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OPPORTUNITIES FOR AUSTRALIA FROM HYDROGEN EXPORTS

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ACKNOWLEDGEMENTS

ACIL Allen Consulting would like to acknowledge the contribution to this report made by the team from the CSIRO’s Hydrogen Roadmap project. Their information on the costs of production, storage and transport were important inputs into the modelling of the opportunities for Australia from potential hydrogen exports. We would also like to acknowledge the many independent experts who reviewed and provided comments on the draft report, including:

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- Cédric Philibert, International Energy Agency.

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ABBREVIATIONS

AEMO	Australian Energy Market Operator
ARENA	Australian Renewable Energy Agency
AAC	ACIL Allen Consulting
ABS	Australian Bureau of Statistics
BEVs	Battery Electric Vehicles
C	Celsius (degrees)
CAGR	Compound annual growth rate
CCS	Carbon capture and storage
CGE	Computable General Equilibrium
CHP	Combined heating and power
CIF	Cost, insurance and freight
CO_2	Carbon dioxide
DEWA	Dubai Electricity and Water Authority
EJ	Exajoule (10^{18} Joules)
EU	European Union
FCEV(s)	Fuel Cell Electric Vehicle(s)
FTE	Full time equivalent
GCI	Global Competitiveness Index
GDP	Gross Domestic Product
GHG	Greenhouse gas
GJ	Gigajoule (10^9 Joules)
H_2	Hydrogen
ICE	Internal Combustion Engine
IEA	International Energy Agency
IPHE	International Partnership for Hydrogen Economy
IRENA	International Renewable Energy Agency

JAEPA	Japan–Australia Economic Partnership Agreement
kg	Kilogram
KHI	Kawasaki Heavy Industries
kt	Kilotonne
kWh	Kilowatt hour
LCOE	Levelised Cost of Electricity
LCOH	Levelised Cost of Hydrogen
LHV	Lower Heating Value
LNG	Liquefied Natural Gas
MENA	Middle East and North Africa
METI	Ministry of Economy, Trade and Industry (Japan)
MWh	Megawatt hour
NDCs	Nationally Determined Contributions
NPS	New Policies Scenario (of the IEA)
NRE	New and Renewable Energy
PEM	Proton exchange membrane
PEVs	Plug-in Electric Vehicles
PJ	Petajoule (10^{15} Joules)
R&D	Research and Development
R,D&D	Research, Development and Demonstration
SDS	Sustainable Development Scenario (of the IEA)
SMR	Steam Methane Reforming
TCP	Technology Collaboration Program
tkm	Tonne kilometre
TWh	Terawatt hour
UK	United Kingdom
USA	United States of America
VRE	Variable renewable energy
WEF	World Economic Forum
WEO	World Energy Outlook
ZEV	Zero Emission Vehicles

EXECUTIVE SUMMARY

Countries around the world are under increasing pressure to decarbonise their economies. There is growing interest in the production and use of hydrogen as a potential scalable and versatile mechanism for achieving this aim. If the global demand for hydrogen increases as a consequence, then it is likely that a global market in hydrogen will emerge to satisfy that demand.

The Australian Renewable Energy Agency (ARENA) engaged ACIL Allen Consulting (ACIL Allen) to prepare a report to identify the opportunities for Australia to export hydrogen to help meet the potential global demand for hydrogen.[1]

Overview of the emerging global hydrogen market

- Current global hydrogen production, which is typically not produced through low emissions methods, is relatively stable at around 55 million tonnes (6,600 PJ) per year.[2]
- Currently, non-energy uses of hydrogen dominate consumption, with production of ammonia accounting for around half of hydrogen demand. Use of hydrogen for energy purposes is estimated to be between 1 and 2 per cent of total consumption.
- This report focusses on the potential demand for low emissions hydrogen for energy use. There may also be demand for low emissions hydrogen to replace existing hydrogen use in industrial uses.[3] [4] For example, as a chemical feedstock to produce 'green' commodities such as ammonia, methanol and other chemicals or as a reductant in steel making. However, the latter use is unlikely to see wide-spread adoption within the timeframe examined in this report.
- Increased demand from the industrial sector is more likely to occur after its use for energy has grown. The Hydrogen Council has estimated that the first demonstrations of this use of hydrogen might be deployed in 2030.[5]
- The need for signatories to the 2015 Paris Accord to reduce their greenhouse gas emissions to meet their abatement commitments is the primary driver for a potentially significant increase in the global demand for hydrogen.[6] That requirement is being manifested in different ways, including:
  - ensuring personal mobility needs, as internal combustion engines are phased out
  - decarbonising natural gas networks
  - using hydrogen to store energy to help ensure the reliability of variable renewable energy supplies
  - increasing energy security

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[1] Throughout this report references to 'hydrogen' should (unless otherwise specified) be interpreted as referring to hydrogen that has been produced with little or no associated greenhouse gas emissions. For example, hydrogen produced by electrolysis using electricity produced from a renewable source such as wind or the sun or using fossil fuels combined with carbon capture and storage (CCS).

[2] *Hydrogen - Scaling Up*, Hydrogen Council, November 2017

[3] Renewable Energy for Industry, International Energy Agency, 2017

[4] Decarbonization of industrial sectors: the next frontier, McKinsey & Company, June 2018

[5] Hydrogen - Scaling Up, Hydrogen Council, November 2017

[6] Others include enabling large-scale renewable energy generation and integration or as a buffer to increase energy system resilience.

  - significant funding for hydrogen related R,D&D, which will help to reduce costs and build confidence in a hydrogen supply system
  - policies and programs that support hydrogen.
- If hydrogen becomes a globally important source of energy, then it is likely that a global market for hydrogen will emerge. Australia could supply some of this global market.
- Several potential importers of hydrogen have been examined to estimate their potential demand for imported hydrogen. (See Section 2.2.2)
- Four were identified as being more prospective markets for Australian hydrogen by 2025, namely China, Japan, Republic of Korea and Singapore.
  - This selection was based a combination of factors such as: size of market; scope for the country to meet its hydrogen demand from its own production; existing policies and existing energy trade relationships with Australia. (See Section 2.3)
- Other countries (e.g. Norway, Iceland, the USA, various Middle East or North African countries and Brunei) are likely to compete with Australia to supply hydrogen for export.

Analysis of hydrogen demand

- This report presents the results of modelling the potential demand for hydrogen (whether domestically produced or imported) for each of the four potential markets for exports of Australian hydrogen.
- ACIL Allen has modelled the potential opportunities for hydrogen exports from Australia under three hydrogen demand scenarios. The scenarios represent possible future worlds with low, medium and high hydrogen uptake rates in each application area. They are based on the IEA's Sustainable Development Scenario (SDS). This means that future energy consumption by industry, by country is based on the SDS forecasts.
- The scenarios are based on different assumptions regarding climate change and global warming, adoption of hydrogen technologies, and alternative fuel prices across the sectors where hydrogen might enter the market. They reflect worlds in which there is progressively greater attention and effort put towards achieving the climate change outcomes in the Paris Climate Accord.
- The scenarios adopt a wide range of other assumptions regarding population and labour market growth, productivity growth, fuel prices, resource availability and technological developments.
- It is important to understand that this report does not provide forecasts of potential hydrogen demand. Rather the hydrogen demand scenarios are designed to provide alternative views of what the future opportunities for hydrogen exports might be under different circumstances.
  - Section 3.1.1 provides additional information on the scenario assumptions.
- The models draw on a range of data sources, including: the IEA; country energy statistics and energy outlooks; the United Nations; and other sources listed in the literature review (see Appendix A).
- The models (see **Figure 3.4**) have been used to develop projections of total hydrogen demand, the share of that demand supplied by imports and the share of imports supplied by Australia for the four selected countries and globally. The projected demand for hydrogen (in PJ) for 2025, 2030 and 2040 for the four selected countries and the rest of the world is shown in **Table ES 1**. ACIL Allen's projected demand for hydrogen in the high scenario is similar to that projected by the Hydrogen Council (see **Figure 2.1**).

TABLE ES 1 PROJECTED GLOBAL DEMAND FOR HYDROGEN (PJ)

Country	2025			2030			2040		
	Low	Medium	High	Low	Medium	High	Low	Medium	High
Japan	10.6	62.0	160.7	105.1	211.5	463.3	227.7	496.1	1,149.7
Republic of Korea	8.9	26.7	59.3	44.8	87.4	187.5	120.2	261.2	637.1
Singapore	0.3	1.8	3.8	3.3	6.1	12.4	11.5	20.2	57.7
China	5.8	27.1	83.8	123.5	398.5	841.8	943.1	2,093.3	4,922.7
Rest of the World	11.7	53.8	140.6	126.5	321.6	688.0	595.5	1,312.4	3,093.6
Total	**37.4**	**171.6**	**448.1**	**403.2**	**1,025.2**	**2,193.1**	**1,898.0**	**4,183.2**	**9,860.8**

NOTE: PETAJOULE FIGURES ARE BASED ON LOWER HEATING VALUE (LHV) OF HYDROGEN
SOURCE: ACIL ALLEN ANALYSIS

The projected demand for hydrogen (in tonnes) for 2025, 2030 and 2040 for the four selected countries and the rest of the world is shown in **Table ES 2**.

TABLE ES 2 PROJECTED GLOBAL DEMAND FOR HYDROGEN ('000 TONNES)

Country	2025			2030			2040		
	Low	Medium	High	Low	Medium	High	Low	Medium	High
Japan	88	516	1,338	875	1,761	3,858	1,896	4,131	9,573
Republic of Korea	74	223	493	373	728	1,562	1,001	2,175	5,304
Singapore	3	15	31	27	51	103	96	168	481
China	48	226	698	1,028	3,318	7,009	7,853	17,430	40,989
Rest of the World	98	448	1,170	1,053	2,678	5,729	4,958	10,927	25,758
Total	**311**	**1,429**	**3,731**	**3,357**	**8,536**	**18,260**	**15,804**	**34,831**	**82,105**

SOURCE: ACIL ALLEN ANALYSIS

The above results are based on assumptions and analysis that includes CSIRO's projected prices for hydrogen supplied from Australia (production, storage and transport). In some cases, ACIL Allen's modelling leads to projections that are higher than current government targets for future hydrogen demand.[7] The results from ACIL Allen's modelling merely reflect the assumptions made under each of the scenarios. They should not be interpreted as a comment on the accuracy of any official figures for hydrogen demand.

The assumptions take into account the potential capacity of importing countries to supply their own hydrogen (from any source).

Australia's competitive position

- If a global market for hydrogen does emerge then Australia would need to compete with other countries that might want to export hydrogen.
- This report examines Australia's competitive position relative to other potential suppliers of hydrogen for export. With regard to potential exports of hydrogen to the four selected markets in Asia, Australia is in a relatively good competitive position due to factors such as:
  - the landed cost of hydrogen (**Figure ES 1** shows the estimated landed cost of hydrogen in Japan from different countries in 2025. **Table 4.7** provides more detail and information on the landed cost of hydrogen in the other target countries.)
  - proximity to the market
  - having well established energy trading relationships
  - experience in large scale energy infrastructure construction

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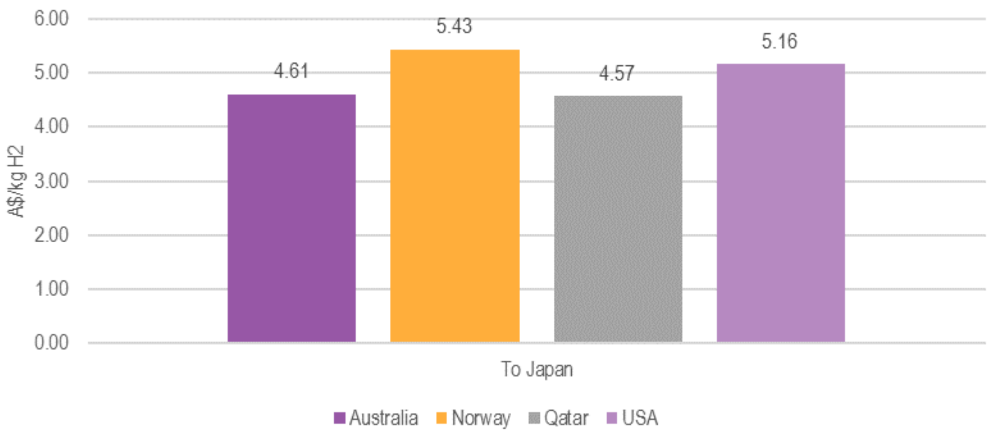
[7] For example, some the projections for hydrogen demand in Japan under the scenarios are well above the current estimates outlined in the Japanese METI's Strategic Roadmap for Hydrogen and Fuel Cells. This merely represents an alternative view of what the future demand for hydrogen might be under different circumstances.

  - an ability to supply low or zero carbon hydrogen from a range of sources.

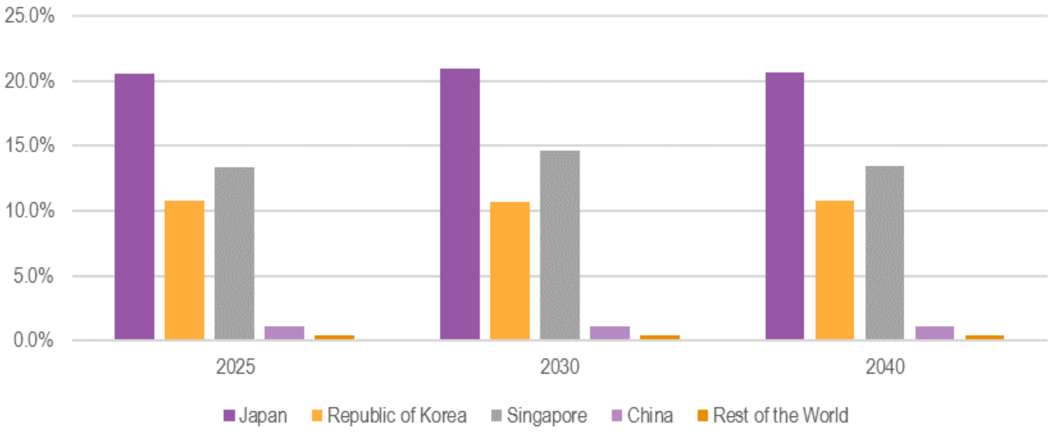
FIGURE ES 1 ESTIMATED CIF PRICE OF HYDROGEN IN JAPAN (IN 2025)



NOTE: CIF REFERS TO COST, INSURANCE AND FREIGHT BASIS SHIPPING (I.E. COST LANDED IN BUYERS COUNTRY). FOB IS FREE ON-BOARD BASIS AT EXPORT TERMINALS (I.E. THE BUYER PAYS FOR SHIPPING)
SOURCE: ACIL ALLEN

- It is important to understand that no hydrogen exporting country is likely to entirely capture any future medium to long term demand for hydrogen imports by any of the potential importing countries examined. Energy security concerns will ensure that countries that need to import hydrogen will seek to do so from a range of countries, much as they do with other energy sources now.
  - Australia's estimated share of hydrogen imports by Japan, Korea, Singapore, China and the rest of the World is shown in **Figure ES 2**.

FIGURE ES 2 AUSTRALIA'S SHARE OF HYDROGEN IMPORTS



SOURCE: ACIL ALLEN

- A summary of the estimated opportunity for Australia to supply hydrogen to meet the potential demand for hydrogen imports from selected countries and the rest of the world in PJ and tonnes are provided in **Table ES 3** and **Table ES 4** respectively. The estimated value of those potential exports is shown in **Table ES 5**.
  - For all three scenarios, we have conservatively assumed that Australia's share of the market for imports of hydrogen is below Australia's share of LNG imports.

TABLE ES 3 AUSTRALIA'S POTENTIAL EXPORTS OF HYDROGEN (PJ)

Country	2025			2030			2040		
	Low	Medium	High	Low	Medium	High	Low	Medium	High
Japan	2.1	12.7	33.0	21.9	44.2	96.4	47.1	102.3	237.7
Republic of Korea	1.0	2.9	6.4	4.8	9.4	20.1	12.9	28.1	68.4
Singapore	0.04	0.2	0.5	0.5	0.9	1.8	1.5	2.7	7.5
China	0.1	0.3	0.9	1.4	4.5	9.5	10.7	23.7	55.7
Rest of the World	0.05	0.2	0.6	0.5	1.3	2.8	2.4	5.4	12.7
Total	**3.2**	**16.4**	**41.4**	**29.1**	**60.3**	**130.7**	**74.6**	**162.2**	**382.0**

SOURCE: ACIL ALLEN ANALYSIS

TABLE ES 4 AUSTRALIA'S POTENTIAL EXPORTS OF HYDROGEN ('000 TONNES)

Country	2025			2030			2040		
	Low	Medium	High	Low	Medium	High	Low	Medium	High
Japan	17	106	275	182	368	803	392	852	1,979
Republic of Korea	8	24	53	40	78	167	107	234	570
Singapore	0.3	2	4	4	7	15	13	23	63
China	1	3	8	12	38	79	89	197	464
Rest of the World	0.4	2	5	4	11	23	20	45	106
Total	**26**	**136**	**345**	**242**	**502**	**1,088**	**621**	**1,350**	**3,180**

SOURCE: ACIL ALLEN ANALYSIS

ACIL Allen has projected the demand for hydrogen imports out to 2040. If the scenarios that we have developed are realised, then it is highly likely that demand would continue to grow out to 2050.

TABLE ES 5 CIF VALUE OF AUSTRALIA'S POTENTIAL HYDROGEN EXPORTS (A$ MILLION)[8]

Country	2025			2030			2040		
	Low	Medium	High	Low	Medium	High	Low	Medium	High
Japan	80	489	1,268	807	1,631	3,557	1,655	3,597	8,354
Republic of Korea	37	111	245	178	347	744	455	988	2,410
Singapore	1	9	19	17	32	66	52	94	259
China	3	12	36	52	167	352	376	835	1,963
Rest of the World	2	8	22	19	48	104	86	188	444
Total	**122**	**629**	**1,590**	**1,072**	**2,225**	**4,822**	**2,623**	**5,703**	**13,430**

NOTE: DOLLARS ARE IN CURRENT PRICES
SOURCE: ACIL ALLEN ANALYSIS

Implications for Australia

The potential direct and indirect economic contribution to the Australian economy of hydrogen production for exports have been estimated using input-output (I/O) multiplier analysis. Benefits include value added and direct and indirect employment in the sector.

The economic footprint of hydrogen production in Australia for export in the medium hydrogen demand scenario is summarised in **Figure ES 3**.

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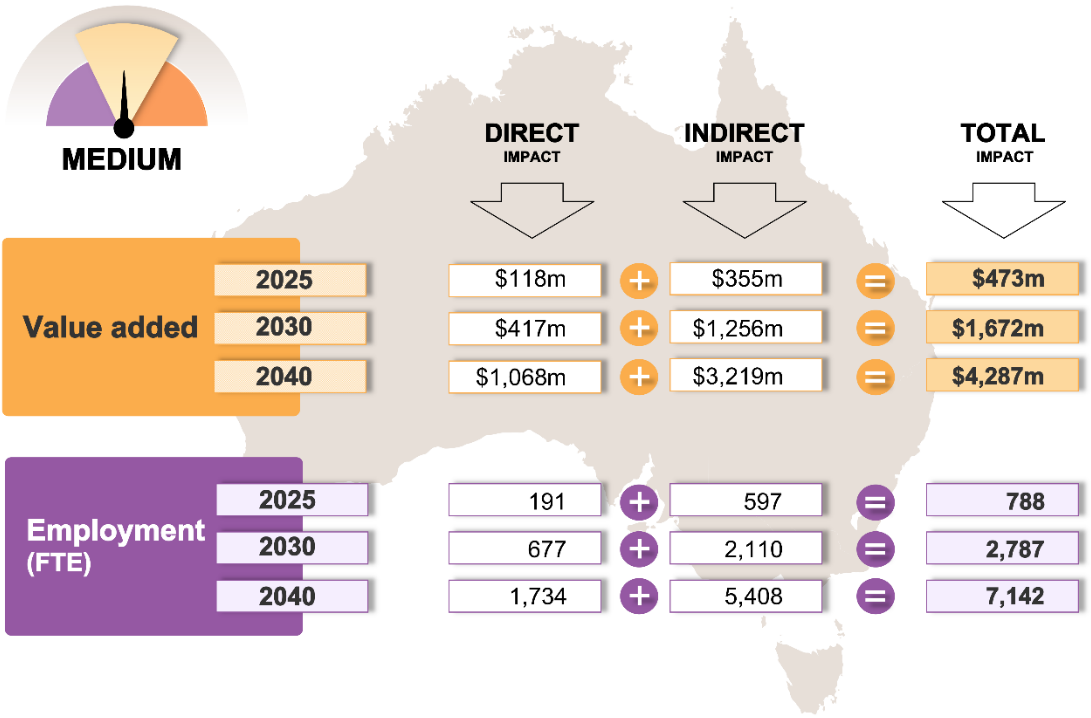
[8] CIF refers to Cost, Insurance and Freight. This means that the seller pays the costs and freight (including insurance) to bring the goods to the port of destination (in effect this is the 'landed cost').

The direct economic contribution (value-add) embodied in the value of hydrogen production for export is estimated to be A$201 million in the low scenario, A$417 million in the medium scenario and A$903 million in the high scenario in 2030. The contribution to the economy comprises mainly employee wages and gross operating surplus of the hydrogen producers and exporters (see **Table 5.2**).

If the above outcomes of the hydrogen scenarios are realised, the business of supplying global hydrogen demand is likely to be a substantial one. The estimated number of jobs are considerable (see the next section). In the high scenario they are comparable to the numbers employed in the LNG industry and its direct supply chain.[9]

If electrolysis is used to produce hydrogen for export it will lead to demand for additional electricity. That demand could be somewhere between 1 TWh (2025 low demand scenario) and 200 TWh (2040 high hydrogen demand scenario). The fact that AEMO's Annual Consumption Overview forecasts annual operational electricity consumption in the NEM to increase by just over 10 TWh over the 20 year period to 2036-37 provides an indication of the scale of the potential increase in electricity demand.[10] (see also **Table 5.1**).

FIGURE ES 3 FOOTPRINT OF THE HYDROGEN PRODUCTION SECTOR IN AUSTRALIA – MEDIUM HYDROGEN DEMAND SCENARIO



		DIRECT IMPACT		INDIRECT IMPACT		TOTAL IMPACT
Value added	2025	$118m	+	$355m	=	$473m
	2030	$417m	+	$1,256m	=	$1,672m
	2040	$1,068m	+	$3,219m	=	$4,287m
Employment (FTE)	2025	191	+	597	=	788
	2030	677	+	2,110	=	2,787
	2040	1,734	+	5,408	=	7,142

SOURCE: ACIL ALLEN ESTIMATES

Most of the jobs associated with any future hydrogen exports will be located where hydrogen production or export facilities are built.[11] It is most likely that the facilities will be located close to the supply of renewable energy. Renewables, particularly large scale solar PV or concentrated solar thermal projects are most likely to be located where the solar irradiance is high in Australia. Such areas of high solar irradiance (and reasonable ease of access to appropriately sized areas of land)

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[9] A report by McKinsey Australia in 2016, *Sustaining impact from Australian LNG operations*, found that 55,000 to 65,000 people are expected to be employed in the wider LNG industry and its direct supply chain during the operations phase.

[10] https://www.aemo.com.au/Electricity/National-Electricity-Market-NEM/Planning-and-forecasting/Electricity-Forecasting-Insights/2017-Electricity-Forecasting-Insights/Summary-Forecasts/Annual-Consumption, accessed 2 August 2018.

[11] The estimated number of jobs are for the projected hydrogen export industry in isolation and does not take into account the potential transfer of jobs between sectors.

tend to be in regional locations. Hydrogen production for export may therefore particularly benefit regional communities, traditional owners of the land, and the broader Australian community through the direct employment associated with hydrogen production facilities.

The results of the economic contribution analysis for the hydrogen demand scenarios is presented in Chapter 5.

Emissions implications

The use of hydrogen is one way that is increasingly being considered as a means of reducing greenhouse gas emissions and air pollution. CSIRO has estimated the carbon emission footprint (CO_2 emissions/kg H_2) for various hydrogen production technologies (see **Table 5.5**).

It is important to recognise that while emissions in Australia could increase due to hydrogen production here, emissions in end-use countries will decrease when hydrogen is used as an alternative to a conventional source of energy.

For example, if one PJ of diesel consumption was replaced by hydrogen consumption this would result in emissions savings of just over 69 kilo tonnes of CO_2 in the end use country.[12] Emissions in Australia associated with the production of one PJ of hydrogen using SMR with CCS would increase by around 6,300 tonnes.[13] However, there would be a net global emissions reduction of 63,037 tonnes of CO_2.

If Australia's exports of hydrogen were produced using PEM or alkaline electrolysis and electricity from renewable energy sources, then there would be no operational emissions associated with the production of the hydrogen and the global emissions reduction from replacing the use of 1 PJ of diesel by 1 PJ of hydrogen would be 69,337 tonnes of CO_2.

Next steps

The modelling in this report shows how a global hydrogen market could develop over the next 20 years, and that there is scope for Australia to become a significant exporter of hydrogen. Of course, as with any attempt to project future outcomes, the results are dependent upon the assumptions made. Different assumptions could lead to quite different outcomes.

Nonetheless, the increasing attention being paid to hydrogen globally and the growing investment in hydrogen related R,D&D suggests that it would be appropriate to ensure that Australia was well placed to take advantage of any hydrogen export opportunities that might arise.

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[12] CO_2 Emissions Calculator, https://www.eecabusiness.govt.nz/tools/wood-energy-calculators/co2-emission-calculator/ accessed 18 July 2018

[13] The emission analysis assumes that there is a 95% capture of the emissions for coal gasification and 90% for SMR.

1

INTRODUCTION

1.1 Scope of the report

ARENA engaged ACIL Allen Consulting (ACIL Allen) to prepare a report that identifies the opportunities for Australia to export hydrogen as an energy source.[14]

There is currently a very significant international trade in fossil fuels. Over 3,200 million tonnes of coal and oil, and more than 850 billion cubic metres of gas is traded between nations every year.[15] As countries look to progressively decrease their emissions, the future trade in energy is likely to increasingly include trade in low and zero emissions energy.[16] Australia has very large renewable resources, a well-established track record of exporting energy and long-standing trading relationships with key energy importers. Australia is therefore relatively well positioned to become a significant exporter of low or zero emissions energy.

Hydrogen has attracted increasing attention to its potential to play an important role in global decarbonisation efforts. There is growing investment in research and development effort and governments around the world have announced many projects aimed at supporting the use of hydrogen as a source of energy. However, the sector is still very much in its infancy, and there is considerable uncertainty about when (or even if) the demand for hydrogen might become significant enough to support an international market. Nonetheless, there are ample precedents for the emergence of a global trade in an energy commodity. For example, the LNG market grew from almost nothing in 1970 to almost a third of global gas trade in 2015.[17]

This report seeks to identify and quantify the market opportunities for Australia from exporting hydrogen by examining:

- drivers for market demand for hydrogen
- potential markets for Australian hydrogen
- Australia’s net competitive advantage relative to other potential hydrogen exporters
- Australia’s potential market share of a global hydrogen export market.

The report also considers the national implications of establishing a hydrogen export industry if the potential opportunity for exports of low and zero emissions hydrogen from Australia is realised.

‘Clean’ hydrogen (generally referred to as ‘hydrogen’ within this report), includes zero emissions hydrogen produced from renewable energy via electrolysis, and low emissions hydrogen produced

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[14] The majority of the hydrogen produced in the world today is used for industrial purposes, such as ammonia production.

[15] http://www.iea.org/publications/freepublications/publication/KeyWorld2017.pdf

[16] Zero emissions refers to a potential, future scenario where all energy in a system, including embodied energy, can be sourced from renewables. Zero emissions therefore excludes any combustion processes that produce greenhouse gases.

[17] BP Statistical review of world energy, 2016. https://www.bp.com/content/dam/bp/pdf/energyeconomics/statistical-review-2016/bp-statistical-review-of-world-energy-2016-full-report.pdf .

from fossil fuels, such as through steam methane reforming (SMR) or coal gasification, in conjunction with carbon capture and storage (CCS).

The demand for hydrogen modelled in this work, is based on an analysis of the demand for hydrogen for energy use. Although hydrogen as a feedstock for industrial processes (such as ammonia production) currently dominates global hydrogen use (7.7 EJ per annum), increases in hydrogen demand for this end-use are predicted to be significantly less than demand growth for use as energy.[18]

In the longer term there is potential for the pressure to decarbonise economies to lead to greater use of clean hydrogen for industrial use.

The analysis presented in this report is intended to accompany the CSIRO's National Hydrogen Roadmap, which explores the potential of, and maps the pathway to achieving a domestic Australian hydrogen industry. The CSIRO report includes a techno-economic assessment of producing hydrogen in Australia and storing and transporting it. The results of CSIRO's analysis have been used as an important input for this report. The analysis for this report has also been provided to CSIRO to help inform their report.

1.2 Why hydrogen for export?

Hydrogen offers a potential solution for the large-scale export of low or zero emissions energy. Unlike renewable electricity which could be transferred through high voltage direct current cables, it can be stored at relatively low cost, exported to any destination with appropriate import facilities, and is less dependent on a single piece of infrastructure. Compared with biofuels and synthetic fuels, hydrogen supply chains produce fewer lifecycle GHG emissions, with none produced at the point of use.[19]

Hydrogen is also very versatile, with potential applications in electricity production, direct combustion and as a transport fuel in fuel cell electric vehicles. This range of applications across energy sectors gives flexibility in being able to meet the demands of the importing country, provides opportunities for wide decarbonisation, and reduces the risk of oversupply and stranded assets, as uptake markets are diverse.

1.3 Why now?

Hydrogen as a globally traded commodity for energy is not a new concept. A 'hydrogen economy' was discussed as long ago as the early 1970s as a means of trading nuclear energy.[20] In the 50 years since then the technology for hydrogen production and its use as a source of energy has continued to progress and the economic competitiveness of hydrogen has continued to improve. However, the main reason for the re-emergence of global interest in hydrogen is the growing pressure on countries to reduce their emissions.

Signatories to the 2015 Paris Climate Accord agreed that addressing climate change requires capping and reducing greenhouse gas emissions as soon as possible if the world is to limit global temperature rise this century to 2 °C at a minimum. As the world transitions to low emission energy sources such as wind and solar, countries without the capacity to produce enough low carbon energy to meet their Paris commitments, will increasingly seek to import low or zero emissions energy. Hydrogen, as a tradable source of low emissions energy, could provide at least part of growing demand for clean energy supplies.

Hydrogen is not currently cost competitive with exported fossil fuels, however the increasing maturity of relevant technologies have reduced the cost gap significantly in recent years, with technologies predicted to become even cheaper in the future.[21] In combination with recent cost reductions in large scale renewable energy production, this cost gap could be small enough to be closed by policy drivers

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[18] Hydrogen Scaling Up, Hydrogen Council, 2017

[19] High temperature hydrogen combustion (>800 °C), used in gas turbines to produce electricity, results in NOx emissions that need to be scrubbed from stacks. M. Ilbas et al., Int. J. Energy Res. 2005, 29, 973-990

[20] Bockris JO'M Science, 1972, Vol. 176, Issue 4041, pp. 1323

[21] CSIRO, National Hydrogen Roadmap, 2018

that aim to help countries to meet their national emissions targets, making hydrogen an economically viable energy option.

BOX 1.1 summarises the factors that could help drive the emergence of a global hydrogen export market.

BOX 1.1 DRIVERS FOR HYDROGEN DEMAND

Drivers that will encourage the emergence of a global hydrogen market include:

- the need to reduce greenhouse gas emissions to meet international commitments
- the lack of sufficient in-country resources to meet own demand
- meeting transport needs as internal combustion engines are phased out
- decarbonising natural gas networks
- the use of hydrogen as a means of energy storage to help manage the variability of renewable energy
- support for hydrogen related R,D&D (that will help to drive down costs)
- established energy trading relationships and infrastructure
- policies and programs that support hydrogen

SOURCE: ACIL ALLEN

1.4 Why Australia?

Australia’s availability of land, high quality renewable energy resources and fossil energy resources located close to potential carbon sequestration sites, position Australia well for becoming a key exporter in a future global hydrogen market. Australia’s well-established reputation for undertaking large-scale projects and being a reliable supplier of conventional energy resources also reduces risks particularly for first movers in this space. This further reinforces Australia’s position as a favoured potential hydrogen trading partner.

Although other countries are also seeking to develop their own hydrogen production capabilities, not all will be able to scale up production sufficiently to meet potential future domestic demand. Australia’s competitive advantage could be particularly relevant in the near to mid-term in several key markets (see discussion in Chapter 4) which may have demand for imported hydrogen.

1.5 The structure of this report

This report provides an analysis of the hydrogen export market opportunity for Australia, in the near (2025), medium (2030) and long term (2040).

The first element to this analysis was a review of the current literature, the findings of which are presented in Chapter 2. This research informed the agreed methodology and underlying assumptions for the modelling used in this study and provided a basis for identifying the drivers and criteria for assessing the future demand for hydrogen from potential markets and what countries might compete with Australia to supply that demand. From this, four key potential markets for hydrogen from Australia, and countries that could compete for these markets were identified.

Chapter 3 details the approach used to model the demand (in PJ) for, and price (in dollars) of, hydrogen in the four countries identified as key markets for Australia, and the parameters for low, medium and high scenarios for hydrogen uptake. The results of the modelling were also used to develop the outlook for global hydrogen demand.

Chapter 4 then considers the drivers of competitive advantage in meeting the global demand for hydrogen and analyses Australia’s position compared to other potential suppliers. Australia’s likely market share of demand for hydrogen in each key market is then analysed to derive Australia’s likely total hydrogen export market.

The potential economic benefits, including employment, that might result if Australia is able to capture the projected demand for hydrogen from the priority markets and globally is discussed in Chapter 5.

This Chapter also considers some of the possible next steps that Australia could take to help realise the identified opportunities for exporting hydrogen.

More detail on the modelling, the underlying assumptions and data used for of each of the identified priority markets, and the literature review are provided in the appendices to this report.

2

OVERVIEW OF THE EMERGING GLOBAL HYDROGEN MARKET

2.1 Aims of literature review

As outlined in Chapter 1, a literature review of current analyses of hydrogen market uptake was undertaken. A summary is provided here, with the full review at Appendix A.

Several reports on the future demand for hydrogen, roadmaps for uptake, and scenarios under which hydrogen is likely to see significant growth were reviewed. The review sought to compile and compare the findings and analysis conducted in these publications to inform and provide a basis for this study. The literature review also assessed national strategies, planned developments and stated intentions regarding the use of energy and, in particular, the role of hydrogen. Its five main objectives were to:

- inform the methodology and assumptions used in the modelling for this study
- identify the criteria and drivers that influence future hydrogen demand
- determine the key markets for hydrogen exported from Australia
- identify Australia's key competitors for supplying potential markets
- provide an outlook of the global hydrogen landscape.

Quantities of hydrogen are presented in the literature in a variety of units. To aid comparison, this study reports hydrogen in joules and or kilograms. A conversion table is provided in Appendix A.

It should be noted that at the time of this study there was a high level of commentary and analysis about the hydrogen sector. The literature review sought to draw on the most reliable, up-to-date information.

2.2 The findings of the literature review

2.2.1 Global drivers of hydrogen

As discussed in Chapter 1, there is growing interest in the production and use of hydrogen for use as an energy carrier. A key driver for this is the need to meet the emissions reductions that countries have agreed to under the 2015 Paris Climate Accord. Signatories to the Accord have agreed that addressing climate change requires capping greenhouse gas emissions as soon as possible to limit global temperature rise this century to 2°C at a minimum and ideally to 1.5°C.[22]

The 2017 edition of the International Energy Agency's *World Energy Outlook* identifies hydrogen as a potentially important mechanism for reducing emissions. It states that:

> *Hydrogen could play a role in the low-carbon transition in a variety of ways. At present the largest user of hydrogen in the energy sector is industry, where hydrogen is created by steam reformation of natural*

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[22] de Valladres M-R 2017, Global Trends and Outlook for Hydrogen, IEA Hydrogen Technology Collaboration Program, December 2017.

gas and consumed on-site in the manufacture of ammonia and methanol or in the refining sector. To be useful in the energy transition, however, hydrogen will need to be generated using low- or zero-carbon energy sources and is likely to need to be transported over longer distances.[23]

Current world production of hydrogen is around 55 million tonnes (6,600 PJ), almost all of which is for non-energy purposes. Most hydrogen is used in petroleum refining, fertiliser production, methanol production, metallurgy and food production.

Estimates of the proportion of hydrogen currently used for energy vary but are all very small,[24] estimated to be around 1 or 2 per cent of total consumption of hydrogen.[25, 26] The Hydrogen Council's vision for hydrogen, however, envisages that the current main uses of hydrogen will be replaced by the following seven applications:[27] [28]

1. Enabling large-scale renewable energy integration and power generation
2. Distributing energy across sectors and regions
3. Acting as a buffer to increase energy system resilience
4. Decarbonizing transportation
5. Decarbonizing industrial energy use
6. Helping to decarbonize building heat and power
7. Providing a clean feedstock for industry.

These applications are also explored in the CSIRO National Hydrogen Roadmap.[29]

Projecting the future global demand for hydrogen in applications where hydrogen is used as an energy source (energy applications as opposed to industrial applications) is a challenging task as the use of hydrogen in energy applications is still at a relatively early stage of adoption. As noted above, current utilisation of hydrogen in energy applications is a very small percentage of total hydrogen consumption and projecting increases from such a very low base introduces a large degree of uncertainty.

The literature review identified a small number of estimates of growth in the total demand for hydrogen, and of the total demand for hydrogen for energy use (see **Table 2.1**).

Figure 2.1 illustrates several potential hydrogen demand projections. These projections vary significantly. One difference arises from the different volumes of hydrogen demand used as a starting point, the majority of which is in the non-energy sector. Another difference lies in their period of projection, with the Hydrogen Council Report giving a forecast which reaches 2050, compared to the Persistence Market Research projection which reaches only to 2020.

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[23] World Energy Outlook 2017, International Energy Agency, Paris, 2017, page 467

[24] Unless otherwise specified, references to hydrogen supply or demand in this report relate solely to its use as an energy carrier.

[25] Kim J-W 2008, Current Status of R&D on Hydrogen Production and Storage in Korea, presentation to the Materials Innovations in an Emerging Hydrogen Economy Conference, February 2008.

[26] Bakenne A, Nuttall W and Karzantzis N 2016, Sankey Diagram-based insights into the hydrogen economy of today, International Journal of Hydrogen Energy, 41(19) pp. 7744–7753, accessed on 14 March 2018, https://www.sciencedirect.com/science/article/pii/S0360319916308795?via%3Dihub .

[27] The Hydrogen Council is an industry-led group seeking to promote the development of the hydrogen economy. It was launched in January 2017 at the World Economic Forum. Its members include companies that invest along the hydrogen value chain.

[28] Hydrogen Council 2017, Hydrogen scaling up: A sustainable pathway for the global energy transition accessed on 18 June 2018 at http://hydrogencouncil.com/wp-content/uploads/2017/11/Hydrogen-Scaling-up_Hydrogen-Council_2017.compressed.pdf

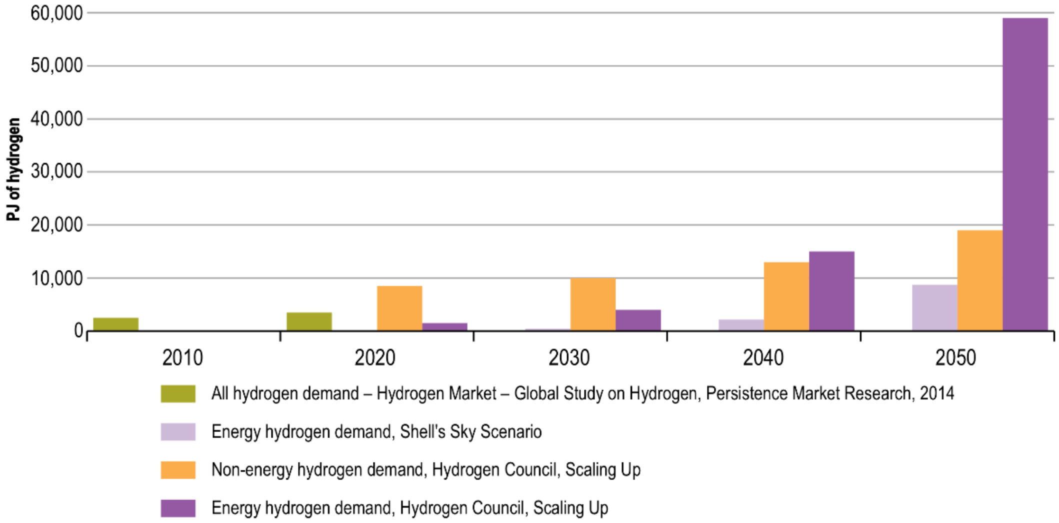
[29] CSIRO 2018, CSIRO, National Hydrogen Roadmap

TABLE 2.1 EXAMPLES OF VARIOUS PROJECTIONS FOR THE GROWTH OF HYDROGEN DEMAND

Source	Period of Projection	CAGR	Comments
Persistence Market Research	2014 to 2020	3.5%	The projection was for total hydrogen demand. The Asia Pacific market accounted for much of the growth.[30]
Research and Markets	2017 to 2021	6%	The projection was for total hydrogen demand.[31]
Shell's Sky Scenario	2020 to 2040 (only projections to 2050 are shown)	23%	The Sky Scenario models and energy mix was specifically designed to reach the Paris Agreement's goal in a technically possible manner.[32].
Hydrogen Council Scaling Up	2020 to 2050	35% to 2040 28% to 2050	The CAGRs shown are for demand for the use of hydrogen for energy use. Presents an ambitious vision of the future hydrogen sector.[33]

SOURCE: ACIL ALLEN BASED ON VARIOUS SOURCES

FIGURE 2.1 GLOBAL DEMAND FOR HYDROGEN ACCORDING TO DIFFERENT SOURCES



SOURCES: PERSISTENCE MARKET RESEARCH, SHELL AND HYDROGEN COUNCIL

Although the projected rate of growth for demand for hydrogen for energy varies, current analyses agree that the sector will grow rapidly between 2030 and 2040. There are also several other market indicators that point to an upward trend, including:

- fuel cell shipments grew five-fold from 100 MW in 2011 to nearly 500 MW in 2016
- the absence of technical barriers to commercialisation of light duty FCEVs (there may be other barriers such as safety (real and perceived, capital costs of infrastructure, etc)
- investment in hydrogen refuelling station infrastructure
- the number of FCEV deployment projects
- the development of large-scale projects such as the H21 Leeds City Gate gas network conversion project[34]
- Japan's strategy around development of its hydrogen sector (further outlined in Chapter 3)

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[30] Hydrogen Market – Global Study on Hydrogen, Persistence Market Research, 2014

[31] Global Hydrogen Generation Market Report 2017 – Forecasts to 2021, https://www.researchandmarkets.com/research/2n49kh/global_hydrogen , accessed April 2018

[32] Sky Scenario 2018, accessed on 27 April 2018 at https://www.shell.com/energy-and-innovation/the-energy-future/scenarios/shell-scenario-sky.html

[33] Hydrogen Council 2017, Hydrogen scaling up: A sustainable pathway for the global energy transition accessed on 18 June 2018 at http://hydrogencouncil.com/wp-content/uploads/2017/11/Hydrogen-Scaling-up_Hydrogen-Council_2017.compressed.pdf

[34] https://www.northerngasnetworks.co.uk/wp-content/uploads/2017/04/H21-Executive-Summary-Interactive-PDF-July-2016-V2.pdf

- investment in hydrogen technology development.

In addition to indicators that are specific to hydrogen, other related factors indicate the potential for growth in the sector, mainly concerning emissions reduction. One of the major advantages of hydrogen, is its role in decarbonisation of all energy sectors; transport, residential heating and power, electricity storage and industrial processes. This means that drivers that are put into place to lower emissions in any sector is likely to positively influence hydrogen uptake, albeit to differing extents and on different time frames.

Electricity is probably the easiest energy sector to decarbonise, as the technology to produce electricity from renewables is currently commercial. The challenges lie in the large-scale grid integration, and the dispatch of variable renewable energy (VRE), in which hydrogen could play a role. As the proportion of VRE increases, the role of hydrogen for electricity storage and generation is likely to increase. Continued growth in the renewable energy for electricity sector is widely forecast, and this growth is likely to also be reflected in the hydrogen sector.

There are an increasing number of announcements by governments regarding the phasing out of internal combustion engines (ICEs) in order to reduce overall emissions and improve air quality.[35] The two current alternatives, battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs) are likely to see an increase in uptake with the decrease in ICEs. Although BEVs are likely to capture most of the independently owned light vehicle market,[36] FCEVs are likely to replace ICEs in long-distance heavy vehicles (such as trucks[37] and even trains[38]) and could see more uptake in fleet vehicles. Importantly, any drivers to reduce emissions in the transport sector will promote growth in the demand for hydrogen in the transport sector.

BOX 2.1 THE IMPORTANCE OF FCEVs FOR A HYDROGEN MARKET

One of the major advantages of hydrogen in energy applications is its ability to replace liquid hydrocarbons as an energy source in transport applications. This is one of the reasons why hydrogen powered FCEVs have attracted so much attention and why the emergence of FCEVs could become a major driver of demand for low-carbon hydrogen (for example, in Korea, Japan and China). While gas-to-power and household consumption of hydrogen are also important, use of hydrogen in transport applications is seen by many countries as more promising source of hydrogen demand growth over the next decade.

SOURCE: ACIL ALLEN CONSULTING

The replacement of natural gas with hydrogen in distribution networks, for space heating, residential water heating and cooking, provides a possible solution for decarbonisation in a sector with few options for emission reduction (the viable alternatives being electrification or the use of biogas). Although this is likely to be a longer-term application for hydrogen, the potential scale for uptake is vast. The injection of hydrogen into existing networks even at low proportions (10 per cent is accepted as a feasible blend, but up to 25 per cent has been demonstrated) would create huge demand for hydrogen. This sector is forecast to see hydrogen uptake in the longer term as part of deep decarbonisation and will be increasingly used to cut emissions after 'low hanging fruit' solutions are achieved. Injecting hydrogen into natural gas networks is a real possibility — ATCO has just announced an ARENA-supported project in Western Australia which will merge solar, battery storage and gas backup generators as well as feeding hydrogen into a gas pipeline to supplement that State's gas resources.[39] A project in Leeds (United Kingdom) is seeking to fully convert a gas network to carry 100% hydrogen gas.[40]

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[35] The UK has announced a policy to halt production of ICE vehicles by 2040, France has said it intends to ban the sale of petrol and diesel cars in 4040, and Germany, Ireland, Slovenia, Netherlands want to phase out the sale of ICE vehicles by 2030. China and India have also indicated their intention to move away from ICEs.

[36] Bloomberg, New Energy Outlook, June 2018

[37] https://www.theverge.com/2018/5/3/17314606/anheuser-busch-budweiser-hydrogen-trucks-zero-emission-startup-nikola

[38] https://www.telegraph.co.uk/business/2018/05/14/french-train-giant-alstom-set-make-uks-first-hydrogen-fleet/

[39] Evans N 2018, Hydrogen project to turn water into power, The West Australian, 3 July 2018, accessed on 4 July 2018 at https://thewest.com.au/business/energy/wa-hydrogen-project-to-turn-tap-water-into-power-ng-b88883921z

[40] https://www.northerngasnetworks.co.uk/wp-content/uploads/2017/04/H21-Report-Interactive-PDF-July-2016.compressed.pdf

Ultimately, global demand for hydrogen will depend upon a range of factors. The extent to which countries aim to cut emissions, the price consumers are asked to pay for the resource and the suitability of hydrogen as an alternative to existing forms of energy (such as to provide power, heat or mobility) will be important factors influencing demand. As with most new technologies the rate of adoption will be strongly influenced by the relative merits of hydrogen compared to other, low emission technologies, and government policies that are either designed to encourage the use of hydrogen (such as subsidies for fuel cells) or discourage existing use of fossil fuels (such as carbon prices).

The following section examines the outlook for hydrogen demand in several potential markets, and the likely requirement to import hydrogen

2.2.2 Potential demand for hydrogen in various markets

The literature review examined factors that might influence potential demand for hydrogen in nine markets: China, Japan, the Republic of Korea (Korea), Singapore, Taiwan, Thailand, India, California and the European Union. These markets were selected as the most prospective for the emergence of a hydrogen energy sector. Each of these markets was analysed to assess the likelihood that they might become importers of hydrogen from Australia. For more details of the basis for this selection see the full report on the literature review in Appendix A.

The review considered the following factors:

- population, economic growth and energy demand
- existing energy market and reliance on imported energy
- commitments to meeting emission reduction targets
- constrained ability to meet those targets by other means
- current hydrogen-related activity
- support for hydrogen-related development
- government policies.

The Peoples Republic of China

China's primary energy consumption is predicted to grow by a massive 1,213 Mtoe in the period 2014-40.[41] China has gone through a period of rapid construction of modern coal-fired power stations and is now giving more attention to emissions reduction strategies. China's capacity to generate low-carbon hydrogen is limited. There is wind and solar PV power capacity in western China but much of its energy demand is in the east and on the coast.

There is limited reference to hydrogen in China's Strategic Action Plan for Energy Development 2014-2020. However, the 13th National Five-Year Plan identifies "new energy vehicles" as one of six emerging technologies that will receive particular attention. The plan states that there will be a total of 5 million 'new energy' vehicles across the country by the end of the five-year plan.[42]

Several Chinese firms and provinces have announced ambitious plans to produce fuel cells and FCEVs. China plans to have the capacity to produce about 170,000 FCEVs annually.[43]

One of China's leading experts on hydrogen energy and fuel cell research estimates that China is now investing more than RMB 100 billion ($A20 billion) in hydrogen energy R&D.[44]

Based on an analysis of the documents reviewed for this report, ACIL Allen believes that the most likely prospect for hydrogen use in China is as a fuel for FCEVs, although there will of course be competition from BEVs.

There is also scope for hydrogen to be used by households, either directly in combined heat and power fuel systems or indirectly through injecting hydrogen into the natural gas system.

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[41] IEEJ 2016, Asia/World energy outlook 2016, accessed on 3 July 2018 at https://eneken.ieej.or.jp/data/7199.pdf

[42] Unofficial translation of the 13th Five Year Plan, personal communication, 28 April 2018.

[43] Mao ZQ 2018, China Homes in on hydrogen, accessed on 15 April 2018 at https://medium.com/@cH2ange/china-homes-in-on-hydrogen-977b37ddcca9

[44] Mao ZQ 2018 Op cit. This estimate appears to include all hydrogen-related R&D expenditure including fuels cells and R&D by both public and private sectors. It is not clear whether the estimate is for the period of the five-year plan of just one year. In either case, it is a very large figure.

Japan

Japan has taken concrete steps to move towards a ‘hydrogen society’. The Japanese Government’s *Strategic Roadmap for Hydrogen and Fuel Cells* was adopted in 2014[45] and revised in 2017.[46] It has three elements:

- a dramatic expansion of hydrogen utilisation
- full-scale introduction of hydrogen power generation and establishment of a large-scale hydrogen supply system, and
- the eventual establishment of a totally carbon dioxide-free hydrogen supply system which will be provided in part from imports. [47]

Hydrogen also plays a key role in Japan’s 5th Basic Energy Plan, currently under review.[48] The government has also supported the deployment of residential fuel cells. These provide heat and power. Currently Japan is using natural gas to produce hydrogen which is then used to generate electricity and heat from a hydrogen fuel cell. Almost 200,000 residential micro-combined heat and power fuel cells had been sold by 2017.[49] The Japanese Government has signalled that it expects to require 300,000 tonnes (36 PJ) of hydrogen per annum by 2030 and that this will be met in part by “international hydrogen supply chains”.[50]

Japan is making significant investments in hydrogen-related R&D.[51] For example, the METI budget for R&D for fiscal year 2017 is more than ¥ 8 billion (or about $100 million). Japan’s Kawasaki Heavy Industries (KHI) has partnered with the Australian and Victorian governments in a project to demonstrate the ability to create a hydrogen supply chain between Australia and Japan. This project plans to liquefy the hydrogen produced and transport it to Japan in specially-constructed ships.

KHI has also teamed up with Norway’s Nel Hydrogen and Statoil and Japan's Mitsubishi Corp to undertake a project to demonstrate that liquefied hydrogen can be produced using renewables (hydro power) in Norway and delivered to Japan in tankers.[52]

A consortium of four Japanese companies (Mitsubishi, Nippon Yusen, Chiyoda and Mitsui) has announced plans for a demonstration plant in Brunei that will export hydrogen to Japan by January 2020. The demonstration project is scheduled to operate for a year and is expected to supply 210 tonnes of hydrogen to Japan. The hydrogen will be produced by steam reforming of natural gas. It will then be mixed with toluene, converting it to methylcyclohexane, and exported as a liquid. The initiative is being funded by Japan’s New Energy and Industrial Technology Development Organisation.[53]

ACIL Allen believes that the best short-term prospects for hydrogen use in Japan are to fuel FCEVs and in use in fuel cells for heat and power production in domestic households. Japan’s current roadmap also foresees a significant role for hydrogen in large scale power generation. This appears to be a longer-term objective, given where Japan is currently positioned in this area of application. Injection of hydrogen into the natural gas system is another option.

Republic of Korea

The Republic of Korea (Korea) lacks domestic energy resources and is one of the top energy importers in the world, relying on imports for about 98 per cent of its fossil fuel consumption. Korea

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[45] Agency for Natural Resources and Energy 2014, Summary of the Strategic Road map for Hydrogen and Fuel Cells, provisional translation, accessed on 14 March 2018 at http://www.meti.go.jp/english/press/2014/pdf/0624_04a.pdf

[46] METI 2018, Basic Hydrogen Strategy (key points) accessed on 18 June 2018 at http://www.meti.go.jp/english/press/2017/pdf/1226_003a.pdf

[47] Ministry of Economy, Trade and Industry Agency for Natural Resources and Energy, 2016, Compilation of the Revised Version of the Strategic Roadmap for Hydrogen and Fuel Cells, accessed on 15 March 2018 at http://www.meti.go.jp/english/press/2016/0322_05.html

[48] See https://www.numo.or.jp/topics/1-1Nakanishi.pdf

[49] Yamazumi M and Kawamura S 2017, International Partnership for Hydrogen and Fuel cells in the Economy (IPHE), Japan Country Update, April 2017, accessed on 15 March 2018 at https://www.iphe.net/japan

[50] METI 2018, Op cit. page 4.

[51] Akiba E 2017, Hydrogen energy R&D: The roadmap and state of art of Japan, and activities of Kyushu University, presentation to the 8th World Renewable Energy Technology Congress, New Delhi, 22 August 2017, accessed on 28 April 2018 at http://wretc.in/presentation/2017/Day2/Session-7/Akiba.pdf

[52] See https://mobile-reuters-com.cdn.ampproject.org/c/s/mobile.reuters.com/article/amp/idUSKBN17U1QA accessed 23 May 2018.

[53] Chiyoda Corporation, accessed on 18 June 2018 at https://www.chiyodacorp.com/en/service/spera-hydrogen//

ranks among the world's top five importers of liquefied natural gas, coal, crude oil, and refined products.

The Korean Government has recently announced an investment of $2.33 billion over the next five years to accelerate the hydrogen sector. The funds are earmarked for hydrogen projects across several sectors, including the construction of 310 refuelling stations, FCEV and fuel cell stack manufacturing plants, deploying FCEV buses, producing hydrogen from natural gas and developing hydrogen storage technologies.[54] The scheme is a public-private partnership and supports Korean car makers' aims to have the capacity to manufacture more than 200,000 FCEVs a year by 2020. This is projected to be more than 13 per cent of the global market for FCEVs.[55]

The announcement builds on Korea's 4th Basic Plan for New and Renewable Energy (NRE) Technology and Development and Usage/Distribution launched in September 2014, which seeks to promote new and renewable energy (NRE) and to increase the share of NRE in the total energy supply to 11 per cent by 2035. The Korean government subsidises the installation of NRE systems by businesses (by up to 50 per cent of the cost of systems). A subsidy for installation of NRE facilities in homes is also available.

Korea's level of interest in low-carbon hydrogen remains to be established. Nonetheless, their introduction of an emissions trading scheme[56] suggests that low emissions fuels will become increasingly attractive over time, providing an opportunity for Australian exports of hydrogen. The likely prospects for hydrogen use in Korea are in FCEVs and fuel cells for power production. There is also an option to decarbonise the natural gas system by injecting hydrogen into it.

Singapore

The Singapore government has adopted policies that could encourage the introduction of fuel cell electric vehicles (FCEVs). All facilities in Singapore producing over 25,000 tonnes of greenhouse gas emissions a year will pay a carbon tax of $S5 per tonne from 2019. The Government plans to review the carbon tax rate by 2023, with a view to increasing it to between $10 and $15 per tonne of emissions by 2030.[57]

Singapore is conducting R&D into fuel cells and hydrogen technologies.[58] Singapore also has a facility on Semakau Island that produces hydrogen from solar and wind energy. This will support a micro-grid on the Island, which is expected to be operational in October 2018.[59] However, Singapore is not well placed to generate sufficient low-carbon hydrogen to meet all its potential demand for hydrogen in energy applications.

The most likely prospect for hydrogen use in Singapore is as fuel for FCEVs. With some 574,000 vehicles on the island, the market for hydrogen is unlikely to be large. However, it could, in the right circumstances, provide a good opportunity to demonstrate the feasibility of establishing a hydrogen supply chain.

Taiwan

Taiwan is a leader in fuel cell R&D. Fuel cell systems manufactured in Taiwan can be found around the world. However, the adoption of FCEVs has been slow. For a period, there was a lack of government interest in their development.[60]

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[54] See http://www.greencarcongress.com/2018/06/20180625-korea.html

[55] Electric Vehicle Association of Asia Pacific (EVAAP) undated, Korea, accessed on 16 April 2018 at http://www.evaap.org/electric/Psgubun-7_electric.html

[56] International Carbon Action Partnership 2018, Korea Emissions Trading Scheme, accessed on 18 June 2018 at https://icapcarbonaction.com/en/?option=com_etsmap&task=export&format=pdf&layout=list&systems%5B%5D=47

[57] Tan A 2018, Singapore Budget 2018: Carbon tax of $5 per tonne of greenhouse gas emissions to be levied, The Straits Times, 19 February 2018, accessed on 16 April 2018 at http://www.straitstimes.com/singapore/singapore-budget-2018-carbon-tax-of-5-per-tonne-of-greenhouse-gas-emissions-to-be-levied

[58] Chan SH, Stempien JP, Ding OL, Su P-C and Ho HK 2016, Fuel cell and hydrogen technologies research, development and demonstration activities in Singapore – an update, International Journal of hydrogen energy, 41, 13869 -13878

[59] The Straits Times 2017, A tiny island off Singapore may hold answers to energy's future, 25 May 2017, accessed on 4 July 2018 at https://www.straitstimes.com/business/companies-markets/a-tiny-island-off-singapore-may-hold-answers-to-energys-future

[60] Hwang H-S 2012, Progress and prospects for renewable energy in Taiwan, Woodrow Wilson Centre Asia Program, Special Report No 146

Thailand

The Thai government has shown some interest in hydrogen. It has supported a small hydrogen-powered housing project in Chiang Mai (producing hydrogen from photovoltaic roof panels, with battery storage). Thailand has set a new renewable energy target of 30 per cent of total final energy consumption by 2036 in its 2015 Alternative Energy Development Plan.[61]

However, documents reviewed for this report suggest that the Thai market for hydrogen is very limited with limited prospects for growth in the near to medium term.

India

India's first National Hydrogen Energy Road Map was released in 2006. However, there is little evidence of any movement towards a hydrogen economy since then. A New Road Map on hydrogen energy and fuel cells was issued in 2016.[62] It projected that there would be one million FCEVs and a total of 1000 MW hydrogen-based power generating capacity in India by 2020.

India could eventually be a significant market for hydrogen. A recent report on India's economic strategy to 2035 identified hydrogen as an area where there were emerging prospects.[63] However, the slow rate of progress to date suggests that it is unlikely to be a market for imported hydrogen in the short to medium term.

California

The California state government is highly pro-active in adopting measures to reduce CO_2 (and other airborne emissions) to improve air quality (particularly in Los Angeles) and to reduce greenhouse gas emissions. Its policies favour renewable / clean energies including hydrogen. It subsidises the installation of combined heat and power co-generation systems including fuel cells.

In February 2013, California issued the 2013 Zero Emission Vehicles (ZEV) Action Plan that includes actions for state agencies to meet a goal of 1.5 million ZEVs by 2025. A 2013 State law provided funding for at least 100 hydrogen fuelling stations with a commitment of $US20 million per annum. In May 2014, the California Energy Commission approved almost $US50 million to add 28 new hydrogen refuelling stations to the nine existing stations and the 17 stations currently being developed. There are also state government incentives to use hydrogen to power fuel cell buses.[64]

The availability of cheap local hydrogen from steam reforming of methane makes it unlikely that California would import Australian renewable hydrogen, particularly since California also has the potential to install its own solar power stations to produce renewable hydrogen. However, the difficulty of storing significant quantities of hydrogen in earthquake-prone California could make supply from Australia attractive because the ships carrying hydrogen to California would, in effect, provide the equivalent of storage.

The European Union

In 2016, the Hydrogen Mobility Europe Initiative launched a six-year Hydrogen Mobility Europe 2 (H2ME 2) project[65] across Europe to promote the deployment of hydrogen refuelling infrastructure and passenger and commercial fuel cell vehicles.[66] This includes the deployment of 1,230 fuel cell vehicles and the addition of twenty hydrogen refuelling stations to the existing European network.

Several EU member countries have developed hydrogen policies and road maps. For example, Germany's National Hydrogen and Fuel Cell Technology Innovation Program recently announced it

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[61] International Renewable Energy Agency (IRENA) 2017, Renewable Energy Outlook-Thailand, accessed on 15 April 2018 at http://www.irena.org/publications/2017/Nov/Renewable-Energy-Outlook-Thailand

[62] Hydrogen Energy and Fuel Cells in India - A way forward, Ministry of New and Renewable Energy, June 2016

[63] An India Economic Strategy to 2035 - Navigating from Potential to Delivery, A report to the Australian Government by Mr Peter N Varghese AO, April 2018.

[64] IEA 2015, National Strategies and Plans for Fuel Cells and infrastructure

[65] FCH 2018, H2ME 2, accessed on 18 June 2018 at http://www.fch.europa.eu/project/hydrogen-mobility-europe-2

[66] FCH 2016, Europe prepares to expand hydrogen refuelling infrastructure network and vehicle fleet, accessed on 16 April 2018 at http://www.fch.europa.eu/press-releases/h2me-2-europe-prepares-expand-hydrogen-refuelling-infrastructure-network-and-vehicle

would provide Siemens and RWTH Aachen with €12 million to support research into next-generation fuel cells.[67]

In June 2018 France announced a €100 million ($156 million) Hydrogen Deployment Plan.[68] The objectives of the Plan reportedly include:

- Creating a carbon-free industrial sector, with targets of 10 per cent decarbonised hydrogen for industrial use by 2023 and between 20 and 40 per cent by 2028.
- Establishing a hydrogen certification scheme by 2020 and ensuring that the regulation of greenhouse gases will classify hydrogen according to its mode of production.
- Developing renewable energy storage demonstration projects in remote areas.
- Preparing a report on the technical and economic feasibility of hydrogen injection into gas networks by end 2018.
- Deploying systems to allow H_2 mobility. Targets include 5 000 light commercial vehicles and 200 heavy vehicles 100 hydrogen refuelling stations by 2023, 20,000 to 50,000 light commercial vehicles, 800 to 2,000 heavy vehicles and 400 to 1,000 stations by 2028.
- Putting in place regulations on safety and risk prevention, including a specific regulatory framework for hydrogen distribution stations by mid-2018.
- Supporting the creation of an international training centre to provide certification of high-pressure hydrogen components for hydrogen in uses such as vehicles, aviation, marine, and railways.

The UK published a hydrogen and fuel cell road map in 2016,[69] which argued that there would be significant benefits to the UK from early adoption of hydrogen fuel cell technology. Significant government support is being provided to the H21 Leeds City Gate project which aims to demonstrate the feasibility of converting the existing natural gas network in Leeds (one of the UK's largest cities) to 100 per cent hydrogen.

Several countries in Europe are moving quite rapidly to adopt hydrogen as a fuel source. The major gas supply companies and Shell are already starting to provide low-carbon hydrogen in Europe using renewable energy sources. Iceland is also a potential source of hydrogen supplies to Europe, although earlier plans to develop hydrogen production have not proceeded.[70] In addition, there is an EU-funded project in the Orkney Islands to generate hydrogen from surplus renewable sources (tidal, wind and wave).[71]

ACIL Allen does not see significant prospects for exports of Australian hydrogen to the EU over the time period for this study because of the EUs capacity to supply its own demand and the potential for trade in hydrogen between EU countries to occur via pipeline.

2.3 Selection of four prospective importing countries

The literature review was used to help identify those countries most likely to see an increase in their hydrogen use and which were also likely to be potential importers of hydrogen from Australia.

Four countries were selected for further modelling using the following criteria:

- the likely size of the potential hydrogen import market—an indicator which combines:
  - expected energy demand and growth
  - reliance on imported energy
  - inability to supply own hydrogen
  - likely growth in demand for hydrogen

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[67] Smith K 2018, International Railway Journal, 26 February 2018, German government supports hydrogen fuel cell research, accessed on 16 April 2018 at http://m.railjournal.com/index.php/rolling-stock/german-government-supports-hydrogen-fuel-cell-research.html

[68] https://mcphy.com/en/press-releases/a-national-plan-for-hydrogen-launched-in-france/

[69] E4tech and Element Energy 2016, Hydrogen and fuel cells: Opportunities for growth, accessed on 16 April 2018 at http://www.e4tech.com/wp-content/uploads/2016/11/UKHFC-Roadmap-Final-Main-Report-171116.pdf

[70] Worldwatch Institute 2018, Missing in action: Iceland's hydrogen economy, accessed on 18 June 2018 at http://www.worldwatch.org/node/4664

[71] Ward A, 2018, Orkney project shows potential of hydrogen as a fuel source, Financial Times, 8 January 2018, accessed on 16 April 2018 at https://www.ft.com/content/f5e8c5aa-d8ee-11e7-9504-59efdb70e12f

- government policies encouraging the use of hydrogen, which reflects:
  - incentives for low-carbon hydrogen and FCEVs
  - provision of hydrogen infrastructure
  - rate of introduction of FCEVs (as noted earlier, a major driver of demand)
  - rate of introduction of other uses of hydrogen (e.g. combined heating and power—CHP)
  - R&D support for fuels cells, hydrogen production, storage, transport and distribution
  - greenhouse gas and air pollution concerns that lead to a need to adopt lower emission fuels
- Australia's competitive position for providing hydrogen compared to other potential hydrogen producers.

ACIL Allen's assessment of hydrogen market potential, against the criteria listed above, is presented in **Table 2.2**. The final row compares Australia's position to other potential suppliers of hydrogen.

TABLE 2.2 HEAT MAP OF HYDROGEN MARKET POTENTIAL OF VARIOUS COUNTRIES, CALIFORNIA & THE EU

Criteria	China	Japan	Korea	Singapore	India	Taiwan	Thailand	California	Europe
Size of potential H_2 import market	🟩	🟩	🟩	🟨	🟩	🟩	🟥	🟩	🟩
– Energy demand and growth	🟩	🟩	🟩	🟨	🟩	🟨	🟨	🟩	🟩
– Reliance on imported energy	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
– Inability to supply own H_2	🟨	🟩	🟩	🟩	🟨	🟩	🟩	🟩	🟩
– Likely growth in demand for H_2	🟩	🟩	🟩	🟩	🟨	🟩	🟥	🟨	🟩
Govt policies that support H_2	🟩	🟩	🟩	🟩	🟨	🟨	🟥	🟩	🟩
– Incentives for H2/FCEVs	🟨	🟩	🟩	🟩	🟥	🟥	🟥	🟩	🟩
– Provision of infrastructure	🟨	🟩	🟩	🟩	🟥	🟨	🟥	🟨	🟨
– Introduction of FCEVs	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟨	🟨
– Introduction of other uses for H_2	🟩	🟩	🟩	🟨	🟨	🟩	🟥	🟨	🟨
– R&D support	🟩	🟩	🟩	🟩	🟨	🟨	🟥	🟩	🟩
– GHG/air pollution concerns	🟩	🟩	🟩	🟩	🟥	🟩	🟥	🟩	🟩
Aust's position vs. other suppliers	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟨	🟥

NOTES: Green Boxes indicate a high rating, yellow boxes a medium rating and red boxes indicate a low rating

SOURCE: ACIL ALLEN ANALYSIS

The assessment suggests that China, Japan, the Republic of Korea and Singapore are suitable candidates for further analysis and modelling of their potential to import hydrogen from Australia. All four countries have policies that serve to encourage increased use of hydrogen in the transport sector. Government hydrogen-related R&D investment in China, Japan and Korea is significant. There is also considerable support from the private sector for R&D related to hydrogen and fuel cells. Importantly, Australia has already got well established trading relationships with all four countries.

Three of the four countries chosen have the potential to be significant markets for Australian hydrogen. While the potential market for hydrogen in Singapore is much smaller than the other three, it might prove to be an important market to demonstrate the viability of establishing a hydrogen supply chain.

2.3.1 Hydrogen supply markets

If hydrogen becomes a globally important source of energy, then it is highly likely that there will be many countries that will be unable to produce sufficient hydrogen to meet their own needs. These countries will need to import hydrogen. Many countries will seek to export hydrogen to meet that demand. A global market for hydrogen will emerge, much as there is now a global market for other sources of energy.

Australia's ability to capture a share of any eventual global export market for hydrogen will be determined by a range of factors. These factors will be similar to those that determine its current ability to supply a share of the global market for other energy resources. Australia currently exports liquefied natural gas and, as a result, has experience in establishing energy export markets with some characteristics that are similar to those that would be involved in hydrogen exports. This includes provision of infrastructure (ports, compression facilities), experience in working with shipping companies, negotiation and management skills, etc. The most important factor in determining Australia's ability to capture a share of the global market for hydrogen exports is likely to be the price at which Australia can supply the hydrogen to potential overseas buyers.

Other factors will, of course, also have a bearing, for example:

- The carbon footprint of Australia's hydrogen exports (see **Box 2.2**)
- Australia's record as a reliable supplier of energy exports.
- Australia's reputation as a politically and economically stable country with a strong legal system.

BOX 2.2 THE IMPORTANCE OF THE CARBON FOOTPRINT OF HYDROGEN

The carbon footprint of hydrogen varies. Hydrogen made from 100% renewable electricity and electrolysis has no direct emissions associated with its production, whereas hydrogen made from fossil fuels (such as steam reforming of methane) will have associated greenhouse gas emissions. Those emissions can be reduced by utilising carbon capture and storage and / or offsets. However, this will impact on the cost of production.

Supplies of hydrogen, at least initially, are likely to have a mix of different carbon footprints. However, many of the countries examined in the literature review have made it clear that their long-term intention is to only use hydrogen with low or zero associated greenhouse gas emissions.

The EU has established a certification scheme for hydrogen. The scheme is expected to issue its first Green Hydrogen Guarantee of Origins (GOs) soon. CertifHy GOs will provide information of the source of the product to the customers and allow hydrogen users to track the origin of the product. EU-wide transferable GOs for renewable and low-carbon hydrogen create a new and transparent hydrogen market, enhance market pull and empower consumers.[72]

SOURCE: ACIL ALLEN CONSULTING

2.3.2 Competitor suppliers

The emergence of a global market for hydrogen will see prices set by the competition between different suppliers. ACIL Allen has considered what countries might be potential competitors to supply hydrogen. Such countries could have access to low-cost natural gas and depleted oil wells for CCS. They could also have large areas of land available for PV installations. Proximity to hydrogen markets would also be a significant factor.

MENA countries

Brunei[73] and Middle East and North Africa (MENA) countries[74] could supply Asian (and European) hydrogen markets. Other competitors are more distant from Asian markets and are therefore disadvantaged by the additional transport costs. MENA countries, like Australia, have the potential to access abundant solar energy. They also have well-established export trade in other forms of energy, large reserves of natural gas that could be converted to hydrogen and access to depleted wells to store CO_2 produced in that process. Several MENA countries have already made sizable investments in developing their renewable energy resources.

The International Renewable Energy Agency (IRENA) recently noted that the renewable energy landscape in MENA countries is rapidly evolving and significant developments have taken place. For example, investments in renewables across the region increased almost tenfold from US$1.2 billion to US$11 billion between 2008 and 2016. IRENA notes that:

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[72] http://www.certifhy.eu/news-events/162-the-1st-green-hydrogen-guarantee-of-origins-are-on-the-market.html accessed 1 September 2018.

[73] Brunei was selected because it has a hydrogen demonstration project with Japan. However, other Asian countries could potentially supply hydrogen.

[74] The following countries are typically included in MENA: Algeria, Bahrain, Djibouti, Egypt, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Libya, Malta, Morocco, Oman, Qatar, Saudi Arabia, Syria, Tunisia, United Arab Emirates, West Bank and Gaza, and Yemen. Ethiopia and Sudan are sometimes included.

…several countries in the region are among the global frontrunners in renewable energy development.[75]

IRENA notes that the ambitious targets set by all countries in the region are expected to translate into a combined renewable capacity of 80 GW by 2030, based on national plans to fulfil the countries' ambitions. Examples of such investments include:

- Plans by the Dubai Electricity and Water Authority (DEWA) to invest 81 billion dirhams (A$22 billion) in energy projects in Dubai over the next five years — the bulk of which will be invested into renewables. The DEWA CEO stated that the Authority's strategy is to be 75 per cent renewable by 2050. DEWA expects to exceed their 2020 target of 7 per cent.[76]
- Recent auctions resulted in the world-record solar prices, including, 17.8 US$/MWh for the Sakaka project in Saudi Arabia, 24.2 and 29.9 US$/MWh in Abu Dhabi and Dubai, respectively.
- Morocco has set an ambitious renewable energy target, pledging to increase renewable energy capacity to 42 per cent of total installed capacity by 2020, and 52 per cent by 2030. Implementing this strategy is expected to require investments in renewable energy of more than US$40 billion by 2030.[77]

Other potential competitors

Another potential supplier of hydrogen for export is Iceland. Nearly all of Iceland's electricity and space heating is provided by hydropower or geothermal energy. This constitutes over 70 per cent of all local energy consumption.[78]

Iceland's substantial geothermal energy resources could be used to produce hydrogen. According to Iceland's Ministry for Foreign Affairs and the Department of Natural Resources and Environmental Affairs, the economic and environmentally viable potential for electrical production from renewable resources in Iceland has been estimated at over 50 TWh a year. Currently some 17 per cent of this amount has been harnessed.

Iceland has a longstanding stated intention to develop a Sustainable Hydrogen Economy. There is strong interest in using hydrogen produced using Iceland's renewable energy resources to power on-land transportation and fishing vessels. Iceland is a founding member of the International Partnership for Hydrogen Economy (IPHE) and participates in the Hydrogen Implementation Agreement of the IEA. Several cooperative projects have already been initiated for developing and introducing hydrogen as a fuel carrier for ships and to explore the possibility of exporting hydrogen.

However, Iceland does not have a history of exporting energy and lacks existing infrastructure for exports. It is likely that much of any future hydrogen production in Iceland will be for domestic use, particularly by the power intensive industries that Iceland is striving to attract to use its sustainable energy resources.

Norway is another potential exporter of green hydrogen. It has substantial hydropower resources for producing hydrogen via electrolysis and access to natural gas for steam reformation (and depleted gas and oil wells for storing the CO_2 produced as a result). As mentioned above, KHI from Japan is already collaborating with Norway to explore the potential for low-carbon hydrogen exports. It is questionable whether such exports would be permitted to pass through the Suez Canal. If not, the sea voyage would increase from 13,725 nautical miles (57 days) to approximately 18,361 nautical miles (76 days) around the Cape of Good Hope. In 2017, an LNG tanker made the journey from Hammerfest in Norway to Boryeong in South Korea (via the northern polar route) in only 19 days.[79] By comparison, the sea voyage from Brisbane to Tokyo is 4,248 nautical miles (18 days) and Dubai to Tokyo is 7,708 nautical miles (32 days).

As noted above, Brunei is another potential competitor. Brunei is only 2,980 nautical miles from Tokyo (12.5 days) by sea. The Brunei pilot facility currently under construction will combine hydrogen with toluene to produce methylcyclohexane, a stable liquid at ambient temperature and pressure, which is

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[75] International Renewable Energy Agency undated, accessed on 30 April 2018 at http://www.irena.org/mena

[76] https://www.pv-magazine.com/2018/02/14/siemens-to-work-with-dewa-on-dubais-first-solar-hydrogen-electrolysis-plant/ accessed 30 April 2018.

[77] "Energy & Mines: Renewable for Mines Driving Competitive, Secure and Low-Carbon Power Stations for Mines", Ministry of Energy, Mines, Water and Environment, January 28 – 29, 2016, http://www.mem.gov.ma/SiteAssets/Dicsours/Discours2016/London%20speech%20English.pdf

[78] United Nations undated, accessed on 4 May 2018 at www.un.org/esa/agenda21/natlinfo/countr/iceland/energy.pdf

[79] It is not clear if and when the Northern Sea route is likely to be reliably open all year round.

then shipped to Japan where the hydrogen is then recovered. The remaining toluene can then be shipped back to Brunei to be reused as a carrier. The process could make use of existing infrastructure, and does not require refrigeration or compression.[80] A full life cycle analysis would be required to understand the emissions impact of both chemical conversion steps and the shipping in both directions.

Other countries such as the USA, Chile and various EU member countries could become significant producers of low-carbon hydrogen. However, ACIL Allen expects that most of these countries would, in the first instance, use that hydrogen to meet their own domestic demand rather than produce it for export. In the longer term, if a global market for hydrogen develops, it is possible that other countries could emerge as exporters of hydrogen.

The State of California, which leads the USA in interest in hydrogen, has significant desert land that could be used to generate low-carbon hydrogen from PV sources. However, California's high earthquake risk raises safety concerns for hydrogen storage and port facilities and legislative approvals for such facilities is considered very unlikely.

Transporting hydrogen

This report examines markets for imports of hydrogen, regardless of the form in which the hydrogen is transported. As noted above, there is interest in transporting hydrogen in forms that are more easily handled in shipping, such as ammonia or methylcyclohexane. The fact that ammonia has a higher energy density than liquid hydrogen may make it an attractive mechanism for transporting hydrogen by ship. However, as with any carrier, this needs to be balanced against the energy requirements (and associated emissions) for the conversion of hydrogen to ammonia, and reconversion back to hydrogen at the point of use.

Some 67 per cent of the world's ammonia is manufactured from hydrogen using the Haber-Bosch process, in which hydrogen is manufactured by steam reforming natural gas and combined with nitrogen from the air under pressure at an elevated temperature. This process is very energy and carbon intensive, generating 1.5 kg of CO_2 for every kilogram of ammonia produced.[81] It is possible to reduce these emissions by using renewables to produce the energy required for the Haber-Bosch process. Other production methods are also being investigated.[82] [83]

Hydrogen-powered fuel cells are poisoned by small traces of ammonia, so there are additional costs involved in cleaning hydrogen sourced from ammonia before it can be used in these cells. An alternative would be to use ammonia directly as a fuel. The CSIRO has recently announced trials of a new approach for producing ultra-high purity hydrogen from ammonia using a unique membrane technology that they have developed.[84] If the trials are successful, then the technology could prove to be an important enabler for the export of hydrogen as ammonia.

Japan is researching the direct combustion of low carbon ammonia to produce electricity. The Green Ammonia Consortium was formed under the 'Energy Carriers' element of the cross-ministerial Strategic Innovation Promotion Program.[85] Current research is focussed on reducing NOx emissions at high combustion temperatures.[86] Any eventual development of ammonia-fuelled turbines could lead to increased demand for low carbon ammonia. Ammonia-based fuel cells do exist, but they would need massive performance improvements before they could be used in FCEVs.[87] [88]

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[80] Chiyoda Corporation, Ibid

[81] Gilbert P and Thornley P undated, Energy and carbon balance of ammonia production from biomass gasification, accessed on 4 July 2018 at https://www.research.manchester.ac.uk/portal/files/33615474/FULL_TEXT.PDF

[82] http://www.sciencemag.org/news/2018/07/ammonia-renewable-fuel-made-sun-air-and-water-could-power-globe-without-carbon

[83] Brown T 2017, The Future of Ammonia: Improvement of Haber-Bosch … or Electrochemical Synthesis? Accessed on 4 July 2018 at https://ammoniaindustry.com/the-future-of-ammonia-improvement-of-haber-bosch-or-electrochemical-synthesis/

[84] http://mobile.abc.net.au/news/2018-08-08/hydrogen-fuel-breakthrough-csiro-game-changer-export-potential/10082514

[85] http://www.ammoniaenergy.org/major-development-for-ammonia-energy-in-japan/

[86] Feibelman PJ and Stumpf R undated, Comments on Potential Roles of Ammonia in a Hydrogen Economy – A Study of Issues Related to the Use of Ammonia for On-Board Vehicular Hydrogen Storage, accessed on 4 July 2018 at http://www.pc.gov.au/inquiries/completed/climate-change-adaptation/submissions/sub046-attachment7.pdf

[87] Thomas G and Parks G (US Department of Energy) 2006, Potential roles of ammonia in a hydrogen economy, accessed on 4 July 2018 at https://www.energy.gov/sites/prod/files/2015/01/f19/fcto_nh3_h2_storage_white_paper_2006.pdf

[88] Feibelman PJ and Stumpf R undated, Comments on Potential Roles of Ammonia in a Hydrogen Economy – A Study of Issues Related to the Use of Ammonia for On-Board Vehicular Hydrogen Storage, accessed on 4 July 2018 at http://www.pc.gov.au/inquiries/completed/climate-change-adaptation/submissions/sub046-attachment7.pdf

3

ANALYSIS OF HYDROGEN DEMAND

3.1 Discussion of scenarios

A key objective of this study is to identify the potential export market opportunities for hydrogen from Australia to help meet the energy needs of the four selected key countries over the period to 2040. To carry out this forward-looking analysis, it is important to understand the trends and patterns of energy demand and supply, and the energy policies of the key countries.

The energy supply and demand projections provided by the IEA in the 2017 edition of its World Energy Outlook (WEO), cover a range of scenarios (including the Sustainable Development Scenario (SDS)) . However, these projections do not provide any information regarding the potential role of hydrogen in the energy mix to 2040. The IEA's projections have fossil fuels continuing to dominate primary and final energy consumption, although there is a shift towards greater use of electricity rather than oil in the transport sector.

Any analysis of the demand for hydrogen and implications for Australia is necessarily concerned with the long-term. Obviously, there is a great deal of uncertainty about how the future might unfold, and this uncertainty is exacerbated by the long-time frames that are generally accepted as being associated with any transition towards the greater use of hydrogen.

Rather than replicating the analysis contained within the IEA's WEO but with alternative assumptions, ACIL Allen has based future energy consumption by fuel by industry by country on the IEA's forecasts.

More specifically, to understand the potential size of the global hydrogen industry, the WEO projections have been used as the core starting point. Doing this removes the need to replicate the extensive analysis and assumptions contained within the WEO on factors such as population and labour market growth, productivity growth, fuel prices, resource availability, changes in economic trends and a suite of government policies. Within the IEA's projections on fuel consumption by industry by country, ACIL Allen has allowed for the growth of the hydrogen economy within the sectors where it is likely to be the most competitive.

Rather than try to develop a single projection of future hydrogen demand, the demand analysis in this report uses a set of scenarios that reflect a range of possible futures. This approach draws on the targets and actions announced by the key countries along with a range of assumptions about the timing and nature of hydrogen uptake in each country. The scenario assumptions are discussed in Section 3.1.1.

3.1.1 Key scenarios

ACIL Allen has developed three scenarios to estimate the hydrogen demand potential in each of the four selected countries. This report presents the projected level of hydrogen demand in 2025, 2030 and 2040 for each of the three scenarios. Economic, technological and social factors vary across the scenarios.

The characteristics of the three potential hydrogen scenarios are summarised in **Table 3.1**.

Future energy consumption by industry by country are based on the IEA's Sustainable Development Scenario (SDS) projections, with fuel and carbon prices in the medium hydrogen potential scenario being the same as those in the SDS scenario. This means that the scenarios implicitly reflect a wide range of current and future policy settings including future greenhouse gas policies and prices that are likely to be conducive to the future development of a hydrogen economy.

Key relevant assumptions that are incorporated in the three scenarios are:

- Climate policy goals: These are an important global driver for hydrogen demand. ACIL Allen's hydrogen scenarios are based on the IEA's SDS, which anticipates that countries will be able to limit atmospheric greenhouse gas concentrations to 450ppm. The differences between the three hydrogen scenarios, in terms of climate change policy, relate primarily to the degree of effort made by countries to address climate change and hence the probability of restricting global temperature increases.
- Technology innovation, deployment and costs: The pace of technology change and innovation has the potential to alter the demand for hydrogen
- The scope and level of carbon pricing: Depending on the country, the SDS's implicit carbon price ranges between US$43–US$63/tonne CO_2 in 2025 and US$125–US$140/tonne CO_2 in 2040.
- International energy prices: Coal, oil and natural gas prices provided by IEA already take into account the impact of implicit carbon prices in their respective scenarios. Lower conventional fuel prices in SDS relative to the NPS are driven by lower demand for these fuels caused by high implicit carbon prices.

TABLE 3.1 SUMMARY DESCRIPTION OF THIS REPORT'S HYDROGEN POTENTIAL 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

The baseline scenario

The baseline scenario is broadly consistent with the New Policies Scenario in the IEA's 2017 World Energy Outlook.[90] It incorporates not just the policies and measures that governments around the world have already put in place, but also the likely effects of announced policies, as expressed in official targets or plans. This scenario provides a sense of where today's policy ambitions seem likely

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[89] The existence of a carbon price in an importing country will be an important factor in the demand for low carbon hydrogen, even if Australia does not have a carbon price. **Figure C.1** shows the assumed carbon prices for the three hydrogen scenarios.

[90] International Energy Agency (2017), World Energy Outlook 2017, OECD/IEA, Paris

to take the energy sector. The IEA does not expect that this scenario would lead to a significant role for hydrogen.

The Nationally Determined Contributions under the Paris Agreement provide important guidance as to the policy intentions in many countries, although in some cases these are now supplemented or superseded by more recent announcements. The baseline scenario provides projections of energy supply and demand based on the assumption that countries proceed to implement broad policy commitments and plans that have been announced, including national pledges to reduce greenhouse-gas emissions and plans to phase out fossil-energy subsidies, even if the measures to implement these commitments have yet to be identified or announced. This scenario provides a simple, transparent and internally consistent picture of a baseline energy demand and supply in each chosen country against which the hydrogen demand scenarios are assessed.

Hydrogen demand scenarios

Three hydrogen demand scenarios have been developed. The hydrogen demand scenarios can be simply categorised as being for *low, medium* and *high* hydrogen uptake rates in each application area relative to the baseline scenario. As discussed above, the scenarios are based on different assumptions regarding climate change and global warming, adoption of hydrogen technologies, and alternative fuel prices across the sectors where hydrogen might enter the market.

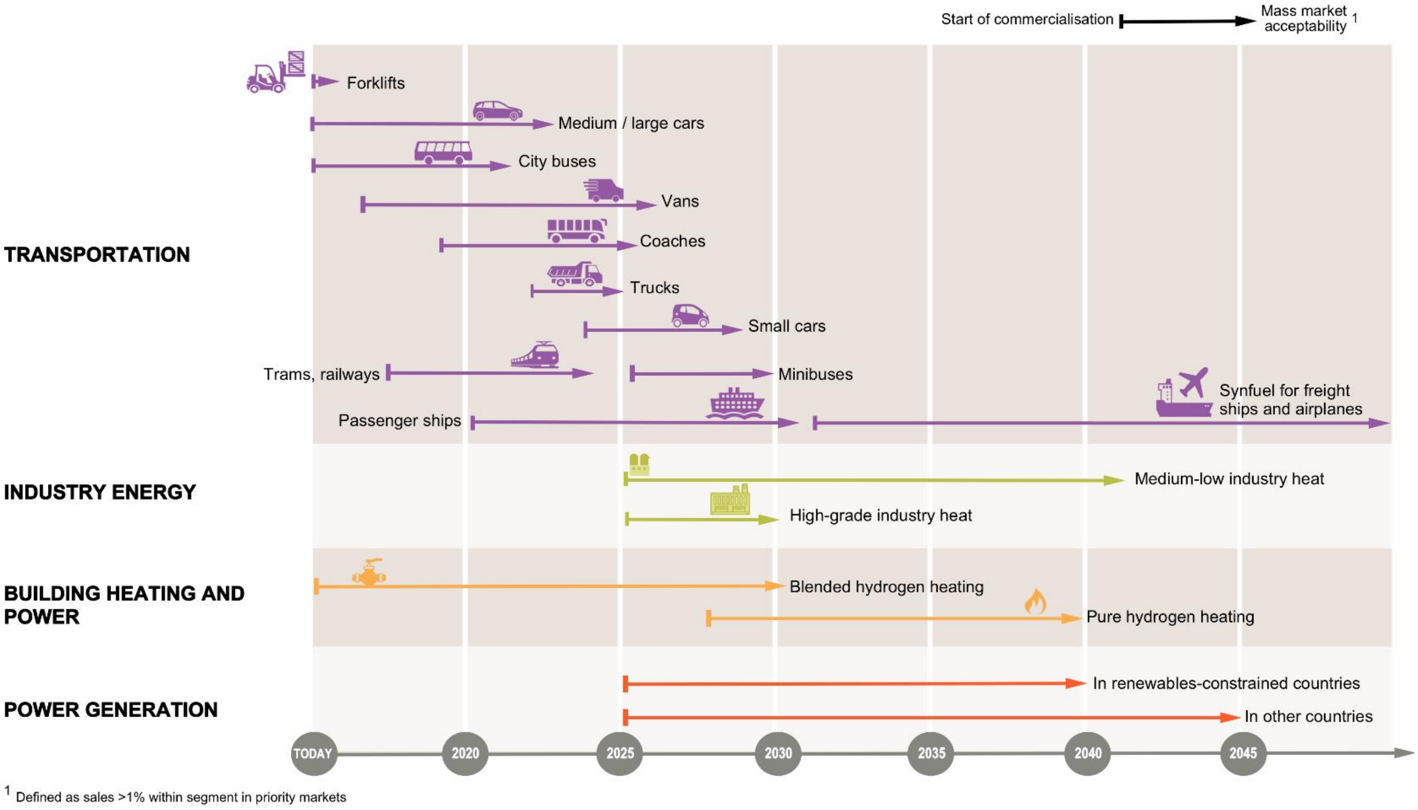
The three hydrogen demand scenarios provide depictions of possible futures in which hydrogen plays different roles in meeting energy demand. It is important to understand that this report is not providing *forecasts* of potential hydrogen demand. Rather these hydrogen demand scenarios are designed to provide alternative views of how the future might look under different circumstances.

Based on the current state of knowledge regarding hydrogen production and consumption technologies, the main potential end uses for hydrogen in the period to 2040 are expected be in:

- the transport sector
- space heating and cooling applications
- large scale, centralised power generation and decarbonising natural gas distribution networks.

This is consistent with the Hydrogen Council’s timing of hydrogen applications shown in **Figure 3.1**. The industrial use of hydrogen, particularly as a feedstock, is not expected to grow significantly out to 2040 and demand is assumed to largely continue to be met by existing production technologies (mostly SMR).

FIGURE 3.1 AN INDICATIVE TIMING RANGE FOR HYDROGEN OPPORTUNITIES



SOURCE: HYDROGEN COUNCIL (2017), HYDROGEN SCALING UP, A SUSTAINABLE PATHWAY FOR THE GLOBAL ENERGY TRANSITION. PAGE 26-27, EXHIBIT 7.

It is entirely possible that other uses for hydrogen — for example, providing backup power — might emerge over the period covered by this report. However, this study has not sought to quantify these other potential uses due to the uncertainty around them and an expectation that they are unlikely add significantly to total hydrogen demand.

The hydrogen demand scenarios are based on the review of literature and hydrogen roadmaps and policies of the chosen countries and reasonable hydrogen uptake outcomes from the models developed for this study. Existing projections and discussions for the timing of commercial hydrogen applications and the transitions to a hydrogen economy have been used as a guide when developing the scenarios.

Indicative timing

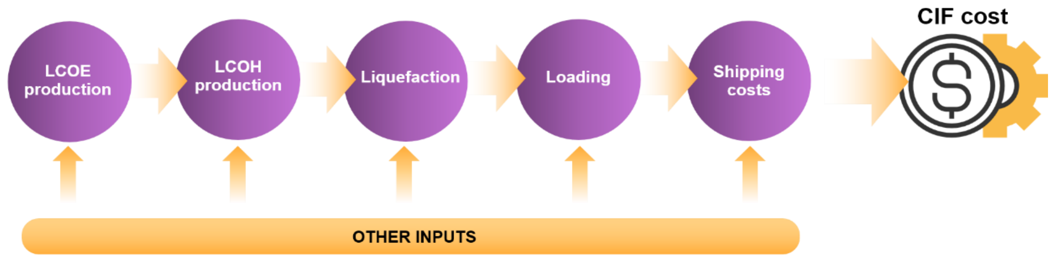
Indicative timings for the uptake of different hydrogen end-use applications is provided in **Figure 3.1**. The figure shows how the Hydrogen Council envisages hydrogen technology evolving across the hydrogen supply chain. The figure does not provide numerical forecasts, rather it provides an indication of the relative timing of different sources of potential hydrogen demand.

Estimating the hydrogen cost

Hydrogen cost depends on the choice of production technology and pathway for delivering hydrogen to the end-user.

To estimate the cost of imported hydrogen for various countries we have used a bottom up approach. That approach has used estimates of the production cost and then added the other costs in the supply chain to derive a cost for hydrogen at the country's import terminal. The key steps in the process are illustrated in **Figure 3.2**. More detailed cost estimates of hydrogen supply costs can be found in Chapter 4.

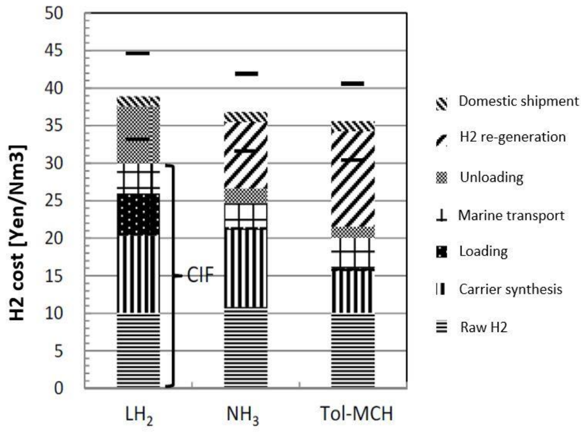
FIGURE 3.2 KEY STEPS IN ESTIMATING HYDROGEN IMPORT COST (LIQUEFACTION PATHWAY)



SOURCE: ACIL ALLEN CONSULTING

The steps could be different for other pathways. For example, the results of a Japanese analysis of supply costs of hydrogen in 2030 are shown in **Figure 3.3**. The analysis shows that for liquid hydrogen the carrier synthesis (liquefaction) cost is similar to the cost of production and that loading and unloading costs are higher than the shipping cost. In the case where hydrogen is transported as ammonia, hydrogen regeneration costs are a significant component landed cost.

FIGURE 3.3 AN EXAMPLE OF HYDROGEN SUPPLY COST IN 2030 IN JAPAN



SOURCE: MIZUNO ET AL 2017, ECONOMIC ANALYSIS ON INTERNATIONAL HYDROGEN ENERGY CARRIER SUPPLY CHAINS, JOURNAL OF JAPAN SOCIETY OF ENERGY AND RESOURCES, 38 (3) 11-17

The main message based on the data shown in **Figure 3.3** is that the delivered cost of hydrogen is broadly similar for the different technologies shown. We have not sought to estimate hydrogen end-use prices as importing countries' end-use prices will vary based how much it costs to store, transport and distribute hydrogen, as well as the competitive landscape in each country. This will in turn depend on market dynamics. These factors will be the same irrespective of where the imported hydrogen has come from.

3.2 Methodology for projecting demand, cost and price

3.2.1 Hydrogen demand projections

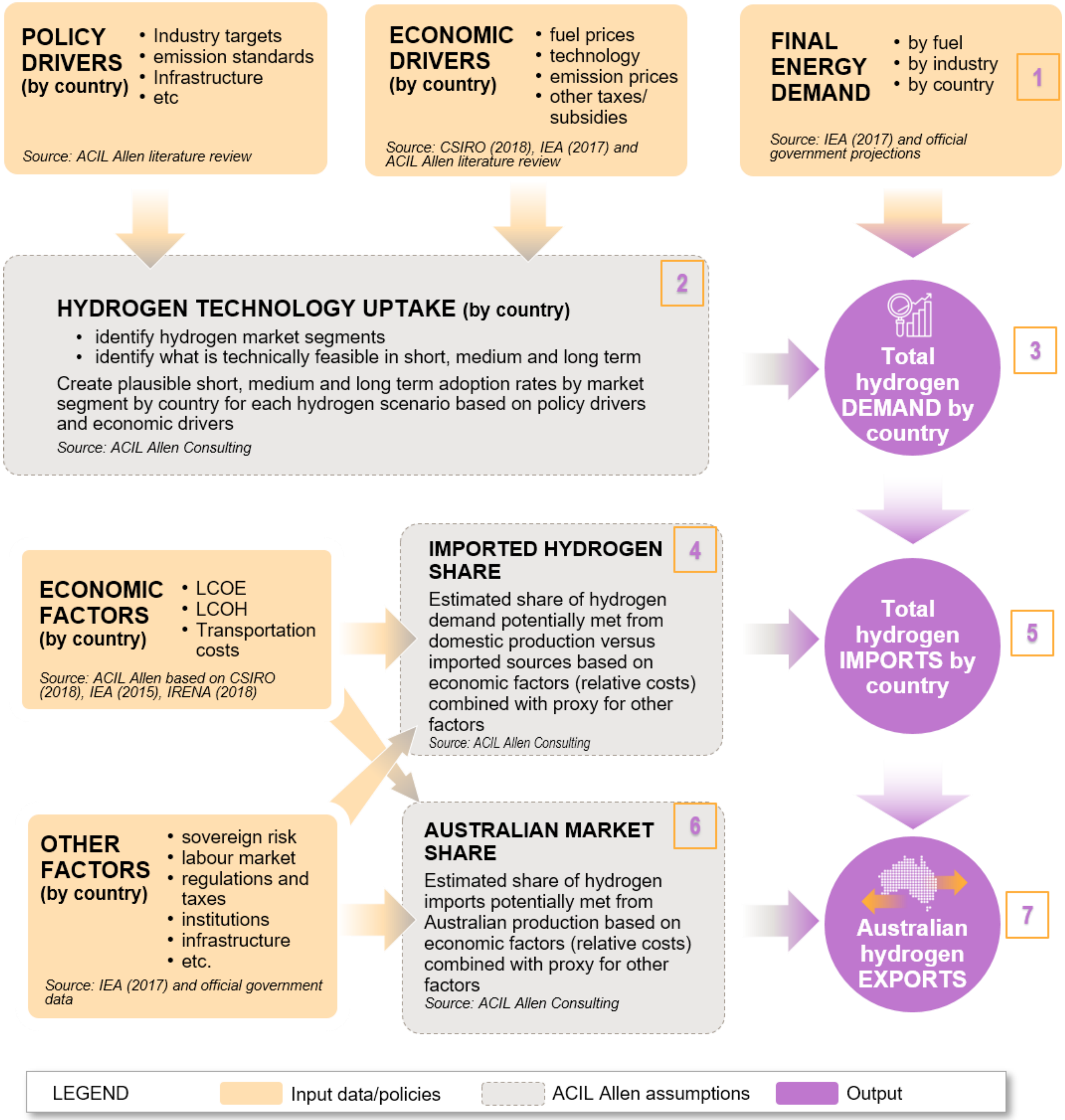
ACIL Allen's broad approach to hydrogen demand projections in each economy is illustrated in **Figure 3.4**. The methodology is a combination of top-down energy demand projections integrated with the bottom-up supply potential. The approach considers announced targets and relevant policies in each economy. Any growth in hydrogen consumption will start from a very low base and there are no consistent official hydrogen demand projections to 2040 for the four selected importing economies.

In addition, there is uncertainty about how hydrogen might substitute for other energy sources in various sectors. For example, it is unclear what proportion of the future energy needs of the transport sector will be met by FCEVs versus battery electric vehicles. Key energy and environmental policy drivers also differ across the four selected economies.

The methodology used to develop projections of hydrogen export for Australia is based on the elements shown in **Figure 3.4**, these are:

1. projecting final energy demand by fuel by industry and by country (broadly consistent with IEA scenarios)
2. developing hydrogen technology uptake rates based on the technically feasible hydrogen market segments (short, medium and long-run) based on the policy and economic drivers.
   a) Some policy drivers include:
      i) Emission standard for vehicles
      ii) Fuel standards
      iii) Renewable technology targets
      iv) Planning regulations related low emission zones
      v) Alternative fuel infrastructure provisions
   b) Some economic drivers include:
      i) Technology costs
      ii) End use effective energy prices — fuel prices, carbon prices and other taxes and subsidies
3. deriving hydrogen demand for each country in selected key application areas
4. estimating the proportion of hydrogen sourced from imports, based on an analysis of historical energy import patterns, estimated LCOE and LCOH and assumed domestic hydrogen production for each economy
5. deriving total hydrogen imports in each country
6. estimating imports from Australia, based on the relative competitiveness (LCOE, LCOH, liquefaction and shipping) and historical energy trade
7. deriving Australian hydrogen export sales.

FIGURE 3.4 APPROACH TO HYDROGEN DEMAND PROJECTIONS



SOURCE: ACIL ALLEN CONSULTING

Australia's market share

A number of price and non-price factors determine Australia's market share in key importing countries. Relative cost competitiveness is one. Other factors include existing supply chain relationships, investment and trading relationships, macroeconomic frameworks and institutional linkages.

ACIL Allen has aggregated the estimated import demand from four countries, along with import demand from rest of the world, to estimate potential demand for Australian exports of hydrogen. Australia's share of share of imports into the four countries examined in this report is shown in

Figure ES 2. Additional information on how Australia's market share is estimated is provided in Appendix C.

3.2.2 Hydrogen price projections

An important factor affecting the development of the hydrogen economy is the cost to the end user of hydrogen fuel and associated end-use products relative to existing conventional fuels and products, such as gasoline or diesel in vehicles with internal combustion engines (ICEs).

There are several other factors that will help determine whether a hydrogen economy develops and, if so, how quickly it does so. As with almost all new technologies their adoption by the market will be strongly influenced by government regulations, policies and economic drivers. For example:

- any price that may be attached to emissions associated with the use of conventional fuels (a higher emissions price would improve the relative competitiveness of hydrogen as a fuel)
- the amount of spending on R&D will influence the rate of technological progress and innovation in the hydrogen supply chain, which, in turn, could help drive down the cost of hydrogen production, compression, storage and transport
- the level of support provided for in-country infrastructure (such as hydrogen refuelling stations) will help enable the development of domestic hydrogen supply chains, which are an important precursor to any eventual imports of hydrogen.

The hydrogen scenarios for each country analysed in this study could result from distinctly different paths involving markedly different trends of the key economic drivers. Furthermore, the economic implications of a hydrogen economy in each country could differ markedly depending on what potential application areas eventuate and what the key economic drivers are. For example, the economic implications of a hydrogen economy driven by high conventional fuel prices could be different to those resulting from government policies driven by energy security and climate change concerns that support some technologies over others. The former would come about naturally within the economy in response to meeting the needs of consumers in the most cost-effective way, while the latter would be implemented *exogenously*. Similarly, irrespective of conventional fuel prices, a country could achieve high hydrogen penetration as a result of rapid technological progress that enabled hydrogen use in different sectors and applications.

Projecting prices for hydrogen is a complex task. This depends on:

- the hydrogen supply chain pathway (i.e. the processes needed to produce, distribute and dispense hydrogen)
- the feedstock and/or major energy source from which the hydrogen is produced
- the size of the facility at which the hydrogen is produced and the transportation requirements to deliver it to the customer
- the state of the technology used to produce hydrogen and expected improvements in production technologies
- whether any CO_2 produced as a by-product of hydrogen production is sequestered or offset.

The hydrogen price will be set by the market based on the above factors and the price of substitute sources of energy in end use industries. The transport and distribution costs of hydrogen are especially important in determining the final price. Hence, the price paid by an importer will depend on their location relative to the exporter and how the hydrogen is produced and delivered (as a liquid or as a gas).

To estimate hydrogen import prices in the four selected importing countries, ACIL Allen has used bottom-up estimates of the production cost for hydrogen and added supply chain costs to provide a price for hydrogen delivered to the import terminal in the destination country. These costs are based on the cost estimates provided in the CSIRO's Hydrogen Roadmap.

The CSIRO hydrogen production costs in 2025 are lower than 2018 and there is a possibility that the production costs could fall further beyond 2025 due to potential declines in renewable electricity prices, costs of electrolysers and other technological improvements in hydrogen production and supply.

The resulting price projections can be seen in **Table 4.7**.

3.3 Estimated total global hydrogen demand

This section summarises the projected demand for hydrogen in each of the four key markets and in the rest of the world. More details of the assumptions underlying these estimates are provided in Appendices C to F.

The estimated total demand for hydrogen under each of the three hydrogen demand scenarios by country are shown in **Table 3.2** and **Table 3.3**.

TABLE 3.2 ESTIMATED TOTAL HYDROGEN DEMAND (PJ) BY COUNTRY

Country	2025			2030			2040		
	Low	Medium	High	Low	Medium	High	Low	Medium	High
Japan	10.6	62.0	160.7	105.1	211.5	463.3	227.7	496.1	1,149.7
Korea	8.9	26.7	59.3	44.8	87.4	187.5	120.2	261.2	637.1
Singapore	0.3	1.8	3.8	3.3	6.1	12.4	11.5	20.2	57.7
China	5.8	27.1	83.8	123.5	398.5	841.8	943.1	2,093.3	4,922.7
Rest of the World	11.7	53.8	140.6	126.5	321.6	688.0	595.5	1,312.4	3,093.6
Total	37.4	171.6	448.1	403.2	1,025.2	2,193.1	1,898.0	4,183.2	9,860.8

NOTE: REFERENCES TO KOREA IN THESE TABLES ARE TO THE REPUBLIC OF KOREA

SOURCE: ACIL ALLEN ESTIMATES

TABLE 3.3 ESTIMATED TOTAL HYDROGEN DEMAND ('000 TONNES) BY COUNTRY

Country	2025			2030			2040		
	Low	Medium	High	Low	Medium	High	Low	Medium	High
Japan	88	516	1,338	875	1,761	3,858	1,896	4,131	9,573
Korea	74	223	493	373	728	1,562	1,001	2,175	5,304
Singapore	3	15	31	27	51	103	96	168	481
China	48	226	698	1,028	3,318	7,009	7,853	17,430	40,989
Rest of the World	98	448	1,170	1,053	2,678	5,729	4,958	10,927	25,758
Total	311	1,429	3,731	3,357	8,536	18,260	15,804	34,831	82,105

SOURCE: ACIL ALLEN ESTIMATES

The estimated total demand for hydrogen under each of the three hydrogen demand scenarios by application type are shown in **Table 3.4**.

TABLE 3.4 ESTIMATED TOTAL HYDROGEN DEMAND (PJ) BY SECTOR

	2025			2030			2040		
	Low	Medium	High	Low	Medium	High	Low	Medium	High
Japan	**10.6**	**62.0**	**160.7**	**105.1**	**211.5**	**463.3**	**227.7**	**496.1**	**1,149.7**
Transport	7.7	16.0	41.5	14.7	20.5	63.4	46.1	114.3	241.7
Space heating and cooling	1.0	17.4	45.0	34.9	73.8	154.3	70.9	148.9	354.6
Power sector	1.8	28.6	74.2	55.5	117.2	245.6	110.6	232.9	553.4
Korea	**8.9**	**26.7**	**59.3**	**44.8**	**87.4**	**187.5**	**120.2**	**261.2**	**637.1**
Transport	3.1	11.0	21.2	9.1	14.3	28.0	38.2	95.5	210.0
Space heating and cooling	0.9	2.5	5.9	4.9	10.0	21.6	11.0	22.0	54.9
Power sector	4.9	13.3	32.1	30.8	63.2	138.0	71.0	143.8	372.1

	2025			2030			2040		
	Low	Medium	High	Low	Medium	High	Low	Medium	High
Singapore	**0.3**	**1.8**	**3.8**	**3.3**	**6.1**	**12.4**	**11.5**	**20.2**	**57.7**
Transport	0.3	0.8	1.6	0.9	1.4	2.9	5.7	8.5	28.3
Space heating and cooling	0.0	0.2	0.4	0.4	0.8	1.7	1.0	2.0	5.1
Power sector	0.0	0.9	1.7	1.9	3.8	7.8	4.9	9.7	24.4
China	**5.8**	**27.1**	**83.8**	**123.5**	**398.5**	**841.8**	**943.1**	**2,093.3**	**4,922.7**
Transport	5.2	11.3	52.1	100.2	152.2	304.5	414.0	1,035.0	2,277.0
Space heating and cooling	0.1	2.2	4.4	3.1	32.8	71.7	68.0	136.1	340.2
Power sector	0.5	13.7	27.4	20.2	213.4	465.7	461.1	922.2	2,305.5
Rest of World	**11.7**	**53.8**	**140.6**	**126.5**	**321.6**	**688.0**	**595.5**	**1,312.4**	**3,093.6**
Transport	10.6	22.4	87.3	102.7	122.9	248.9	261.4	648.9	1,431.0
Space heating and cooling	0.2	4.3	7.3	3.2	26.5	58.6	43.0	85.3	213.8
Power sector	1.0	27.1	45.9	20.7	172.2	380.6	291.1	578.2	1,448.8
Demand by sector	**37.4**	**171.6**	**448.1**	**403.2**	**1,025.2**	**2,193.1**	**1,898.0**	**4,183.2**	**9,860.8**
Transport	26.9	61.5	203.8	227.6	311.4	647.6	765.4	1,902.2	4,188.0
Space heating and cooling	2.2	26.5	63.0	46.5	144.0	307.8	193.9	394.3	968.6
Power sector	8.3	83.6	181.3	129.1	569.8	1,237.7	938.7	1,886.7	4,704.2

SOURCE: ACIL ALLEN ESTIMATES

4

AUSTRALIA'S COMPETITIVE POSITION

Australia is a significant energy exporter and competes with other energy exporters in the global market. If a global market for hydrogen does emerge then it is likely that countries with the capacity to export hydrogen will compete to supply hydrogen to energy importing countries.

4.1 Australia's competitive position

The relative competitiveness of different potential suppliers of hydrogen will play an important role in determining the shares of any future hydrogen export market captured by exporting countries.

Having access to good renewable energy resources is generally seen as an important factor for hydrogen supply due to renewable energy's role in producing hydrogen without any associated emissions. The factors that contribute to Australia's competitiveness in supplying hydrogen include:

- The cost of electricity produced by renewable energy (input)
- Cost of electrolysers (cost of capital) and utilisation of electrolyser
- Water and other costs
- Storage, liquification and transport costs

Some location and country specific factors that may contribute to competitiveness include:

- Capacity factors for renewable energy
- The cost of human resources (labour and skills)
- Port infrastructure
- The distance to destination countries (transport costs)
- The level of sovereign risk (cost of capital)
- Access to overseas sources of funding for energy investment
- The existence of established trading relationships

As competitiveness is a relative concept, the Australian potential to supply hydrogen to four potential target markets (Japan, Republic of Korea (Korea), Singapore and China) is compared to that of possible competing suppliers, namely Norway, Qatar and the USA.

The selection of Australia's potential competitors is based on a combination of factors, including their renewable energy costs, their existing energy trading relationships and any existing collaborative arrangements they might have with potential importers. Note that although more than 90 per cent of Brunei gas exports are destined for Japan, it is assumed that Brunei is unlikely become a major competitor for Australia in a Japanese hydrogen market. The recently announced collaborative project between Brunei and Japan is a small-scale demonstration project (total of only 210 tonnes of hydrogen). It also involves steam methane reforming (SMR) with no mention of CCS. This project is part of the broader collaborative research effort that Japan is currently undertaking on hydrogen (including with Australia and Norway).[91] In addition, Japan and Saudi Arabia are jointly exploring the possibility of extracting hydrogen from Saudi crude oil for conversion to ammonia and transportation to Japan in that form.[92]

4.2 Cost of hydrogen production

The cost of hydrogen production is a crucial element of any assessment of market opportunities for Australian produced hydrogen. Production costs of hydrogen depend on the scale, capacity, feedstock prices and investment costs. Estimated production costs reported in the literature vary considerably. Assumptions made about the point at which the cost is quoted can lead to large variations in the numbers reported. There is also scope for hydrogen production technologies to improve as new and innovative technology is developed, leading to cost reductions. Hence, hydrogen production cost estimates reported in the literature can quickly become outdated.

CSIRO has estimated the levelised cost of hydrogen (LCOH) for various production technologies and feedstocks as part of its work to develop the *National Hydrogen Roadmap* of Australia. The LCOH is the net present value of the unit-cost of hydrogen over the lifetime of a hydrogen production asset. It is often taken as a proxy for the average price that the asset must achieve to break even over its lifetime. It is a first-order economic assessment of the cost competitiveness of a hydrogen-generating system that incorporates all costs over its lifetime. CSIRO's analysis of costs is summarised in **Table 4.1**.

TABLE 4.1 HYDROGEN PRODUCTION TECHNOLOGIES AND COSTS IN AUSTRALIA

Technology	2018 A\$/kg H_2	2025 A\$/kg H_2
Proton exchange membrane (PEM) electrolysis	\$6.08–\$7.43	\$2.29–\$2.79
Alkaline electrolysis	\$4.78–\$5.84	\$2.54–\$3.10
SMR with CCS	\$2.27–\$2.77	\$1.88–\$2.30
Black coal gasification with CCS	\$2.57–\$3.14	\$2.02–\$2.47
Brown coal gasification with CCS		\$2.14–\$2.62

Note: CSIRO has reported 2018 as base case and 2025 as best case. PEM and alkaline electrolysis are based on grid-connected renewables with 93% capacity factor.

SOURCE: CSIRO 2018, NATIONAL HYDROGEN ROADMAP

CSIRO has suggested that proton exchange membrane (PEM) electrolysis is the most suitable production method for Australia to use to produce hydrogen for the export market. The current cost estimates range between A\$6.08–\$7.43/kg H_2. The cost is expected to decline to A\$2.29–\$2.79/kg H_2 by 2025. PEM electrolysers consume a significant amount of electricity as an input, which, in addition to the capital cost of the equipment itself, makes this technology more expensive than the other hydrogen production technologies reported in **Table 4.1**. However, electrolyser technology is very flexible, allowing it to operate with variable renewable supply, which helps to minimise the cost of electricity inputs during periods of peak pricing. Electrolyser operators can produce and store hydrogen during times of surplus electricity generation and low demand/prices. Similarly, they can decrease hydrogen production if renewable generation decreases and demand is putting pressure on the electricity grid.

For large scale production of hydrogen, operators could opt to build stand-alone production capacity, bypassing the grid.

CSIRO has estimated that hydrogen production costs would reduce significantly between 2018 and 2025. For example, hydrogen production using PEM electrolysis could decline in cost by over 60 per cent due to improvements in the scale of operation and improved capacity factors from 85 per cent in 2018 to 95 per cent in 2025.

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[91] https://www.bizbrunei.com/ahead-to-begin-worlds-first-international-supply-of-hydrogen-from-brunei-in-2020/

[92] http://www.ammoniaenergy.org/japan-saudi-arabia-explore-trade-in-hydrogen-ammonia/

4.2.1 Cost of renewables

The different ways of generating low emission electricity incur significantly different costs, which impacts on the cost of hydrogen. A key driver of the cost of renewable electricity is the capacity factor. This is highly location and project specific. Wind turbines, hydro projects and solar farms generally tend to have relatively low capacity factors due to the variability of the energy source used to produce electricity. The global capacity factors for renewables compiled by IRENA are provided in **Figure 4.1**. Capacity factors for renewables have improved over the past eight years.

Hydroelectric plant production may be affected by requirements to keep the water level in associated dams from getting too high or low. When hydroelectric power plants have water available, they are also useful for baseload because of their high dispatchability. Wind farms are highly variable and location specific due to the natural variability of the wind. Wind farm capacity factors are determined by the availability of wind, the swept area of the turbine and size of the generator. Solar PV is variable due to the daily rotation of earth and seasonal conditions. Renewable energy capacity factors in selected countries are summarised in **Table 4.2**. In broad terms, the average capacity factor indicates the relative cost competitiveness of renewables production.

Australia's renewable capacity factors, particularly for solar PV, are higher compared with the four target markets Japan, Republic of Korea, Singapore and China, but are comparable to the other countries listed in **Table 4.2**.

Hydroelectricity is a major form of electricity production in Norway. Over 95 per cent of power generation is from hydroelectric projects. In 2016, the Norwegian government published a White Paper regarding their future energy intentions through 2030. This announcement emphasized four main goals: improving security in the supply of their power; improving the efficiency of their renewables; making their energy more efficient and environmentally and climate sensitive; and fostering economic development and value through fiscally responsible and renewable technology.[93]

With average daily sunshine of around 9.5 hours, low-cloud cover conditions and plentiful space, there is considerable scope for small, medium and large-scale solar power projects in Qatar. Its global horizontal irradiance is 2,140 kWh per m^2 per year which makes it well-suited for solar photovoltaic (PV) systems. It has set a target of 2 per cent renewable energy contribution in the national energy mix by 2022. In addition to solar PV, Qatar has very good potential for concentrated solar power (CSP) as its direct normal irradiance value is around 2,008 kWh per m^2 per year which is above the minimum threshold of 1,800 kWh per m^2 per year.

Qatar's concentrated solar power potential can be effectively utilised in seawater desalination processes as well as large-scale power generation. Qatar is a large exporter of LNG and competes with Australia in LNG markets. Recent market developments have put the Qatar and Gulf Cooperative Council (GCC) region on the global map with some of the lowest levelised costs for electricity from solar PV. This rising cost competitiveness, coupled with country-specific policy frameworks, can pave the way for greater deployment of solar PV. The levelised cost of electricity from solar PV in GCC in 2018 is estimated around US$0.05/kWh.[94]

The USA has strength in photovoltaics and concentrated solar power and several of the world's largest utility scale installations are in the South West of that country.

The renewable electricity costs of technologies in various countries are summarised in **Table 4.3**. The data indicates that Australian production costs are comparable with the other countries.

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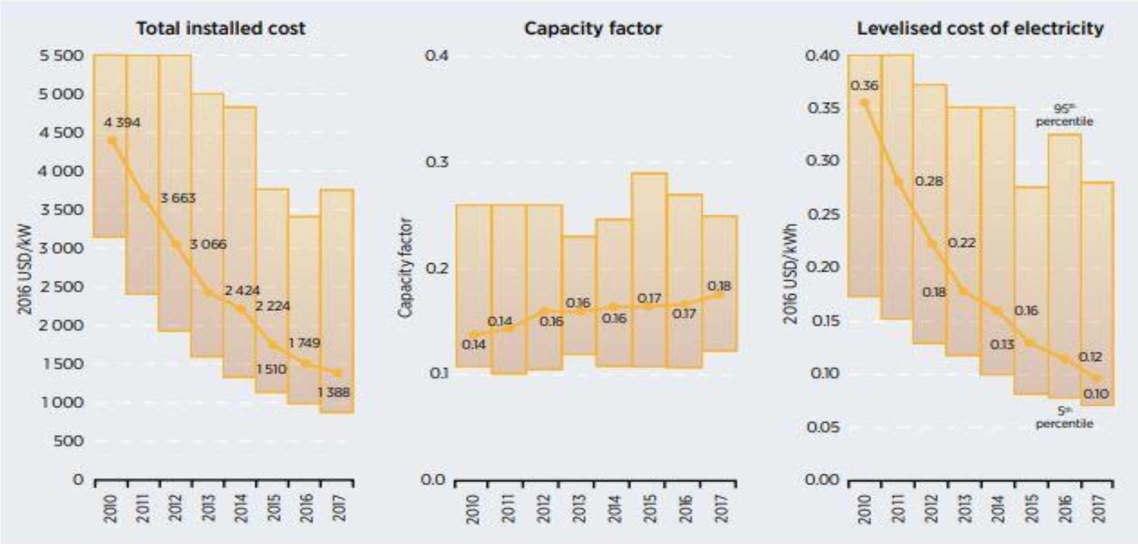
[93] Norwegian Government 2016, *White Paper on Norway's energy policy: Power for Change*, accessed on 21 June 2018 at https://www.regjeringen.no/en/aktuelt/white-paper-on-norways-energy-policy-power-for-change/id2484248/

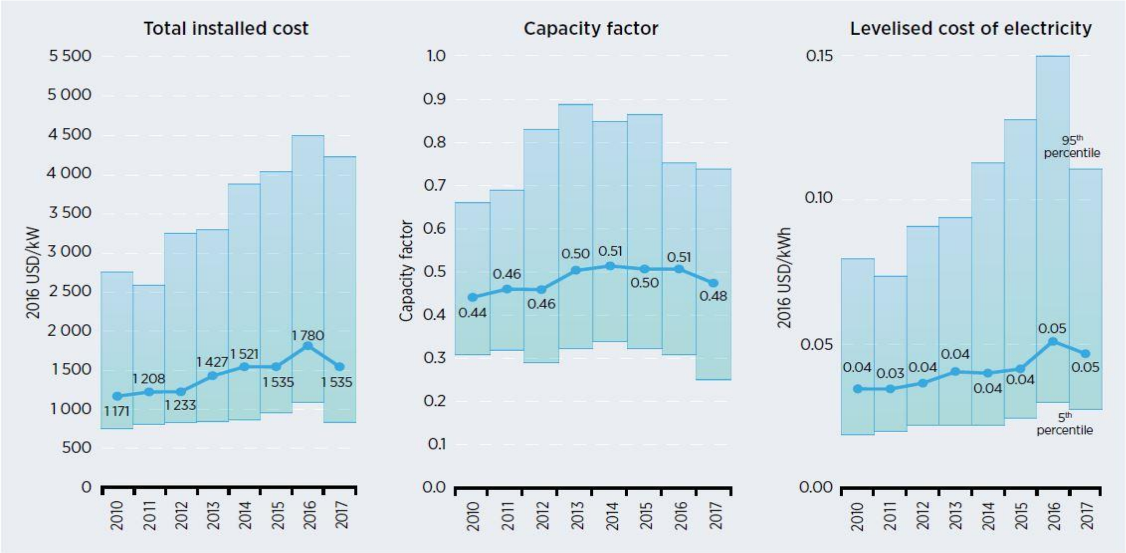
[94] Based on IRENA 2016, *Renewable Energy Market Analysis*, *The GCC Region*, accessed on 19 June 2018 at https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2016/IRENA_Market_GCC_2016.pdf

FIGURE 4.1 GLOBAL CAPACITY FACTORS AND LCOE FOR RENEWABLES

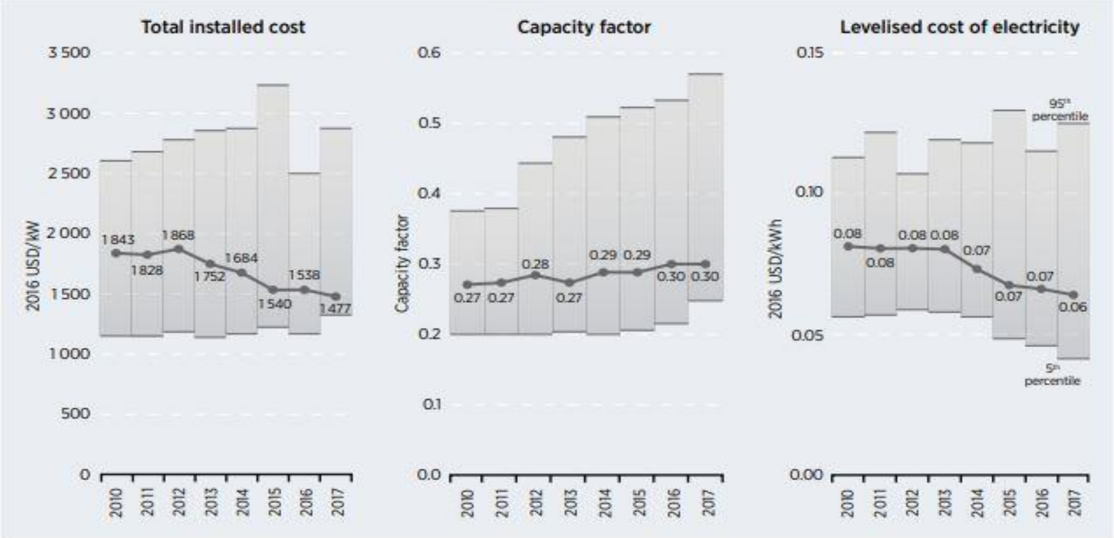
Global weighted average total installed costs, capacity factors and LCOE for solar PV, 2010-2017



Global weighted average total installed costs, capacity factors and LCOE for Hydropower, 2010-2017



Global weighted average total installed costs, capacity factors and LCOE for Onshore wind, 2010-2017



SOURCE: IRENA (2018), RENEWABLE POWER GENERATION COSTS IN 2017, INTERNATIONAL RENEWABLE ENERGY AGENCY, ABU DHABI.

TABLE 4.2 CAPACITY FACTORS FOR RENEWABLES IN SELECTED COUNTRIES (PER CENT)

	2018			2025			2030			2040		
	lower	average	upper	lower	average	upper	lower	average	upper	lower	average	upper
Australia												
Solar PV – large	27	28	29	27	28	29	27	28	29	27	28	29
Onshore wind	37	40	43	37	40	43	37	40	43	37	40	43
Hydro – large	5	17	34	5	17	34	5	17	34	5	17	34
Norway												
Offshore wind	16	31	42	16	31	42	16	31	42	16	31	42
Onshore wind	25	40	51	25	40	51	25	40	51	25	40	51
Hydro – large	22	40	55	22	40	55	22	40	55	22	40	55
Qatar												
Solar PV – large	28	29	33	28	29	33	28	29	33	28	29	33
Solar thermal (CSP)	36	62	70	36	62	70	36	62	70	36	62	70
USA												
Solar PV – large	18	21	28	22	29	33	22	29	33	22	29	33
Solar thermal (CSP)	34	55	65	34	55	65	34	55	65	34	55	65
Onshore wind	35	43	49	35	43	49	35	43	49	35	43	49
Offshore wind	42	45	48	42	45	48	42	45	48	42	45	48
Hydro – large	58	62	68	58	62	68	58	62	68	58	62	68
Japan												
Solar PV – large	8	14	20	8	14	20	8	14	20	8	14	20
Onshore wind	12	20	25	12	20	25	12	20	25	12	20	25
Hydro – large	30	45	51	30	45	51	30	45	51	30	45	51
Korea												
Solar PV – large	8	15	20	8	14	20	8	14	20	8	14	20
Onshore wind	15	23	28	15	23	28	15	23	28	15	23	28
Offshore wind	19	30	40	19	30	40	19	30	40	19	30	40
Singapore												
Solar PV – residential	13	14	15	13	14	15	13	14	15	13	14	15
China												
Solar PV – large	13	17	23	13	17	23	13	17	23	13	17	23
Onshore wind	20	26	30	20	26	30	20	26	30	20	26	30
Hydro – large	32	52	55	32	52	55	32	52	55	32	52	55

SOURCE: FOR AUSTRALIA AND SINGAPORE, ACIL ALLEN BASELINE. UPDATED IEA 2015 FOR OTHER COUNTRIES

The ‘learning rates’ for technologies, particularly solar PV and wind, are similar across countries. If there are no physical constraints, costs would be expected to stabilise in the long-run. Among the other factors, the relative end-points for costs may result in a cost competitiveness advantage for hydrogen production.

The data in **Table 4.2** suggest that Australian production costs are comparable with the other countries. The ‘learning rates’ for technologies, particularly solar PV and wind, are similar across countries. **Table 4.3** presents the LCOE for different renewable electricity generation technologies in various countries over time. As noted earlier, the LCOE figures over time will have an impact on the relative cost competitiveness of hydrogen production by different countries. The projected LCOE values for Australia are competitive with those of other countries for several of the technologies.

TABLE 4.3 LCOE OF RENEWABLE TECHNOLOGIES (A CENTS/kWh) IN SELECTED COUNTRIES

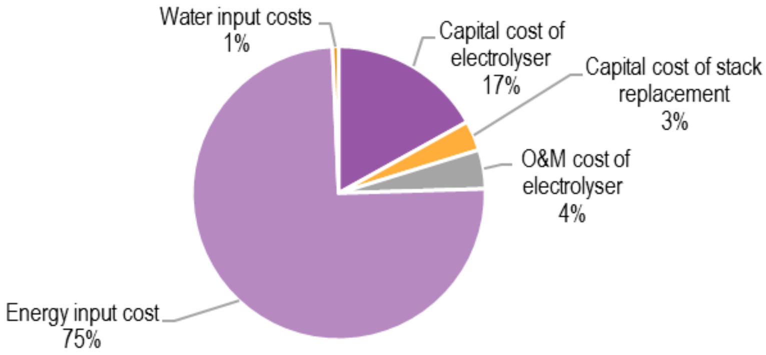
Technology	Country	2018	2025	2030	2040
Large solar PV	Australia	6.0	4.0	3.9	3.4
	Qatar	5.8	5.5	5.3	4.7
	USA	6.7	6.4	5.9	5.2
	Japan	30.0	28.8	27.8	24.7
	Korea	15.5	14.8	14.3	12.7
	Singapore	13.6	13.1	12.6	11.2
	China	11.8	8.5	7.6	6.4
Hydro	Norway	4.9	4.3	4.2	4.0
Onshore wind	Australia	6.8	6.9	6.8	6.1
	USA	6.7	6.8	6.7	6.0
	Japan	18.0	18.0	17.1	15.4
	Korea	18.5	18.8	18.5	16.6
	China	8.6	8.3	8.2	8.0
Offshore wind	USA	24.1	24.5	24.1	21.7

NOTE: FOR AUSTRALIA, THE DATA IS FROM THE CSIRO'S NATIONAL ROADMAP
SOURCE: ACIL ALLEN ESTIMATES BASED ON VARIOUS SOURCES—CSIRO 2018, IEA 2015, IRENA 2017, IRENA 2018

Importance of renewable electricity in PEM

The composition of PEM hydrogen production costs in Australia is shown in **Figure 4.2**. Three-quarters of the annualised production cost is from electricity inputs. This illustrates the important role that the cost of renewable electricity plays in determining the competitiveness of hydrogen production. The capacity factor has been calculated by CSIRO assuming grid-connected renewables with larger plant size (100,000kW) and a renewable electricity price of A$0.04/kWh.

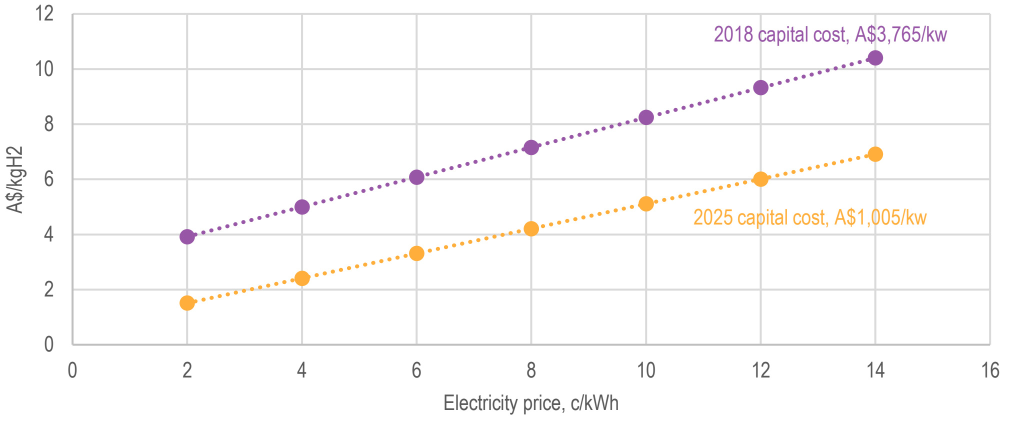
FIGURE 4.2 COMPONENTS OF HYDROGEN PRODUCTION COSTS IN AUSTRALIA



Note: Annualised cost shares. CSIRO has assumed 93 per cent capacity for renewable electricity.
SOURCE: CSIRO NATIONAL HYDROGEN ROADMAP 2018

The relationship between the electricity price and hydrogen production costs in Australia is shown in **Figure 4.3**. The hydrogen production cost varies linearly with the renewable electricity price.

FIGURE 4.3 RELATIONSHIP BETWEEN RENEWABLE ELECTRICITY PRICES AND HYDROGEN PRODUCTION COSTS IN AUSTRALIA



SOURCE: CSIRO NATIONAL HYDROGEN ROADMAP 2018

Renewable electricity prices in Australia are relatively low compared with the four selected countries analysed in this report. However, China also has relatively low LCOE number for renewable electricity and is actively pursuing a hydrogen economy. China could potentially become a major competitor to Australia for supplying hydrogen to Japan and Korea in the longer term. However, it does not have an established energy trading relationship with either country.

4.2.2 Impact of variable renewable energy on hydrogen production

Variable renewable energy price impacts are not accounted for in the LCOE calculations reported above. However, the impacts of variable renewable energy costs should be similar across countries that produce hydrogen. As increasing amounts of variable renewable generation are installed, concerns about system flexibility, capacity, and ability to match load are likely to increase. Hydrogen has the potential to support the grid in addressing each of these concerns. However, there is limited information available about the economic competitiveness of using hydrogen in this way for the countries analysed in this study.

4.2.3 Impact of electrolyser capacity on hydrogen production costs

Using the PEM electrolysis process to provide flexible load management requires different features and operational strategies than for hydrogen production. For hydrogen production, the capacity factor — the average power the electrolyser operates at, divided by its maximum capacity — also drives costs. An illustration of the influence of the capacity factor and plant size on hydrogen production costs in Australia is shown in **Figure 4.4**. This suggests that countries producing large quantities of hydrogen will achieve some economies of scale, but that incremental reductions in cost become quite small for facilities above 5,000 kg per day. In addition, changes in the capacity factor decline in importance as the capacity factor increases.

4.2.4 Financing costs

Generally, the investment costs of any project consist of 'overnight' cost[95] along with contingency and financing costs. Countries could gain a competitive advantage through the use of production subsidies and/or tax incentives, at least during the earlier stages of development of a hydrogen production industry.

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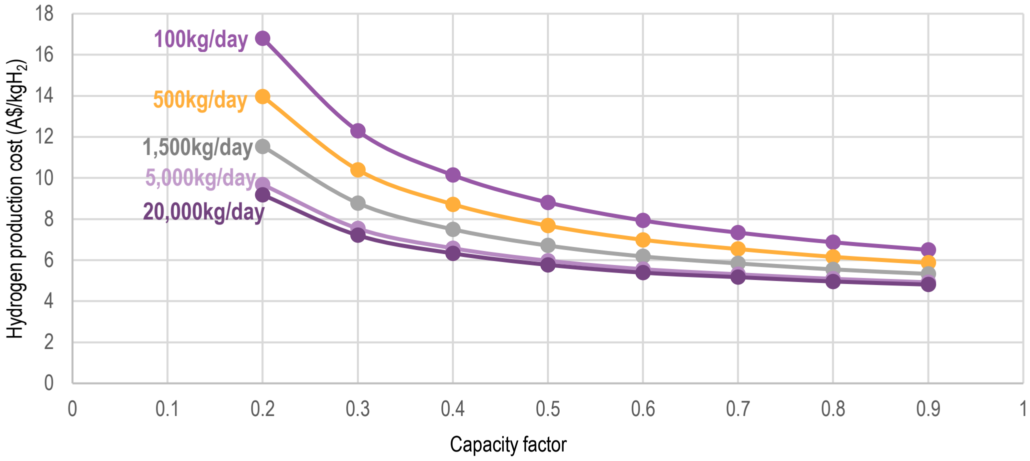
[95] Overnight cost is the cost of a construction project if no interest was incurred during construction as if the project was completed "overnight." The overnight cost is frequently used when describing power plants.

FIGURE 4.4 IMPACT OF CAPACITY FACTOR ON HYDROGEN PRODUCTION COSTS IN AUSTRALIA (AT A$0.06/kWh RENEWABLE ELECTRICITY PRICE, 2018)



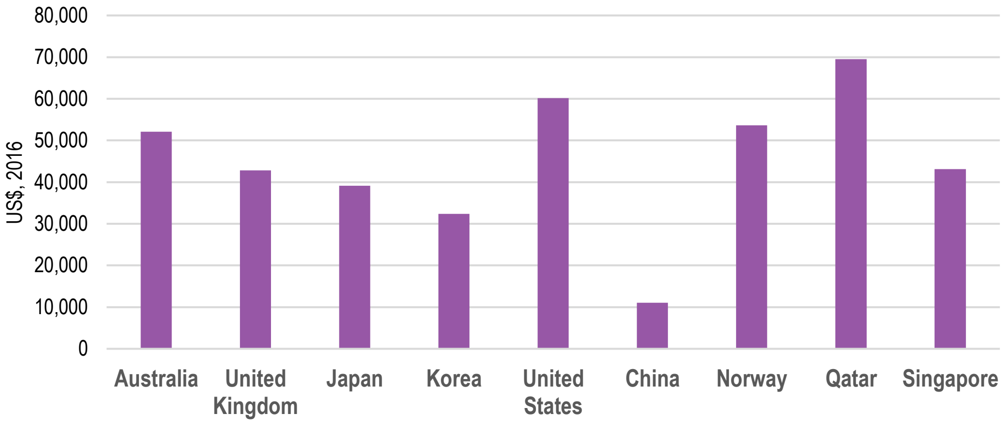
SOURCE: BASED ON CSIRO 2018, NATIONAL HYDROGEN ROADMAP

4.2.5 Labour costs, skills and capabilities

Australia has an educated and skilled workforce. CSIRO and Australian universities have several research and development programs related to hydrogen. In addition, the private sector is also exploring hydrogen opportunities in Australia. It is unlikely that Australia's opportunities to develop a hydrogen industry would be constrained by a lack of appropriately skilled people.

Average annual wages in selected economies are shown in **Figure 4.5**. China currently has the lowest average annual wage costs across the countries reviewed. However, since labour costs make up a relatively small proportion of the cost of hydrogen production, it is unlikely that this factor would have a significant impact on Australia's competitiveness.

FIGURE 4.5 AVERAGE ANNUAL WAGE IN SELECTED ECONOMIES, 2016



SOURCE: OECD EMPLOYMENT OUTLOOK 2017.STATISTICS SINGAPORE, 2014 GULF SALARY SURVEY

4.2.6 Water costs

A PEM electrolyser requires about 50kWh of electrical energy to electrolyse nine litres of water to obtain 1kg of hydrogen. Access to water, the purity of water and the price all impact on water costs. CSIRO has used A$1.82 per kilolitre in their calculations of hydrogen production costs.

The cost of water is a small proportion of the cost of hydrogen production (see **Figure 4.2**). Therefore, water costs are unlikely to be a significant barrier for hydrogen production. Even in Qatar, desalination plants could provide the required water at a reasonable cost.

Estimates of the total volume of water needed for the projected Australian hydrogen export industry are shown in **Table 4.4**. We have estimated that in 2040 Australia would require 5.6 gigalitres of water to produce hydrogen for export markets in the low demand scenario, 12.2 gigalitres for the medium demand scenario and 28.6 gigalitres for the high hydrogen demand scenario.

TABLE 4.4 WATER NEEDED FOR AUSTRALIAN PRODUCTION OF HYDROGEN FOR EXPORT (GIGALITRES)

Scenarios	2025	2030	2040
Low H_2 demand scenario	0.238	2.179	5.592
Medium H_2 demand scenario	1.228	4.519	12.154
High H_2 demand scenario	3.103	9.796	28.623

SOURCE: ACIL ALLEN CONSULTING ESTIMATES

Total consumption of water in Australia in 2015-16 was 16,132 gigalitres, of which 9,604 gigalitres was used by the Agriculture, Forestry, and Fishing industry and 2,014 gigalitres was used by the Water Supply, Sewerage and Drainage Services industry. A further 2,615 gigalitres was consumed by all other industries and 1,899 gigalitres was used by households.[96] The potential demand for water for hydrogen production are significantly less that any of the above amounts.

4.3 Hydrogen storage and transport costs

Production is just one component of the hydrogen supply chain. Other costs associated with the supply chain include storage and transportation.

4.3.1 Storage costs

Hydrogen can be stored in different ways prior to its use or export. Each storage method incurs different costs. CSIRO has estimated costs of various hydrogen storage technologies (see **Table 4.5**). Like LNG, liquefaction of hydrogen would add to production costs but drastically reduce the transportation costs. Subject to the cost of capital, these costs are likely to be similar for each of the four potential exporting countries considered in this report.

TABLE 4.5 STORAGE COSTS OF HYDROGEN (A\$/KG H_2)

Method of storage	2018 (Base case)			2025 (Best case)		
	35 bar	150 bar	350 bar	35 bar	150 bar	350 bar
Compression and storage in tanks	0.43–0.53	0.30–0.37	0.34–0.42	0.37–0.45	0.23–0.28	0.24–0.29
Compression and storage in salt caverns		0.22–0.26			0.16–0.20	
Ammonia production and storage		0.24–0.29			0.19–0.23	
Liquefied hydrogen production and storage		2.57–3.14			1.30	

SOURCE: CSIRO 2018, NATIONAL HYDROGEN ROADMAP, UNPUBLISHED

4.3.2 Transport costs

CSIRO has also estimated hydrogen transport costs. The results are summarised in **Table 4.6**. The table shows the estimated transport costs in 2018. It is expected that transport costs will decline over time, as is projected to occur for the storage costs (see **Table 4.5**).

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[96] ABS 2017, Water Account, Australia 2015-16, Cat no: 4610.0 accessed on 3 July 2018 at http://www.abs.gov.au/ausstats/abs@.nsf/mf/4610.0

TABLE 4.6 HYDROGEN TRANSPORT COSTS IN 2018 (A$/tkm)[97]

Transport method	Compression 350 bar	Compression 430 bar	Liquefaction	Ammonia
Truck	2.98	2.33	0.92	0.33
Rail	0.62	0.55	0.28	0.04
Shipping	0.59	0.52	0.09 (loading cost included)	0.03

SOURCE: CSIRO 2018, NATIONAL HYDROGEN ROADMAP, UNPUBLISHED

In the short term, hydrogen destined for local market applications is likely to be transported by road tankers, since demand will generally be small and geographically dispersed. Countries that are likely to compete with Australia to export hydrogen to the selected countries are likely to transport hydrogen using shipping. Shipping costs vary depending upon the extent of compression or carrier used for the hydrogen and are estimated to range between A$0.03 and A$0.61/tkm.

Comparing the transportation costs in **Table 4.6** alone can be misleading because:

— As with any carrier, there are costs in converting hydrogen to ammonia and then converting it from ammonia back to hydrogen.[98] CSIRO have not reported on the cost of re-converting ammonia back to hydrogen because in their view it is too early to do so with any confidence.

— It is also important to recognise that the presence any ammonia in the hydrogen would poison the catalysts used in fuel cells so additional precautions are necessary to ensure that hydrogen produced from ammonia for use in fuel cells does not contain any traces of ammonia. [99] This level of purity is not required for the direct combustion of hydrogen.

— While direct use of ammonia in fuel cells or ammonia fuelled turbines could be an option in the future, the required technology is still in development. It is too early to estimate costs and use of ammonia in these ways is unlikely to be significant within the time frame covered by this report.

4.4 Hydrogen import price

The estimated CIF[100] equivalent hydrogen costs from various exporting countries to each of the four selected importing countries are shown in **Table 4.7**. The information in the table provides an indication of the competitiveness of Australian exports to the four selected importing countries. Australia's proximity to the selected importing countries is an important factor as it reduces Australia's shipping costs compared to the other potential competing exporters listed in the table.

4.5 Australia's standing vs other potential hydrogen suppliers

4.5.1 Trading relationships

Australia has free trade agreements with many countries, including Japan, the Republic of Korea, China and Singapore. The established trading relationships between Australia and these countries, including significant trade in energy, could provide a competitive advantage to Australia over other potential suppliers of hydrogen without such established trading relationships.

For example, the Japan–Australia Economic Partnership Agreement (JAEPA) entered into force on 15 January 2015. Australia's exports of resources and energy products to Japan were worth an estimated A$30 billion in 2016 and accounted for more than 76 per cent of Australia's total exports to Japan. Many of Australia's major resource exports, such as coal, iron ore and liquefied natural gas already entered duty-free before JAEPA, but tariffs of up to 11.7 per cent were charged on a range of transformed energy and resource products. Under JAEPA, all tariffs on energy and mineral products

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[97] tkm is a tonne-kilometer, represents the transport of one tonne of goods by a given transport mode over a distance of one kilometer.

[98] However, Ammonia has a higher energy density than liquid hydrogen as one cubic metre of liquid hydrogen contains 71 kg of hydrogen, whereas a cubic metre of anhydrous liquid ammonia contains 105 kg of hydrogen.

[99] The recent demonstration of CSIRO's membrane technology for separating high-purity hydrogen from ammonia could address this issue.

[100] Cost, Insurance and Freight

will be eliminated by 2024.[101] Hence any hydrogen exports to Japan from Australia are unlikely to incur tariffs.

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[101] DFAT, Japan -Australia Economic Partnership Agreement (JAEPA), accessed on 30 May 2018 at http://dfat.gov.au/trade/agreements/in-force/jaepa/Pages/japan-australia-economic-partnership-agreement.aspx

TABLE 4.7 ESTIMATED HYDROGEN IMPORT PRICE IN 2025, A$/KG H_2

		Production costs									
Importing country	Exporting country	Electrolyser cost	Stack replacement cost	O&M costs	Electricity cost	Water cost	TOTAL	Liquefaction costs	Loading cost	Shipping cost (a)	CIF
Japan	Australia	0.41	0.09	0.11	1.87	0.02	2.50	1.30	0.45	0.36	4.61
	Norway	0.47	0.09	0.11	1.95	0.01	2.63	1.39	0.49	0.92	5.43
	Qatar	0.45	0.09	0.14	1.44	0.03	2.14	1.42	0.53	0.48	4.57
	USA	0.43	0.08	0.12	2.03	0.02	2.67	1.28	0.52	0.68	5.16
Korea	Australia	0.41	0.09	0.10	1.87	0.02	2.49	1.30	0.45	0.38	4.62
	Norway	0.47	0.09	0.11	1.95	0.01	2.63	1.39	0.49	0.89	5.40
	Qatar	0.45	0.09	0.14	1.44	0.03	2.14	1.42	0.53	0.45	4.54
	USA	0.43	0.08	0.12	2.03	0.02	2.67	1.28	0.52	0.71	5.19
Singapore	Australia	0.41	0.09	0.10	1.87	0.02	2.49	1.30	0.45	0.28	4.52
	Norway	0.47	0.09	0.11	1.95	0.01	2.63	1.39	0.49	0.71	5.22
	Qatar	0.45	0.09	0.14	1.44	0.03	2.14	1.42	0.53	0.27	4.36
	USA	0.43	0.08	0.12	2.03	0.02	2.67	1.28	0.52	0.87	5.34
China	Australia	0.41	0.09	0.10	1.87	0.02	2.49	1.30	0.45	0.38	4.62
	Norway	0.47	0.09	0.11	1.95	0.01	2.63	1.39	0.49	0.87	5.38
	Qatar	0.45	0.09	0.14	1.44	0.03	2.14	1.42	0.53	0.43	4.52
	USA	0.43	0.08	0.12	2.03	0.02	2.67	1.28	0.52	0.75	5.22

[a] Assuming the Suez and Panama canals allow ships carrying hydrogen to pass through

Note: CIF refers to cost, insurance and freight basis shipping (i.e. cost landed in buyers country). FOB is free on-board basis at export terminals (i.e. the buyer pays for shipping)

SOURCE: ACIL ALLEN CONSULTING ESTIMATES BASED ON CSIRO AND OTHER SOURCES

4.5.2 Global competitiveness index

Since 2004 the World Economic Forum (WEF) has published the Global Competitiveness Report which tracks and ranks the performance of nearly 140 countries based on the Global Competitiveness Index (GCI). The GCI is compiled from a detailed list of over 100 indicators that capture concepts that influence productivity and long-term prosperity. The indicators are grouped into a list of twelve 'pillars':

1. Institutions
2. Appropriate infrastructure
3. Stable macroeconomic framework
4. Good health and primary education
5. Higher education and training
6. Efficient goods markets
7. Efficient labour markets
8. Developed financial markets
9. Ability to harness existing technology
10. Market size—both domestic and international
11. Production of new and different goods using the most sophisticated production processes
12. Innovation

While the GCI is more of a general measure of Australia's competitiveness rather than a specific measure of Australia's competitiveness with respect to hydrogen production and export, the Global Competitiveness Report provides a consistent and useful indicator of the relative strengths and weaknesses of different countries.

In the most recent report (published in 2017), Australia is ranked 21st out of 137 countries. Australia ranks below Norway and the USA. According to the WEF, Australia ranks outside of the top 25 countries in most of the pillars. The most problematic issues in relation to doing business in Australia were deemed to be restrictive labour regulations, tax rates, inefficient government bureaucracy, and policy instability. Australia performs comparatively better in the higher education and training pillar (9th), which reflects a strong ability to produce a large pool of qualified workers. Australia was also ranked highly in the financial market development pillar (6th), which is driven mostly by a stable and well-regulated banking sector.

Notwithstanding Australia's GCI, there is a strong track record of Australia successfully attracting and maintaining large-scale LNG and other energy sector investments. Australia also has a gained a reputation as a reliable producer and exporter of energy.

4.6 Opportunities for Australian hydrogen exports

4.6.1 Australia's opportunity to help meet Japanese hydrogen demand

ACIL Allen estimates that Japan would import around 85 per cent of its hydrogen demand (see Appendix C for further detail). Some 21 per cent of demand would be supplied by imports from Australia and around 64 per cent by imports from the rest of the world (see **Figure 4.6**).

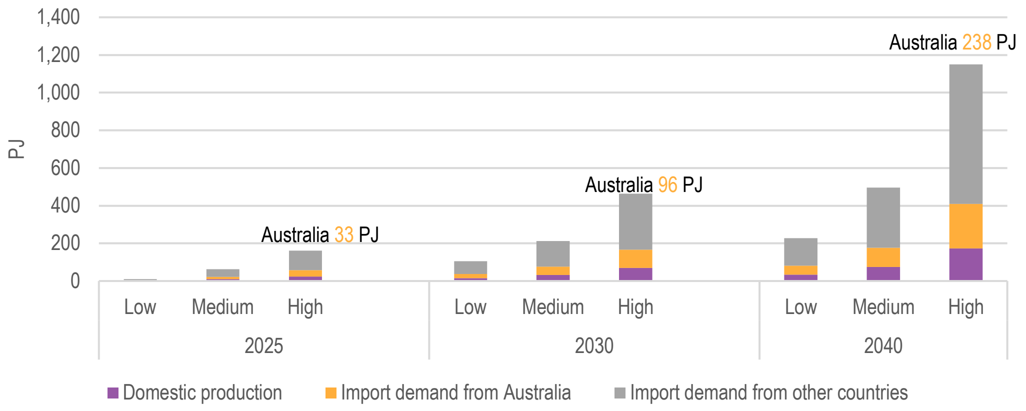
TABLE 4.8 GLOBAL COMPETITIVENESS INDEX (2017-18) – TOP 30 COUNTRIES

Rank	Country	2017-18	Previous	Highest	Lowest
1	Switzerland	5.86	5.81	5.86	5.54
2	**USA**	**5.85**	**5.70**	**5.85**	**5.42**
3	Singapore	5.71	5.72	5.72	5.44
4	Netherlands	5.66	5.57	5.66	5.32
5	Germany	5.65	5.57	5.65	5.37
6	Hong Kong	5.53	5.48	5.53	5.22
7	Sweden	5.52	5.53	5.61	5.4
8	United Kingdom	5.51	5.49	5.56	5.18
9	Finland	5.49	5.44	5.54	5.36
10	Japan	5.49	5.48	5.5	5.36
11	**Norway**	**5.40**	**5.44**	**5.44**	**5.14**
12	Denmark	5.39	5.35	5.58	5.17
13	New Zealand	5.37	5.31	5.37	4.91
14	Canada	5.35	5.27	5.37	5.2
15	Taiwan	5.33	5.28	5.34	5.2
16	Israel	5.31	5.18	5.31	4.79
17	United Arab Emirates	5.30	5.26	5.32	4.49
18	Austria	5.25	5.22	5.25	5.08
19	Belgium	5.23	5.25	5.25	5.05
20	Luxembourg	5.23	5.2	5.23	4.85
21	**Australia**	**5.19**	**5.19**	**5.20**	**5.08**
22	France	5.18	5.2	5.21	5.05
23	Malaysia	5.17	5.16	5.23	4.87
24	Ireland	5.16	5.18	5.18	4.74
25	**Qatar**	**5.11**	**5.23**	**5.38**	**4.58**
26	Korea	5.07	5.03	5.39	4.93
27	China	5.00	4.95	5.00	4.55
28	Iceland	4.99	4.96	5.12	4.66
29	Estonia	4.85	4.78	4.85	4.56
30	Saudi Arabia	4.83	4.84	5.19	4.54

Note: Indexes are scored on a scale of 1 to 7.

SOURCE: WORLD ECONOMIC FORUM (2017), THE GLOBAL COMPETITIVENESS REPORT 2017-2018, GENEVA

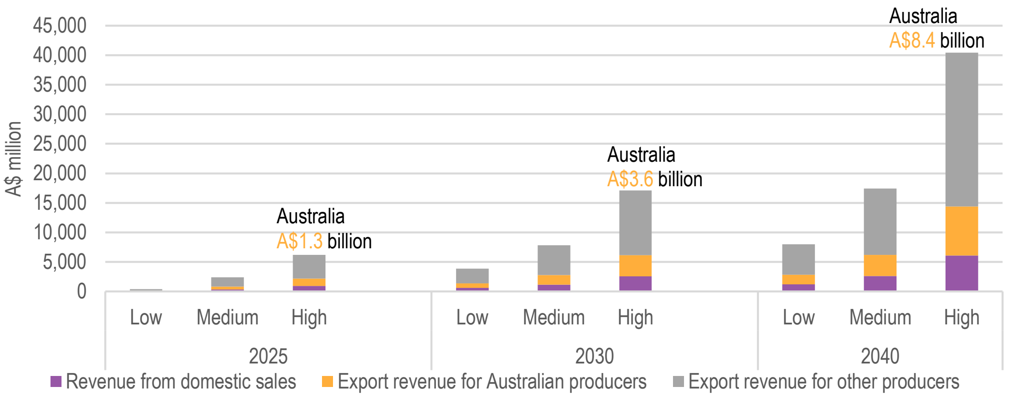
FIGURE 4.6 HYDROGEN DEMAND IN JAPAN, 2025, 2030 AND 2040



SOURCE: ACIL ALLEN ESTIMATES

The estimated CIF value of hydrogen demand in Japan in the three hydrogen scenarios is shown in **Figure 4.7**.

FIGURE 4.7 VALUE OF HYDROGEN DEMAND IN JAPAN, 2025, 2030 AND 2040

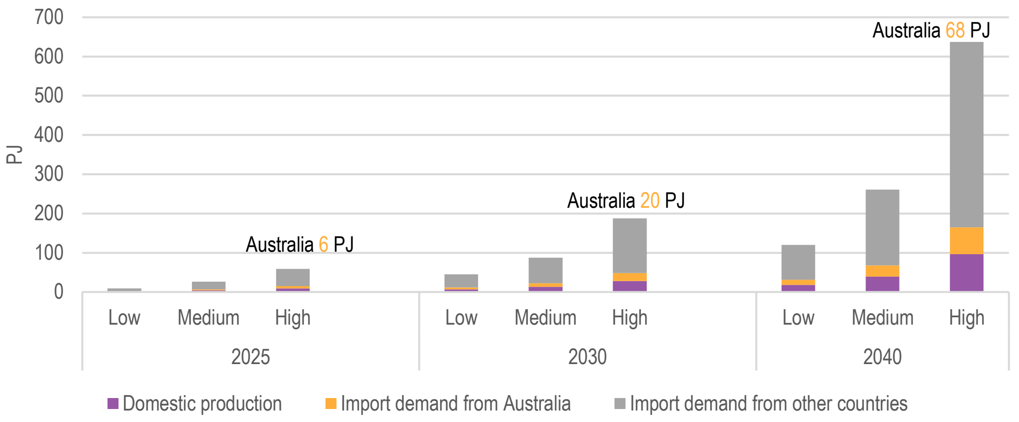


SOURCE: ACIL ALLEN ESTIMATES

4.6.2 Australia’s opportunity to help meet the Republic of Korea’s hydrogen demand

ACIL Allen estimates that domestic production would supply around 15 per cent of the Republic of Korea’s hydrogen demand (see Appendix C for more detail). A further 11 per cent of demand could be imported from Australia and around 74 per cent imported from the rest of the world (see **Figure 4.8**).

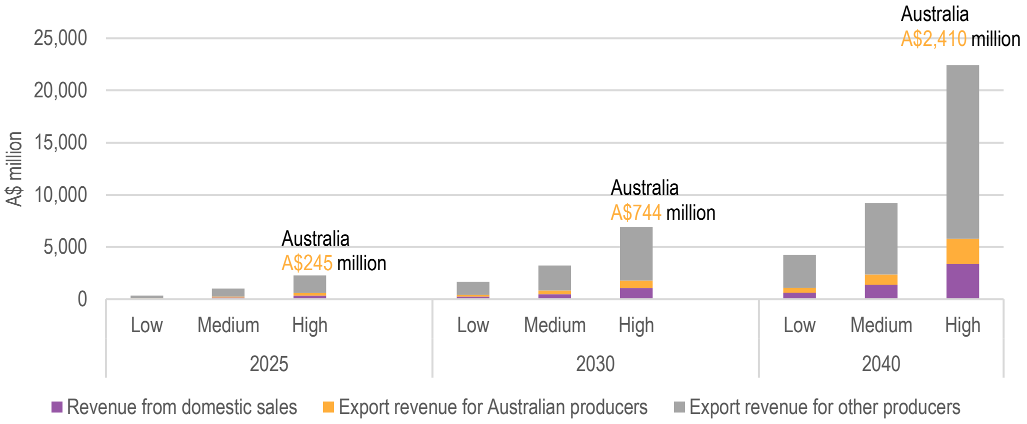
FIGURE 4.8 HYDROGEN DEMAND IN REPUBLIC OF KOREA, 2025, 2030 AND 2040



SOURCE: ACIL ALLEN ESTIMATES

The estimated value of hydrogen demand in Korea in the three hydrogen scenarios is shown in **Figure 4.9**.

FIGURE 4.9 VALUE OF HYDROGEN DEMAND IN REPUBLIC OF KOREA, 2025, 2030 AND 2040

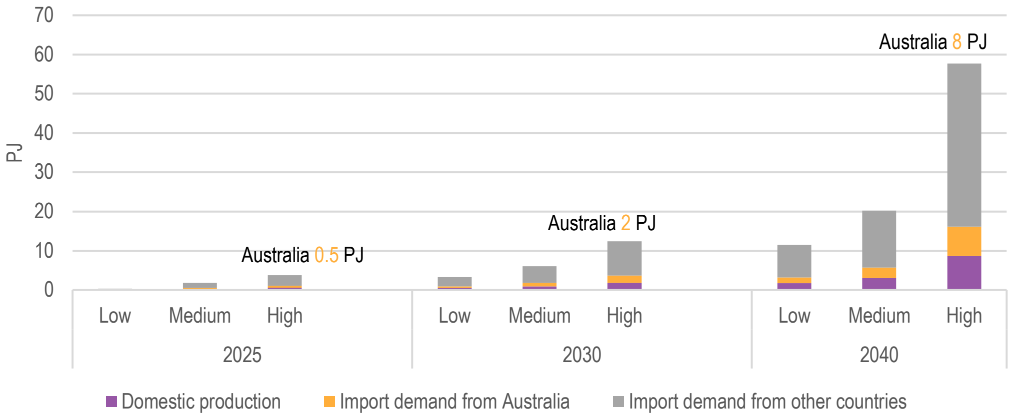


SOURCE: ACIL ALLEN ESTIMATES

4.6.3 Australia’s opportunity to help meet Singapore’s hydrogen demand

ACIL Allen estimates that Singapore would import around 85 per cent of its demand for hydrogen (see Appendix C for more detail). Some 11 per cent of demand could be imported from Australia and around 74 per cent imported from the rest of the world (see **Figure 4.10**).

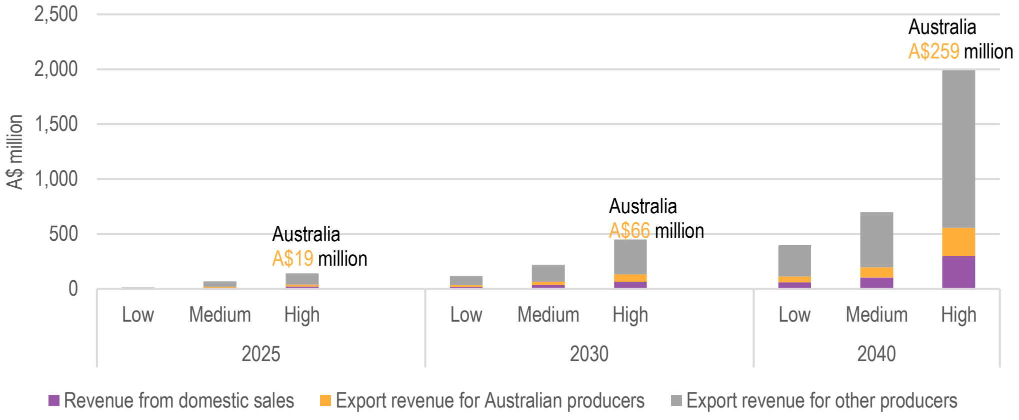
FIGURE 4.10 HYDROGEN DEMAND IN SINGAPORE, 2025, 2030 AND 2040



SOURCE: ACIL ALLEN ESTIMATES

The estimated value of hydrogen consumption in Singapore in the three hydrogen scenarios is shown in **Figure 4.11**.

FIGURE 4.11 VALUE OF HYDROGEN DEMAND IN SINGAPORE, 2025, 2030 AND 2040

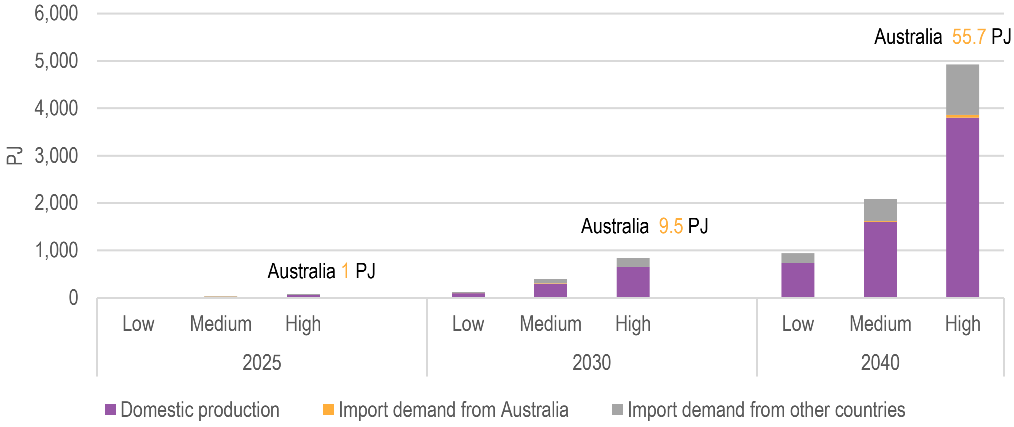


SOURCE: ACIL ALLEN ESTIMATES

4.6.4 Australia’s opportunity to help meet Chinese hydrogen demand

ACIL Allen estimates that China would import nearly 23 per cent of its demand for hydrogen (see Appendix C for more detail). Australia could supply nearly 5 per cent of hydrogen imports, or just over 1 per cent of projected hydrogen demand in China (see **Figure 4.12**).

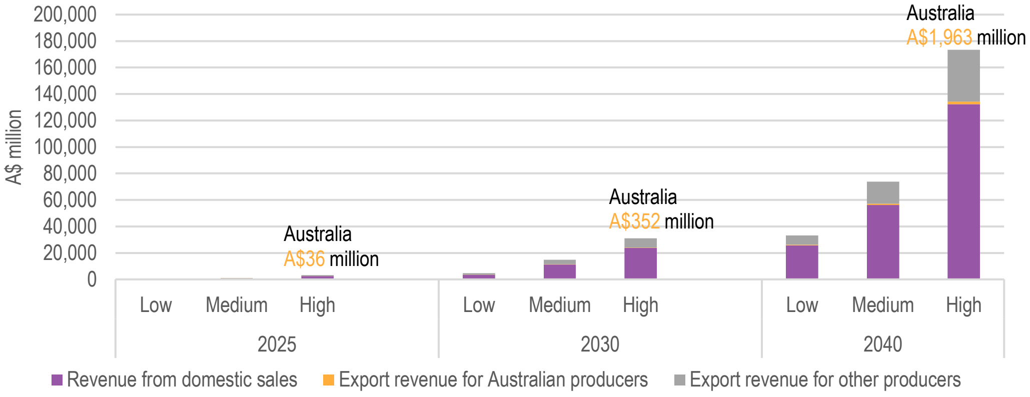
FIGURE 4.12 HYDROGEN DEMAND IN CHINA, 2025, 2030 AND 2040



SOURCE: ACIL ALLEN ESTIMATES

The estimated value of hydrogen consumption in China in the three hydrogen scenarios is shown in **Figure 4.13**.

FIGURE 4.13 VALUE OF HYDROGEN DEMAND IN CHINA, 2025, 2030 AND 2040

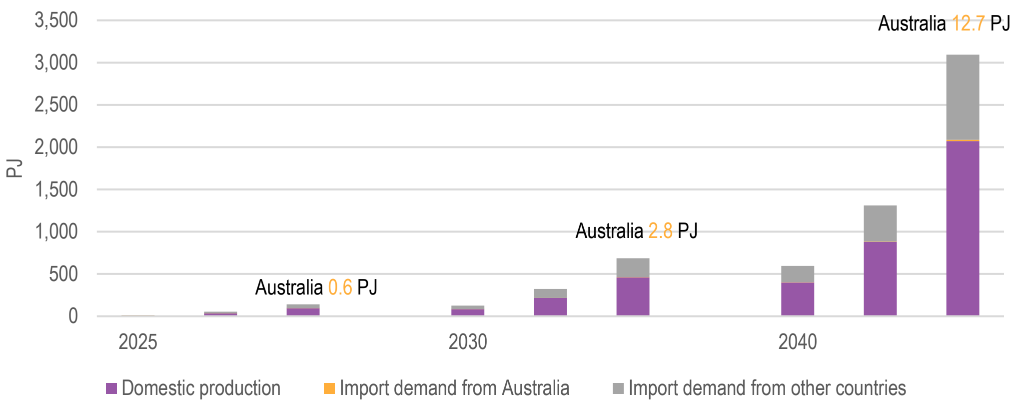


SOURCE: ACIL ALLEN ESTIMATES

4.6.5 Australia’s opportunity to help meet hydrogen demand in the rest of the world

It is estimated rest of the world would import nearly 32 per cent of its hydrogen demand (see Appendix C for more detail). Australia would supply around 0.4 per cent of projected hydrogen demand in the rest of the world (see **Figure 4.14**).

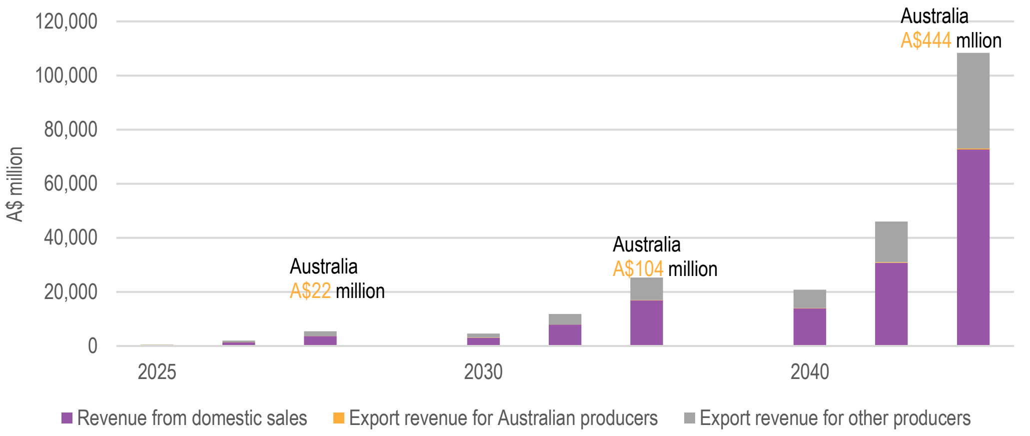
FIGURE 4.14 ESTIMATED HYDROGEN DEMAND IN THE REST OF THE WORLD, 2025, 2030 AND 2040



SOURCE: ACIL ALLEN ESTIMATES

The estimated value of hydrogen in the rest of the world in the three hydrogen scenarios is shown in **Figure 4.15**.

FIGURE 4.15 ESTIMATED VALUE OF HYDROGEN DEMAND IN THE REST OF THE WORLD, 2025, 2030 AND 2040



SOURCE: ACIL ALLEN ESTIMATES

4.6.6 Summary of hydrogen export opportunities

A summary of Australia’s opportunity to supply hydrogen to meet demand for imports is provided in **Table 4.9**.

TABLE 4.9 AUSTRALIA'S POTENTIAL EXPORTS OF HYDROGEN

Scenario	Country	2025		2030		2040	
		PJ	'000 tonnes	PJ	000 tonnes	PJ	000 tonnes
Low hydrogen scenario	Japan	2.1	17.3	21.9	182.2	47.1	392.1
	Korea	1.0	8.0	4.8	40.1	12.9	107.4
	Singapore	0.04	0.3	0.5	3.9	1.5	12.5
	China	0.1	0.5	1.4	11.6	10.7	88.9
	Rest of the World	0.05	0.4	0.5	4.3	2.4	20.3
	Total	**3.2**	**26.5**	**29.1**	**242.1**	**74.6**	**621.3**
Medium hydrogen scenario	Japan	12.7	106.1	44.2	368.1	102.3	852.2
	Korea	2.9	23.9	9.4	78.1	28.1	233.6
	Singapore	0.2	2.1	0.9	7.4	2.7	22.6
	China	0.3	2.6	4.5	37.6	23.7	197.3
	Rest of the World	0.2	1.8	1.3	11.0	5.4	44.8
	Total	**16.4**	**136.5**	**60.3**	**502.1**	**162.2**	**1,350.4**
High hydrogen scenario	Japan	33.0	275.0	96.4	803.0	237.7	1,978.8
	Korea	6.4	53.0	20.1	167.4	68.4	569.5
	Singapore	0.5	4.2	1.8	15.1	7.5	62.5
	China	0.9	7.9	9.5	79.3	55.7	463.9
	Rest of the World	0.6	4.8	2.8	23.5	12.7	105.6
	Total	**41.4**	**344.8**	**130.7**	**1,088.4**	**382.0**	**3,180.4**

SOURCE: ACIL ALLEN ESTIMATES

A summary of value of Australia's opportunity to supply hydrogen to meet demand for imports is provided in **Table 4.10**.

TABLE 4.10 CIF VALUE OF AUSTRALIA'S POTENTIAL HYDROGEN EXPORTS (A$ MILLION)

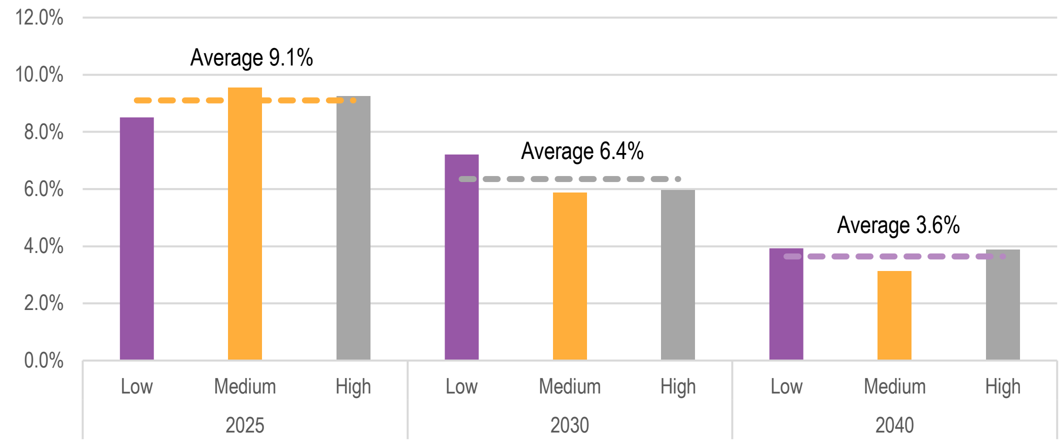
Scenario	Country	2025	2030	2040
Low hydrogen scenario	Japan	80	807	1,655
	Korea	37	178	455
	Singapore	1	17	52
	China	3	52	376
	Rest of the World	2	19	86
	Total	**122**	**1,072**	**2,623**
Medium hydrogen scenario	Japan	489	1,631	3,597
	Korea	111	347	988
	Singapore	9	32	94
	China	12	167	835
	Rest of the World	8	48	188
	Total	**629**	**2,225**	**5,703**
High hydrogen scenario	Japan	1,268	3,557	8,354
	Korea	245	744	2,410
	Singapore	19	66	259

Scenario	Country	2025	2030	2040
	China	36	352	1,963
	Rest of the World	22	104	444
	Total	**1,590**	**4,822**	**13,430**

SOURCE: ACIL ALLEN ESTIMATES

Australia's estimated share of the potential global hydrogen export market is summarised in **Figure 4.16**. Australia may have an initial advantage due to factors such as our existing supply chain relationships, but this advantage will decline as the technology matures and other countries become more competitive.

FIGURE 4.16 AUSTRALIA'S SHARE OF GLOBAL HYDROGEN EXPORT DEMAND (PER CENT)



SOURCE: ACIL ALLEN ESTIMATES

Australia's share of imports by country and by scenario is summarised in **Table 4.11**.

TABLE 4.11 AUSTRALIA'S SHARE OF HYDROGEN EXPORTS IN KEY MARKETS (PER CENT)

Country	2025			2030			2040		
	Low	Medium	High	Low	Medium	High	Low	Medium	High
Japan	19.5	20.5	20.5	20.8	20.9	20.8	20.7	20.6	20.7
Republic of Korea	10.7	10.7	10.7	10.7	10.7	10.7	10.7	10.7	10.7
Singapore	10.8	13.4	13.3	14.4	14.6	14.7	13.0	13.4	13.0
China	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1
Rest of the World	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Total	8.5	9.6	9.2	7.2	5.9	6.0	3.9	3.9	3.9

SOURCE: ACIL ALLEN ANALYSIS

5

IMPLICATIONS FOR AUSTRALIA

5.1 Potential size of Australian market

Estimating Australian domestic use of hydrogen for energy purposes was outside the scope of this project. The analysis therefore represents the impact of a hydrogen export industry alone. To the extent that there was any domestic use of hydrogen in Australia this would likely add to the estimated impacts of a purely export driven hydrogen industry.

The estimated potential scale of an Australian hydrogen export industry ranges between 3.2 PJ (36.5 kilo tonnes) in 2025 in the low scenario and 382 PJ (3,180 kilo tonnes) in 2040 in the high scenario as noted in **Table 4.9**.

It is important to provide a perspective of the scale of this potential export opportunity. If we assume an efficiency of around 50 per cent for the steps from electrolysis through to liquefaction, this implies an additional electricity demand of between 1 TWh (2025 low demand scenario) and 200 TWh (2040 high hydrogen demand scenario) (see **Table 5.1**). The 200 TWh in 2040 is more than the entire current generation of the NEM.[102] The potential export of around 60 PJ (502 kilo tonnes) in the medium scenario in 2030 implies an additional demand of around 33 TWh, which is equivalent to the amount of Australia's Large-scale Renewable Energy Target.

TABLE 5.1 POTENTIAL ADDITIONAL GENERATION REQUIRED FOR HYDROGEN EXPORTS (TWH)

Heading	2025			2030			2040		
	Low	Medium	High	Low	Medium	High	Low	Medium	High
Japan	1.09	6.67	17.29	11 .46	23.15	50.50	24.66	53.59	124.44
Republic of Korea	0.50	1.50	3.33	2.52	4.91	10.53	6.76	14.69	35.81
Singapore	0.50	0.13	0.26	0.24	0.47	0.95	0.79	1.42	3.93
China	0.02	0.16	0.50	0.73	2.36	4.99	5.59	12.40	29.17
Rest of the World	0.03	0.12	0.30	0.27	0.69	1.48	1.28	2.82	6.64
Total	**1.67**	**8.58**	**21.68**	**15.22**	**31.58**	**68.45**	**39.07**	**84.92**	**200.00**

SOURCE: ACIL ALLEN

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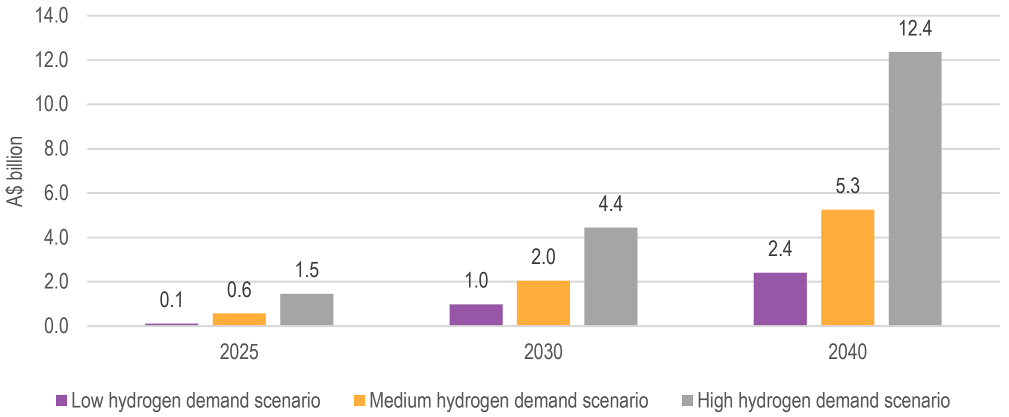
[102] AEMO's Annual Consumption Overview forecast annual operational electricity consumption in the NEM to increase by just over 10 TWh over the 20 year period to 2036-37. https://www.aemo.com.au/Electricity/National-Electricity-Market-NEM/Planning-and-forecasting/Electricity-Forecasting-Insights/2017-Electricity-Forecasting-Insights/Summary-Forecasts/Annual-Consumption

5.2 Economic benefits

The potential direct and indirect economic and employment contribution to the Australian economy of hydrogen production for exports has been estimated using input-output (I/O) multiplier analysis (see Appendix B for more details on the I/O methodology).

The total estimated potential value of Australian hydrogen exports in the three hydrogen scenarios are provided in Chapter 4. Those estimates are summarised in **Figure 5.1**.

FIGURE 5.1 POTENTIAL FOB VALUE OF AUSTRALIAN HYDROGEN EXPORTS



SOURCE: ACIL ALLEN ESTIMATES

5.2.1 Direct economic contribution

The direct economic and employment contribution from hydrogen production in Australia is summarised in **Table 5.2**.

For example, it has been estimated that the direct contribution that hydrogen exports could make to the Australian economy in 2025 would range between A$23 million in the low hydrogen demand scenario and A$298 billion in the high scenario. The contribution to the economy comprises mainly employee wages and gross operating surplus of the hydrogen producers and exporters.

TABLE 5.2 DIRECT ECONOMIC CONTRIBUTION OF HYDROGEN PRODUCTION FOR EXPORT

	Value-add			Employment		
	2025	2030	2040	2025	2030	2040
	A$m	A$m	A$m	FTE	FTE	FTE
Low H_2 demand scenario	23	201	491	37	326	798
Medium H_2 demand scenario	118	417	1,068	191	677	1,734
High H_2 demand scenario	298	903	2,516	484	1,467	4,084

Note: FTE refers to the number of full-time equivalent employees

SOURCE: ACIL ALLEN ESTIMATES

Direct employment in the hydrogen production industry for export is estimated to be equivalent to 37 full-time equivalent (FTE) persons in 2025 in the low hydrogen demand scenario. This could increase to over four thousand FTE employees in 2040 in the high hydrogen scenario.

Most of these jobs will be located where hydrogen production facilities are built. It is most likely that the facilities will be located close to the supply of renewables. Renewables, particularly large solar PV projects, are most likely to be located is areas where the solar irradiance is high. In Australia, the areas of high solar irradiance (and reasonable access to land) tend to be in regional locations. Hydrogen production for export may therefore particularly benefit regional communities, traditional owners of the land as well as the broader Australian community through the direct employment associated with hydrogen production facilities.

To fully understand the estimated number of jobs supported by the industry, it is important to recognise that they are presented as FTE jobs for convenience. However, the estimated FTE jobs represent the summation of many shares of individual jobs, including part-time and casual jobs with different skill and occupational categories. Consequently, the number of people whose employment is supported (partially or wholly) by the activities associated with hydrogen production for export will be greater than the estimated number of FTE jobs.

5.2.2 Indirect economic contribution

Allocating Australian intermediate inputs to their corresponding input-output industries and applying the appropriate multipliers for Australian value added and employment, it is possible to estimate the total Australian value added and employment embodied in Australian produced inputs and services demanded by the potential hydrogen production industry.

We estimate that Australian hydrogen producers would spend between A$78.5 million in the low hydrogen demand scenario and A$1,021.3 million in the high hydrogen demand scenario on goods and services producing hydrogen in 2025.

It is estimated that, of these amounts, about A$67.2 million in low hydrogen demand scenario and A$874.7 million in high hydrogen demand scenario would be spent on domestically produced goods and services.

The estimated indirect impacts of potential hydrogen production for export are provided in **Table 5.3**. For example, ACIL Allen has estimated that the domestic spend on goods and services by hydrogen producers in Australia will indirectly contribute A$69 million to the Australian economy in 2025 in the low hydrogen demand scenario.

Similarly, ACIL Allen has estimated that hydrogen production will support indirect employment in the supply chain of 127 FTE in 2025 in the low hydrogen demand scenario.

Depending on the demand for Australian hydrogen, how the sector develops in Australia and the extent to which Australian companies become involved in the hydrogen supply chain, there could be some innovation and education spill-over benefits.

TABLE 5.3 INDIRECT ECONOMIC CONTRIBUTION OF HYDROGEN PRODUCTION FOR EXPORT

	Value-add			Employment		
	2025 A$m	2030 A$m	2040 A$m	2025 FTE	2030 FTE	2040 FTE
Low H_2 demand scenario	69	605	1,481	127	1,113	2,721
Medium H_2 demand scenario	355	1,256	3,219	597	2,110	5,408
High H_2 demand scenario	898	2,722	7,580	1,414	4,288	11,940

SOURCE: ACIL ALLEN ESTIMATES

5.3 Total economic contribution

Adding the direct and indirect contributions will provide the total economic footprint of a potential Australian industry producing hydrogen for export in 2025, 2030 and 2040 for each of the hydrogen demand scenarios. The estimated total contribution of hydrogen production to the Australian economy in 2025, 2030 and 2040 is summarised in **Table 5.4**.

TABLE 5.4 TOTAL ECONOMIC CONTRIBUTION OF HYDROGEN PRODUCTION FOR EXPORT

	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

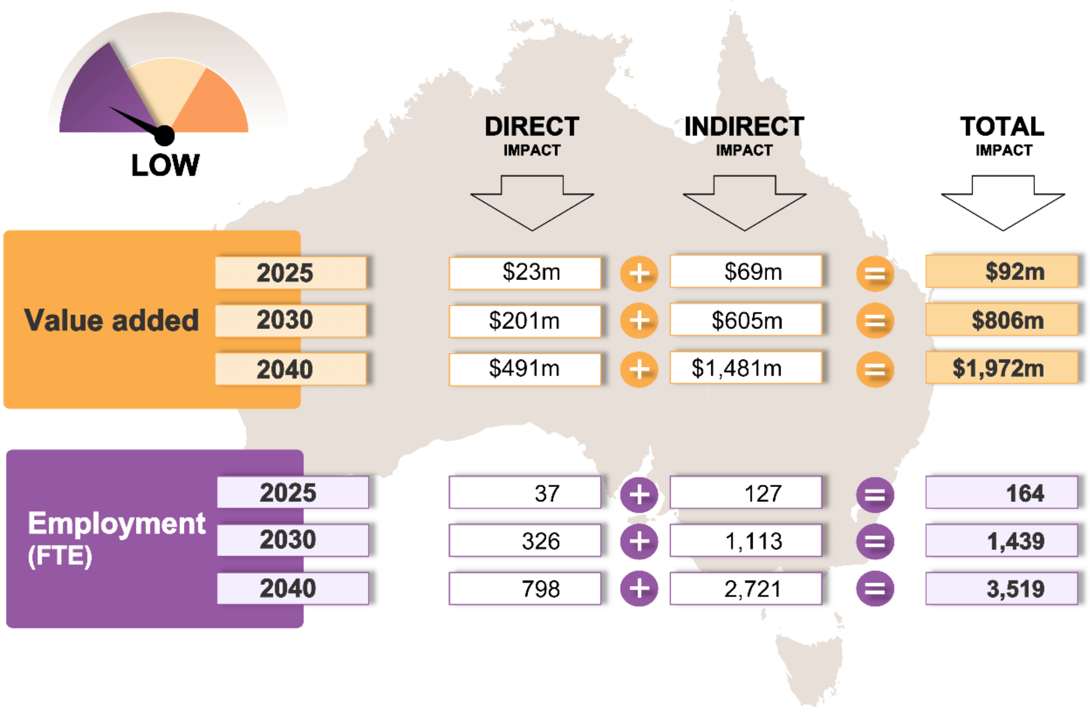
SOURCE: ACIL ALLEN ESTIMATES

The impacts over time on the Australian economy and employment for each scenario are summarised in the sub- sections below

5.3.1 Impacts under the low hydrogen demand scenario

The economic and employment impacts of hydrogen production for export in the low hydrogen demand scenario is summarised in **Figure 5.2**.

FIGURE 5.2 FOOTPRINT OF THE HYDROGEN PRODUCTION SECTOR IN AUSTRALIA—LOW HYDROGEN EXPORT DEMAND SCENARIO

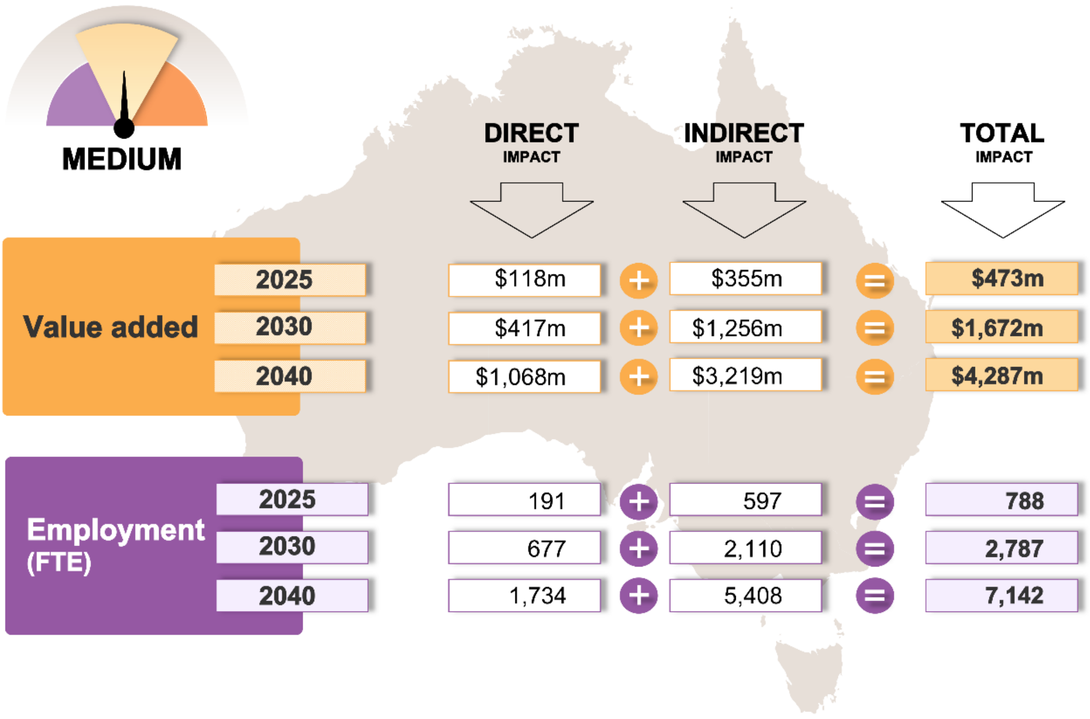


SOURCE: ACIL ALLEN ESTIMATES

5.3.2 Impacts under the medium hydrogen demand scenario

The economic and employment impacts of hydrogen production for export in medium hydrogen demand scenario is summarised in **Figure 5.3**.

FIGURE 5.3 FOOTPRINT OF THE HYDROGEN PRODUCTION SECTOR IN AUSTRALIA—MEDIUM HYDROGEN DEMAND SCENARIO



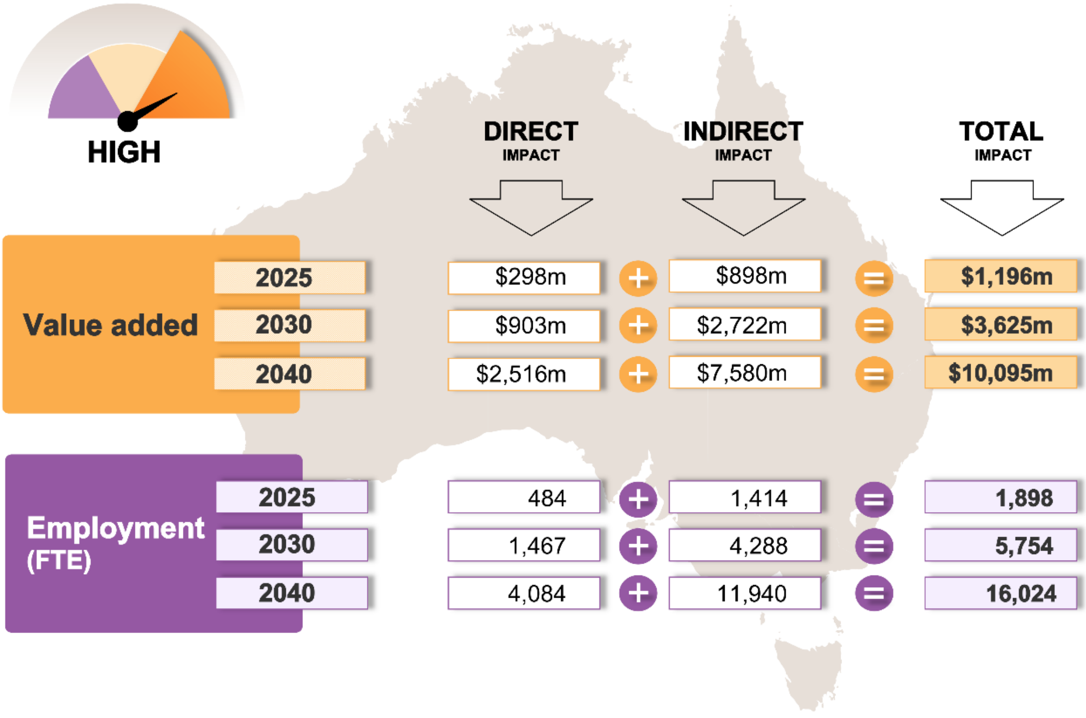
		DIRECT IMPACT		INDIRECT IMPACT		TOTAL IMPACT
Value added	**2025**	$118m	+	$355m	=	**$473m**
	2030	$417m	+	$1,256m	=	**$1,672m**
	2040	$1,068m	+	$3,219m	=	**$4,287m**
Employment (FTE)	**2025**	191	+	597	=	**788**
	2030	677	+	2,110	=	**2,787**
	2040	1,734	+	5,408	=	**7,142**

SOURCE: ACIL ALLEN ESTIMATES

5.3.3 Impacts under the high hydrogen demand scenario

The economic and employment impacts of hydrogen production for export in medium hydrogen demand scenario is summarised in **Figure 5.4**.

FIGURE 5.4 FOOTPRINT OF THE HYDROGEN PRODUCTION SECTOR IN AUSTRALIA—HIGH HYDROGEN DEMAND SCENARIO



SOURCE: ACIL ALLEN ESTIMATES

5.4 Emission impacts

Greater use of hydrogen is one way that is increasingly being considered as a means of reducing greenhouse gas emissions and air pollution. However, the potential impact on emissions of a transition to a hydrogen economy will vary depending on the technology used to produce the hydrogen.

CSIRO has estimated the carbon emission footprint (CO_2 emissions/kg H_2) for various hydrogen production technologies (see **Table 5.5**).

TABLE 5.5 CARBON EMISSION FOOTPRINT OF HYDROGEN PRODUCTION TECHNOLOGIES

Production process	Primary energy source	Operational CO_2 emissions (kg CO_2/kg H_2)
Steam Methane Reforming with CCS	Natural Gas	.76 [1]
Coal Gasification with CCS	Coal	.71 [2]
Alkaline Electrolysis	Renewable Electricity	zero
PEM Electrolysis	Renewable Electricity	zero

NOTES: 1. CALCULATED BASED ON THE CO2CRC AUSTRALIAN POWER GENERATION TECHNOLOGY REPORT (2015). 2. INTERNAL CSIRO CALCULATION
SOURCE: CSIRO 2018, NATIONAL HYDROGEN ROADMAP

Indicative estimates of the extent to which Australian hydrogen exports could contribute to global emissions are provided in **Table 5.6**. Hydrogen production using PEM or alkaline electrolysis and electricity from renewable energy sources of energy would have no emissions. Producing hydrogen from coal or natural gas would produce some emissions.

TABLE 5.6 GHG EMISSIONS FROM AUSTRALIAN HYDROGEN PRODUCTION – SMR WITH CCS (KT CO_2)

Scenarios	2025	2030	2040
Low H_2 demand scenario	20.2	183.3	470.0
Medium H_2 demand scenario	103.3	379.9	1021.9
High H_2 demand scenario	260.8	823.4	2406.6

NOTE: THE ABOVE NUMBERS ASSUME THE USE OF SMR TECHNOLOGY TO PRODUCE HYDROGEN
SOURCE: ACIL ALLEN ESTIMATES BASED ON CSIRO DATA

For example, **Table 5.6** shows that if natural gas was used to produce hydrogen for export through SMR with CCS this would increase Australia's emissions by around 20.2 kt CO_2 in 2025 in the low scenario.

It is important to recognise that while emissions in Australia could increase due to hydrogen production here, emissions in end-use countries will decrease when hydrogen is used as an alternative conventional source of energy. **Table 5.7** shows the estimated emissions that would result from the end-use of one PJ of various energy sources. The table illustrates the emissions reduction that could be delivered if hydrogen replaced a particular energy source.

For example, if one PJ of diesel consumption was replaced by hydrogen consumption this would result in emissions savings of just over 69 kilo tonnes of CO_2 in the end use country. By comparison, emissions in Australia associated with the production of one PJ of hydrogen using SMR and CCS would increase by around 6,300 tonnes. However, this would still represent a net global emissions reduction of 63,037 tonnes of CO_2.

TABLE 5.7 GHG EMISSIONS FROM THE USE OF ONE PJ OF DIFFERENT ENERGY SOURCES

Energy Source	Emissions from one PJ
	(Tonnes of CO_2)
Natural gas	53,700
Coal (bituminous)	88,574
Coal (sub bituminous)	96,918
Coal (lignite)	93,872
Diesel	69,337
Petrol	71,560
Fuel oil	76,722
Hydrogen	zero

SOURCE: CO2 EMISSIONS CALCULATOR, HTTPS://WWW.EECABUSINESS.GOVT.NZ/TOOLS/WOOD-ENERGY-CALCULATORS/CO2-EMISSION-CALCULATOR/ ACCESSED 18 JULY 2018

5.5 Next steps

The modelling in this report suggests that a global market for hydrogen could develop over the next 20 years. If this occurs, then there is scope for Australia to become a significant exporter of hydrogen. Of course, as with any attempt to project future outcomes, the results are dependent upon the assumptions made. ACIL Allen generally aims to be conservative when we make our assumptions. However, different assumptions could lead to quite different outcomes.

Nonetheless, the level of attention being paid to hydrogen globally and the level of investment in hydrogen related R,D&D suggests that it would be appropriate to ensure that Australia was well placed to take advantage of any hydrogen export opportunities that might arise.

A

LITERATURE REVIEW

A.1 Introduction

ARENA has engaged ACIL Allen Consulting (ACIL Allen) to conduct a study that will produce a companion report to the work that CSIRO is doing to prepare a Hydrogen Roadmap for Australia. The CSIRO project will examine the pathways for how hydrogen might enter the market in Australia, the domestic opportunities that might arise as a result and how Australia might best capture those opportunities.

ACIL Allen's task is to carry out a study that identifies the factors that may have an impact on the international demand for hydrogen, identify what, if any, competitive advantages Australia might have for supplying that eventual demand and, based on this information, seek to quantify the potential opportunities for exporting hydrogen and the benefits that might flow from such exports.

A key element of our methodology is developing a strong understanding of the forward path for hydrogen supply and consumption in conjunction with a strong understanding of the growth and economic outlook of regional economies, in particular any plans or stated intentions regarding their use of energy, including hydrogen.

We have conducted a thorough review of existing documentation on the long term global outlook for hydrogen demand. In particular, we have sought to identify any existing roadmaps and or emissions/renewables targets and other policies of key countries. The purpose of this literature review is to gather material on the potential future global demand for hydrogen and information about potential competitors that might also seek to export hydrogen. In addition, we want to investigate the likely impact of policies and regulations on hydrogen demand.

We have conducted multiple search rounds across several databases, journals and websites (usually up to three rounds of searching). At the completion of each search round, the search results were reviewed by the ACIL Allen team to select articles that best meet the criteria for inclusion in the review. The literature identified from each search round was analysed and key information gaps highlighted, prior to undertaking further search rounds. In addition, ACIL Allen drew on its international contacts to supplement the information gained from the literature review.

We also drew on the input of stakeholders we were able to identify as part of the review process. In particular, to identify and obtain copies of reports that might not be in the public domain or to test findings from the literature review.

The literature on hydrogen reports quantities of the gas in a number of different ways. **Table A.1** is provided below to assist the reader of this report with conversions.

TABLE A.1 UNIT CONVERSION DATA FOR HYDROGEN

	Weight		Gas		Liquid		Energy [a]	
	Pounds (lb)	**kilograms (kg)**	**cubic feet (scf)**	**Cu meters (Nm^3)**	**gallons (gal)**	**litres (l)**	**MJ**	**kWh**
1 pound	1.0	0.4536	192.0	5.047	1.6928	6.408	54.4	15.1
1 kilogram	2.205	1.0	423.3	11.126	3.377	14.128	120	33.3
1 scf gas	0.00521	0.00236	1.0	0.02628	0.00882	0.03339	0.283	0.079
1 Nm^3 gas	0.19815	0.08988	38.04	1.0	0.3355	1.2699	10.8	2.99
1 gallon liquid	0.5906	0.2679	113.4	2.981	1.0	3.785	32.15	8.92
1 litre liquid	0.15604	0.07078	29.99	0.7881	0.2642	1.0	8.49	2.36
1 MJ	0.018	0.0083	3.534	0.0926	0.0311	0.1178	1.0	0.278
1 kWh	0.0662	0.0300	12.66	0.3344	0.1121	0.4237	3.60	1.0

[a] Unless otherwise specified the energy content is based on lower heating value (LHV)

Note: SCF (Standard Cubic Foot) gas measured at 1 atmosphere and 70 degrees Fahrenheit, Nm^3 (normal cubic meter) gas measured at 1 atmosphere and 0 degrees Celsius,
1 PJ Hydrogen (LHV) = 8.333 tonnes

SOURCE: THE ENGINEERING TOOLBOX,[103] AND THE HYDROGEN ECONOMY: OPPORTUNITIES, COSTS, BARRIERS AND R&D NEEDS (APPENDIX H), THE NATIONAL ACADEMIES PRESS, 2004

The remainder of this report is arranged as follows:

- Section 2 cover the review into the global outlook for the hydrogen market
- Section 3 covers the investigation of the potential export destinations for Australian renewable hydrogen
- Section 4 presents the conclusions we have drawn from the literature survey.

A.2 The global outlook for hydrogen

Currently very little hydrogen is used as a form of energy. However, there is increasing interest in the production and use of hydrogen for this purpose. A key driver of this renewed interest is the need for countries to plan for how they will meet the emissions reductions they have agreed to under the 2015 Paris Climate Accord.[104]

Signatories to the Accord have agreed that addressing climate change requires capping greenhouse gas emissions as soon as possible to limit global temperature rise this century to 2°C at a minimum and ideally to 1.5°C.[105]

The most recent edition of the International Energy Agency's *World Energy Outlook* publication identifies hydrogen as an important mechanism for reducing emissions, stating that:

> *Hydrogen could play a role in the low-carbon transition in a variety of ways. At present the largest user of hydrogen in the energy sector is industry, where hydrogen is created by steam reformation of natural gas and consumed on-site in the manufacture of ammonia and methanol or in the refining sector. To be useful in the energy transition, however, hydrogen will need to be generated using low- or zero-carbon energy sources and is likely to need to be transported over longer distances.*[106]

The establishment of the Hydrogen Council is a good example of the increased interest in hydrogen. The Council is a large industry-led group that seeks to promote the development of the hydrogen economy. It was launched in January 2017 at the World Economic Forum. Its members include major companies that invest along the hydrogen value chain, including transportation, industry, and energy exploration, production, and distribution. In 2017 the Hydrogen Council identified seven ways in which

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[103] The Engineering Toolbox undated, accessed on 18 June 2018 at https://www.engineeringtoolbox.com/fuels-higher-calorific-values-d_169.html

[104] https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement Accessed 1 September 2018.

[105] COP 21 Paris, Parties to the UNFCCC agreement, https://unfccc.int/resource/docs/2015/cop21/eng/10a01.pdf

[106] World Energy Outlook 2017, International Energy Agency, Paris, 2017, page 467

hydrogen can contribute towards meeting the global emissions reductions required under the Paris Climate Accord, namely by:

- *Enabling large-scale renewable energy integration and power generation*
- *Distributing energy across sectors and regions*
- *Acting as a buffer to increase energy system resilience*
- *Decarbonizing transportation*
- *Decarbonizing industrial energy use*
- *Helping to decarbonize building heat and power*
- *Providing clean feedstock for industry.*[107]

While there is some variation between estimates, current world production of hydrogen is around 55 million tonnes (6,600 PJ) per year.[108] Currently non-energy uses of hydrogen dominate consumption. Hydrogen used in petroleum refining, fertiliser production, methanol production, metallurgy and food production account for almost all of current hydrogen consumption. **Table A.2** lists the main uses of hydrogen.

Estimates of the proportion of hydrogen used for energy use vary but are all very small. ACIL Allen has sighted references that estimate the proportion to be around 1 or 2 per cent of total consumption of hydrogen.[109, 110] However, the Hydrogen Council's vision for hydrogen envisages that current main uses of hydrogen will be overtaken by new uses in the seven applications identified above.

TABLE A.2 MAIN USES OF HYDROGEN

Application
Chemical industry
– Conversion of hydrocarbons to saturated products
– Various polymer manufacturing processes
– Removing sulphur from raw naphtha
– Production processes for specialty chemicals
Fertiliser production
Semiconductor industry
Food processing industry (e.g. margarine)
Transport sector
Power / heat generation

SOURCE: ACIL ALLEN

Forecasts sighted by ACIL Allen for the future demand for hydrogen all project continued growth. However, the amount of growth forecast varies considerably. A 2013 market report found that the demand for hydrogen grew at a compound annual growth rate (CAGR) of 3.2 per cent between 2010 and 2013. It projected that the CAGR between 2014 and 2020 would increase slightly to 3.5 per cent.[111] The report noted that the Asia Pacific region was the fastest growing market between 2010 and 2013, growing at a CAGR of 6.8 per cent over that period. The report found that the use of hydrogen in refinery hydro-processing was a major driver of demand growth. However, it also stated that the increasing demand for clean transportation was supporting the growth of the hydrogen market.

A 2017 market report by a different firm projected somewhat higher rates of growth. It concluded that the global market for hydrogen would grow at a CAGR of almost 6 per cent over the period from 2017

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[107] Hydrogen scaling up - A sustainable pathway for the global energy transition, Hydrogen Council, November 2017.

[108] Hydrogen Council 2017, *Ibid*

[109] Jong-Won Kim, Current Status of R&D on Hydrogen Production and Storage in Korea, presentation to the Materials Innovations in an Emerging Hydrogen Economy Conference, February 2008.

[110] Bakenne A, Nuttall W and Karzantzis N 2016, Sankey Diagram-based insights into the hydrogen economy of today, International Journal of Hydrogen Energy, 41(19) pp. 7744–7753, accessed on 14 March 2018, https://doi.org/10.1016/j.ijhydene.2015.12.216 .

[111] Hydrogen Market – Global Study on Hydrogen, Persistence Market Research, 2014

to 2021.[112] The same report stated that the main driver for this growth was expected to be the growing demand for fertilizers. However, it also flagged that the use of hydrogen in fuel cells and as a means of storing electricity were both developing markets for hydrogen. However, it also noted that clear government policies and regulations for these market segments were required to enable their growth.

Shell's 'Sky Scenario' outlines what they believe to be a technologically, industrially, and economically possible route forward, consistent with limiting the global average temperature rise to well below 2°C from pre-industrial levels.113 The Sky Scenario identifies hydrogen as a possible solution for industrial processes requiring intense heat, the metallurgical sector, home heating, and air transport.114 The Sky Scenario states that:

> *Onshore and offshore hydrogen electrolysis systems also begin to emerge around the world in Sky. Initially, they make use of the growing off-peak surplus of electricity from renewable sources, but later become fully integrated base-load systems.*

Shell's Sky Scenario projects that after 2040 hydrogen emerges as a material energy carrier and hydrogen consumption grows to account for 25 per cent of all transport demand and 10 per cent of global final energy consumption by 2100. The Sky Scenario data for World Total Final Consumption by carrier for hydrogen implies a CAGR of 23 per cent over the period 2020 to 2040.

In 2017 the engineering firm ARUP published a document that discussed what the energy market would look like in the UK in 2035. It postulated that hydrogen production would be a major industry and an important part of the energy system in 2035. Hydrogen was seen as an important source of energy for transport and domestic heating.

Table A.3 illustrates several potential hydrogen demand projections. These projections vary significantly. One difference arises from the different volumes of hydrogen demand used as a starting point, the majority of which is in the non-energy sector. Another difference lies in their period of projection, with the Hydrogen Council Report giving a forecast which reaches 2050, compared to the Persistence Market Research projection which reaches only to 2020. The Hydrogen Council's Scaling Up report projections for total hydrogen demand and hydrogen demand for energy use follow the same rate of increase. This seems unlikely.

TABLE A.3 EXAMPLES OF VARIOUS PROJECTIONS FOR THE GROWTH OF HYDROGEN DEMAND

Source	Period of Projection	CAGR	Comments
Persistence Market Research	2014 to 2020	3.5%	The projection was for total hydrogen demand. The Asia Pacific market accounted for the majority of the growth.[115]
Research and Markets	2017 to 2021	6%	The projection was for total hydrogen demand.[116]
Shell's Sky Scenario	2020 to 2040 (only projections to 2050 are shown)	23%	The Sky Scenario models and energy mix was specifically designed to reach the Paris Agreement's goal in a technically possible manner.[117].
Hydrogen Council Scaling Up	2020 to 2050	35% to 2040 28% to 2050	The CAGRs shown are for demand for the use of hydrogen for energy use. Presents an ambitious vision of the future hydrogen sector.[118]

SOURCE: ACIL ALLEN BASED ON VARIOUS SOURCES

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[112] Global Hydrogen Generation Market Report 2017 – Forecasts to 2021, https://www.researchandmarkets.com/research/2n49kh/global_hydrogen, accessed April 2018,

[113] https://www.shell.com/energy-and-innovation/the-energy-future/scenarios/shell-scenario-sky.html, accessed 27 April 2018

[114] The Sky Scenario is targeted through the assumption that society reaches the Paris Agreement's goal of holding global average temperatures to well below 2°C. Unlike Shell's other scenarios which unfolded in an open-ended way based upon plausible assumptions and quantifications, the Sky Scenario was specifically designed to reach the Paris Agreement's goal in a technically possible manner.

[115] Hydrogen Market – Global Study on Hydrogen, Persistence Market Research, 2014

[116] Global Hydrogen Generation Market Report 2017 – Forecasts to 2021, ibid

[117] Sky Scenario 2018, ibid

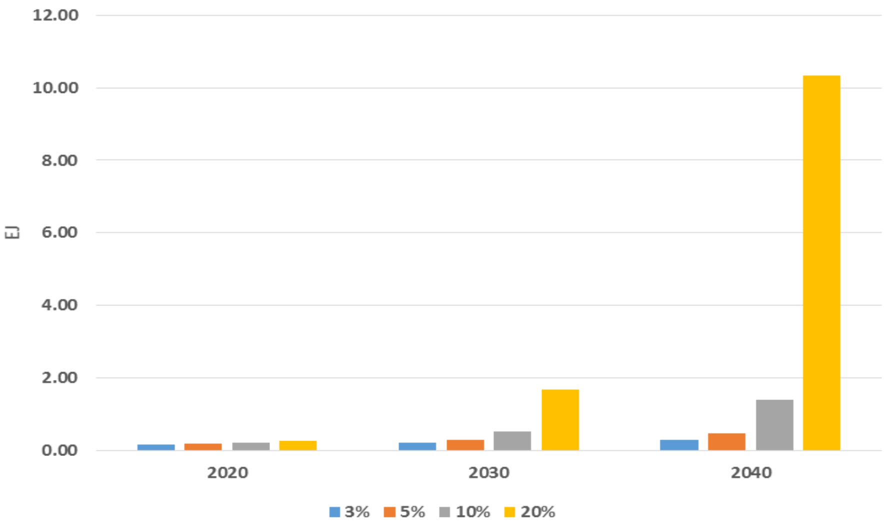
[118] Hydrogen Council 2017, ibid

Projecting the future global demand for hydrogen for use as a source of energy is an extremely challenging task, particularly coming from such a low base. Small variations in assumptions about growth can lead to significantly different projections of long term hydrogen demand (see **Figure A.1**). In addition, this is an area where there is still considerable technological development under way and those developments can have a significant impact on the rate of uptake of hydrogen utilisation. For example, achieving some of the research and development targets for cost reductions for the production, storage and use of hydrogen that some of the countries discussed in the following chapter have set would have a major impact on the relative economic competitiveness of hydrogen as a source of energy.

Similarly, the nature and timing of policies and regulations adopted by governments will have a strong influence on the rate of uptake of hydrogen technologies such as Fuel Cell Electric Vehicles (FCEVs). Several of the countries examined in the following section have introduced targets for the uptake of FCEVs or the use of fuel cells to produce heat and power for domestic households. In addition, there is scope to introduce hydrogen into existing natural gas distribution networks to 'green' them. Small amounts of hydrogen can be added to natural gas streams without the need to make any significant adjustments to reticulation or consumer equipment. Some cities, such as Leeds in the UK, are moving towards completely converting existing natural gas networks to hydrogen.[119]

Figure A.1 shows how the projected demand for hydrogen for energy related use varies according to the assumed annual growth rate used.

FIGURE A.1 PROJECTED DEMAND FOR HYDROGEN FOR ENERGY USE, BY CAGR



Note: Assumes that annual production of hydrogen in 2017 was 55 million tonnes and that 2 per cent of that was used as energy.

SOURCE: ACIL ALLEN

While it may provide some insights into how different growth rates would influence the potential future demand for hydrogen for energy related uses, the value of such 'straight line' projections in forecasting future demand for Australian renewable hydrogen is limited. The best that can be said about such projections is that they provide a possible reality check for any forecasts that are ultimately developed by other means.

A recent report by the IEA Hydrogen Technology Collaboration Program makes a number points that all suggest increased use of hydrogen in the future,[120] including:

- Fuel cell shipments grew five-fold from 100 MW in 2011 to nearly 500 MW in 2016 (this corresponds to a CAGR of 38 per cent).

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[119] H21 Leeds City Gate, July 2016, accessed April 2018, https://www.northerngasnetworks.co.uk/archives/document/h21-leeds-city-gate

[120] Mary-Rose de Valladres 2017, Global Trends and Outlook for Hydrogen, IEA Hydrogen Technology Collaboration Program, December 2017

- There are no technical barriers to commercialization of light duty FCEVs. Automakers are now launching products rather than prototypes.
- The Global Automotive Executive Survey 2017 on “evolutionary, revolutionary and key disruptive technology” reports that FCEVs are the number three trend in the marketplace. According to 78 per cent of executives polled, FCEVs are “the real breakthrough for e-mobility.”
- Japan’s hydrogen strategy calls for FCEV production of 3,000 in 2017; 40,000 (including buses) in 2020; about 200,000 by 2025; and around 800,000 by 2040.
- Two cities in China have placed an order for 300 fuel cell buses
- South Korea plans to replace around 26,000 CNG buses with fuel cell buses by 2030.
- In Japan, the “ENE-farm” residential heat and power units were first deployed in 2009 and by 2014 around 250,000 units had been installed. Japan’s goal is to install 1.4 million units by 2020 and 5.3 million by 2030. It is intended to introduce similar systems for commercial and industrial use in 2017. The long-term plan is to replace natural gas pipelines with hydrogen pipelines.
- Hydrogen can be blended with natural gas to ‘green’ the natural gas grid.
- The global count of hydrogen refuelling stations (HRS) that are open to the public or fleets is growing. In 2017 there were over 200 stations open.
- Japan’s Strategic Roadmap for Hydrogen and Fuel Cells forecasts Japan will have 320 HRSs by 2025. Korea plans to build around 200 HRS nationwide and China anticipates that 100 HRSs will be built by 2020
- The Kawasaki Australia project plans to make liquid hydrogen from brown coal with CCS and ship this product to Japan. Chiyoda has plans to produce hydrogen in the Middle East and react it with toluene as an energy carrier, also for shipment to Japan. This incurs energy costs on conversion and on recovery.[121]
- Japan intends to import 900,000 tons of hydrogen by 2030.[122]

The above discussion suggests that there are good prospects for growth in the hydrogen market. However, as noted above, seeking to develop a robust top down projection of demand over the medium to long term is likely to be difficult. Using a similar approach to develop forecasts of possible scope for Australian green hydrogen (e.g. hydrogen from renewable sources) to help meet that future demand would be even more challenging.

We have therefore chosen to adopt a bottom up approach to develop our estimates of future demand for hydrogen. In the following section we have examined a range of counties and assessed the relative likelihood that they might be a potential market for Australian produced hydrogen.

Potential hydrogen suppliers

If hydrogen becomes a globally important source of energy, then it is highly likely that there will be many countries that will be unable to produce sufficient hydrogen to meet their own needs. To meet their domestic demand these countries will need to import hydrogen. Similarly, there are likely to be many countries that will seek to supply that export demand. In effect, a global market for hydrogen will emerge, much as there is now a global market for other sources of energy.

Australia’s ability to capture a share of any eventual global export market for hydrogen will be determined by a range of factors. These factors will be similar to those that determine our ability to supply a share of the global market for a range of energy resources now. Australia is already a major exporter of energy resources, including uranium, liquefied natural gas (LNG) and coal. The key factor in determining our ability to capture a share of the global market for hydrogen exports will be the price at which we are able to supply the hydrogen to importers.

Other factors will of course also have a bearing. For example, factors such as:

- The ‘quality’ of Australian hydrogen, i.e. what will be the carbon footprint of Australia’s hydrogen exports?

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[121] Chiyoda undated, Hydrogen Storage and Transportation System for Large-Scale - “SPERA Hydrogen®” System, accessed on 28 April 2018 at https://www.jase-w.eccj.or.jp/technologies/pdf/factory/F-02.pdf

[122] Mary-Rose de Valladres 2017, Global Trends and Outlook for Hydrogen, IEA Hydrogen Technology Collaboration Program, December 2017, page 15.

- Australia's reliability as a supplier. Our history as a reliable supplier of other energy resources will be important here.
- Australia's record as a politically and economically stable country with a strong legal system.

However, it is likely that other countries will compete with Australia to supply hydrogen in any future global market. Any emergence of a global market for hydrogen will include a global price for hydrogen. That price will be set by the competition between different suppliers of hydrogen.

ACIL Allen has considered what countries, in addition to Australia, might be potential suppliers of green hydrogen for export. The Middle East and North Africa (MENA) countries are well positioned to be among that group. Many of them, like Australia, have the potential to access abundant solar energy. They also have well established export trade in other forms of energy and large reserves of natural gas and access to depleted wells to store any CO_2 associated with steam reforming of that gas to make hydrogen. Several MENA countries have already made sizable investments in developing their renewable energy resources.

The International Renewable Energy Agency (IRENA) recently noted that the renewable energy landscape in MENA countries is rapidly evolving and significant developments have taken place. For example, renewables investments across the region increased almost tenfold from US$1.2 billion to US$11 billion 2008 and 2016. IRENA notes that:

> *…several countries in the region are among the global frontrunners in renewable energy development.*[123]

IRENA expects that the ambitious targets set by all countries of the region are expected to translate into a combined 80 GW of renewable capacity by 2030 based on national plans to fulfil the countries' ambitions. Examples of such investments include:

- Plans by the Dubai Electricity and Water Authority (DEWA) to invest 81 billion dirhams ($22 billion) in energy projects in Dubai over the next five years – the bulk of which will be invested into renewables. The DEWA CEO stated that the Authority's strategy is to be 75 per cent renewable by 2050. DEWA expects to exceed their 2020 target of 7 per cent.[124]
- Recent auctions resulted in the world-record solar prices, including, 17.8 US$/MWh for the Sakaka project in Saudi Arabia, 24.2 and 29.9 US$/MWh in Abu Dhabi and Dubai, respectively.
- Morocco has set an ambitious renewable energy target, pledging to increase renewable energy capacity to 42 percent of total installed capacity by 2020, and 52 percent by 2030. Implementing this strategy is expected to require investments in renewable energy of more than US$40 billion by 2030.[125]

Another potential supplier of hydrogen for export is Iceland. Nearly all of Iceland's electricity and space heating is provided hydropower or geothermal energy. This constitutes over 70 per cent of all local energy consumption. The remaining 30 per cent are provided by imported fossil fuels which are used for vehicles, vessels and some industrial processes.[126]

Iceland has access to substantial geothermal energy resources that could be used to produce green hydrogen. According to Iceland Ministry for Foreign Affairs and the Department of Natural Resources and Environmental Affairs, the economic and environmentally viable potential for electrical production from renewable resources in Iceland has been estimated at over 50 TWh a year. Currently some 17 per cent of this amount has been harnessed.

Iceland has a longstanding stated intention to develop a Sustainable Hydrogen Economy. There is strong interest in using hydrogen produced using Iceland's renewable energy resources to power on-land transportation and fishing vessels. It is a founding member of the International Partnership for Hydrogen Economy (IPHE) and participates in the Hydrogen Implementation Agreement of the IEA. A

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[123] http://www.irena.org/mena accessed 30 April 2018

[124] https://www.pv-magazine.com/2018/02/14/siemens-to-work-with-dewa-on-dubais-first-solar-hydrogen-electrolysis-plant/ accessed 30 April 2018.

[125] "Energy & Mines: Renewable for Mines Driving Competitive, Secure and Low-Carbon Power Stations for Mines", Ministry of Energy, Mines, Water and Environment, January 28 – 29, 2016, http://www.mem.gov.ma/SiteAssets/Dicsours/Discours2016/London%20speech%20English.pdf

[126] www.un.org/esa/agenda21/natlinfo/countr/iceland/energy.pdf accessed 4 May 2018.

number of cooperation projects have already been initiated for developing and introducing hydrogen as a fuel for ships and for exploring possibilities of exporting hydrogen.

However, Iceland does not have a history of exporting energy and it therefore has less existing infrastructure to do so. It is likely that much of any future hydrogen production in Iceland will be for domestic use, particularly by the power intensive industries that Iceland is striving to attract to use its sustainable energy resources.

Many other countries such as the US, Chile and various EU members could become significant producers of green hydrogen. However, ACIL Allen expects that most of these countries would in the first instance use that hydrogen to meet their own domestic demand rather than for export.

A.3 Potential demand for Australian Hydrogen

This literature review has examined potential demand for hydrogen in nine markets: China, Japan, Korea, Singapore, Taiwan, Thailand, India, California and the European Union.

The factors which are expected to influence demand for hydrogen in coming decades include:

- Population
- Energy market
- Current hydrogen-related activity
- Government policies
  - general policies relating to hydrogen
  - incentives to promote the use of hydrogen
  - plans for hydrogen use in transport
  - plans for other uses of hydrogen
  - greenhouse gas policies
  - air pollution reduction policies
- Research and development (R&D) expenditure related to hydrogen

Below we consider these factors for each the above countries.

A.3.1 Peoples Republic of China

China’s population is 1.4 billion, making it a potentially very large hydrogen market.

Energy supply and demand

Coal continues to be the main source of energy in China accounting for 66 per cent of energy consumption in 2014.[127] In that year China:

- consumed 4.12 billion tonnes of coal, 510 million tonnes of crude oil and 184 billion tonnes of natural gas, and
- imported 291 million tons of coal. 308 million tonnes of crude oil and 59 billion m^3 of natural gas.

China’s energy consumption continues to show steady growth.

Government policies

In 2014 the Chinese Government adopted a *Strategic Action Plan for Energy Development 2014-2020* (not available in English). This followed the adoption in 2013 of an *Action Plan for Air Pollution Control*. The Energy Development Plan focussed on clean coal utilisation, including improvements in mining and power station technology, adoption of carbon capture and storage (CCS), de-sulphurisation and de-NOx. It is not clear how the latter two elements will be addressed. The 2015 presentation by Li Haofeng did not mention hydrogen.

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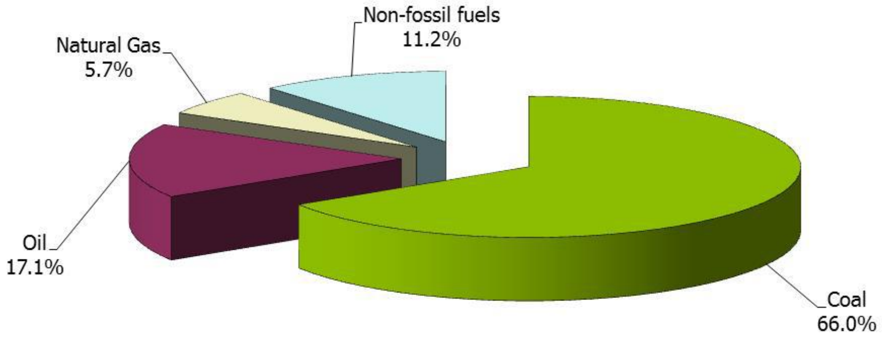
[127] Li Haofeng 2015, China medium and long term strategies and action for green development and clean utilization of coal, accessed on 12 March 2018 at https://www.usea.org/sites/default/files/event-/Li%20Haofeng-EN.pdf

China's commitment to the environment was more recently reiterated in a speech by premier Xi Jinping in October 2017 in which he stated that China would be actively involved in global environmental governance and fulfil its commitments on emissions reduction.[128]

The Society of Automotive Engineers of China estimates that, by 2030, there will be one million fuel cell powered vehicles in China. In 2016, this organisation published a *Technology Roadmap for Energy Saving and New Energy Vehicles* which predicts that hydrogen fuel cell vehicles will be developed from demonstration operation to mass application between 2020 and 2030.[129]

FIGURE A.2 CHINA ENERGY CONSUMPTION 2014



SOURCE: LI HAOFENG, 2015

In 2017, the Shenzhen Center Power Tech Co. announced that it would invest up to around $US76 million to establish a wholly-owned subsidiary to develop hydrogen fuel cells.[130] Late in 2017 this company announced that it will also invest approximately $US754 million to build a hydrogen cell industrial park in Hubei Province's capital of Wuhan and promote hydrogen vehicles in the Province. Wuhan, which sits on the middle reaches of the Yangtze River, is home to several car companies, including Dongfeng Motor Corporation, one of China's big four car-makers.

The industrial park will conduct research and development into hydrogen cells and related generator systems, and in the advancement of hydrogen refuelling stations and other ancillary products such as hydrogen production systems. The industrial park aims to build a hydrogen-fuelled propulsion system production base with an annual capacity of at least 100,000 units over the coming three to five years as part of China's "policy to promote hydrogen power".[131]

The Wuhan industry park authority plans to help form an industrial supply chain incorporating the research, manufacturing, and sale of hydrogen fuel-powered generators. It will also develop and produce hydrogen fuel cells for coaches in cooperation with coachbuilders from other Chinese cities.

Wuhan has announced that it will build itself into a "hydrogen city" through developing hydrogen energy industry, according to the city development plan. The city plans to build up to twenty hydrogen fuelling stations over the period 2018 to 2020 to support the operation of about 3,000 hydrogen fuel cell-powered vehicles. Wuhan sees itself as becoming a world hydrogen city by 2025, with three to five world leading hydrogen enterprises and 30 to 100 hydrogen fuelling stations. The annual production value of hydrogen fuel cells is expected to exceed $US16 billion.[132]

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[128] Premier Xi Jinping's report at 19th CPC National Congress, accessed on 6 August 2018 at http://www.chinadaily.com.cn/china/19thcpcnationalcongress/2017-11/04/content_34115212.htm

[129] Business Wire 2017, Hydrogen Fuel Cell Vehicle Market in China 2017-2022 - Research and Markets, accessed on 12 March 2018 at https://www.businesswire.com/news/home/20170918006193/en/Hydrogen-Fuel-Cell-Vehicle-Market-China-2017-2022

[130] Tang Shihua 2017, Shenzhen Center Power Plans to Invest USD75 Million to Develop Hydrogen Fuel Cells, Yicai Global, accessed on 12 March 2018 at https://www.yicaiglobal.com/news/shenzhen-center-power-plans-invest-usd75-million-develop-hydrogen-fuel-cells

[131] Dou Shicong 2017, Shenzhen Center Power Tech Plans to Spend USD754.15 Million to Build Hydrogen Cell Industrial Park, Yicai Global, accessed on 12 March 2018 at https://www.yicaiglobal.com/news/shenzhen-center-power-tech-plans-spend-usd75415-million-build-hydrogen-cell-industrial-park

[132] Xinhua 2018, "Hydrogen city" to be built in central China, accessed on 12 March 2018 at http://xinhuanet.com/english/2018-01/21/c_136913339.htm

Also, late in 2017, the Zhangjiagang Furui Hydrogen Power Equipment Co. announced that it will cooperate with the hydrogen fuel company, Kohodo Hydrogen Energy Co., in Shenzhen, Guangdong Province, to build and operate a hydrogen refuelling station. The plan is to build a water electrolysis-based hydrogen refuelling station early in 2018 and start operations of two commercial hydrogen refuelling stations. The companies will jointly work on the development of national standards for water electrolysis-based hydrogen refuelling stations and carry out international research and development (R&D) cooperation. The project is expected to facilitate the promotion and commercial operation of fuel cell cars.[133]

The Shanghai Science and Technology Commission adopted a plan in 2017 that aims to provide between five and ten hydrogen stations to service 3,000 fuel-cell electric vehicles (FCEVs) including buses, rising to 30,000 by 2025.[134]

Nationally, China plans on having the capacity to produce about 170,000 FCEVs annually.[135] The national plans talk about "millions of FCEVs" by 2030.

Research and development

Prof Zong Qiang Mao, of Tsinghua University is one of China's leading experts on hydrogen energy and fuel cell research. He estimates that China is now investing more than $A20 billion per annum in hydrogen energy.[136]

Analysis

ACIL Allen believes that the best prospects for hydrogen use in China are:

- To fuel FCEVs
- Use in residential combined heat and power fuel systems, and
- Injection of hydrogen into the natural gas system (note that this is not a current use but it could be easily done).

Based on recent announcements, it is likely that the numbers of FCEVs in China will grow rapidly in Shanghai, Guandong and Hubei Provinces, rising steadily from around 10,000 vehicles in 2020 to at least one million by 2030. Assuming that the average distance travelled annually is 10,000km (some vehicles will provide public transport and government services) and that their hydrogen consumption is 0.01kg per km,[137] the demand for hydrogen for use as a transport fuel will rise from 1,000 tonnes (141,900MJ) in 2020 to 100,000 tonnes (14,190,000MJ) in 2030.

A.3.2 Japan

The population of Japan is 128 million.

Energy supply and demand

Approximately 90 per cent of Japan's primary energy, and 90 per cent of Japan's electricity currently comes from fossil fuels.[138] For detailed reviews, see Lundin[139] and the IEA's Advanced Fuel Cell Technology Collaboration Program's report on National Strategies and Plans for Fuel Cells and

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[133] Fuel Cell Works 2017a, Zhangjiagang Furui, Kohodo to Build and Operate Hydrogen Refuelling Station in South China, accessed on 12 March 2018 at https://fuelcellsworks.com/news/zhangjiagang-furui-kohodo-to-build-and-operate-hydrogen-refueling-station-in-south-china

[134] FuelCellWorks 2017b, Shanghai releases its development Plan for Fuels Cell Vehicles, accessed on 12 March 2018 at https://fuelcellsworks.com/news/shanghai-releases-its-development-plan-for-fuel-cell-vehicles

[135] Mao Z Q 2018, China Homes in on hydrogen,

[136] Mao ZQ 2018 Chian homes in on hydrogen, accessed on 15 April 2018 at https://medium.com/@cH2ange/china-homes-in-on-hydrogen-977b37ddcca9

[137] The Hyundai Nexo FCEV can reportedly travel 120 km on 1 kilogram of hydrogen.

[138] Maruta A 2015, Energy situation in Japan: Challenges and future plans, presentation on behalf of Technova Inc, accessed on 15 March 2018 at https://www.sintef.no/contentassets/9b9c7b67d0dc4fbf9442143f1c52393c/2-energy-situation-in-japan-challenges-and-future-plans-akiteru-maruta-technova.pdf

[139] Lundin M 2016, Hydrogen Technology Market in Japan, a report for the EU-Japan Centre for industrial cooperation, accessed on 15 March 2018 at https://www.eubusinessinjapan.eu/sites/default/files/hydrogen_technology_market_in_japan.pdf

Infrastructure.[140] Japan had a significant reliance on nuclear power prior to the earthquake and tsunami in 2010. Japan's nuclear plants were all shut down following the earthquake and tsunami. Many of these reactors have not yet been restarted. Given Japan's reliance of fossil fuels and reduced amount of nuclear power being generated, Japan is taking a strong interest in hydrogen.

Government policies

Japan has taken a number of steps to move towards a 'hydrogen society'. These include:

- The introduction of Stationery Fuel Cells for heat and power (see below for discussion of the ENE-FARM Program)
- Creating an environment to support the accelerated introduction of fuel-cell vehicles (e.g. the development of a 'hydrogen town' athletes' village for the 2020 Tokyo Olympic and Paralympic Games)
- Realising new technologies such as hydrogen power generation for large-scale use of hydrogen
- Promoting development of production and storage/transportation technology for stable supply of hydrogen
- Formulating a roadmap. The Japanese Government *Strategic Roadmap for Hydrogen and Fuel Cells* was adopted in 2014[141] and revised in 2016. It has three elements:[142]
  - a dramatic expansion of hydrogen utilisation
  - full-scale introduction of hydrogen power generation and establishment of a large-scale hydrogen supply system, and
  - the establishment of a totally carbon dioxide-free hydrogen supply system.

The 2016 road map sets several revised targets for the adoption of hydrogen technologies and target prices for those technologies and the supply of hydrogen, namely:

- The future price targets for household fuel cells are: Polymer electrolyte fuel cells (PEFC): ¥800,000 ($A9,600) by 2019 and solid oxide fuel cells (SOFC): ¥1 million ($A12,000) by 2021 9both these are for 1kW household systems)
- Targets for the dissemination of fuel cell vehicles were set at about 40,000 vehicles by 2020, about 200,000 vehicles by 2025, and about 800 thousand vehicles by 2030
- Targets for residential installations are 1.4 million by 2020 and 5.3 million (about 10 per cent of Japanese homes) by 2030, with the possibility of piping hydrogen rather than natural gas
- Targets for the construction of hydrogen stations are 160 stations by 2020 and about 320 stations by 2025.

To implement the Roadmap, the Japanese Ministry of Economy, Trade and Industry (METI) has a three-phase program. Phase 1 focusses on fuel cell technology with the aim of developing fuel cell vehicles which are more than competitive against hybrid electric vehicles by around 2025. Phase 2 will see the creation of a hydrogen mass supply chain with the aim of achieving a hydrogen cost (CIF) of ¥30/Nm^3 (around $A0.36/Nm^3 or $A28.4/GJ , approximately $A4/kg at current exchange rates) by the second half of the 2020s—METI is subsidising the refuelling stations and expects to import hydrogen and to build a full-scale hydrogen plant in Japan around 2030. Phase 3, from around 2040, will see full-scale operation of the hydrogen society using CO_2-free hydrogen provided from renewable energy or through the use of carbon capture and storage.

Government and collaborative hydrogen and fuel cell investment is significant. In the fiscal year 2017, the relevant METI budget was ¥39 billion, including:

- Promotion of stationary fuel cells ¥9.4 billion
- Promotion of fuel cell vehicles: subsidies for CAPEX and OPEX of refuelling stations ¥4.5 billion, subsidies for clean-energy vehicle sales (including fuel cell electric vehicles ¥12.3 billion, and

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[140] IEA 2015, National Strategies and Plans for Fuel Cells and Infrastructure, a report under the Programme of Research, Development and Demonstration on Advanced Fuel Cells, accessed on 15 March 2018 at http://www.ieafuelcell.com/documents/NatStratandPlansforFuelCellsandInfraStruct_v10.pdf

[141] Agency for Natural Resources and Energy 2014, Summary of the Strategic Road map for Hydrogen and Fuel Cells, provisional translation, accessed on 14 March 2018 at http://www.meti.go.jp/english/press/2014/pdf/0624_04a.pdf

[142] Ministry of Economy, Trade and Industry Agency for Natural Resources and Energy, 2016, Compilation of the Revised Version of the Strategic Roadmap for Hydrogen and Fuel Cells, accessed on 15 March 2018 at http://www.meti.go.jp/english/press/2016/0322_05.html

- Establishing hydrogen supply-chain ¥4.7 billion.

Japan's car industry has developed several hydrogen-powered cars. For example, Toyota delivered its first hydrogen powered car (the Mirai) in January 2015. By the end of 2017 production had totalled 5,700 units. Toyota expects to sell 30,000 FCEVs world wide by 2030.[143] Honda has also developed a hydrogen powered vehicle.

As of March 2017, around 1,800 FCEVs and two commercial-based fuel cell buses were on the road. There were 90 hydrogen refuelling stations (70MPa) in operation.

The ENE-FARM Program has supported the deployment of residential fuel cells. These provide heat and power, turning piped natural gas into hydrogen, and then generating electricity from a hydrogen fuel cell. The heat generated in the conversion is captured and used for heating or for hot water. Some 194,710 units of ENE-FARM, residential micro-combined heat and power fuel cell had been sold.[144] New residential fuel cell models coming on the market are smaller, more efficient, cheaper and more easily installed than in the past. Models are also being offered as a customer option by apartment complex developers.[145] In the cities, the ENE FARM systems could be converted to operate on piped hydrogen.

For the 2020 Olympic Games, the Tokyo Metropolitan Government is planning to have 35 refuelling stations in operation servicing 6,000 fuel cell vehicles and more than 50 buses. The cost sharing for refuelling stations is METI ¥ 220 million, Tokyo Metropolitan Government ¥180 million and operator ¥ 100 million. The fuel cell vehicles will also be subsidised: METI ¥ 302 million, Tokyo Metropolitan Government ¥ 1 million and user ¥ 4 million.

In December 2017 the Ministerial Council on Renewable Energy, Hydrogen and related Issues decided on a Basic Hydrogen Strategy to achieve a "world-leading hydrogen society".[146]

In 2012, Japan legislated for a carbon tax of approximately ¥289 per tonne ($A3.30 per tonne) by increasing existing taxes on fossil fuels (coal and LPG/LNG). Half the revenue from this tax funds low-emissions technologies. Japan has emissions trading schemes operating in the Tokyo and Saitama regions, covering 20 million people.

Research and development

Japan is making significant investments in hydrogen-related R&D.[147] For example, the METI budget for R&D for fiscal year 2017 is:

- ¥ 3.1 billion for fuel cells R&D
- ¥ 4.1 billion on refuelling stations
- ¥ 1 billion on hydrogen production, transport and storage (including hydrogen production from renewables).

The total expenditure on R&D totals ¥ 8.3 billion (approximately $A100 million at current exchange rates).

Under the Cross-ministerial Strategic Innovation Promotion (SIP) Program there is a project on energy carriers which includes the development of large scale international transport for hydrogen power generation. SPI is a five-year plan with an annual budget of ¥ 3.5 billion ($A42 million at current exchange rates), started in 2017.[148]

Of relevance to this report, Japan's Kawasaki Heavy Industries has teamed up with the Australian and Victorian governments in a project to turn brown coal from the Latrobe Valley into liquid hydrogen. The

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[143] Yokomoto M 2016, IEA Advanced Fuel Cells Collaborative Programme, reported in Newsletter 8, Autumn 2016, accessed on 15 March 2018 at http://www.ieafuelcell.com/newsletter.php?view=october2016

[144] Yamazumi M and Kawamura S 2017, International Partnership for Hydrogen and Fuel cells in the Economy (IPHE), Japan Country Update, April 2017, accessed on 15 March 2018 at https://www.iphe.net/japan

[145] Maruta 2015, ibid

[146] METI 2017, Basic Hydrogen Strategy Determined, accessed on 28 April 2018 at http://www.meti.go.jp/english/press/2017/1226_003.html and http://www.meti.go.jp/english/press/2017/pdf/1226_003a.pdf

[147] Akiba E 2017, Hydrogen energy R&D: The roadmap and state of art of Japan, and activities of Kyushu University, presentation to the 8th World Renewable Energy Technology Congress, New Delhi, 22 August 2017, accessed on 28 April 2018 at http://wretc.in/presentation/2017/Day2/Session-7/Akiba.pdf

[148] See What is the Cross-ministerial Strategic Innovation Promotion Program? accessed on 28 April 2018 at http://www8.cao.go.jp/cstp/panhu/sip_english/5-8.pdf

initial investment will lead to a pilot plant. Kawasaki is also developing ships design specifically to transport liquid hydrogen.

Analysis

Japan is undertaking a significant level of fuel cell R&D and is undertaking a FCEV demonstration program. The demand for hydrogen in Japan will be from both the transport and residential heat and power applications.

The ENE-FARM units appear to have some advantages and, while they do produce CO_2 emissions, they are reported to reduce the average household carbon footprint associated with domestic energy usage in half.[149] The units are also reported to be helping to reduce the energy costs of the households using them.

Japan's car industry is using the domestic market to develop hydrogen-powered cars for the world market. Thus, government policies and subsidies that support the development of FCEVs are important to these companies.

Facilities to generate hydrogen from natural gas are likely to be built in Japan to meet growing demand. However, the Japanese government has signalled its intention to import 300,000 tonnes of hydrogen by 2030. The decision by Kawasaki Heavy industries to develop purpose-built ships and other facilities necessary to import hydrogen reinforces the likelihood that Japan will import green hydrogen.

ACIL Allen believes that the best prospects for hydrogen use in Japan are:

- To fuel FCEVs
- Fuel cells for heat and power production in domestic households. (This would be dependent on a decision to progressively convert the existing fuels cells using natural gas to operate on hydrogen).
- Injection of hydrogen into the natural gas system.

A.3.3 Republic of Korea

The population of Korea is 51 million.

Energy supply and demand

Korea imports around 96 per cent of its energy and is a very large consumer of energy (10th largest in the world).

In 2008 Korea produced around 1 million tons of hydrogen.[150] Since 2008, use of hydrogen as an energy source appears to have doubled.[151]

Government policies

In 2014, the Korean Government announced the 4th Basic Plan for New and Renewable Energy (NRE) Technology and Development and Usage/Distribution. This initiative seeks to promote NRE and to increase the NRE share of the total energy supply to 11 per cent by 2035. To achieve this goal, the government has adopted a number of relevant policies. One of the drivers for the government's desire to encourage NRE adoption is the poor air quality in the Seoul region.

The Renewable Portfolio Standard (RPS) requires electricity generators to supply a specified amount of power from NRE sources. Thirteen companies, including the Korea Water Resources Corporation, Korea District Heating Corporation and electricity generators with a capacity of more than 500MW (NRE power plants excluded), are required to meet RPS targets by installing renewable energy power plants or purchasing a Renewable Energy Certificates (RECs) from renewable energy producers. The RPS targets started at 3 per cent in 2015 and rises to 10 per cent in 2024.

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[149] Williams J 2017, Why have I never heard of the Ene-Farm? Accessed on 15 March 2018 at https://makewealthhistory.org/2017/08/11/why-have-i-never-heard-of-the-ene-farm/

[150] Kim JW 2008, Current Status of R&D on Hydrogen Production and Storage in Korea, accessed on 15 April 2018 at http://ceramics.org/wp-content/uploads/2009/06/international_korea_kim21.pdf

[151] Kim JW 2013, Recent Achievements in Hydrogen and Fuel Cells in Korea, accessed on 15 April 2018 at http://hydrogenius.kyushu-u.ac.jp/ci/event/ihdf2013/pdf/2-3kim.pdf

The Korean government also provides subsidies for NRE demonstration projects (up to 80 per cent of costs) and for the installation of NRE systems by businesses (up to 50 per cent of costs). A subsidy for home installation of NRE facilities is also available. Since 2010, the home subsidy has been available for a variety of NRE sources including fuel cells.[152] The One Million Green Homes Program aims, by 2020, to install fuel cell and photovoltaic systems in residential, multifamily and public housing. A hydrogen project (H-Town) is being undertaken in Ulsan.

Korean car makers started production of mid-size FCEV in 2015 and are expected to produce hundreds of thousands of FCEVs by 2020. By 2020, Korean automobile makers aim to have the manufacturing capacity to produce more than 200,000 FCEVs annually. This is projected to be more than 13 per cent of the global market for FCEVs.[153]

Most FCEVs in Korea have been developed to utilize hydrogen fuel-cells. This has required the development of standards. Globally, the Sub Group Safety Committee of the International FCEV Development Organization has been responsible for international consideration of technical aspects of the regulation of hydrogen FCEVs, including hydrogen storage facilities, hydrogen supply infrastructure, and electrical safety. Korea participates in the work of this organisation.

The Korean government has developed a range of policies to encourage the uptake of FCEVs. This includes subsidies and grants, tax incentives, infrastructure expansion and institutional changes to create an initial FCEV market. The government has provided subsidies, including tax exemptions, for FCEVs since 2014. In addition, FCEVs pay reduced parking fees in public parking lots and congestion tolls and taxes for urban centres. There are also parking places that are exclusively for green cars in downtown areas.

The government has provided significant government subsidies for hydrogen refuelling stations for cars. The aim is to have 310 such stations by 2022. The government is reported to have set an import target price for hydrogen of $US2.5/kg (with a pump price of $US5/kg). This is equivalent to $A3.22/kg and $A6.44/kg, or $A22.7/GJ and $A45.4/GJ respectively at current exchange rates.

Korea passed legislation in May 2012 for an emissions trading scheme. The scheme began operation in 2015. The emissions trading scheme covers facilities producing more than 25,000 tonnes of greenhouse gas emissions–around 450 of the country's largest emitters.

In June 2018 the Korean Ministry of Industry, Trade and Energy announced that the government and businesses will invest some 2.6 trillion won ($A3.1 billion) over the next five years in a public-private partnership to speed up the development of the country's hydrogen fuel cell vehicle ecosystem.[154]

The target to install 310 hydrogen stations by 2022 remains unchanged. The funds will be spent on building plants for fuel cell vehicles and fuel cell stacks, manufacturing fuel cell buses and developing hydrogen storage systems. Some 125 billion won ($A151 million) will go to supporting R&D for major components such as the fuel cell stack.

The new plan envisions investing 150 billion won ($A181 million) in 2018 to establish a special corporation for hydrogen filling stations, with the goal of reducing the cost of filling station construction by 30 per cent.

The plan envisions spending 420 billion won ($A506 million) in 2019 to manufacture hydrogen buses and conduct demonstrations, manufacturing hydrogen storage vessels for buses, and the mass production of a domestic CNG reforming device to produce hydrogen. From 2020 to 2022, the plan foresees the expenditure of 2 trillion won ($A2.4 billion) on the expansion of plants to produce hydrogen, fuel cell stacks, and the construction of hydrogen filling stations.

Research and development

POSCO Energy has developed molten carbonate fuels cells and is a leader in this technology. Annual production is 50MW and systems have been installed in several cities, including the world's largest fuel cell power plant of 59MW in Hwaeseong. This plant comprises twenty-one 2.8MW hydrogen fuel

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[152] IEA 2015, National Strategies and Plans for Fuel Cells and Infrastructure

[153] Electric Vehicle Association of Asia Pacific (EVAAP) undated, Korea, accessed on 16 April 2018 at http://www.evaap.org/electric/Psgubun-7_electric.html

[154] http://www.greencarcongress.com/2018/06/20180625-korea.html

cells. Several other companies have also developed fuel cells. Hyundai has developed fuel cells for the automotive sector. Hyundai started producing the ix35 Fuel Cell vehicle in 2013. Korea made hydrogen a focus of the 2018 Winter Olympics in Pyeongchang. Hyundai used the occasion to debut its next generation fuels cell car. Korea is planning to replace around 26,000 CNG-powered buses with fuel cell-powered buses by 2030.

The Ministry of Oceans and Fisheries is investing $US11 million to develop microbial sources of hydrogen from sea water. A demonstration facility is expected to produce 480 tons of hydrogen per year from 2019 at a cost of $US3.50/kg ($A4.51/kg or $A31.8/GJ at current exchange rates).[155]

Analysis

Korea is a significant user of hydrogen. However, Korea's level of interest in green hydrogen remains to be established. Nonetheless, the introduction of an emissions trading scheme suggests that low emissions fuels will become increasingly attractive over time.

ACIL Allen believes that the best prospects for hydrogen use in Korea are:

- FCEVs
- Fuel cells for power production, and
- Injection of hydrogen into the natural gas system.

A.3.4 Singapore

The population of Singapore is only 5.8 million.

Energy supply and demand

Singapore imports nearly all its energy needs. The country has switched from fuel oil to natural gas as its main energy source for electricity generation. Natural gas consumption (excluding gas used in power generation) is around 55,000 TJ per annum. As at March 2017, Singapore had an installed photovoltaic capacity of around 100MW.

Government policies

The Singapore government has adopted policies that could encourage the introduction of fuel cell electric vehicles (FCEVs). For example, all facilities in Singapore producing 25,000 tonnes or more of greenhouse gas emissions per annum will have to pay a carbon tax from 2020. The carbon tax will initially be $S5 per tonne of greenhouse gas emissions from 2019 to 2023. However, the Government plans to review the carbon tax rate by 2023, with a view to increasing it to between $10 and $15 per tonne of emissions by 2030.[156]

Research and development

Singapore has active R, D and D programs in fuel cell and hydrogen technologies.[157] Research is underway to reduce the cost and improve the efficiency of water electrolysis (Nanyang Technology University is working with Schneider). Singapore is also reported to be interested in making hydrogen from biomass gasification.[158]

There have been some visits by Singapore officials to Australia and reportedly some interest in R&D collaboration on hydrogen R&D.

Analysis

Singapore is likely to be a relatively small market for hydrogen. However, the demand for hydrogen could develop quickly if Singapore takes steps to encourage the use of FCEVs.

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[155] Kim JW 2013, ibid

[156] Tan A 2018, Singapore Budget 2018: Carbon tax of $5 per tonne of greenhouse gas emissions to be levied, The Straits Times, 19 February 2018, accessed on 16 April 2018 at http://www.straitstimes.com/singapore/singapore-budget-2018-carbon-tax-of-5-per-tonne-of-greenhouse-gas-emissions-to-be-levied

[157] Chan SH, Stempien JP, Ding OL, Su P-C and Ho HK 2016, Fuel cell and hydrogen technologies research, development and demonstration activities in Singapore – an update, International Journal of hydrogen energy, 41, 13869 -13878

[158] Chan *et al*, ibid

French company Energie SA is building a facility on Semakau Island to produce hydrogen from solar and wind energy. This will support a micro-grid on the Island, to be operational in October 2018, with the expectation that it will export hydrogen to other islands in the region.

ACIL Allen believes that the best prospect for hydrogen use in Singapore would be as fuel for FCEVs. With only some 574,000 vehicles on the island, we recognise that the market for hydrogen is unlikely to be large. However, it could, in the right circumstances, provide a good opportunity to demonstrate the feasibility of establishing a green hydrogen supply chain.

A.3.5 Taiwan

The population of Taiwan is 23.6 million.

Energy supply and demand

Taiwan imports nearly all its energy needs.

Taiwan produced 444 million cubic meters of hydrogen (approximately 40,000 tonnes) in 2017,[159] mostly for use in its petrochemical and semiconductor sectors.

Government policies

In March 2016, President-elect Tsai Ing-wen announced that developing hydrogen energy will be one of her administration's future strategic options for achieving the goal of phasing out nuclear power.[160]

In response to climate change, the Taiwan government has set a renewable energy target of 20 per cent by 2025, with expected total renewable power generation capacity of 27.4GW, an increase from 4.3GW in 2015. The Taiwan government has listed hydrogen as one of the focuses in its green energy development plan, aiming to boost power from this source to 60MW by 2025.

An amendment to the Electricity Act, passed by the Legislative Yuan in January 2017, established the goals of eliminating nuclear power by 2025, providing further incentives for renewable energy, and eventually liberalising the energy market.[161]

Research and development

Taiwan is a leader in fuel cell research and development. Taiwan has been very active in patenting hydrogen-powered fuel cells. Fuel cell systems manufactured in Taiwan can be found around the world.

Taiwan has also developed fuel cell electric scooters and a fuel cell-powered phone charger, with both these fuel cells use hydrogen as fuel.

Analysis

While the petrochemical and semiconductor industries in Taiwan are major users of hydrogen, the adoption of FCEVs has been slow because until recently there were legislative barriers to their use.

A.3.6 Thailand

The population of Thailand is 69 million.

Energy supply and demand

Thailand imports more than half of its energy needs.

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[159] Statistica 2018, Production volume of hydrogen in Taiwan from 2008 to 2017 (in million cubic meters), accessed on 16 April 2018 at https://www.statista.com/statistics/813692/taiwan-hydrogen-production-volume/

[160] Focus Taiwan News Channel 2016, Hydrogen energy option for nuclear-free Taiwan: president-elect, 5 March 2016, accessed on 14 April 2018 at http://focustaiwan.tw/news/aipl/201603050018.aspx

[161] Austrade not dated, Renewable energy and natural resources to Taiwan Trends and opportunities, accessed on 14 April 2018 at https://www.austrade.gov.au/australian/export/export-markets/countries/taiwan/industries/Clean-energy

Government policies

There are some signs of Thai government interest in hydrogen. The government has supported a small hydrogen-powered housing project in Chiang Mai (hydrogen from photovoltaic roof panels, with battery storage).

Thailand has set a new renewable energy target of 30 per cent of total final energy consumption by 2036 in its 2015 Alternative Energy Development Plan.[162]

In 2016, a contract for a megawatt-scale renewable hydrogen-based energy storage project was awarded by the Electricity Generating Authority. This will convert surplus electricity from the Lam Takhong Wind Turbine Generation Project to hydrogen during off-peak hours.

Research and development

A UK company, AFC Energy, is working with Thai partners to convert organic waste to hydrogen.

Analysis

The Thai market for hydrogen appears to be very limited with limited prospects for growth in the near to medium term.

A.3.7 India

The population of India is 1.3 billion.

Energy supply and demand

India imports around 45 per cent of its energy needs. Total energy consumption in India is the third highest in the world (after the USA and China). Coal is the dominant source of energy.

Government policies

The Indian government funded the development of a National Hydrogen Energy Road Map in 2006. However, there are few signs of any movement towards a hydrogen economy since then.

A New Road Map on hydrogen energy and fuel cells was prepared in 2016. This road map proposed more than $US400 million in additional funding. The road map projects that there will be one million hydrogen fuelled vehicles and 1000 MW aggregate hydrogen-based power generating capacity in India by 2020.

In March 2018, Tata Motors announced the development of a hydrogen fuel cell-powered bus.[163] However in a review of the Honda FCEV, Clarity, published in The Hindu in January 2018, the author concludes:

> *You can safely rule out fuel cells coming to India in the next decade or two.*[164]

In July 2010, India introduced a nationwide carbon tax of 50 rupees per tonne (less than $A1) on coal.

Research and development

The Ministry of New and Renewable Energy supports hydrogen and fuel cell R, D and D, including a Hydrogen Energy Centre in Varanasi.

Analysis

India could eventually be a big market for hydrogen. However, in the short to medium term it appears unlikely to be a market for imported hydrogen.

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[162] International Renewable Energy Agency (IRENA) 2017, Renewable Energy Outlook-Thailand, accessed on 15 April 2018 at http://www.irena.org/publications/2017/Nov/Renewable-Energy-Outlook-Thailand

[163] Singh A 2018, India's first-ever hydrogen fuel cell powered bus by Tata Motors is here! Made in India bus emits only water, Financial Express 15 March 2018, accessed on 15 April 2018 at http://www.financialexpress.com/auto/car-news/tata-motors-indianoil-corporation-flag-off-countrys-first-hydrogen-fuel-cell-powered-bus/1096895/

[164] Bhatia N 2018, The fuel cell experience, The Hindu, 3 January 2018, accessed on 15 April 2018 at http://www.thehindu.com/life-and-style/motoring/the-fuel-cell-vehicle-experience/article22357536.ece

A.3.8 California

The population of California is 40 million. If it were a separate country, California would be the sixth largest economy in the World.

Energy supply and demand

Hydrogen from steam reforming methane can be produced for on-site in the USA for less than $US1/kg ($A1.29/kg or $A9.09/GJ at current exchange rates).[165] Refuelling stations in California have been selling hydrogen at between $US8-13/kg ($A10.30-16.74/kg or $A72.6-118/GJ at current exchange rates).

The Department of Energy (DoE) target price is $US2-4 per gallon gasoline equivalent without tax.[166] One US gallon of gasoline contains the same energy content as one kilogram of hydrogen (on a lower heating value basis). Thus, the DoE target translates to $US2-4/kg ($A2.58-5.15/kg or $A18.2-36.3/GJ) for production only, not including compression or delivery.

Government policies

Although US federal policies on climate change are relatively weak, California is highly pro-active in adopting measures to reduce CO_2 and other airborne emissions.

California state government policies favour renewable energies including hydrogen. California has a Self-Generation Incentive Program that subsidises the installation of combined heat and power (CHP) co-generation systems through a state rebate. The rebate for fuel cells (CHP or electric only) is $US1.83/W. The incentive payment is only available for fuel cell installations with a capacity below 3MW.

California continues to lead the United States with policies and funding programmes that advance fuel cells and hydrogen infrastructure. In February 2013, California issued the 2013 Zero Emission Vehicles (ZEV) Action Plan that includes actions for state agencies to meet a goal of 1.5 million ZEV by 2025.

State law AB8 came into force in September 2013, providing funding for at least 100 hydrogen fuelling stations with a commitment of $US20 million per annum. In May 2014, the California Energy Commission approved almost $US50 million to add 28 new hydrogen refuelling stations to the nine existing stations and 17 stations under development. There are also state government incentives to use hydrogen to power buses.[167]

At the federal level, the Emergency Economic Stabilization Act of 2008 provided an investment tax credit incentive to reduce the cost of fuel cells.

California has a cap-and-trade auction for greenhouse gas emissions which raised $US600 million in 2017. There is continuing debate about replacing this scheme with a carbon tax in the State, while the Trump administration is proposing to legislate to prevent states from having such legislation.

Research and development

In 2005, Congress authorised investment, in partnership with the private sector, on the development of “safe, durable and efficient fuel cells.” This was reinforced by the Energy Independence and Security Act of 2007. As a result, the US Government (in particular the Department of Energy) has made large investments in hydrogen-related R&D.

Analysis

Manufacturers of hydrogen-powered vehicles see California as a useful test market. However new FCEVs will need to compete with an established market for electric cars.

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[165] Bakenne *et al*, 2016, op cit.

[166] Eichman J, Townsend A, and Melain M 2016, Economic Assessment of Hydrogen Technologies Participating in California Electricity Markets, NREL report accessed on 17 April 2018 at https://www.nrel.gov/docs/fy16osti/65856.pdf

[167] IEA 2015, National Strategies and Plans for Fuel Cells and infrastructure

The availability of cheap hydrogen from steam reforming of methane makes it unlikely that California would import Australian renewable hydrogen, particularly since California also has the potential to install its own solar power stations to produce renewable hydrogen. However, the difficulty of storing significant quantities of hydrogen in earthquake-prone California could make supply from Australia attractive because the ships carrying hydrogen to California would effectively provide storage.

A.3.9 European Union

The population of the European Union (EU) is 508 million.

A high-level expert group appointed by the European Commission to develop a vision for the future of hydrogen energy and fuel cells in Europe reported in 2003.[168] Subsequently, individual member countries have developed their own policies and road maps. A number of these are briefly discussed below.

In 2016, the Hydrogen Mobility Europe Initiative launched a six-year H2ME 2 project across Europe to promote the deployment of hydrogen refuelling infrastructure and passenger and commercial fuel cell vehicles.[169] This includes the deployment of 1,230 fuel cell vehicles and the addition of twenty hydrogen refuelling stations to the existing European network.

The European Union's emissions trading scheme began in 2005. It covers the 27 countries of the EU and three non-EU members: Iceland, Liechtenstein, and Norway. Their current emissions target is to reduce emissions by 21 per cent compared to 2005 emissions by 2025. Several European countries have enacted carbon taxes, including Denmark, Finland, Ireland, the Netherlands, Norway, Slovenia, Sweden, Switzerland, and the UK.

A current EU-supported project is developing an EU-wide Guarantee of Origin (GO) scheme to certify green and low carbon hydrogen.[170] This demonstrates that the market is interested in green hydrogen and wants to differentiate between hydrogen produced from steam reforming of methane (without CCS) and hydrogen produced with low or zero associated carbon emissions.

A.3.10 Germany

Germany's federal government adopted a number of policies in 2010 that have influenced the development of hydrogen as an energy source in that country.[171] Greenhouse gases are to be cut by 55 per cent by 2030 and at least 80 per cent by 2050 compared with 1990 levels. Renewables are to supply the bulk of Germany's future energy needs. Energy consumption is to be reduced and energy efficiency increased.

Germany's National Hydrogen and Fuel Cell Technology Innovation Program continues, with a recent announcement of the provision by federal Ministry for Transport and Digital Infrastructure (BMVI) to provide Siemens and RWTH Aachen with €12 million to support research into next-generation fuel cells.[172]

The federal government supports research on energy technologies (€3.5 billion between 2011 and 2014). The state (Länder) governments are also active in hydrogen-related research and have policies to encourage the take up of fuel cells. Hydrogen production from biomass, and the storage of large quantities of hydrogen are being investigated.[173]

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[168] European Commission 2003, Hydrogen energy and fuel cells: A vision of our future, accessed on 15 April 2018 at http://www.fch.europa.eu/sites/default/files/documents/hlg_vision_report_en.pdf

[169] FCH 2016, Europe prepares to expand hydrogen refuelling infrastructure network and vehicle fleet, accessed on 16 April 2018 at http://www.fch.europa.eu/press-releases/h2me-2-europe-prepares-expand-hydrogen-refuelling-infrastructure-network-and-vehicle

[170] Vanhoudt W, 2017, CertifHy: Creating the 1st EU-wide Guarantee of Origin for Green Hydrogen, accessed on 18 April 2018 at http://www.hinicio.com/file/2017/01/CertifHy-Presentation-short-final.pdf

[171] Federal Ministry of Economics and Technology (BMWi) and Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) 2010, Energy concept for an Environmentally sound. Reliable and affordable energy supply, accessed on 16 April 2018 at https://www.osce.org/eea/101047?download=true

[172] Smith K 2018, International Railway Journal, 26 February 2018, German government supports hydrogen fuel cell research, accessed on 16 April 2018 at http://m.railjournal.com/index.php/rolling-stock/german-government-supports-hydrogen-fuel-cell-research.html

[173] IEA 2015, ibid.

Germany is also investing in demonstration project, with a milestone of 3,000 installed domestic fuel cell systems in 2016. Recently, Hamburg has promoted hydrogen-fuelled cars but the take up is reported to be slow.[174]

Shell, in partnership with ITM Power, plans to install a large-scale electrolyser to produce hydrogen at the Wesseling refinery site within its Rheinland Refinery Complex. This will have a capacity of 10MW making it the largest unit of its kind in Germany and the world's largest PEM (Polymer Electrolyte Membrane) electrolyser.

A.3.11 United Kingdom

The UK hydrogen and fuel cell road map was published in 2016.[175] This report was commissioned by a consortium of UK government agencies and other parties. It argues that there would be significant benefits to the UK from early adoption of hydrogen fuel cell technology. A more recent White Paper, commissioned by the UK Hydrogen and Fuel Cell (H2FC) SUPERGEN Hub, considered the potential for hydrogen and fuel cell systems in the UK.[176]

The H21 Leeds City Gate project, currently underway, aims to demonstrate the feasibility of converting the existing natural gas network in Leeds (one of the UK's largest cities) to 100 per cent hydrogen. This project has received significant government support. Since 2002, the UK has been undertaking the Iron Mains Pipeline Replacement Program, upgrading the majority of Leeds' distribution pipes to polyethylene which is suitable for transporting hydrogen.[177]

A.3.12 France

The French Environment and Energy Management Agency (ADEME) is continuing to make investments in renewable energy. The four programs involved are: renewable, low-carbon energy and green chemistry (€1.35 billion), Vehicles of the future (€1 billion), Smart grids (€250 million) and Circular Economy (€250 million). A strategic roadmap was published in 2011.[178]

A French start-up company has just commenced selling hydrogen-powered bicycles.[179]

In June 2018 the French Minister for Ecological and Solidary Transition announced that ADEME will be allocated €100 million in 2019 to support the nation's hydrogen industry.[180]

A.3.13 Netherlands

The Northern Netherlands Innovation Board has developed a detailed plan to make the region a green hydrogen economy.[181]

A.3.14 Denmark

Denmark aims to be independent of fossil fuels by 2050. Wind power currently provides more than 40 per cent of the electricity generated in Denmark.

Electric and hydrogen vehicles were exempt from vehicle registration tax until the end of 2015 inclusive. Since 2016, they have benefitted from a reduced vehicle registration tax, which is gradually

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[174] Reed S 2017, Hamburg Is Ready to Fill Up With Hydrogen. Customers Aren't So Sure, New York Times, 4 July 2018, accessed on 16 April 2018 at https://www.nytimes.com/2017/07/04/business/hydrogen-cars-trains-planes-hamburg.html

[175] E4tech and Element Energy 2016, Hydrogen and fuel cells: Opportunities for growth, accessed on 16 April 2018 at http://www.e4tech.com/wp-content/uploads/2016/11/UKHFC-Roadmap-Final-Main-Report-171116.pdf

[176] Staffell I, Dodds P, Scamman D, Velazquez Abad A, Mac Dowell N, Ward K, Agnolucci P, Papageorgiou L, Shah N and Ekins P 2017, The role of hydrogen and fuel cells in future energy systems a H2FC SUPERGEN White Paper, accessed on 16 April 2018 at http://www.h2fcsupergen.com/wp-content/uploads/2015/08/J5212_H2FC_Supergen_Energy_Systems_WEB.pdf

[177] Northern Gas Networks 2016, H21 Leeds City Gate, accessed on 16 April 2018 at https://www.northerngasnetworks.co.uk/wp-content/uploads/2017/04/H21-Report-Interactive-PDF-July-2016.compressed.pdf

[178] ADEME 2011, Hydrogen energy and fuel cells, accessed on 16 April 2018 at http://www.ademe.fr/sites/default/files/assets/documents/hydrogen-energy-fuel-cells-strategic-roadmap-2011-6924.pdf

[179] Reuters 2018, French startup launches hydrogen-powered bicycles, 17 January 2018, accessed on 16 April 2018 at https://www.reuters.com/article/us-france-bicycles-hydrogen/french-startup-launches-hydrogen-powered-bicyles-idUSKBN1F52AP

[180] PV magazine 2018, France looks to hydrogen to become 100% renewables, accessed on 1 August 2018 at https://www.pv-magazine.com/2018/06/01/france-wants-hydrogen-to-become-100-renewable/

[181] Van Wijk A, for the Noordelijke Innovation Board 2017, The Green Hydrogen Economy in the Northern Netherlands, accessed on 16 April 2018 at http://profadvanwijk.com/wp-content/uploads/2017/04/NIB-BP-EN-DEF-webversie.pdf

increased every year. The reduced rate is to be maintained until Denmark reaches the government's objective to have 5 000 electric vehicles (by the end of 2018).[182]

Copenhagen aims to be carbon neutral by 2025. To achieve this, the city is promoting FCEVs and installing hydrogen refuelling stations.[183]

Research and development

There are significant R&D programs across the EU developing fuel cell technology, hydrogen storage and other aspects of hydrogen technology.

Analysis

Some countries in Europe such as Germany are moving quite rapidly to adopt hydrogen as a fuel source. There is significant interest in green hydrogen and strong commitments to reducing CO_2 emissions.

The major gas supply companies and Shell are already starting to provide green hydrogen in Europe using renewable energy sources. Iceland is also a potential source of green hydrogen supplies to Europe.[184] In addition, there is an EU-funded project in the Orkney Islands to generate hydrogen from surplus renewable sources (tidal, wind and wave).[185]

ACIL Allen does not see significant prospects for exports of Australian green hydrogen to the EU over the time period for this study.

A.4 Conclusions

The literature review was used to help identify those countries most likely to see an increase in their hydrogen use and which were also likely to be potential importers of hydrogen from Australia.

Four countries were selected for further modelling using the following criteria:

- the likely size of the potential hydrogen import market—an indicator which combines:
  - expected energy demand and growth
  - reliance on imported energy
  - inability to supply own hydrogen
  - likely growth in demand for hydrogen
- government policies encouraging the use of hydrogen, which reflects:
  - incentives for low-carbon hydrogen and FCEVs
  - provision of hydrogen infrastructure
  - rate of introduction of FCEVs (as noted earlier, a major driver of demand)
  - rate of introduction of other uses of hydrogen (e.g. combined heating and power—CHP)
  - R&D support for fuels cells, hydrogen production, storage, transport and distribution
  - greenhouse gas and air pollution concerns that lead to a need to adopt lower emission fuels
- Australia's competitive position for providing hydrogen compared to other potential hydrogen producers.

ACIL Allen's assessment of hydrogen market potential, against the criteria listed above, is presented in **Table A.4**. The final row compares Australia's position to other potential suppliers of hydrogen.

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[182] IEA 2017,

[183] IEA 2015, ibid.

[184] Salameh MG 2009, How Viable is the Hydrogen Economy? The Case of Iceland, International Association of Energy Economics, second quarter 2009, p11, accessed on 16 April 2018 at https://www.iaee.org/en/publications/newsletterdl.aspx?id=59

[185] Ward A, 2018, Orkney project shows potential of hydrogen as a fuel source, Financial Times, 8 January 2018, accessed on 16 April 2018 at https://www.ft.com/content/f5e8c5aa-d8ee-11e7-9504-59efdb70e12f

TABLE A.4 HYDROGEN MARKET POTENTIAL IN VARIOUS COUNTRIES, CALIFORNIA AND THE EU

Criteria	China	Japan	Korea	Singapore	India	Taiwan	Thailand	California	Europe
Size of potential H_2 import market	🟩	🟩	🟩	🟨	🟩	🟩	🟥	🟩	🟩
– Energy demand and growth	🟩	🟩	🟩	🟨	🟩	🟨	🟨	🟩	🟩
– Reliance on imported energy	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
– Inability to supply own H_2	🟨	🟩	🟩	🟩	🟨	🟩	🟩	🟩	🟩
– Likely growth in demand for H_2	🟩	🟩	🟩	🟩	🟨	🟩	🟥	🟨	🟩
Govt policies that support H_2	🟩	🟩	🟩	🟩	🟨	🟨	🟥	🟩	🟩
– Incentives for H2/FCEVs	🟨	🟩	🟩	🟩	🟥	🟥	🟥	🟩	🟩
– Provision of infrastructure	🟨	🟩	🟩	🟩	🟥	🟨	🟥	🟨	🟨
– Introduction of FCEVs	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟨	🟨
– Introduction of other uses for H_2	🟩	🟩	🟩	🟨	🟨	🟩	🟥	🟨	🟨
– R&D support	🟩	🟩	🟩	🟩	🟨	🟨	🟥	🟩	🟩
– GHG/air pollution concerns	🟩	🟩	🟩	🟩	🟥	🟩	🟥	🟩	🟩
Aust's position vs. other suppliers	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟨	🟥

NOTES: Green Boxes indicate a high rating, yellow boxes a medium rating and red boxes indicate a low rating

SOURCE: ACIL ALLEN ANALYSIS

This analysis suggests that China, Japan, Korea and Singapore could be suitable candidates for further analysis of their potential to be the recipient of Australian hydrogen exports.

China, Japan and Korea are potentially large markets for green hydrogen and have plans that could result in a rapidly growing market. Singapore is a much smaller market, but it could well play a role as an early adopter of hydrogen for use in FCEVs, in effect as a demonstration of the potential to establish a hydrogen supply chain.

All four target countries have policies to promote the use of green hydrogen, even if initially they will use hydrogen from steam reforming of methane for applications in transport, domestic CHP and electricity generation.

All four countries have policies that would serve to encourage increased use of hydrogen in the transport sector. Government hydrogen-related R&D investment in China, Japan and Korea is significant. There is considerable effort being made with R&D related to hydrogen and fuel cells. There is also R&D investment in niche areas such as purification technology and small fuel cells to power mobile devices.

While some countries in Europe have policies to expand the use of hydrogen as an energy source, there are significant sources of green hydrogen coming on line in Europe. In California, the potential for cheap low-carbon hydrogen together with the scope for producing green hydrogen in California make it unlikely that imported green hydrogen will be competitive.

The projected growth of FCEV numbers in China, Korea and Japan suggest that, by 2025, there will be 600,000 of these vehicles and that by 2030 there could be three million. Assuming that these vehicles travel 10,000km per year and that their hydrogen consumption is 0.01kg per km, the FCEV demand for hydrogen will increase from 60,000 tonnes in 2020 to 300,000 tonnes in 2030.

Singapore might prove to be an important demonstration market for a green hydrogen supply chain. Assuming that the average distance travelled by a private vehicle in Singapore is around 15,000 km[186] then for every 100,000 FCEVs there would be a demand for 15,000 tonnes of hydrogen per year to fuel these vehicles.

In addition, there are expected to be 5.4 million domestic CHP installations in Japan and Korea by 2030. While these are currently fuelled by natural gas, post 2030 it is possible that these (and any additional CHP installations) may progressively be converted to operate on hydrogen.

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[186] https://data.gov.sg/dataset/annual-mileage-for-private-motor-vehicles accessed 19 April 2018.

B

ECONOMIC CONTRIBUTION ANALYSIS

This chapter discusses the analytical framework used to estimate the economic contribution of production and export of hydrogen from Australia.

B.1 Economic contribution analysis

ACIL Allen has used IO multiplier analysis to estimate the economic contribution (or footprint) of hydrogen production and exports under each scenario. This is a methodology that is frequently used to understand the full linkages of an industry throughout the economy at a point in time. The analysis describes:

- the *direct* contributions that this new industry makes to the Australian economy, plus
- the full extent of the *indirect* contributions the industry makes to the economy through their demand for intermediate inputs from other industries (electricity generated from renewables, machinery etc.).

For this analysis, the estimates of the economic footprint, or the net economic contribution attributable to hydrogen production, have been made using what are known as 'simple multipliers'. For example, the estimates in this report include the direct contribution made by this potential new industry to Australia's GDP and employment, along with the contribution embodied in the new industry's supply chain, up to the point of exports. They do *not* include what is referred to as the 'consumption-induced effect'. That is, they do not include the economic effects associated with workers within the new industry (or its supply chain) spending their after-tax income on other Australian goods and services (such as hairdressers, travel, retail trade, etc.).

A summary of economic contribution and economic impact analysis is provided in **Box B.1**.

When properly calculated[187], estimates of value-add attributable new hydrogen production from simple multipliers can be added to similar estimates for other non-overlapping industries (such as fishing, forestry, petroleum, aluminium, etc.) without summing to more than Australia's total GDP or employment. While these estimates of footprint are useful in many contexts, they provide a conservative estimate of the total economic activity or employment that could be affected by the creation of this potential new industry.

More details of direct and indirect contribution (footprint) analysis are provided below.

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[187] In particular, it is important to avoid double counting related to the intra-sectoral purchases and vertical supply chain activities. For example, when adding the impact of related industries (where industry A supplies to industry B, for example) it is necessary to exclude the value of A's sales to B when calculating industry B's contribution. Ensuring that industries are completely non-overlapping is complex and certain simplifying assumptions generally need to be made.

BOX B.1 ECONOMIC FOOTPRINT ANALYSIS AND ECONOMIC IMPACT ANALYSIS

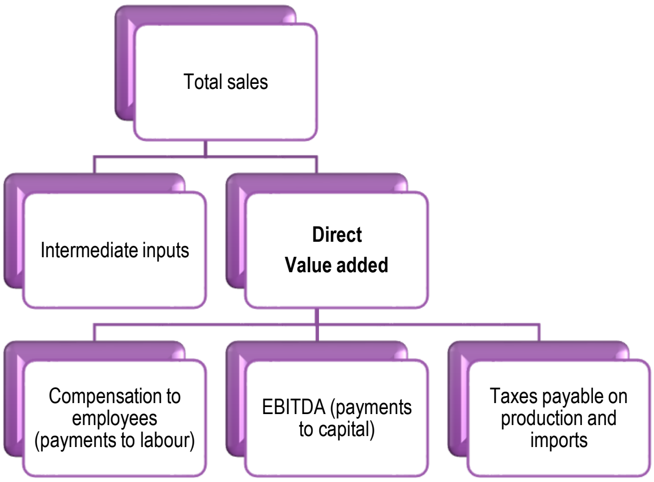
An economic **contribution** (or **footprint**) analysis differs from an analysis of economic **impact** in that it does not purport to consider how the economy would respond to the closure, contraction or expansion of an industry. More specifically, a footprint analysis considers how much of the economy or how many people are *currently* affected by the activities of this new green hydrogen industry. In contrast, an economic impact analysis would consider how the overall economy would look before and after there had been a 'shock' to the industry and consumers and other parts of the economy had adjusted. An impact analysis recognises that there are competing uses for scarce factors of production and therefore considers how, for example, the renewable sector would change in response to, say, increased production and exports from a new hydrogen industry. While IO multiplier analysis can (and is) used for economic impact analysis, it is not the preferred methodology for assessing the impacts of major industry adjustments (particularly when applied at the national level). The preferred approach for the analysis of economic impacts is CGE modelling. A key feature of CGE models is their ability to incorporate market constraints, particularly regarding the key factors of labour and capital and relative price impacts.

SOURCE: ACIL ALLEN CONSULTING

B.2 Direct economic contribution

The standard measure of economic contribution is the extent to which an activity increases the value of goods and services generated by the economy as a whole – in other words, the extent to which it increases economic activity as measured by gross domestic product (GDP). An economy has a range of factors of production (including labour and capital stock) and access to various intermediate inputs. By using the factors of production appropriately, industries can add value to intermediate inputs by converting them into a range of goods and services more suited for use by consumers or other industries. An industry's' *contribution to GDP* measures the total value added generated and is defined as the income that an industry or business generates, less the cost of the inputs that it uses to generate that income, plus certain taxes paid. The direct contribution of an industry to the Australian economy can therefore be estimated by determining their payments to the factors of production plus the taxes (less subsidies) payable on production and imports. The direct economic contribution is shown graphically in **Figure B.1**.

FIGURE B.1 CALCULATION OF DIRECT VALUE ADDED



Note: EBITDA is equivalent to the SNA93 definition of gross operating surplus

SOURCE: ACIL ALLEN CONSULTING

Box B.2 provides a summary of the definitions used by the ABS as part of the SNA93.

BOX B.2 ABS DEFINITIONS OF VALUE ADDED

An industry’s direct contribution to Gross Domestic Product is well defined under the standard national accounting framework used by the Australian Bureau of Statistics (ABS), which is known as the System of National Accounts 1993 (SNA93). SNA93 recognises three different measures of value added:

- Value added at Purchasers’ Prices. This is defined as output valued at purchasers’ prices, less intermediate consumption valued at producer prices. This measure is equivalent to the traditional measure of value added at market prices.
- Value added at Basic Prices. In this measure, the output is valued at basic prices while intermediate consumption is valued at producer prices.
- Value added at factor Cost. This measure excludes all production taxes net of subsidies. In other words, it excludes all production taxes – such as payroll taxes, fringe benefit taxes etc – and not just those that are levied on output.

The measure of value added to be used depends on the nature of the analysis that is being conducted. When presenting an industry view of GDP for example, the ABS uses value added at basic prices and adds an aggregate estimate of net taxes on products in question to give a total measure of GDP at purchasers’ prices.

SOURCE: ABS

B.3 Indirect economic contribution

The intermediate inputs used by a new hydrogen production industry can be sourced either from within the Australian economy or from foreign economies. If purchased from within Australia, then the portion of value added embodied in the intermediate input is indirectly associated with the activity of the purchaser. IO tables and the associated ‘multipliers’ can be used to estimate the indirect economic contributions. IO multipliers are summary measures generated from IO tables that can be used for predicting the total impact on all industries in the economy of changes in demand for the output of any one industry. The tables and multipliers can also be used to measure the relative importance of the production chain linkages to different parts of the economy.

It should be noted that some of the assumptions underpinning input-output multipliers can be an impediment to credible analysis. Understanding these assumptions is necessary to prevent the inappropriate application of input-output multipliers – for example, in situations where economic constraints are present or when the profile of a business or project differs substantially from the industry average. ACIL Allen does not consider that these conditions apply to the analysis presented in this report as it is only an indicative and that the use of IO multipliers to estimate the economic footprint of new hydrogen industry is appropriate.

Further information on IO tables and the calculation of multipliers can be found in ABS Catalogue number 5246.0.[188]

Input-output tables can be used to derive input-output multipliers. These multipliers show how changes to a given part of an economy impact on the economy as a whole.

The input-output multipliers allow analysis of the economic footprint of a particular facility, industry or event for the region of interest. Although input-output multipliers may also be suitable tools for analysing the impact of various types of economic change, caution needs to be adopted in their application for this purpose. Misuse of input-output multipliers for impact analysis has led to scepticism of their general use in favour of other tools such as CGE modelling. Notwithstanding this, they are still eminently suitable for understanding the economic linkages with a given industry to gain an appreciation of the wider interactions of the industry beyond its direct contribution.

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[188] ABS 1995, Information Paper, Australian National Accounts: Introduction to Input-Output Multipliers, 1989-90, Cat No: 5246. http://www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/5246.01989-90?OpenDocument

B.4 Multiplier types

Input-output multipliers estimate the economic impact on economy from a one dollar change in final demand for the output of industry. Generally, four types of multipliers are used:

- Output – measures the impact on the output of all industries in the economy
- Income – measures the effect on the wages and salaries paid to workers within the economy
- Employment – measures the jobs creation impact, and
- Value-added – measures the impact on wages and salaries, profits and indirect taxes.

The sum of wages and salaries, profits and indirect taxes for a given industry provides a measure of its contribution to the size of the economy – its contribution to GDP. The value-added multiplier can therefore also be the GDP multiplier.

Input-output multipliers are a flexible tool for economic analysis. Their flexibility stems from the different forms of each multiplier type. Multipliers were generally estimated in the following forms:

- initial effects
- first round effects
- industrial support effects
- production induced effects
- consumption induced effects
- simple multipliers
- total multipliers
- type 1A multipliers
- type 1B multipliers
- type 2A multipliers
- type 2B multipliers.

B.4.1 Multiplier effects

When additional sales to final demand are made, for example through increased exports or sales to the public, production increases to meet the increased demand, and this is the initial effect. Since production increases to exactly match the increased final demand, the increase is always equal to one (noting that the multipliers are defined in terms of a one dollar increase in final demand).

An industry producing additional outputs purchases additional inputs to enable it to increase production. These new purchases require production increases in other industries—a first round effect. First-round production increases cause other industries to also increase their purchases, and these purchases cause other industries to increase their production, and so on. These ‘flow-on’ effects eventually diminish, but when 'added together constitute the industrial support effect.

The industrial support effect added to the first-round effect is known as the production induced effect. So far this chain of events has ignored one important factor, the effect on labour and its consumption. When output increases, employment increases, and increased employment translates to increased earnings and consumption by workers, and this translates to increased output to meet the increased consumption. This is the consumption effect.

B.4.2 Multipliers

The simple and total multipliers are derived by summing the effects. The simple multiplier is the sum of the initial and production induced effects. The total multiplier is larger, because it also adds in the consumption effect. All the effects and multipliers listed above have one thing in common — they all measure the impact on the economy of the initial increase in final demand.

The remaining multipliers take a different point of view, they are ratios of the above multiplier types to the initial effect. The type 1A multiplier is calculated as the ratio of the initial and first round effects to the initial effect, while the type 1B multiplier is the ratio of the simple multiplier to the initial effect. The type 2A multiplier is the ratio of the total multiplier to the initial effect, while the type 2B multiplier is the ratio of the total multiplier less the initial effect to the initial effect.

Given the large number of multiplier types to choose from (output, income, employment and value-added multipliers, and each with numerous variations (simple, total, type 2A, etc)) it is important that the analysis uses the most appropriate multipliers. Usually, the multipliers that include consumption effects (i.e. the added impact that comes from wage and salaries earners spending their income) are used. These are the total and type 2A multipliers. The total and type 2A multipliers will generally provide the biggest projected impact. Simple or type 1B (which omit the consumption effect) may be used to provide a more conservative result.

For this analysis, the Simple multipliers were used to estimate the total contribution the new hydrogen industry could make to the Australian economy.

B.5 Limitations of input-output analysis

Although input-output analysis is valid for understanding the contribution a sector makes to the economy, when used for analysing the potential impacts of a change in production of a particular sector, input-output analysis is not without its limitations. Input-output tables are a snapshot of an economy in a given period, the multipliers derived from these tables are therefore based on the structure of the economy at that time, a structure that it is assumed remains fixed over time. When multipliers are applied, the following is assumed:

- prices remain constant;
- technology is fixed in all industries;
- import shares are fixed.

Therefore, the changes predicted by input-output multipliers proceed along a path consistent with the structure of the economy described by the input-output table. This precludes economies of scale. That is, no efficiency is gained by industries getting larger – rather they continue to consume resources (including labour and capital) at the rate described by the input-output table. Thus, if output doubles, the use of all inputs doubles as well.

One other assumption underpinning input-output analysis which is worth considering is that there are assumed to be unlimited supplies of all resources, including labour and capital. With input-output analysis, resource constraints are not a factor. It is thus assumed that no matter how large a development, all required resources are available, and that there is no competition between industries for these resources.

It is important to understand the limitations of input-output analysis, and to remember that the analysis provides an estimate of economic contribution of new hydrogen production industry in Australia up to the point of export terminal.

C

MARKET OPPORTUNITIES FOR HYDROGEN BY COUNTRY

C.1 Overview

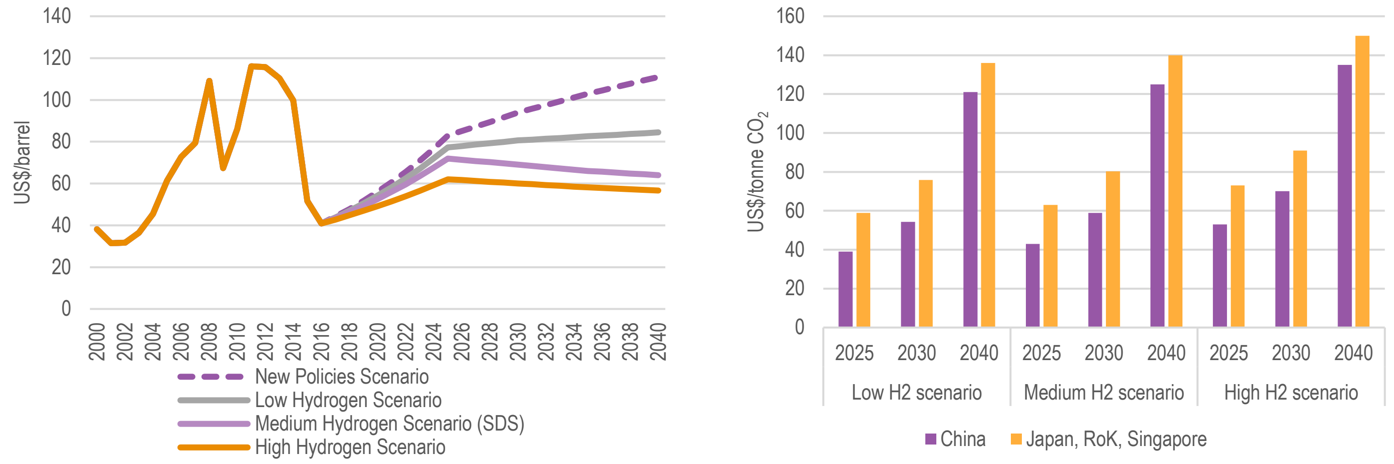
This Appendix provides more details on the key data and assumptions underpinning the projections quantifying the hydrogen opportunities in each country.

In all cases, a baseline *scenario* was developed to 2040 to understand the energy market dynamics in each country. This scenario assumes that the current economic and environmental trends and policies will continue and there will be a limited role for hydrogen in the energy mix. As discussed in Chapter 3, this scenario is similar to the New Policies Scenario in the IEA's World Energy Outlook, 2017. Where data or projections for individual countries is not publicly available from the IEA, estimates from official government agencies (such as the Korean Energy Master Plan) have been used in combination with data for the region from the WEO.

The hydrogen scenarios are based on the levelised cost of energy sources and a variable uptake of hydrogen in various end use industries due to the measures undertaken by government to reduce emissions. The underlying level of energy consumption by industry by country in all three hydrogen scenarios are the same as the WEO's Sustainable Development Scenario (SDS). When combined with the current understanding of hydrogen consumption technologies and possible future hydrogen production prices, this provides an understanding of the potential possible market size within each country. The *medium* H_2 scenario uses the same energy and carbon prices as the SDS to estimate the potential uptake, while the *low* and *high* H_2 scenarios assume that the future energy and carbon prices (see **Figure C.1**) and other supporting factors are lower or higher, and that there is lower or higher success in hydrogen technology development and uptake. The *low* and *high* H_2 scenarios were developed to provide some quantification of the uncertainties rather than as representations of the lowest and highest possible potential hydrogen demand. Therefore, the hydrogen scenarios should be interpreted as indicative 'size of the prize' estimates to help frame the uncertainties rather than as boundaries of potential future outcomes.

Apart from underlying growth and fuel price differences, a key characteristic that distinguish the hydrogen policy scenarios are the hydrogen take-up rates. They vary by market segment and are influenced by the relative cost in their end use industries, particularly the cost of electricity production from renewables within each country in conjunction with other country specific hydrogen production costs (such as labour, water and the cost of capital).

FIGURE C.1 ASSUMED OIL PRICES AND CARBON PRICES



A. Average crude oil import price by scenario

B. Average carbon price by scenario

Notes: Prices in the Medium Hydrogen scenario are the same as the IEA Sustainable Development Scenario. In figure B, Japan, RoK and Singapore all have the same carbon price.

SOURCE: ASSUMPTIONS BASED ON INTERNATIONAL ENERGY AGENCY (2017), WORLD ENERGY OUTLOOK 2017, OECD/IEA, PARIS

C.2 Japan hydrogen policy scenarios

C.2.1 Renewable electricity production costs in Japan

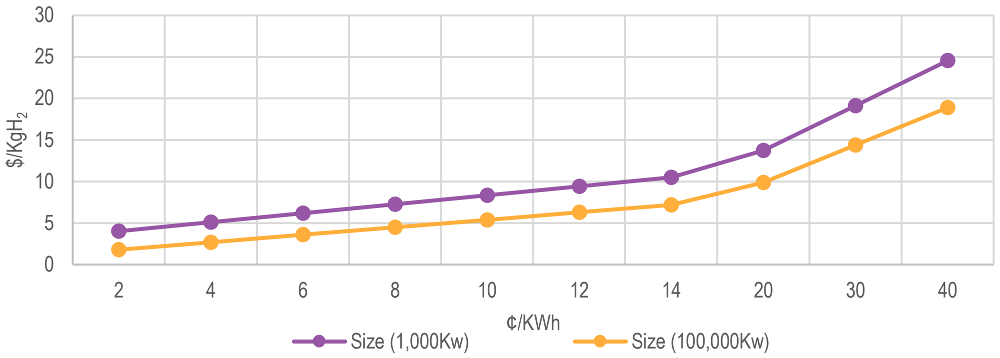
There are many ways of producing electricity and each yields a different cost. The Japanese government has announced an ‘ideal composition’ of power sources in the future (to 2030) that will be realised through implementing policies to achieve energy security, economic efficiency and environmental objectives. The ‘ideal composition’ has already been considered in the business as usual scenario and the renewables — hydroelectric, solar, wind, biomass, geothermal — share is expected at around 24 per cent by 2030. The IEA has estimated the levelised cost of electricity generation technologies in Japan and this data has been updated to estimate the LCOE of renewables in Japan for comparison purposes. In 2018, the levelised cost of producing electricity from large ground mounted solar PV in Japan was 30 cents/kWh (at a 7 per cent discount rate) and it is expected to decline to 24.7 cents/kWh by 2040. This is significantly higher than the estimated cost in Australia or China.

Excluding the potential for using nuclear power, renewables will need to be a major feedstock for producing low emissions hydrogen in Japan using PEM technology.

C.2.2 Hydrogen production costs in Japan

The relationship between the cost of hydrogen production and renewable electricity prices in Japan (in Australian currency) is shown in **Figure C.2**. The cost of production depends on the size of the operation and electricity prices.

FIGURE C.2 COST OF HYDROGEN PRODUCED BY PEM ELECTROLYSIS TECHNOLOGY AS A FUNCTION OF RENEWABLE ELECTRICITY PRICES IN JAPAN



SOURCE: ACIL ALLEN ESTIMATES BASED ON THE IEA (2015) AND CSIRO

ACIL Allen has estimated the levelised cost of hydrogen production using the PEM method in Japan based on the CSIRO parameters. It is estimated that the levelised cost of hydrogen production, using electricity generated from renewables in Japan, is A$8.5/ kgH_2 in 2025.This is significantly higher than the estimated cost in Australia. CSIRO has estimated LCOH production using the same PEM method is A$2.41/ kgH_2. A key assumption driving this lower LCOH in Australia is the assumption of an average electricity price over the life of the plant in 2025 of 4 cents/kWh. Whereas, the estimated average renewable electricity price (solar PV and onshore wind) over the life of the plant in Japan is 17cents/kWh in 2025. This suggests that Australian produced hydrogen is likely to be a competitive source of supply to help Japan meet all its future demand for hydrogen.

C.2.3 Japan’s vision for a hydrogen economy

Japan has developed a hydrogen economy vision and some key targets in 2016.

Key targets include

- 40,000 fuel cell vehicles by 2020, 200,000 fuel cell vehicles by 2025, and 800,000 fuel cell vehicles by 2030[189]
- 1.4 million residential installations with hydrogen pipeline by 2020 and 5.3 million residential installations by 2030 (10 per cent of homes)
- 160 hydrogen fuelling stations by 2020 and 320 stations by 2025.

C.2.4 Hydrogen technology uptake in Japan

The demand for hydrogen in Japan under three hydrogen scenarios has been modelled. The modelling implicitly provides the following hydrogen uptake rates to meet various energy and emission ambitions in Japan:

- For the transport sector, the *low H_2 demand scenario* represents a low uptake of hydrogen technologies of 0.28 per cent by 2025, 0.58 per cent by 2030 and 2.1 per cent by 2040. Under the *medium H_2 scenario* the uptake of hydrogen technologies is 0.58 per cent by 2025, 0.81 per cent by 2030 and 5.2 per cent by 2040. Whereas, the *high H_2 scenario* has an uptake of hydrogen technologies of 1.5 per cent by 2025, 2.5 per cent by 2030 and 11 per cent by 2040.
- For the power sector, the *low H_2 scenario* has an uptake of hydrogen technologies of 0.016 per cent by 2025, 0.52 per cent by 2030 and one per cent by 2040. Under the *medium H_2 scenario* there is an uptake of hydrogen technologies of 0.27 per cent by 2025, 1.1 per cent by 2030 and 2.1 per cent by 2040. Finally, the *high H_2 scenario* has an uptake of hydrogen technologies of 0.7 per cent by 2025, 2.3 per cent by 2030 and 5 per cent by 2040.

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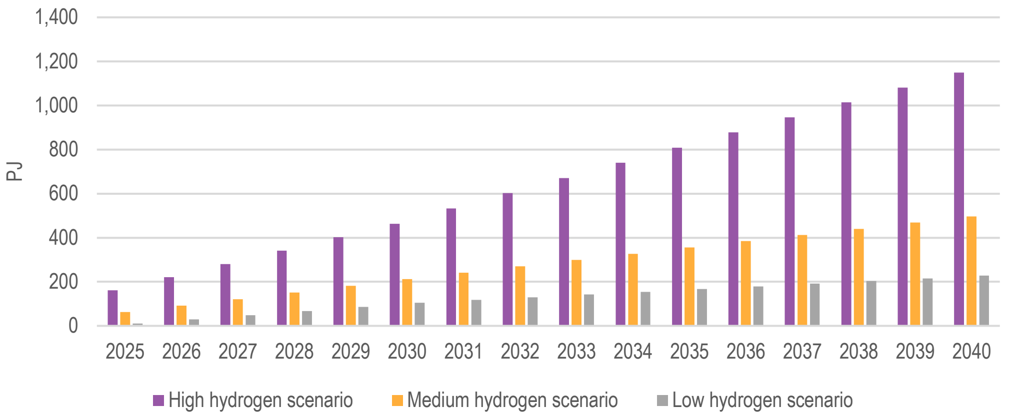
[189] Ministry of Economy, Trade and Industry Agency for Natural Resources and Energy, 2016, Compilation of the Revised Version of the Strategic Roadmap for Hydrogen and Fuel Cells, accessed on 17 May 2018 at http://www.meti.go.jp/english/press/2016/0322_05.html

The three hydrogen scenarios take into account the levelised cost of energy sources and various hydrogen uptake rates in different end use industries due to the measures introduced by the government to reduce emissions that are broadly consistent with the different energy use and emission reduction targets.

C.2.5 Potential hydrogen demand in Japan

The estimated hydrogen demand potential in the *low H_2 scenario* in 2025 is 10.6 PJ increasing to 227.7 PJ by 2040 (**Figure C.3**). The estimated hydrogen demand potential in the *medium H_2 scenario* in 2025 is 62 PJ increasing to 496 PJ by 2040. The estimated hydrogen demand potential in the *high H_2 scenario* in 2025 is 160.7 PJ increasing to 1,150 PJ by 2040.

FIGURE C.3 HYDROGEN DEMAND POTENTIAL IN JAPAN, 2025–2040



SOURCE: ACIL ALLEN ESTIMATES.

C.2.6 Hydrogen demand by application in Japan

A summary of hydrogen demand estimates by application is provided in **Table C.1**.

TABLE C.1 HYDROGEN DEMAND BY APPLICATION IN JAPAN (PJ)

	Transport	Space heating and cooling	Power sector	Total
Low demand scenario				
2025	7.7	1.0	1.8	**10.6**
2030	14.7	34.9	55.5	**105.1**
2040	46.1	70.9	110.6	**227.7**
Medium demand scenario				
2025	16.0	17.4	28.6	**62.0**
2030	20.5	73.8	117.2	**211.5**
2040	114.3	148.9	232.9	**496.1**
High demand scenario				
2025	41.5	45.0	74.2	**160.7**
2030	63.4	154.3	245.6	**463.3**
2040	241.7	354.6	553.4	**1,149.7**

SOURCE: ACIL ALLEN ESTIMATES

C.2.7 Energy import demand

The energy imports discussed below are included in the baseline of the modelling. Under the three hydrogen scenarios different amounts of these energy forms are replaced by hydrogen.

Coal

Total supply of coal in 2016 was 118 mtoe and 27 per cent of total primary energy supply. Japan relies on imports for all its coal demand (domestic production of coal ceased in 2002). Coal imports totalled 192 million tonnes in in 2015 — 73 per cent steam coal and 26.3 per cent coking coal. Nearly 65 per cent of coal imports were from Australia, followed by Indonesia (18.6 per cent), Russia (7.4 per cent) and Canada (4.3 per cent).

Oil

Oil is the largest source of energy in Japan, representing 41 per cent of total primary energy supply in 2016 or 179 mtoe. Japan relies on imports to meet practically all its crude oil needs as there is very little domestic production. It is the world's fourth largest importer of crude oil after the United States, China and India. In 2015, imports amounted to 162miliion tonnes and over 80 per cent was sourced from the Middle East and remainder came from Russia, Indonesia and other countries.

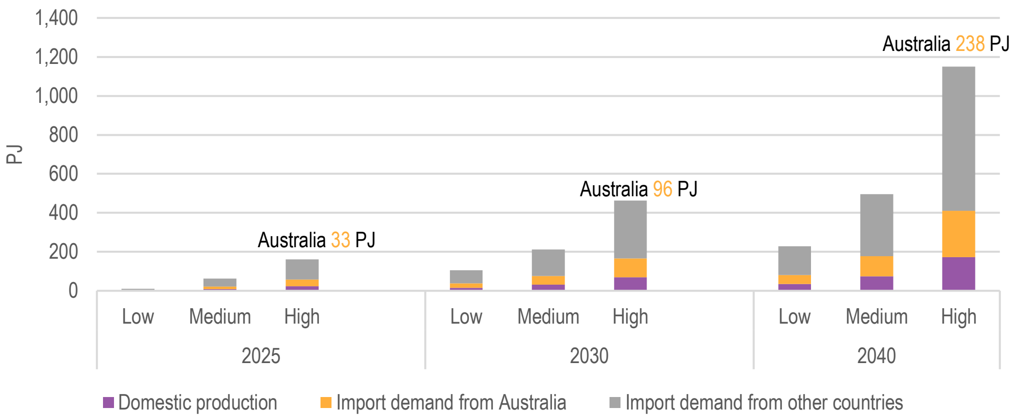
Natural gas

Natural gas accounts for around a quarter of total energy supply in Japan and is the main fuel used for power generation. Japan relies on natural gas imports as domestic production is negligible. Imports totalled 117bcm in 2015, originating from Australia (22.9 per cent), Malaysia (18.7 per cent), Qatar (15.8 per cent), Russia (8,5 per cent), the UAE (6.7 per cent) and others. Natural gas is mainly used to produce electricity and reticulated as city gas. City gas is supplied via pipeline to around 30 million users, of which 28 million are residential customers. Japan imports all its gas as LNG. Japan's pipelines primarily to connect LNG receiving terminals on the coast to demand centres. As a result, the geographic coverage is only 5.7 per cent, serving 65 per cent of domestic demand. In the rest of the country the demand is mostly met by LPG. Retail prices for natural gas for both households and industry are among the highest in the OECD.

C.2.8 Hydrogen import demand in Japan

Based on the relative cost competitiveness of domestic production and imports, it is estimated that more than 85 per cent of hydrogen demand in Japan will be supplied by imports (**Figure C.4**).

FIGURE C.4 ESTIMATED HYDROGEN SUPPLY POTENTIAL IN JAPAN, 2025, 2030 AND 2040



SOURCE: ACIL ALLEN ESTIMATES

C.3 Republic of Korea

C.3.1 Electricity production costs in South Korea

There are many ways of producing hydrogen. Currently most of the hydrogen produced in South Korea is made from fossil fuels. A South Korean Ministry of Oceans and Fisheries is working to produce environmentally friendly hydrogen fuel and it is expected to begin producing hydrogen in 2019.

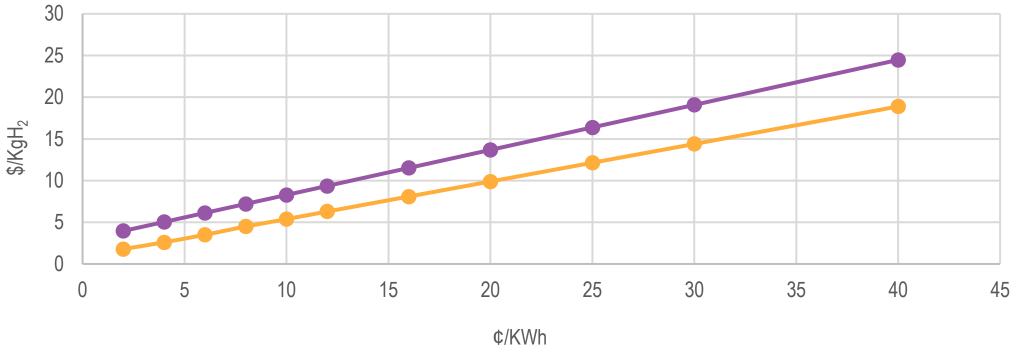
Every five years the IEA produces a comprehensive levelised cost of electricity generation technologies in major economies. At the time of this analysis, the most recent report produced was for the year 2015. These costs have been updated using more recent costs and projections by IRENA.

The levelised cost of producing electricity from large ground mounted solar PV was 14.8 cents/kWh in 2025. Excluding the potential use of nuclear energy, this may be a major source of low emissions hydrogen (using PEM technology) in South Korea.

C.3.2 Hydrogen production costs in South Korea

The relationship between the cost of hydrogen production and electricity prices in Australian dollars is shown in **Figure C.5**.

FIGURE C.5 COST OF HYDROGEN PRODUCED BY PEM ELECTROLYSIS AS A FUNCTION OF ELECTRICITY PRICES IN SOUTH KOREA



SOURCE: ACIL ALLEN ESTIMATES BASED ON THE IEA (2015) AND CSIRO

C.3.3 RoK's vision for a hydrogen economy

In 2008 Kim JW [190] provided a vision for a RoK hydrogen economy out to 2040. Although this vision is 10 years old, it provides some specific targets for hydrogen use, namely that:

- by 2020, hydrogen use will be 2.4 per cent of total energy use, hydrogen fuel cell use for electricity generation will be 3 per cent and use in hydrogen fuel cell vehicles will be 5 per cent.
- by 2030, hydrogen use will be 8 per cent of total energy mix, hydrogen fuel cell use for electricity generation will be 10 per cent, and hydrogen use in fuel cell electric vehicles will be 15 per cent.
- by 2040, hydrogen use will be 15 per cent of total energy mix, hydrogen fuel cell use for electricity generation will be 15 per cent and hydrogen use in fuel cell electric vehicles will be 50 per cent.

C.3.4 Hydrogen technology uptake in RoK

Three hydrogen scenarios (low, medium and high) are assessed for RoK. The modelling implicitly provides the following hydrogen uptake rates to meet various energy and emission ambitions in RoK:

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[190] Jong-Won Kim, Current Status of R&D on Hydrogen Production and Storage in Korea, presentation to the Materials Innovations in an Emerging Hydrogen Economy Conference, February 2008

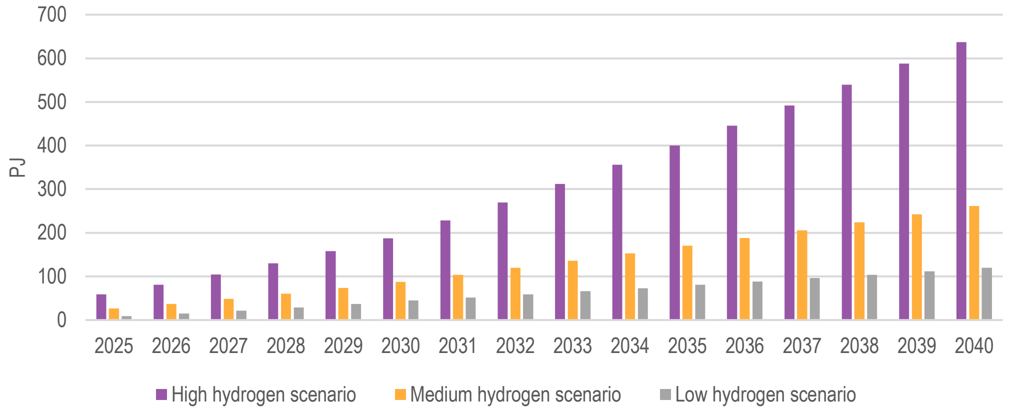
- For the transport sector, the *low H_2 scenario* has an uptake of hydrogen technologies of 0.15 per cent by 2025, 0.45 per cent by 2030 and 2 per cent by 2040. Under the *medium H_2 scenario* there is an uptake of hydrogen technologies of 0.5 per cent by 2025, 0.75 per cent by 2030 and 3 per cent by 2040. The *high H_2 scenario* has an uptake of hydrogen technologies of a 1.2 per cent by 2025, a 1.53 per cent by 2030 and a 11 per cent by 2040.
- For the power sector, the *low H_2 scenario* has an uptake of hydrogen technologies of a 0.01 per cent by 2025, 0.5 per cent by 2030 and 1 per cent by 2040. Under the *medium H_2 scenario* there is an uptake of hydrogen technologies of 0.25 per cent by 2025, 1 per cent by 2030 and 2 per cent by 2040. The *high H_2 scenario* has an uptake of hydrogen technologies of 0.65 per cent by 2025, 2.2 per cent by 2030 and 5 per cent by 2040.

The three hydrogen scenarios are based on the levelised cost of energy sources and a variable uptake of hydrogen in various end use industries driven by measures undertaken by the government to reduce emissions in a manner that is broadly consistent with the Paris Agreement.

C.3.5 Potential hydrogen demand in RoK

It is estimated that the hydrogen demand potential in the *low H_2 scenario* in 2025 is 8.5 PJ increasing to 120 PJ by 2040 (**Figure C.6**). It is estimated that the demand for hydrogen would grow in RoK at annual average growth rate of 19 per cent between 2025 and 2040 from a very low base in the *medium H_2 scenario*. The estimated hydrogen demand potential in the *medium H_2 scenario* in 2025 is 24 PJ increasing to 261 PJ by 2040. It is estimated that the hydrogen demand potential in the *high H_2 scenario* in 2025 is 47 PJ increasing to 618 PJ by 2040.

FIGURE C.6 HYDROGEN DEMAND POTENTIAL IN ROK, 2025–2040



SOURCE: ACIL ALLEN ESTIMATES

C.3.6 Energy import demand

According to the BP Statistical Review of World Energy 2017,[191] South Korea was the world's ninth largest energy consumer in 2016. Due to the lack of natural energy reserves, South Korea is one of the top energy importers in the world. It relies on imports for about 98 per cent of its fossil fuel demand. In 2016, South Korea imported 128 million tons of coal and Australia's share was 40 per cent.

South Korea has a large oil refining sector and it relies almost entirely on crude oil imports to supply its refineries. In 2016, it imported nearly 1.1 billion bbl of crude oil and condensate.[192] It is highly dependent on the Middle East for its oil supply and that region accounted for 86 per cent of Korea's crude oil imports in 2016. Australia's share accounted for just over 1 per cent in 2016.

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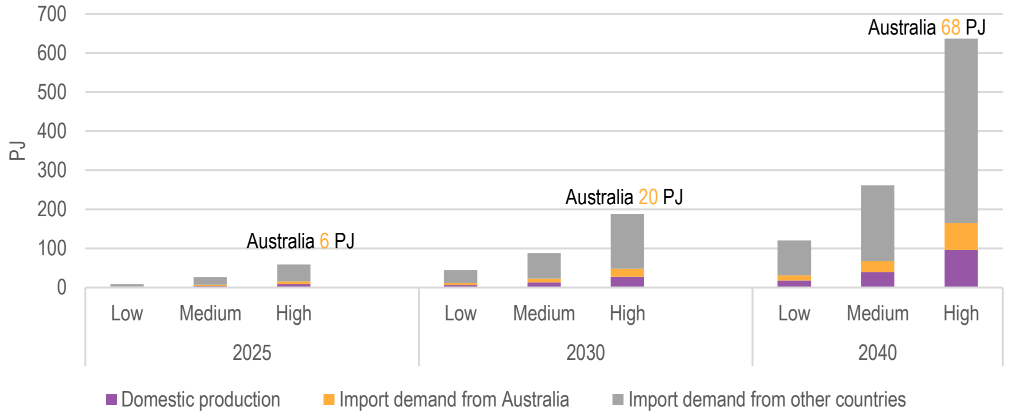
[191] https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html
[192] http://www.kesis.net/

South Korea is the second largest importer of LNG after Japan. It relies on imports to satisfy almost all of its natural gas demand, which has doubled over the past decade. It imports all its gas as LNG. In 2016 Qatar supplied 36 per cent of LNG imports followed by 14 per cent from Australia.

C.3.7 Hydrogen import demand in RoK

Figure C.7 presents the estimated hydrogen supply in RoK in the three hydrogen scenarios. In the *low* H_2 *scenario*, it is estimated that Australia could export just under 1 PJ of hydrogen to RoK in 2025, increasing to 13 PJ by 2040. In the *medium* H_2 *scenario*, it is estimated that Australia could export 2.87 PJ of hydrogen to RoK in 2025, increasing to 28.1 PJ by 2040. In the *high* H_2 *scenario*, it is estimated that Australia could export 6.63 PJ of hydrogen to RoK in 2025, increasing to 68 PJ by 2040.

FIGURE C.7 HYDROGEN SUPPLY IN ROK, 2025, 2030 AND 2040



SOURCE: ACIL ALLEN ESTIMATES

C.4 Singapore hydrogen market opportunities

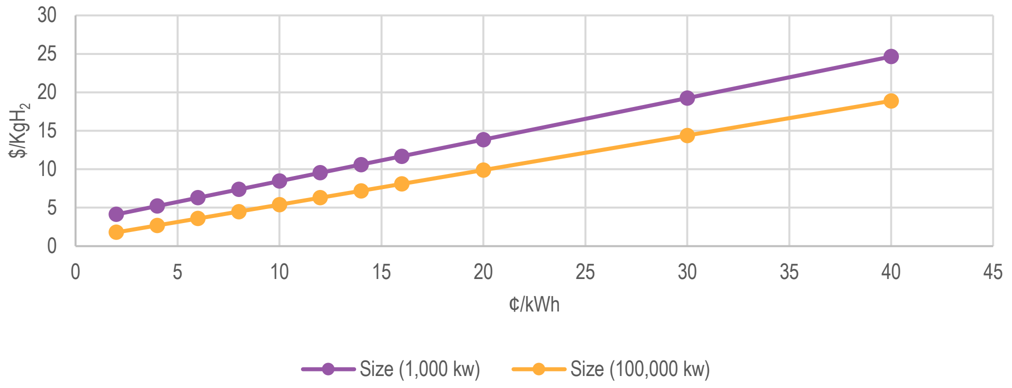
C.4.1 Electricity production costs in Singapore

The IEA does not provide a levelised cost of electricity generation technologies for Singapore. Therefore, for this study, ACIL Allen has relied on estimates provided by the National Solar Repository of Singapore (NSR). Based on the key parameters in the CSIRO model, it is estimated that the levelised cost of electricity production from Solar PV in Singapore is 10.11 Singapore cents/kWh (or 9.9 Australian cents/kWh).

C.4.2 Hydrogen production costs in Singapore

The relationship between the cost of hydrogen production using PEM technology and renewable electricity prices in Singapore (in Australian currency) is shown in **Figure C.8**.

FIGURE C.8 COST OF HYDROGEN PRODUCED BY PEM ELECTROLYSIS AS A FUNCTION OF ELECTRICITY PRICES IN SINGAPORE



SOURCE: ACIL ALLEN ESTIMATES BASED ON CSIRO AND NSR

C.4.3 Singapore’s vision for a hydrogen economy

Electricity from solar PV accounted for less than 1 per cent of the electricity consumed in Singapore in 2016. The low uptake is believed to be primarily due to the high costs and land constraints in installing solar panels. The Singaporean government aims to increase the share to 5 per cent by 2020.

The government’s SolarNova program aims to increase solar demand across government agencies. Under the scheme, the Housing Board has committed to a target of 220MW, by generating power through solar panels at 5,500 blocks. There is limited scope in Singapore to generate electricity from wind with large difficulties of space constraints and low wind speeds. While commercial wind turbines operate at wind speeds of above 4.5m per second, the average wind speed in Singapore is only about 2m per second. Currently, JTC Corp's CleanTech One building is powered by a fuel cell plant. It is estimated that electric motor vehicles could make up as much as 30 per cent to 50 per cent of Singapore's motor vehicles by 2050.[193]

The modelling provides the following hydrogen uptake rates to meet various energy and emission ambitions in Singapore:

- In the transport sector, the *low H_2 scenario* depicts an uptake of hydrogen technologies of 0.175 per cent by 2025, 0.48 per cent by 2030 and 2 per cent by 2040. The *medium H_2 scenario* has an uptake of 0.505 per cent by 2025, 0.758 per cent by 2030 and 3.02 per cent by 2040. Under the *high H_2 scenario* the uptake of hydrogen technologies is 1.05 per cent by 2025, 1.53 per cent by 2030 and 10 per cent by 2040.
- In the power sector, the *low H_2 scenario* has an uptake of hydrogen technologies of 0.12 per cent by 2025, 0.505 per cent by 2030 and 1 per cent by 2040. The *medium H_2 scenario* has an uptake of hydrogen technologies of 0.251 per cent by 2025, 1 per cent by 2030 and 2 per cent by 2040. The *high H_2 scenario* has an uptake of hydrogen technologies of 0.5 per cent by 2025, 2.05 per cent by 2030 and 5 per cent by 2040.

The three hydrogen scenarios are based on the levelised cost of energy sources and a variable uptake of hydrogen in various end use industries driven by measures undertaken by the government to reduce emissions in a manner that is broadly consistent with the announced energy and emission objectives.

C.4.4 Potential hydrogen demand in Singapore

It is estimated that the hydrogen demand potential in the *low H_2 scenario* in 2025 is 0.3 PJ increasing to 11.5 PJ by 2040 (**Figure C.9**). The estimated hydrogen demand potential in the *medium H_2*

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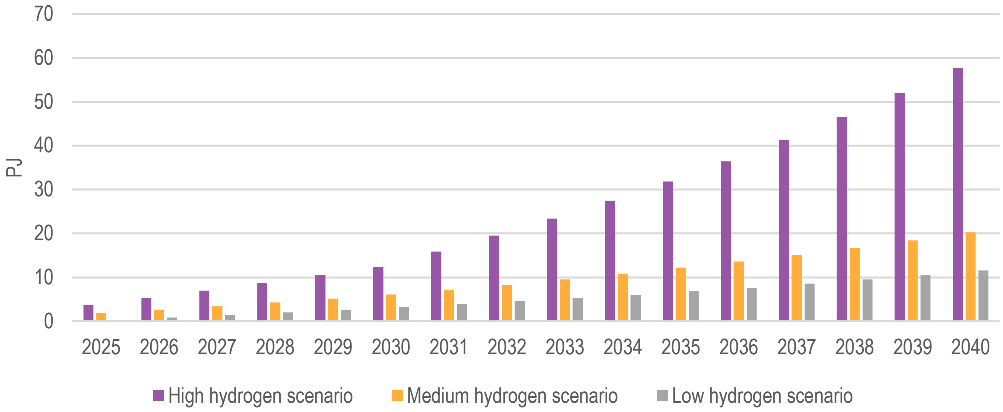
[193] https://www.straitstimes.com/singapore/future-fuel-options

scenario in 2025 is 1.8 PJ increasing to 20.2 PJ by 2040. It is estimated that the hydrogen demand potential in the *high* H_2 *scenario* in 2025 is 3.8 PJ increasing to 57.7 PJ by 2040.

FIGURE C.9 HYDROGEN DEMAND POTENTIAL IN SINGAPORE, 2025–2040



SOURCE: ACIL ALLEN ESTIMATES

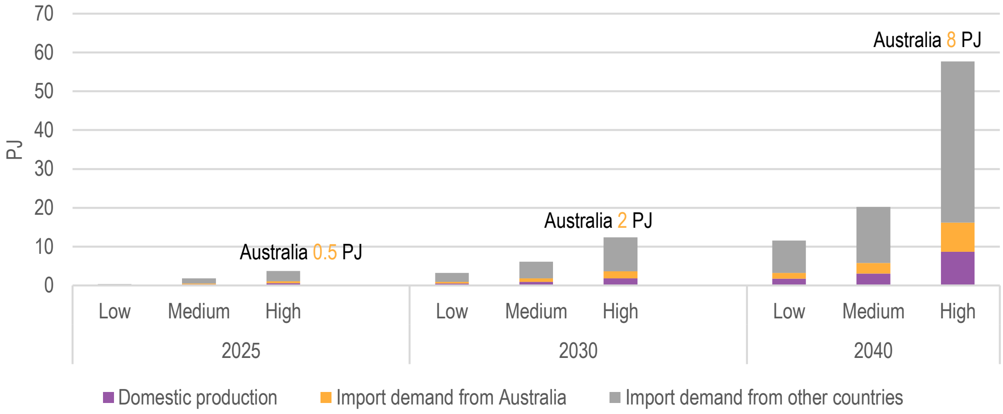
C.4.5 Energy import demand

Australia exported 3.6 million tonnes of LNG to Singapore in 2016-17. Singapore is Australia's fourth largest export market for LNG after Japan, China and RoK. Australia's share of Singapore's LNG imports is over 20 per cent.[194]

C.4.6 Hydrogen import demand in Singapore

Figure C.10 presents the estimated hydrogen supply in Singapore in the three hydrogen demand scenarios. In the *low* H_2 *scenario*, it is estimated that Australia could export just over 0.03 PJ of renewable hydrogen to Singapore in 2025 increasing to 1.5 PJ by 2040. In the *medium* H_2 *scenario*, it is estimated that Australia could export 0.25 PJ of hydrogen to Singapore in 2025 increasing to 2.7 PJ by 2040. In the *high* H_2 *scenario*, it is estimated that Australia could export 0.5 PJ of hydrogen to Singapore in 2025 increasing to 8 PJ by 2040.

FIGURE C.10 HYDROGEN SUPPLY IN SINGAPORE, 2025, 2030 AND 2040



SOURCE: ACIL ALLEN ESTIMATES

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[194] http://www.jtsi.wa.gov.au/about-the-state/close-to-asian-markets/established-regional-trade/singapore

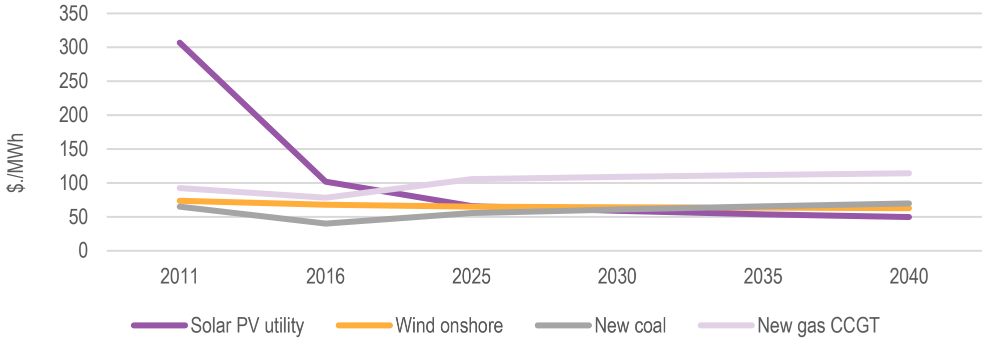
C.5 China hydrogen market opportunities

C.5.1 Electricity production costs in China

In 2017 the IEA's WEO noted that the cost trajectories of different electricity generation technologies are driving the reshaping of electricity supply in China. The costs of new coal- and gas-fired power plants are expected to continue to rise through the period to 2040, due to increasing fuel prices and labour costs. The levelised cost of electricity for new coal-fired power plants is currently about half that of new gas-fired capacity, but the gap is expected to narrow to 40 per cent by 2040 as the CO_2 price increases (see **Figure C.11**).

Renewables are expected to become cheaper as increased deployment pushes down component and installation costs. The average levelised cost of electricity from utility-scale solar PV is currently over $100 per megawatt-hour (MWh) which is not cost-competitive without subsidies. However, falling costs will help the average solar PV project become cheaper than both new and existing gas-fired power plants by around 2020, and cheaper than new coal-fired capacity and onshore wind by 2030. These price points are important for the future competitiveness of hydrogen. By 2040, solar PV costs are also expected to be lower than the operating costs of existing coal-fired power plants, making it the cheapest form of electricity generation in China. Onshore wind is already cost-competitive with gas-fired power plants and the average cost is expected to drop below the cost of new coal-fired power plants by 2035 and approach the operating cost of existing coal by 2040.

FIGURE C.11 LEVELISED COST OF ELECTRICITY BY SELECTED TECHNOLOGY IN CHINA, 2011-2040



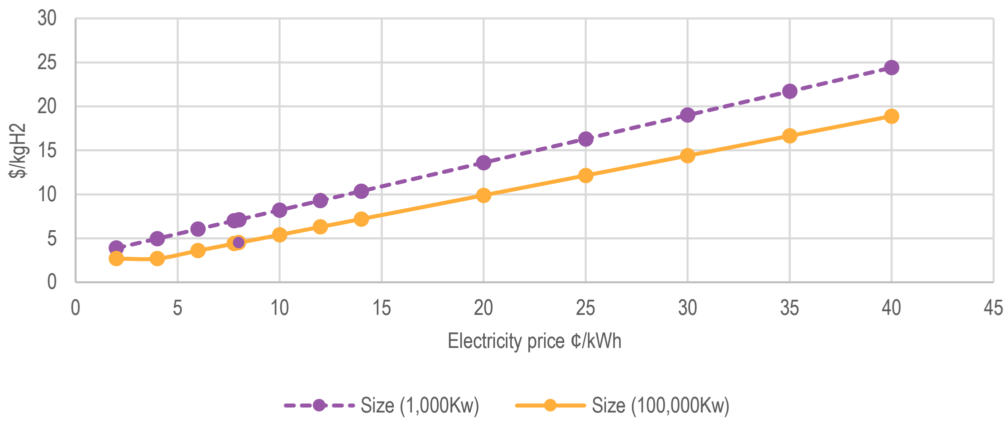
SOURCE: INTERNATIONAL ENERGY AGENCY (2017), WORLD ENERGY OUTLOOK 2017, OECD/IEA, PARIS (FIGURE 13.18, PAGE 543)

The levelised cost of producing electricity from large hydro in China was the cheapest at US¢2.2/kWh or Australian ¢2.8/kWh (with a 7 per cent discount rate). This is likely to be a major source of electricity for producing hydrogen using PEM technology.

C.5.2 Hydrogen production costs in China

The relationship between the cost of hydrogen production and electricity prices in China (in Australian currency) is shown in **Figure C.12**. The cost of production depends on the size of the operation and electricity prices.

FIGURE C.12 COST OF HYDROGEN PRODUCED BY PEM ELECTROLYSIS TECHNOLOGY AS A FUNCTION OF RENEWABLE ELECTRICITY PRICES IN CHINA



SOURCE: ACIL ALLEN ESTIMATES BASED ON THE IEA (2015) AND THE CSIRO NATIONAL HYDROGEN ROADMAP

C.5.3 China's hydrogen economy vision

As reported in the literature review, there are a number of predictions from various organisation on the potential demand for hydrogen as an energy carrier in China. For example, one source suggests that there will be one million FCEVs by 2030[195]. Another says that Wuhan will have the capacity to produce 100,000 hydrogen-fuelled propulsion systems.[196] Also, that Wuhan will construct twenty hydrogen fuelling stations between 2018 and 2020 to support 3,000 hydrogen fuel cell-powered vehicles. Wuhan is scheduled to become a world H_2 city by 2025, with three to five leading H_2 enterprises and between 30 and 100 hydrogen fuelling stations. The annual production value of hydrogen fuel cells is expected to exceed US$15.63 billion.[197]

Shanghai has released its hydrogen development plan, which includes:[198]

- building between 5 and 10 hydrogen refuelling stations and having at least 3,000 fuel cell buses and vehicles by 2020. There are plans to increase the number of hydrogen refuelling stations to 50 in five years, once the target of 20,000 fuel cell cars has been reached
- having 50,000 FCEVs and 300 hydrogen refuelling stations by 2025
- having 1,000,000 FCEVs and 1,000 hydrogen refuelling stations by 2030.

These are small numbers compared to the stock of vehicles on the roads in China. In recent years, China has sought to address the challenge of transforming its domestic energy sector. China's best supplies of renewable energy (especially wind and solar power) are in Western China, while most of China's population and energy demand are concentrated on the Pacific (eastern) seaboard. China has been addressed this problem by building a massive distribution grid based on ultra-high-voltage (UHV) transmission, which minimizes heat loss along the way. Long-distance UHV transmission is efficient and economical, and China has made major strides in developing this technology.[199]

C.5.4 Hydrogen technology uptake in China

The modelling has the following hydrogen uptake rates to meet China's various energy and emission ambitions:

- For the transport sector, the *low H_2 scenario* has an uptake of hydrogen technologies of 0.025 per cent by 2025, 0.5 per cent by 2030 and 2 per cent by 2040. The *medium H_2 scenario* has an uptake of

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[195] https://www.researchandmarkets.com/reports/4394021/hydrogen-fuel-cell-vehicle-market-in-china-2017 (accessed on May 7, 2018)
[196] ttps://www.yicaiglobal.com/news/shenzhen-center-power-tech-plans-spend-usd75415-million-build-hydrogen-cell-industrial-park (accessed on May 7, 2018)
[197] https://www.gasworld.com/central-china-to-gain-hydrogen-city-/2014076.article (accessed on May 7, 2018)
[198] https://fuelcellsworks.com/news/shanghai-releases-its-development-plan-for-fuel-cell-vehicles (accessed 7 May 2018)
[199] Jeffery Sachs (2018), China's bold energy vision, https://www.project-syndicate.org/commentary/china-global-renewable-energy-grid-by-jeffrey-d-sachs-2018-04, (accessed 27 May 2018)

hydrogen technologies of 0.05 per cent by 2025, 0.75 per cent by 2030 and 5 per cent by 2040. Whereas, the *high H_2 scenario* has an uptake of hydrogen technologies of 0.3 per cent by 2025, 1.58 per cent by 2030 and 11 per cent by 2040.

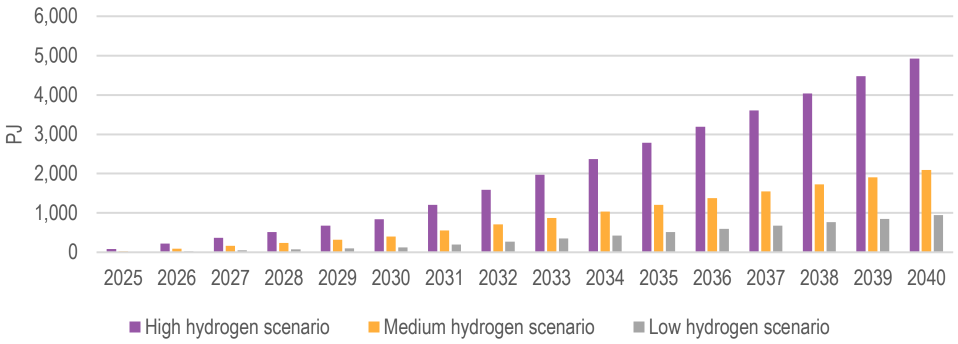
— In the power sector, the *low H_2 scenario* has an uptake of hydrogen technologies of 0.001 per cent by 2025, 0.05 per cent by 2030 and 1 per cent by 2040. The *medium H_2 scenario* has an uptake of hydrogen technologies of 0.025 per cent by 2025, 0.5 per cent by 2030 and 2 per cent by 2040. The *high H_2 scenario* has an uptake of hydrogen technologies of 0.08 per cent by 2025, 1.2 per cent by 2030 and 5 per cent by 2040.

The three hydrogen scenarios are based on the levelised cost of energy sources and a variable uptake of hydrogen by various end use industries due to the measures undertaken by the government to reduce emissions which are broadly consistent with the energy and emission objectives of the government.

C.5.5 Potential hydrogen demand in China

The estimated potential demand for hydrogen in the *low H_2 scenario* in 2025 is 5.8 PJ increasing to 943 PJ by 2040 (**Figure C.13**). The estimated potential demand for hydrogen in the *medium H_2 scenario* in 2025 is 27.1 PJ increasing to nearly 2,100 PJ by 2040. The estimated potential hydrogen demand in the *medium H_2 scenario* is 83.8 PJ in 2025, increasing to just over 4,900 PJ by 2040.

FIGURE C.13 HYDROGEN DEMAND POTENTIAL IN CHINA, 2025–2040

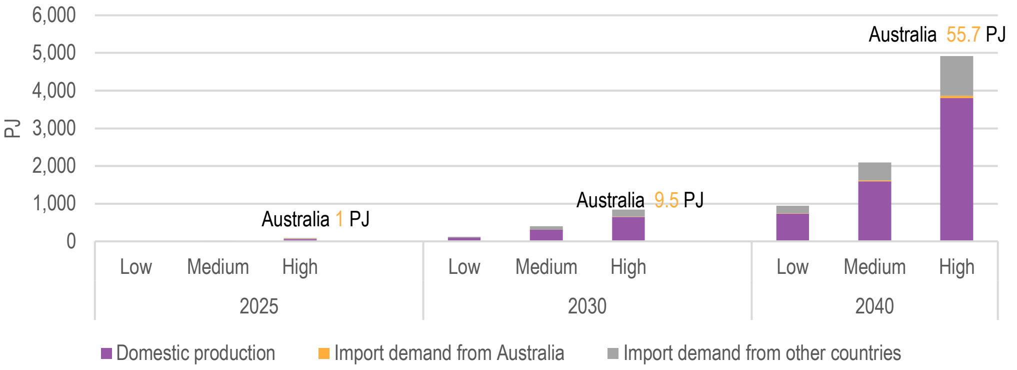


SOURCE: ACIL ALLEN ESTIMATES

C.5.6 Hydrogen import demand in China

The estimated hydrogen import demand in China in the three hydrogen scenarios is shown in **Figure C.14**.

FIGURE C.14 HYDROGEN IMPORT DEMAND POTENTIAL IN CHINA, 2025, 2030 AND 2040



SOURCE: ACIL ALLEN ESTIMATES

C.6 Hydrogen market opportunities in the rest of the world

The hydrogen outlook for the rest of the world (i.e. apart from Japan, RoK, Singapore and China) depends on the outcome of several transitions of transport and energy sectors currently underway in North America, Europe and other countries. These transitions are supported by policies aimed at securing a more sustainable model for economic growth. The rest of the world's demand for hydrogen is not explicitly modelled in this study and is instead estimated as a residual in this report.

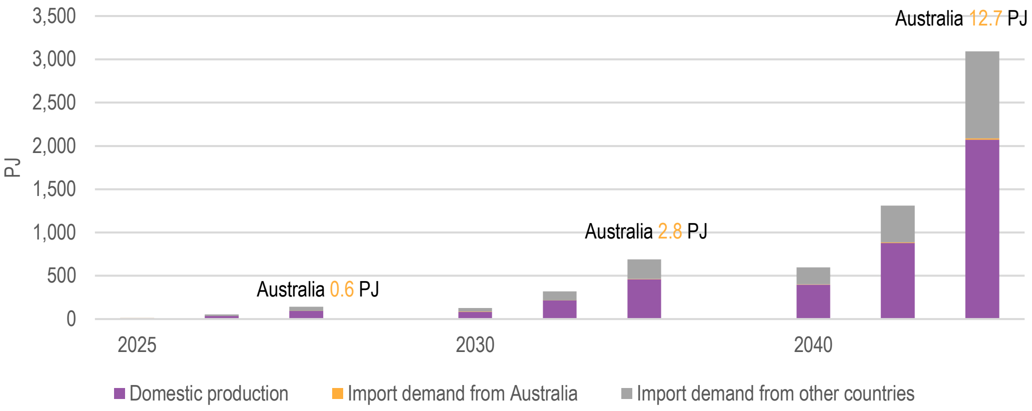
Key steps and assumptions employed to estimate the hydrogen demand in the rest of the world are:

— Total primary energy demand for the world was based on the IEA's 2017 World Energy Outlook's SDS scenario. The selected four countries' energy demand was subtracted from the world primary energy demand to obtain the rest of the world primary energy demand. It is estimated that more than 30 per cent of world primary energy demand is from the four countries selected for this study.

— It is assumed that over 30 per cent of the demand for hydrogen will come from the rest of the world and the remaining demand will be from the four selected countries as the latter already have established strategies and frameworks to include hydrogen in their energy mix.

The estimated hydrogen demand in the rest of the world is shown in **Figure C.15**.

FIGURE C.15 REST OF THE WORLD HYDROGEN DEMAND



SOURCE: ACIL ALLEN ESTIMATES

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