The hydrogen gas will be transported by truck to a liquefaction and loading terminal at the Port of Hastings, the first of its kind in Australia. The liquefied gas will then be loaded onto a specially designed marine carrier for shipment. In March 2021, the two Victorian sites became operational – the gasification and refining of hydrogen, and the liquefaction at Hastings.

In March 2021, it was reported that Andrew Forrest is planning to build a $1 billion gas and hydrogen fuelled power station at Port Kembla to supply industries and households with green energy.[300] The proposed power station would initially use LNG and green hydrogen but would transition to green hydrogen only.

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[298] The information on this project is based on Jemena, *Welcome to Jemena's Western Sydney Green Gas Project*; ARENA, *Jemena Power to Gas Demonstration*, [websites – accessed 16 February 2021]; and NSW Department of Planning, Industry and Environment, *NSW's first Hydrogen Project gets green tick*, Media Release, 12 August 2020.

[299] The information on this project is based on the Hydrogen Energy Supply Chain (HESC) website; and Toscano N and Foley M, Hydrogen project fuels Latrobe Valley job hopes as coal plants close, *Sydney Morning Herald,* 12 March 2021.

[300] Thompson B, Forrest willing to fund $1b green power station in NSW, *Australian Financial Review,* 16 March 2021.

7. CONCLUSION

Clean and low-carbon hydrogen has the potential to be a major industry and export opportunity for countries like Australia that have a competitive advantage in its production. Hydrogen could also help to provide security and reliability to the National Electricity Market as Australia transitions towards renewable energy. However, there are several uncertainties surrounding the potential of hydrogen, including how its cost will compare with alternative clean energy production and storage options as technology continues to develop. The IEA sees hydrogen as having the most potential in long-distance transport and in the manufacturing of chemicals and steel. The hydrogen industry is still in its infancy and government support is recognised as being important for it to develop at scale. The current Legislative Council Committee inquiry will examine the key issues for NSW and develop recommendations. These recommendations will likely be used to inform the NSW Government's upcoming hydrogen strategy.