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Australian and Global Hydrogen Demand Growth Scenario Analysis

COAG Energy Council – National Hydrogen Strategy Taskforce

November 2019

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Deloitte Touche Tohmatsu (Deloitte) is pleased to provide the enclosed report detailing our analysis of hydrogen demand in Australia and globally.

The Council of Australian Governments (COAG) Energy Council and the Department of Industry through the National Hydrogen Strategy Taskforce is developing a National Hydrogen Strategy. The COAG Energy Council has committed to a vision of making Australia a major player in the global hydrogen industry by 2030.

The National Hydrogen Strategy Taskforce engaged Deloitte to undertake this work in May 2019. Under the terms of reference, Deloitte was to:

- review and provide analysis of existing forecasts of international hydrogen industry development, supply cost reductions and expected hydrogen prices to understand expected demand growth globally and the share of this demand that Australia could potentially capture; and,
- undertake scenario modelling to understand potential Australian hydrogen exports and domestic demand growth to 2050 and the scope and distribution of economic and environmental costs and benefits from Australian hydrogen industry development.

The enclosed report provides information on the possible pathways for the development of the hydrogen industry in Australia.

We are grateful to the assistance provided in the preparation of the report from the National Hydrogen Strategy Taskforce members and members of the steering group.

Yours sincerely

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Glossary

Acronym	Full name
ACCU	Australian carbon credit units
AGE	Applied general equilibrium
AGM	Annual general meeting
ARENA	Australian Renewable Energy Agency
AUD	Australian dollar
BEV	Battery electric vehicles
CAGR	Compound annual growth rate
CCS	Carbon capture and storage
CCUS	Carbon capture utilisation and storage
CDE	Constant differences of elasticities
CES	Constant elasticity of substitution
CET	Constant elasticity of transformation
CGE	Computable general equilibrium
CO2	Carbon dioxide
COAG	Council of Australian Governments
CRESH	Constant ratios of elasticities substitution, homothetic
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DAE-RGEM	Deloitte Access Economics regional general equilibrium model
ETC	Etcetera
FCEV	Fuel cell electric vehicle
FTE	Full time equivalent
GDP	Gross domestic product
GJ	Gigajoule

Acronym	Full name
GNI	Gross national income
GTAP	Global trade and analysis project
GW	Gigawatt
GWh	Gigawatt hour
HRS	Hydrogen refuelling station
IAM	Integrated assessment model
IPCC	Intergovernmental panel on climate change
kWh	Kilowatt hour
LNG	Liquefied natural gas
MCA	Multi criteria analysis
MEA	Middle East and Africa
Mt	Million tonnes
MW	Megawatt
MWh	Megawatt hour
NPV	Net present value
OEM	Original equipment manufacturer
PEM	Proton exchange membrane
R&D	Research and development
RET	Renewable energy target
SMR	Steam methane reforming
SSP	Shared socio-economic pathways
tCO2	Tonne of carbon dioxide
UAE	United Arab Emirates
US	United States
USD	United States dollar
Yr	Year

Executive summary

Interest in hydrogen is growing both internationally and domestically, as industry and governments around the world investigate and execute on decarbonisation strategies.

In Australia, State, Territory and Commonwealth governments are agreed significant opportunity exists for Australia to become a major producer of hydrogen for domestic use and for export. To move forward in creating a pathway for Australia to take advantage of this growing hydrogen industry, the Council of Australian Governments (COAG) Energy Council formed the National Hydrogen Strategy Taskforce (the Taskforce) in December 2018.

The aim of the Taskforce is to build "a clean, innovative and competitive hydrogen industry that benefits all Australians and for Australia to be a major global player by 2030."[1] In addition, the COAG Energy Council has agreed to investigate three domestic 'kick start' projects to provide an initial boost to the Australia domestic hydrogen industry. These projects include the use of hydrogen in gas networks, the potential for hydrogen refuelling stations in each state and territory and to undertake co-ordinated international outreach to keep building Australia's profile as a potential supplier to major trading partners.

The opportunity identified by this analysis suggests that, if Australia were to secure the same global market share percentage as Australia has today for Liquefied Natural Gas (LNG), then the hydrogen sector could produce an increase to Australian Gross Domestic Product (GDP) of up to $26 billion on a Net Present Value (NPV) basis and 16,900 jobs by 2050.

Hydrogen as a molecule (H_2) is a colourless, odourless, non-toxic gas. Hydrogen bonds easily with other elements, making it extremely rare in its free form, and requiring transformation to produce hydrogen that is useable for energy storage and transport. Hydrogen is an energy carrier with some of the energy required to produce hydrogen released subsequently at the point of use – usually as heat through combustion or as electricity in a fuel cell.

Hydrogen as a clean energy carrier and feedstock is the subject of growing international interest. This growing interest in the hydrogen sector is underpinned by four long-term trends:

- **Cost of renewables:** the significant decline in the cost of wind and solar photovoltaic (PV) generation in recent years has opened the prospect of large-scale production of 'green' hydrogen. This has prompted serious projects and feasibility studies in countries where wind and solar PV can be produced at very low cost.
- **Industrial decarbonisation:** there is fast-growing acknowledgement that energy systems cannot be decarbonised by greening electrons alone. There is a need for industry, heavy transport and hard to abate sectors to examine and assess decarbonisation strategies. In assessing these strategies, even where electrification gains pace, there are potential benefits to the use of hydrogen.
- **Gas infrastructure decarbonisation:** hydrogen can be transported using existing gas infrastructure with limited adaptation and costs. While there are pipeline integrity issues to consider, hydrogen can be blended into existing gas infrastructure as a transition before potential longer-term conversion to 100% hydrogen. This has the potential to enhance hydrogen utilisation and protect asset valuations.
- **Export opportunity:** there appears to be significant potential relating to the demand of hydrogen as a fuel source by economies such as China, Japan, and South Korea. This government-backed demand growth is driven by decarbonisation policies, energy security and reliability and presents opportunities for the development of major export facilities in Australia. For the purposes of the modelling we have examined potential exports to these three countries. However, it must be recognised that there are other countries that also represent markets which may provide future opportunities for Australian exports. For example, Taiwan is a major importer of energy resources, including as a significant buyer of Australian coal, and could be a potential future off-taker of hydrogen.

Australia has world-class capabilities as an explorer, developer, producer and supplier of energy. Australia can use these attributes to become and remain a dominant player in the emerging hydrogen value chain. However, numerous pathways exist that Australia can take in developing its hydrogen industry. The pathways are not mutually exclusive but rather provide alternatives and turning points as the hydrogen industry develops towards maturity.

Australia is not alone in examining the role of hydrogen going forward, with several other countries exploring hydrogen strategies. Depending on the country, these strategies may focus on implementing policies and reducing barriers to the import of hydrogen, the export of hydrogen, domestic use or a combination.

In developing the National Hydrogen Strategy, it is important to assess the strengths of Australia and to compare these against potential competitors in the export market. Deloitte has used a multi-criteria assessment to understand Australia's relative competitive position.

The criteria assessed include:

Table 1.1. Multi-criteria assessment for Australia's relative competitive position

Element	Criteria	Description
Economic	**Trade Relations**	Any potential hydrogen exporter will need trade relationships with potential importers. These relationships may be developed over time, but existing trade relationships will smooth the path for hydrogen exports.
	Access to finance	Companies seeking to participate in the hydrogen value chain in their respective countries will need a source of finance or funding.
	Ease of doing business	This relates to the ability of a local firm to start and operate within the broad regulatory, political and economic conditions present in the country.
Environmental	**Extent of existing hydrogen applications in-country**	Hydrogen exports to some degree will be tied to a country having some domestic hydrogen applications in use.
	Ports and other infrastructure	Maritime infrastructure is likely to be necessary for countries to export and import large volumes of hydrogen.
	Feedstock for generation	Countries generating hydrogen will need an input energy source to do so.
	Delivery times and distances	Distance from trade partners can have an effect where hydrogen delivery is time-dependent. Further, significant distance can increase shipping costs and cost-competitiveness.
	Availability of electricity for hydrogen production	The consistent supply of electricity and/or gas is necessary for hydrogen supply chain to function successfully.
Political	**Government stability and support**	Given the multiple components of a hydrogen supply chain, it is unlikely that one can come to fruition without a relatively stable government.
	Regulatory settings	Government may seek to actively encourage a hydrogen industry through regulatory settings, including incentives for third parties to invest in hydrogen.
	Government transparency	The ability to understand the process followed by or adopted by a government may allow proponents of new technology or projects to understand what is necessary for development or deployment within the governmental programs or policies.
Technical	**Experience in delivering similar technologies or resources/parallel industries**	A country with an existing supply chain and/or experience in delivering similar products to hydrogen is likely to have a competitive advantage in delivering hydrogen.
	Availability of human and technological resources	The ability to staff the entire value chain of the hydrogen process will be vital for effective competition in the global market.
	Adaptability in a changing environment	Hydrogen processes and value chains are unlikely to remain static in the coming 30 years. The ability to respond to such changes is vital.

Based on the assessment, Australia, relative to the countries examined is a strong competitor. In terms of economic factors:

- Australia has strong existing trade relationships with the growing Asian markets including both Japan and South Korea who have made hydrogen commitments.
- The Australian government has an agenda that aligns with the pursuit of hydrogen, with almost all states and territories as well as the Commonwealth establishing hydrogen roadmaps or focus groups to drive forward hydrogen opportunities.
- Australia rates highly in terms of ease of doing business.

The environmental factors indicate that Australia is strong in some areas and there is room for improvement in relation to some others:

- Australia currently has some in-country hydrogen applications related mostly to industrial feedstock. Australia does produce over 2 Mtpa of ammonia annually that has the potential to require over 350 ktpa of hydrogen as a feedstock. A number of other pilot and demonstration projects are also being developed across the country for other use cases.
- Australia has experience developing the necessary infrastructure, which can be leveraged to develop hydrogen processes and export infrastructure.
- Australia has tremendous land area, renewable energy resources, natural gas and water to support the proposed new hydrogen developments.

Similarly, to environmental criteria, Australia has some strengths and areas for improvements in relation to political factors:

- Australia faces competition from some countries that have higher global political stability index ratings.
- There has been some funding provided for the development of hydrogen however, the domestic hydrogen market has yet to be overly developed and there are opportunities for increasing incentives and funding of hydrogen.
- State, territory and the Commonwealth governments are supporting hydrogen deployment through the development of hydrogen roadmaps and the National Hydrogen Strategy; however due to the structure and rigour of decision making in Australia there can be delays in decisions being made and implemented.

Technically, Australia is in a strong position:

- As a leading producer of natural gas, the country has technical know-how which can be leveraged to deliver hydrogen.
- Australia has high quality of living and high-ranking higher education institutions, resulting in the ability to attract human and technological resources to support the building and deployment of hydrogen.

Other countries examined that are rated as strong competitors against this assessment criteria are the United States, Germany, Norway and Singapore. Similar to Australia however, each faces some challenges in developing a thriving export market. Singapore for example, will need to overcome challenges related to feedstock availability, which may include potential carbon and capture storage (CCS) sites. In addition, there are other countries such as Russia, New Zealand or Chile which have not been examined, yet could become major players in the export market given their current role in the energy or natural resource export markets or ambitions related to hydrogen industry development. New Zealand, for example, recently published a green paper on a vision for hydrogen in New Zealand.

The path to hydrogen deployment, both domestically and internationally, is not certain and could unfold in numerous ways. Therefore, to provide some indication of hydrogen demand and the potential Australian export market, scenario analysis provides some range of possible futures and some signals and signposts of the pathway that is eventuating as we move forward.

Scenarios can signpost key indicators that may alert the economy to a potential opportunity or risk in the future. The signposts discussed can help to indicate which of the pathways is being followed at any one time and can assist in providing decision support as events unfold.

In overview terms, the signpost provides guidance on a factor that may be influential in determining the future pathway and the signal provides the specific trigger point where a direction can be inferred or an action might need to be taken. There is not necessarily a one-to-one relationship between signposts and signals but rather there can be groups of indicators that together provide guidance on a particular element of an industry's development. Further information on the specific signals and signposts used can be in found in Appendix D.

Scenarios were developed to provide information about possible demand outlooks. Scenarios are rich, data-driven stories about tomorrow that can help organisations make better decisions today. They provide a structured way of thinking through and making strategic decisions, can help signpost key indicators and are plausible, distinctly different and internally consistent. However, scenarios are not forecasts or predictions about the future.

Four distinct scenarios have been examined:

1 Scenario 1: *Hydrogen: Energy of the future.* This scenario provides information on the impact that hydrogen demand can have for Australia where all aspects of industry development are favourable for hydrogen.

2 Scenario 2: *Hydrogen: Targeted deployment.* Under this scenario, countries adopt a targeted approach which aims to maximise economic value and benefits for effort in the deployment of hydrogen.

3 Scenario 3: *Business as usual.* Under this scenario, Australia follows a path in which social, economic and technological trends do not shift markedly from historical patterns. However, there are shifts in global markets removing some barriers for hydrogen deployment.

4 Scenario 4: *Electric breakthrough.* Under this scenario, there is rapid technological development in electrification.

One of the factors that impacts possible demand outlooks the most across all of these scenarios is the proportion of end-use applications that are captured by hydrogen, such as pipeline gas, steelmaking and transport fuels. Another key factor that impacts the demand a is the export market share of hydrogen that Australia is able to capture.

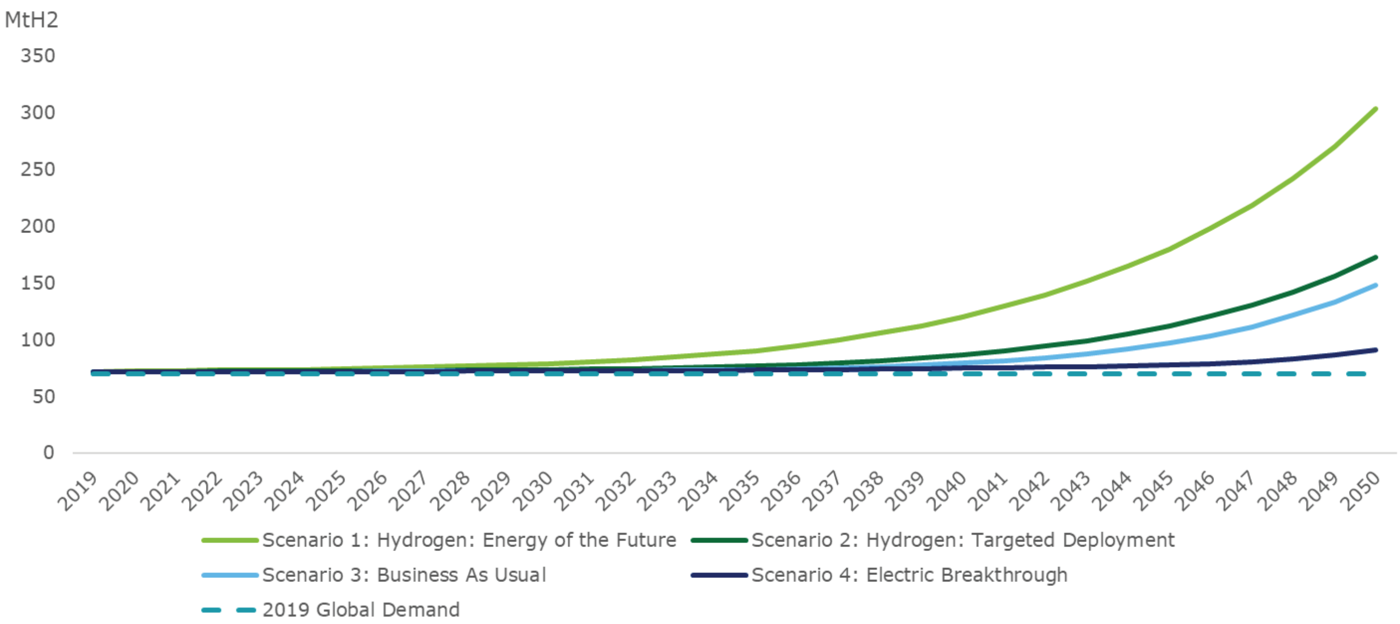
The outcomes of the modelling provide insight into how global demand for hydrogen may change under the various scenarios for the various use cases and how much of that demand Australia may be able to capture.

The below figure shows the range of global forecasted hydrogen demand amongst the four scenarios. The 2019 global demand figure relates to demand for all use-cases. Global hydrogen demand is highest in the *Hydrogen of the future* and *Targeted deployment* scenarios, aided by aggressive reductions in hydrogen technology learning costs and significant proportions of end-use applications captured by hydrogen on a global scale.

The range of demand between the four scenarios by 2050 are significant, with over 304 Mtpa of hydrogen demand globally in 2050 under the *Energy of the future* scenario to just over 90 Mtpa in the *Electric breakthrough* scenario. Demand in *Energy of the future* and *Targeted deployment* are driven heavily by global policies and rapid technological improvements.

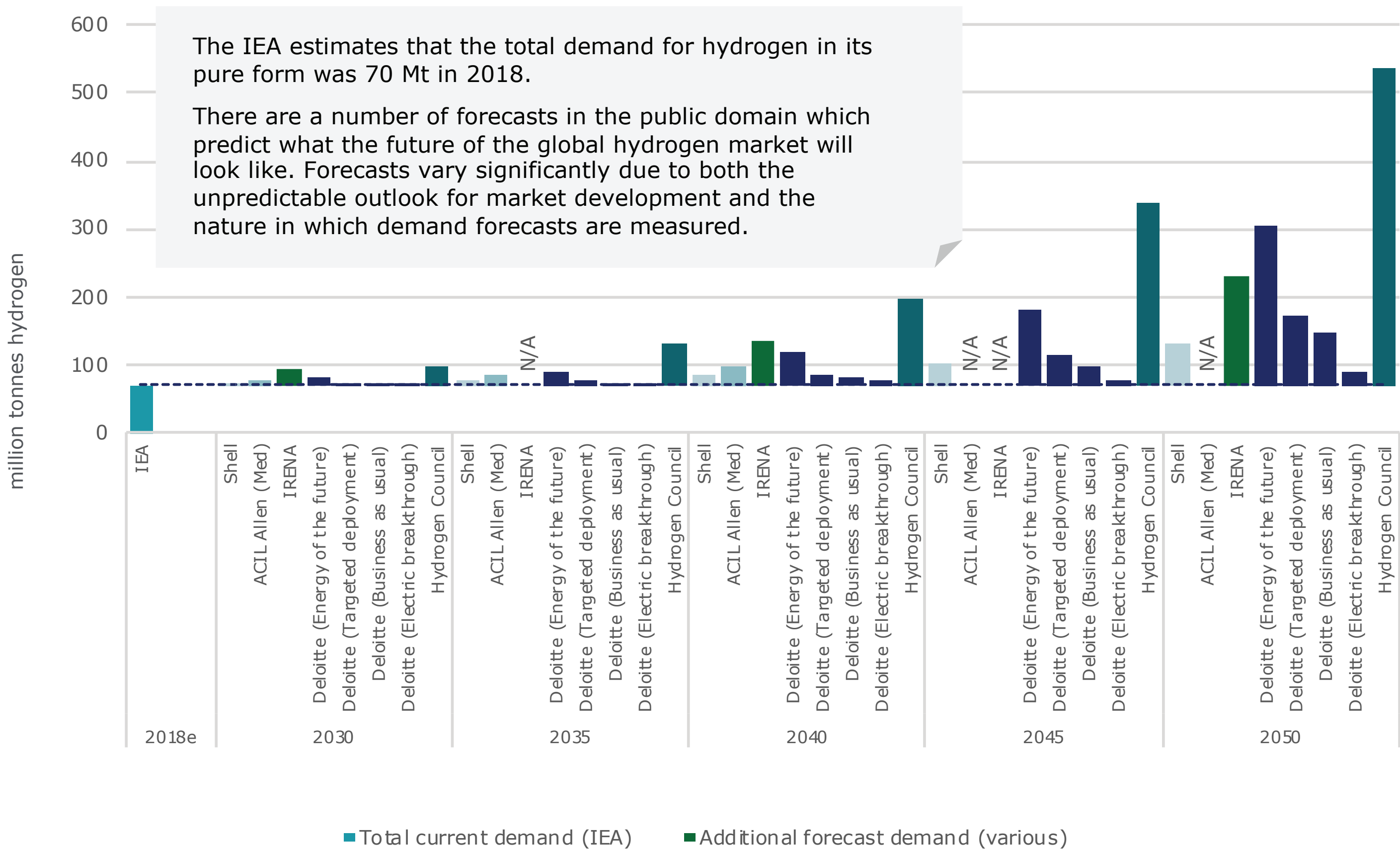
In contrast, demand is comparatively weak in the *Electric breakthrough* scenario, where technological improvements in hydrogen production are slower and hydrogen captures limited proportions of end-use applications. Breakthroughs in electrification technologies in this scenario ensure that electrified technologies generally outcompete hydrogen technologies. In this scenario, even with countries taking decarbonisation action at a national and international level, hydrogen only has relatively minor technological improvements, due to more rapid progression in electrification technology.

Figure 1.1 Global forecasted hydrogen demand (million tonnes hydrogen)



Source: Deloitte Analysis

Figure 1.2 Forecasted global hydrogen demand (million tonnes hydrogen)



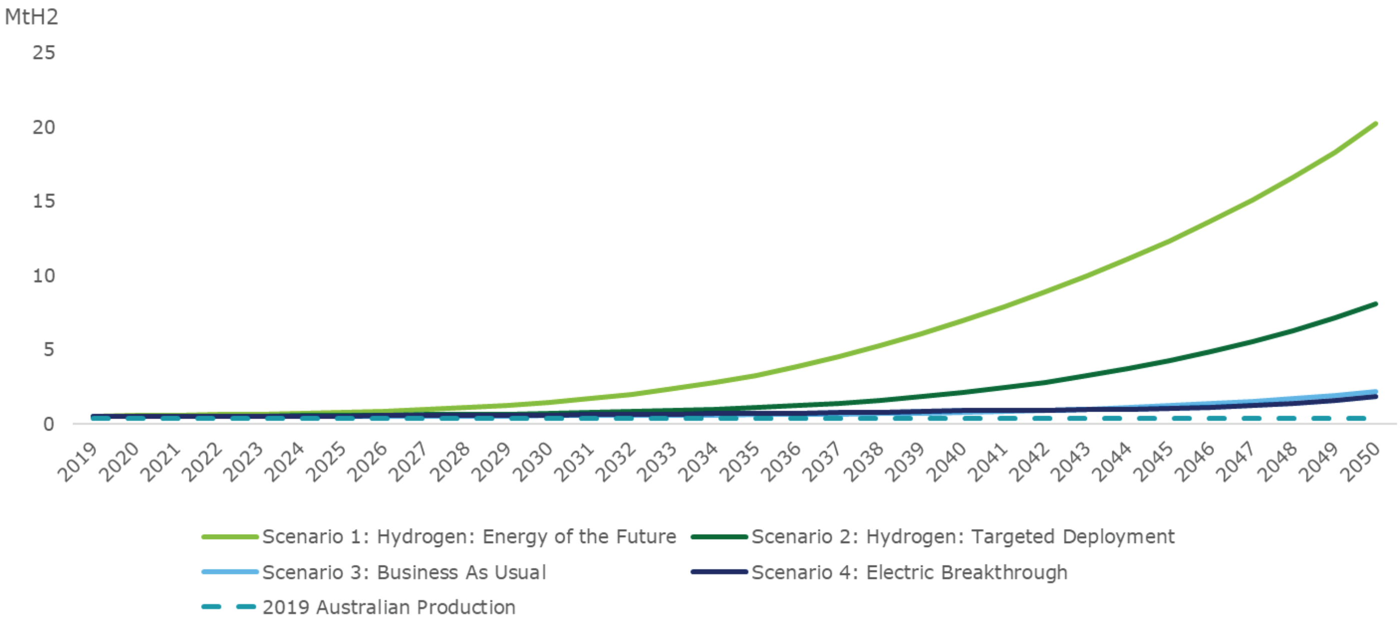
Source: IEA, ACIL Allen, IRENA, Hydrogen Council, Deloitte Analysis

Note:
a) IEA current demand is treated as a universal baseline for all additional demand
b) Where possible, raw inputs have been converted from J to Mt using an assumed energy density of 120 MJ/kg
c) N/A indicates that the data was not available for the given year. ACIL Allen only provided a forecast until 2040
d) The Shell demand forecasts relate only to additional demand for energy use and does not include any additional demand for feedstock.

This figure shows the total demand for hydrogen in 2018 in its pure form is estimated to be around 70 million tonnes of hydrogen per year (MtH2/year), which is predominantly used for refining and ammonia production. This hydrogen is almost entirely supplied from fossil fuels.

Between 2025 and 2050, there are vast differences in projections, with the Hydrogen Council forecasts being significantly higher than any other projections. Deloitte's most optimistic view on hydrogen demand in 2050 is slightly more than half of the Hydrogen Council's forecast – which present an ambitious vision for hydrogen deployment, including a strong push for scaling new technologies throughout the value chain and cross sectors internationally. Shell and IRENA's forecasts for 2050 hydrogen demand are lower than Deloitte's *Energy of the future* scenario. Deloitte's *Targeted deployment* and *Business as usual* scenarios have relatively closer hydrogen forecasts in 2050, with *Electric breakthrough* having the smallest hydrogen demand forecast. More information on these scenarios can be found in Chapter 6.

Figure 1.3 Forecasted hydrogen production from Australia



Source: Deloitte Analysis

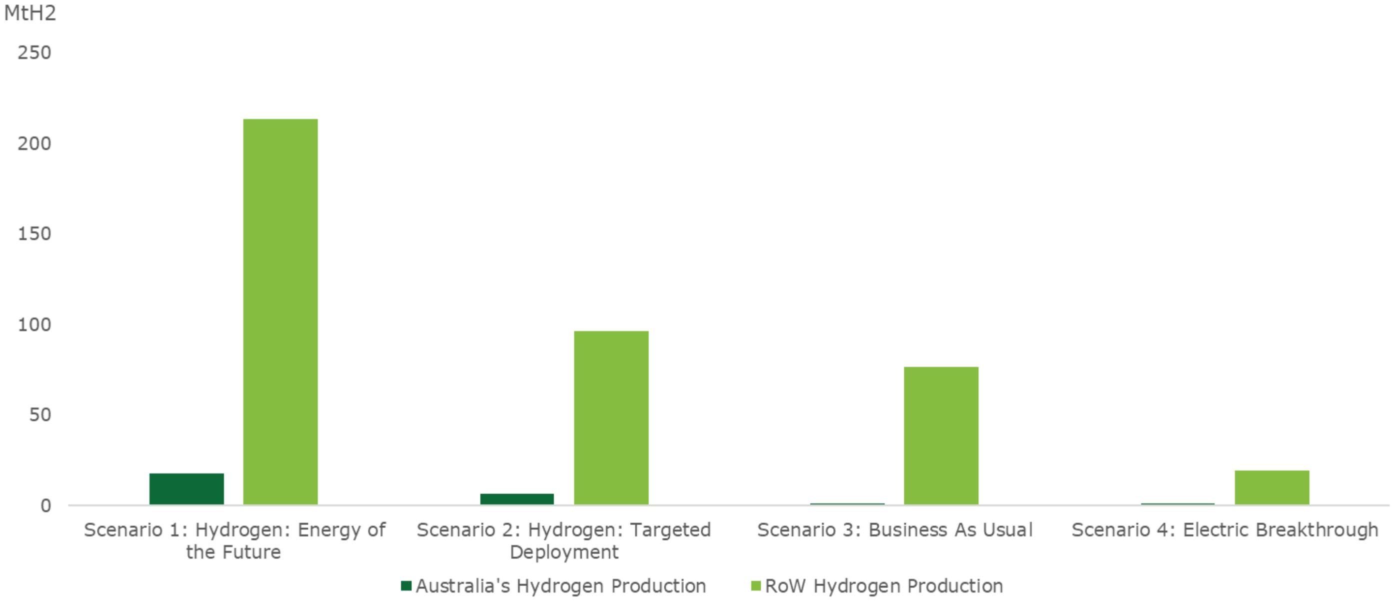
The figure above shows the range of hydrogen production (on top of what is already produced – namely 350 ktpa) by Australia for domestic and international consumption amongst the four scenarios. Like the global hydrogen demand figure, Australia hydrogen production is highest in the *Energy of the future* and *Targeted deployment* scenarios. Drivers behind Australian production mirror those of global demand – where steep reductions in technology costs and large proportions of end-use market share captured by hydrogen encourage a rapid expansion in Australian hydrogen production. In the *Targeted deployment* scenario, large proportions of end-use market share are only captured by hydrogen in certain application, whereas the *Energy of the future* scenario sees large proportions of end-use market share in most applications.

In contrast, the *Business as usual* and *Electric breakthrough* scenarios see subdued demand for Australian produced hydrogen.

In the *Business as usual* scenario, there is growing hydrogen demand internationally; however, Australia is unable to capture a significant share of the export market due to technological development of all aspects of the hydrogen value chain following historical patterns resulting in minimal reductions in technology costs.

In the *Electric breakthrough* scenario, hydrogen technological learning rates keep hydrogen costs relatively expensive compared to its alternatives. At the same time, given countries decarbonisation policies, there is a proliferation of electrification through renewable generation diminishing the demand for hydrogen both domestically and internationally.

Figure 1.4 Australia's hydrogen production relative to the rest of the world (2050)



Source: Deloitte Analysis

Table 1.2 Australia's hydrogen production across scenarios in selected years

Australian Production (Mt)	Scenario 1	Scenario 2	Scenario 3	Scenario 4
2030	1	<1	<1	<1
2040	7	2	<1	<1
2050	20	8	2	1

Source: Deloitte Analysis

Table 1.3 Rest of the world's hydrogen production across scenarios in selected years

RoW Production (Mt)	Scenario 1	Scenario 2	Scenario 3	Scenario 4
2030	9	4	2	2
2040	50	16	9	5
2050	234	103	78	21

Source: Deloitte Analysis

The above figure shows how the additional Australian production compares to the rest of the world under the various scenarios. The important thing to note is how, under the *Business as usual* scenario, the rest of the world's production of hydrogen is larger than under the *Electric breakthrough* scenario but Australia's production is fairly similar.

The economic impacts of a rapidly expanding hydrogen sector were also assessed by modelling the *Energy of the future* and *Targeted deployment* scenarios against *Business as usual*. Under both policy scenarios the hydrogen sector boosts Australia's Gross Domestic Product (GDP) and employment. These impacts are largest under the *Energy of the future* scenario — reflecting the scale of the hydrogen sector — with GDP $26 billion higher than the *Business as usual* scenario in 2050, and employment 16,900 Full Time Equivalents (FTE) higher.

The *Targeted deployment* scenario is estimated to result in GDP being around $11 billion higher than the Business as Usual scenario by 2050, with an additional 7,600 FTEs generated. This result mainly reflects the more targeted growth of the hydrogen sector than in Energy of the Future, with the transitional path of the economy virtually identical in both scenarios.

While the introduction of the hydrogen sector drives a large dollar increase in Australia's GDP, in a relative sense, the economic impacts from a rapid expansion in Australian hydrogen production are muted. Compared to *Business as usual*, GDP in the *Energy of the future* scenario is projected to be 0.8% higher and 0.34% higher under the *Targeted deployment scenario*. This reflects the effects hydrogen has on other industries and the relative size of the industry compared to Australia's established resource sectors.

Hydrogen has varying effects across Australia's different sectors. As would happen with the rapid growth of any new sector, existing industries tend to grow more slowly. In the case of hydrogen, the agriculture, mining and manufacturing sectors compete with hydrogen production for inputs such as capital and labour, and are affected by an appreciation in Australia's real exchange rate – which makes exports more expensive. Industries that benefit from the introduction of hydrogen production are mainly found in the services sector. Here, demand for services is driven by higher real incomes, as well as a redistribution of labour that allows for the provision of greater services.

The effects to employment are muted, similar to that of GDP. By 2050 Australian employment is expected to be 0.09% *(Energy of the future)* and 0.04% *(Targeted deployment)* higher. Much of the growth in employment is in the services sector. Employment figures reflect, in part, the hydrogen sector's intensive use of inputs other than labour.

Employment figures in the *Energy of the future* and *Targeted deployment* scenarios are also a result of modelling assumptions, particularly availability of labour and the 'stickiness' with which it can moves across the economy. 'Stickiness' within the labour market refers to the relative inflexibility of labour to rapidly move to where jobs are. This inflexibility can stem from factors such as spatial or geographical mobility (difficulty in moving between geographical locations), as well as occupational mobility (difficulty in changing skills). Stickiness in the labour market acts as a potential barrier to potential employment growth from a new industry.

In assessing how a hydrogen industry may develop in Australia, it is also helpful to examine how hydrogen may be produced under the various scenarios, as well as the impact on carbon emissions, water and land requirements.

Hydrogen can be produced in a number of different ways, with hydrogen currently largely being produced using fossil-fuel based technologies. However, the type of technology used to produce hydrogen – depending on the scenario – is expected to change into the future. The scenario parameters, such as the decarbonisation policies assumed to be in place, as well as the assumed technology learning rates drive the outcomes for the types and quantity of technology type deployed.

Under all scenarios, there is brown hydrogen in the earlier years with a move towards blue and green hydrogen. (See section 1.1.1 for the description of brown, blue and green hydrogen) The move to blue and green hydrogen occurs at different rates in the various scenarios reflecting the underlying assumptions related to the speed of decarbonisation both domestically and internationally. This reflects that international markets are likely to have increasingly stringent requirements for hydrogen to be clean over time. In addition, these assumptions, relative to the speed of decarbonisation, also impact on the speed of decarbonisation of the electricity grid nationally which is a major element in the quantum of emissions produced from hydrogen production.

In undertaking the modelling, it has been assumed that under the *Energy of the future* scenario, starting in 2020, offsets of 10 per cent are used when hydrogen is produced using either coal gasification (CG) or steam methane reformation (SMR). This then increases to 100 per cent offset for these two technologies by 2030. Under the *Targeted deployment* and *Electric breakthrough* scenarios, starting in 2020, a 5 per cent offset is applied to CG and SMR which increases to 100 per cent by 2035. In the *Business as usual* scenario, we assume that CG and SMR emissions are offset by 5 per cent with a trajectory to get to 100 per cent by 2070. For the purposes of determining the emissions generated by Australian production of hydrogen, the use of offsets would wholly offset emissions while CCS would significantly, but not wholly offset emissions.

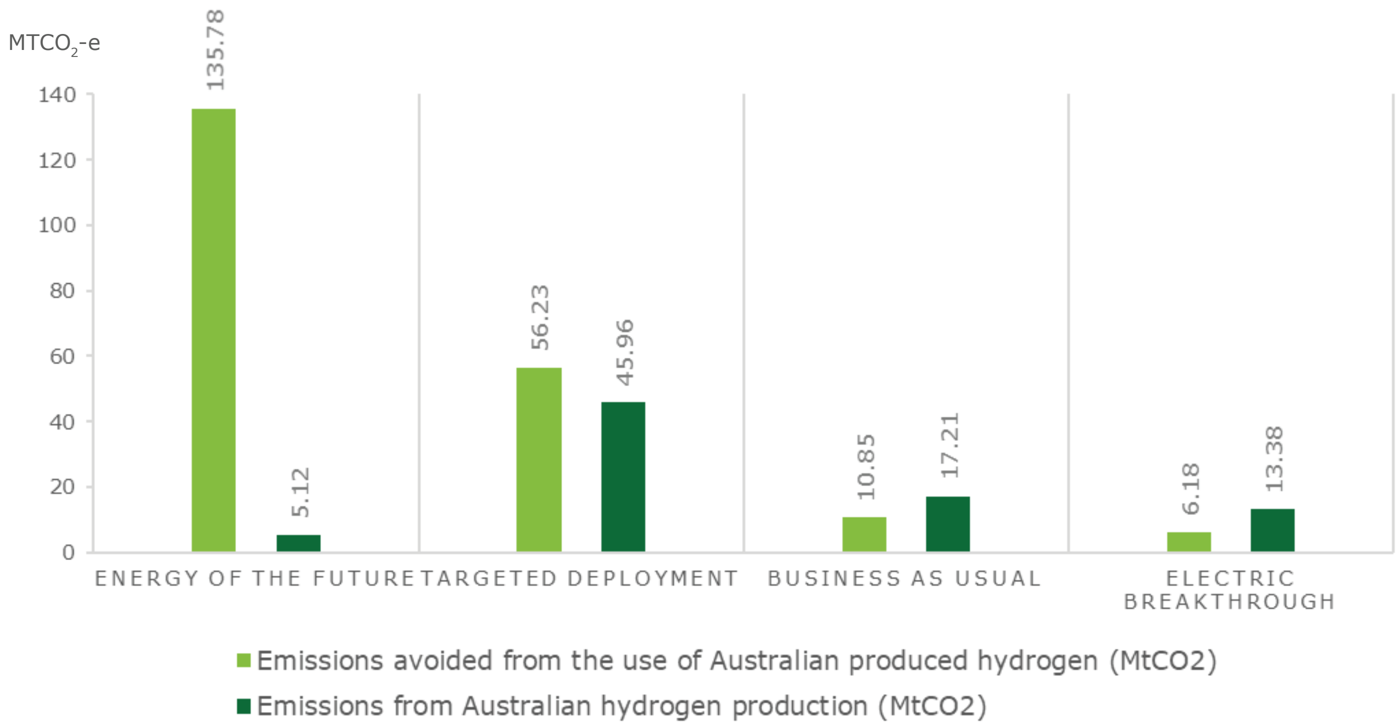
In the *Energy of the future*, green hydrogen becomes the predominant hydrogen production method. Under *Targeted deployment* and *Electric breakthrough* we see increased blue hydrogen. It is assumed that offsets would be used to produce blue hydrogen until it is cheaper to do this using CCS. Under the *Energy of the future* scenario, CCS becomes price competitive with offsets in 2039. In *Targeted deployment* and *Electric breakthrough*, CCS becomes price competitive with offsets in 2041. In the *Business as usual* scenario, hydrogen producers do not use either offsets or CCS technology.

In examining the impact on emissions we have examined:

- The quantum of emissions from Australian Hydrogen Production, which is based on the carbon intensity of the electricity grid broken down by technology type and includes emissions offset conversions for CG and SMR;
- The quantum of emissions avoided from the use of Australian produced hydrogen, which considers the total demand by use case for pipeline gas, industrial heat, steelmaking, transport and feedstock and the carbon intensity of the alternative fuel or feedstock.

The charts depicting emissions produced in Australian hydrogen production show overall emissions after offsets or CCS technology has been applied.

Figure 1.5 2050 impacts on emissions from Australian hydrogen production



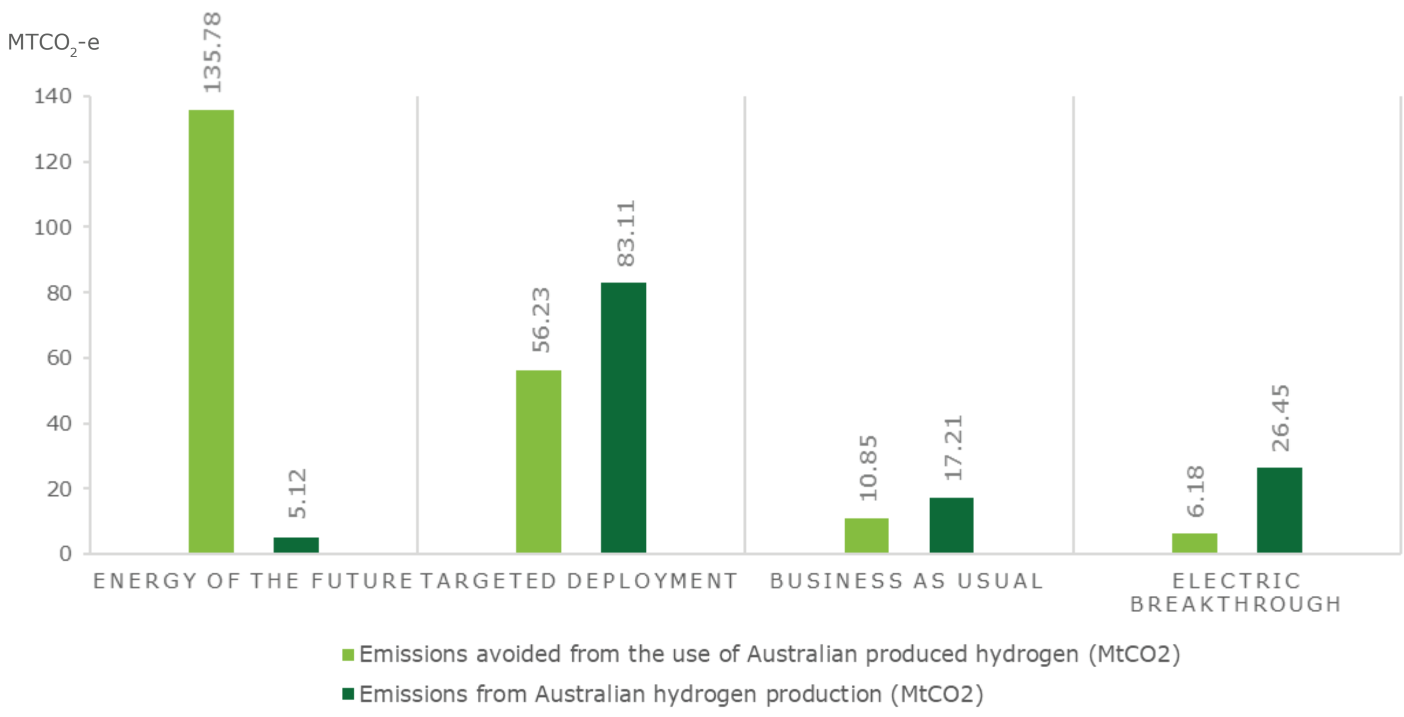
Source: Deloitte Analysis

Not surprisingly, the highest levels of global emissions avoided from using Australian produced hydrogen occurs under the *Energy of the future* scenario. In this scenario, hydrogen is produced through 'green' methods and hydrogen use in other end-uses such as steelmaking, heat and transport, replace fossil-fuel sources. This aligns with early and deep decarbonisation policies that most countries adopt under this scenario both in terms of hydrogen production methods but also decarbonisation of the electricity grid.

The global emissions avoided from Australian produced hydrogen in *Targeted deployment* exceeds emissions from producing hydrogen, although not as much as under *Energy of the future*. This is due, in part, to the greater use of brown hydrogen and blue hydrogen. *Electric breakthrough* and *Business as usual* scenarios are similar even though they have different decarbonisation policies within these two scenarios.

This is due, in part, to the combination of demand under the various scenarios and the rate at which blue hydrogen is deployed. The *Business as usual* and *Electric breakthrough* scenarios have the lowest levels of global emissions avoided from Australian produced hydrogen. This stems from a combination of emission policies, production methods and the lack of hydrogen replacing fossil fuels in various end-uses.

Figure 1.6 2050 impacts on emissions from Australian hydrogen production (if grid decarbonisation for scenarios 2,4 were the same as 3)

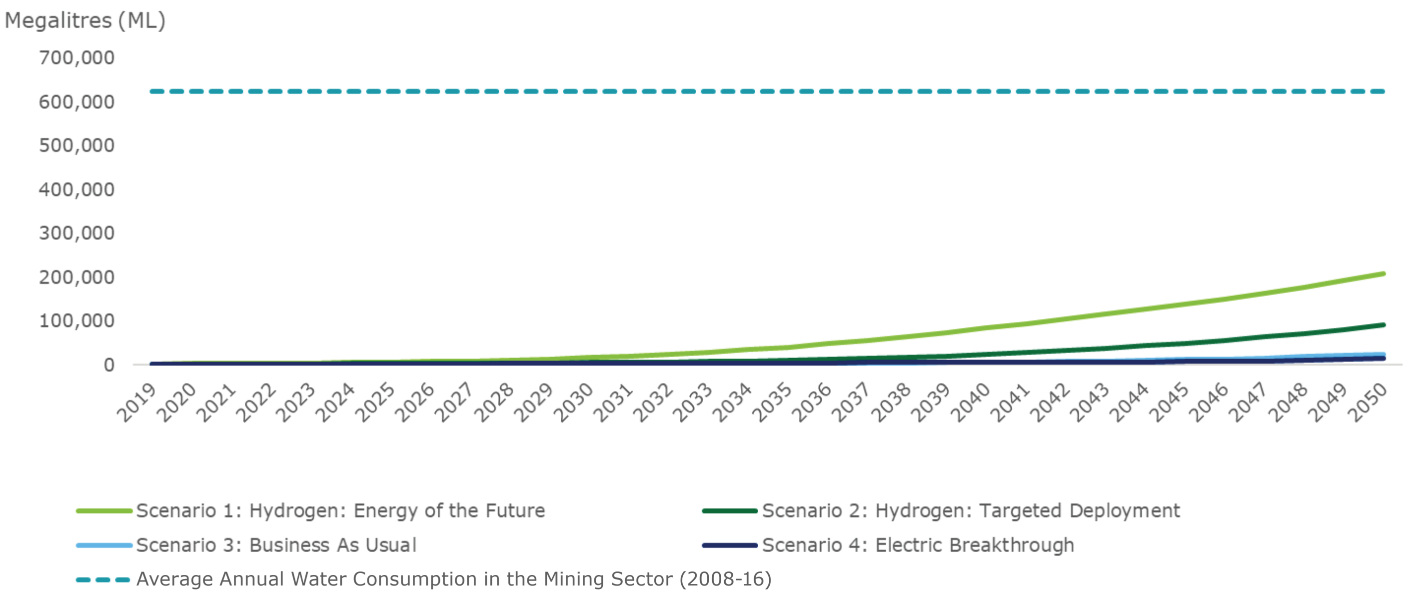


Source: Deloitte Analysis

It is also useful to examine a hypothetical hydrogen industry's carbon emissions reduction potential when Australia's electricity grid is subject to different rates of decarbonisation. In the above figure 1.6, a sensitivity analysis was conducted to determine the emissions impact if Australia's electricity grid's carbon intensity in scenarios *Targeted deployment* and *Electric breakthrough* was to be reduced at the same rate as the *Business as usual* scenario. When this occurs, carbon emissions from producing Australian hydrogen are significantly higher, with emissions from production outweighing emissions avoided.

In addition to examining emissions avoided under the various scenarios, it is also useful to examine the impacts on water usage. Hydrogen production requires water to various degrees depending on the technology used to produce the hydrogen and overall demand.

Figure 1.7 National annual water consumption of hydrogen produced in Australia



Source: Deloitte Analysis, ABS (4610.0)

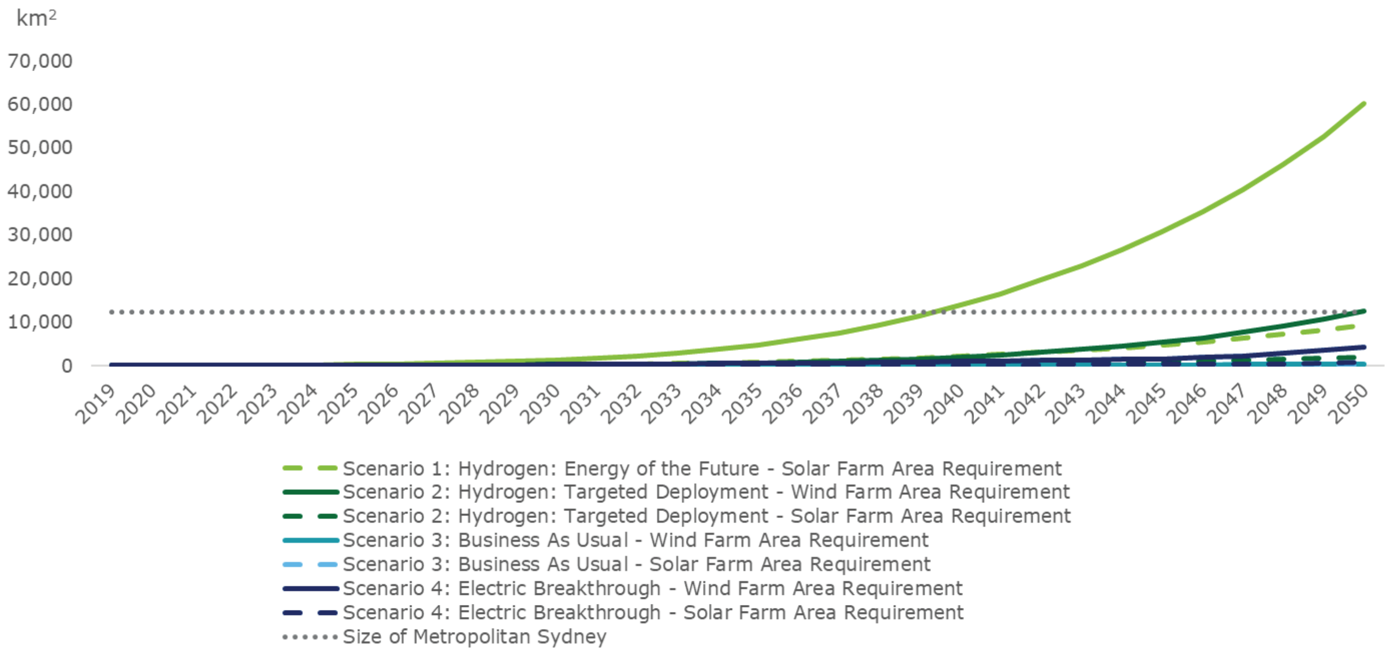
The above figure depicts the annual water consumption for additional hydrogen production in Australia under the four scenarios, when compared to the average annual water consumption in the mining sector (taken between the years 2008 and 2016).

The *Energy of the future* uses the largest quantity of water under the four scenarios. While water required is comparable to other Australian industries, there are numerous considerations that will need to be investigated or assessed.

These considerations may include locating hydrogen production facilities near suitable water resources, the local impacts that may flow from the additional demands, the need or potential availability of climate resilient water sources and the demand in the area for these types of water sources.

Under all four scenarios, there is at least some growth in the amount of electricity required in order to feed hydrogen production. Assuming that all new generation is renewable, it is important to understand the land requirements necessary to site the new generation under the four scenarios. In order to determine the land requirements we have used the average capacity of existing large-scale solar and existing wind in the NEM based on AEMO data, the capacity factor provided in the Australian Power Generation and Technology Report and the average land amount required per megawatt of capacity. These results are detailed in the chart below.

Figure 1.8 Land requirements if the hydrogen produced in Australia was powered purely by renewables



Source: Deloitte Analysis, ABS (4610.0)

A wide range of analysis has been undertaken in relation to demand scenarios, competitive advantage assessment and modelling. This provides valuable insights on a range of futures and the potential role that hydrogen development may play in the future both domestically and globally.

The challenge going forward in developing a resilient pathway for Australia's hydrogen industry is that the size of global markets that may emerge and Australia's potential share of those markets is dependent on multiple connected factors and is unknown. Many aspects of the industry are interconnected and these interconnections are not fully understood. It is therefore necessary to monitor which scenario pathway is most likely to play out and what, if any steps, can be taken to aid development of the pathway to align with Australia's aspirations.

The approach of monitoring 'signals and signposts' provides insight into what to watch for, such as technology development and policy support, and provides measures to determine progress under the different scenarios. In overview terms the signpost provides guidance on a factor that may be influential in determining the future pathway and the signal provides the specific trigger point where a direction can be inferred or an action might need to be taken. By developing signals and signposts that highlight the current path and factors to watch for as the industry develops, it is possible for government and industry to monitor and react.

Consideration of sector linkages may be important in driving the growth of the hydrogen industry. There are three viewpoints that drive the need to consider sector linkages. These viewpoints include that:

- the benefit to Australian communities is maximised when the development of the hydrogen industry includes more than a single use case;
- the value from early adoption is increased when multiple value streams are pursued at the same time thereby increasing the potential that hydrogen may become economic earlier; and,
- a long-term market needs to be fostered to allow time for hydrogen to become truly competitive and not miss the window of opportunity that exists.

Protecting the value of existing assets is a primary consideration for moving forward with the development of the hydrogen industry, including gas pipeline infrastructure and natural resources including natural gas and iron ore. The growth of the hydrogen sector can enhance the future value of these assets. This must be balanced against the other significant growth opportunities that present themselves in relation to hydrogen. Securing all these benefits may require global leadership to create cross-sectoral hydrogen development.

Implementing a suite of policy reforms over time can remove barriers to the hydrogen industry both domestically and internationally. However, it is clear that initial policy goals will go a long way in allowing Australia to meet its stated objectives for the hydrogen industry.

A suggested policy framework is one which enables the following outcomes:

- **Long-term commitment:** the growth of the market is going to take at least a decade to build towards scale which requires Australia to make a concerted long-term effort to take advantage of higher levels of growth if they eventuate.
- **Building capacity:** to be able to meet potential future global demand requires a significant effort to build capability, capacity and understanding across industry and the community.
- **Driving cost reductions:** step-change improvements in technology and the consequent cost reductions are necessary to allow the high end of growth potential to be met.
- **Creating demand:** the key to industry stimulation is a growth in demand that can be driven, to some extent, at the early stage through government policies and programs.

In developing the National Hydrogen Strategy, there is some work that may need to be considered and addressed to move the hydrogen industry forward. These measures fall into several categories: technology and demand support, policy development and a monitoring framework. In terms of technology and demand support, developing sectoral linkage expertise, facilitating export projects to stimulate domestic demand, supporting step-change technology development and supporting alternative carbon sequestration technologies are all important consideration in shaping the aim of the National Hydrogen Strategy.

Policy development includes work both in terms of short-term policy goals, which assess the intermediate impacts required from any policy implemented, but also the development of long-term frameworks that demonstrate Australia’s commitment to the hydrogen industry. Lastly, there is the need to develop a monitoring framework to be able to adapt policies and strategies quickly to address changes in the hydrogen industry. This includes developing comprehensive signals and signposts that guide the understanding of the pathway hydrogen development is progressing and reporting on these to determine if a policy shift is needed.

The COAG Energy Council’s commitment to developing a National Hydrogen Strategy provides a solid base for industry creation. Research that creates opportunities for pilots and demonstrates multiple use cases can reduce barriers to the development of the hydrogen industry in Australia. However, it is necessary for governments and industry to work together to drive demand, allowing for large-scale export-oriented projects.

1 Introduction

Hydrogen is the most abundant element in our universe. Yet, it is rarely found in its natural state. Hydrogen is highly reactive, bonding to other elements creating many of the essential compounds we know today, like water, ammonia and hydrocarbons. As a molecule (H_2), hydrogen is a colourless, odourless, non-toxic gas. Through its unique composition, it has a high amount of energy per kilogram (kg), meaning it can carry a significant amount of energy. Carriers of energy can recover the energy required to produce the carrier at the point of use, meaning they release the energy as power or heat when used as a fuel. Each kilogram of hydrogen contains about 2.4 times as much energy as an equivalent quantity of natural gas.

Global interest in hydrogen is growing. Several countries have already committed to hydrogen targets, while others already have hydrogen electric vehicles on the road. The future role of hydrogen is uncertain and the pace of transformation – technological, economical and natural – has never been this fast.

In this state of change, concerns around the natural world and social equity are growing. Demand for energy is at an all-time high at the same time countries are searching for pathways to achieve their Paris Agreement Commitments. The Paris Agreement aims to strengthen the global response to climate change.[2] Governments agreed to the following:

- a long-term goal of keeping the increase in global average temperature to well below 2 degrees above pre-industrial levels;
- to aim to limit the increase to 1.5 degrees, since this would significantly reduce risks and the impact of climate change;
- on the need for global emissions to peak as soon as possible, recognising that this will take longer for developing countries; and,
- to undertake rapid reductions therefore in accordance with the best available science.[3]

At the Paris conference, or before, countries submitted national climate action plans to address aims to limit global temperature increases.[4] As a signatory to the Paris Agreement, parties are required to put forward nationally determined contributions and to strengthen these efforts in the years ahead. Australia has set its current goals to reach its commitments to the Paris Agreement – these include reducing emissions to 26 to 28 percent on 2005 levels by 2030.[5] Under the Paris Agreement, signatories have recognised the need to achieve net zero emissions in the second half of this century (Article 4.1 of the Paris Agreement).[6] Goals and targets, both for Australia and internationally will continue to be assessed on a 5 year basis to allow countries to move closer and closer to net zero.

No matter the specific interim targets or goals set by countries to achieve the Paris Agreement Commitments, these commitments mean that countries are actively exploring and pursuing different methods to reduce emissions. One way that countries are responding to the state of change is by altering their generation mix and turning to clean energy technologies and electrification to decarbonise. Others are searching for ways to deal with exponential population growth and simply trying to meet increasing demand for energy. Although these are two different overarching contexts, fundamentally the same underlying issues – ensuring energy security while lowering carbon emissions, unite them.

The traditional energy supply chain (such as oil, gas and electricity), which has delivered reliable electricity to consumers for decades, is increasingly being disrupted by innovative ways to produce, supply, store, share and consume energy. Before now, hydrogen has never made it to the forefront of the energy debate and has so far failed to gain commercial acceptance. This is due to some of the key challenges with its uptake, including high capital investment costs, technology readiness, market penetration lead times and the need for enabling infrastructure.

Now technologies are evolving, making hydrogen production cheaper than ever before, allowing it to be competitive with other energy sources.[7] This may lead to hydrogen being the key to decarbonising without impacting negatively on countries ability to use energy as and when needed and to be able to either produce or acquire the energy needed to continue to be able to produce the products that form the backbone of numerous economies.

Increasing energy resilience and the ambitions of countries to decarbonise their energy value chain are some of the recognised benefits attributable to production and end-use of hydrogen. Hydrogen has numerous potential applications including in steelmaking, ammonia production, oil refining, light and heavy transport, heating, power generation and shipping. Given the enormous opportunity hydrogen presents, significant investment has either been committed or planned by numerous countries around the world. While there is growing excitement around the growth in the hydrogen industry between now and 2050, the timing, scale and growth trajectory is less certain.

1.1 Hydrogen value chain

1.1.1 Production

The hydrogen value chain begins with production. Hydrogen does not typically exist by itself in nature but rather is produced from compounds that contain it. All production methods require energy input to isolate hydrogen. The various sources and feedstock used to produce hydrogen include natural gas (through reformation), coal (through gasification) and water (through electrolysis). Driving interest in hydrogen is its potential to be produced through low or zero-emissions methods, which could significantly decarbonise energy value chains. However, the energy input required for isolating hydrogen is vital to determining its decarbonisation potential as hydrogen can be sourced from renewable or non-renewable sources. This impacts the naming conventions placed upon hydrogen.

For example, green or renewable hydrogen refers to hydrogen produced via electrolysis where the electricity comes from renewable sources. Clean hydrogen describes renewable hydrogen and hydrogen produced with minimal emissions, so it can include non-renewable sourced electricity paired with offsets or CCS to mitigate carbon emissions from its production. Similarly, blue hydrogen is hydrogen produced from natural gas through reformation or from coal gasification with CCS and brown hydrogen is produced from fossil fuels without any CCS. This list is not exhaustive. Globally, there are numerous other naming conventions developed for hydrogen production, but these are the most commonly used and are used for this report.[8] For the purposes of this work, the roles of green hydrogen, blue hydrogen and brown hydrogen have been considered in examining the future potential of hydrogen.

1.1.2 Transport and storage

Hydrogen can be stored in a number of ways, in a gaseous, liquid or solid state. The most suitable storage method will depend on a number of factors such as energy demand quantities and characteristics, space constraints, transport needs and costs of storage technology. For gas storage, there are four techniques: low-pressure tanks, pressurised tanks, underground storage and line packing.

Hydrogen can be transported via a pipeline, both high-pressure and distribution pipelines. Mixing hydrogen with natural gas, known as methane enrichment,[9] allows hydrogen to utilise existing distribution pipeline infrastructure with minimal additional costs.[10] However, hydrogen at high pressure in steel pipes raises the risk of pipeline embrittlement,[11] making further research and potentially significant infrastructure enhancement necessary before 100% hydrogen transport is possible in existing, high-pressure transmission pipelines. Many distribution pipelines operate at lower pressure and are constructed with or being replaced with pipes made of materials that do not face the embrittlement issues of steel pipes, such as polyethylene. As a result, the ability to increase the blending of natural gas and hydrogen in distribution pipelines provides opportunities for hydrogen deployment, especially where hydrogen is produced on a distributed basis.

Hydrogen can be transported by any type of vehicle: truck, rail or ship. High compression or liquefaction is typically used for distances greater than 300 km as the additional conversion and reconversion costs to covert hydrogen to ammonia and then back to hydrogen effects on its potential to be used as a method for transport for long-distances.[12] There are various considerations that need to be taken into account in the way that hydrogen is transported to ensure that it is done so safely and in the most efficient manner. This report does not specifically consider the method that is used to transport hydrogen to its end destination whether domestically or internationally. Rather, it is assumed that the most efficient transportation method will be used and that this may change over time as the hydrogen industry matures.

1.1.3 Utilisation

Hydrogen has similar properties to natural gas allowing its use in electricity, power and heat generation. Today, hydrogen is most commonly used in petroleum refining and fertiliser production, while transportation and utilities are emerging markets. Hydrogen utilised through a fuel cell[13] or turbine[14] is able to produce electricity and in some cases heat. Power and heat, depending on the source, can often be a contributing factor to carbon emissions.[15] Therefore, the use of hydrogen in this area can contribute to decarbonisation, where that is a driver of use.

Hydrogen can replace natural gas or even electricity in a range of domestic and industrial applications. A key benefit of hydrogen over electrification of industrial and domestic heat processes would be a reduced conversion cost, as hydrogen can be used in natural gas distribution infrastructure with less conversion than required by electrification. A previous Deloitte study on decarbonisation of the Australian gas network examined the cost of replacing natural gas with hydrogen.[16] This study showed that decarbonising the gas distribution network requires significant investment across the supply chain, from production through to modifications required for final consumption of gas. In determining the cost, the study estimated the cost of producing decarbonised gas, or alternatively decarbonised electricity, by calculating a levelised cost of energy (LCOE, $/MWh or $/GJ) for each technology type. These costs, generally, include the capital cost of building the necessary assets, fuel costs, operating and maintenance costs and financing costs. The study did not undertake a cost/benefit analysis but rather examined various ways to decarbonise the gas distribution network including hydrogen and electrification.

Hydrogen has many applications in the transport sector. It is already used in commercially available passenger vehicles[17] and could potentially be expanded to heavy vehicles and maritime uses. The vehicles tend to be relatively high-price,[18] with limited refuelling infrastructure currently available.[19] They can travel in the ~500km range before refuelling.[20] This is on par with current electric vehicle (EV) models, for example the newest Tesla S model claims 500km range.[21] Similarly, hydrogen may be applicable to a range of heavy vehicles, from trucks to trains, as they have longer routes and more space/weight capacity that is necessary for the installation of fuel cells.[22] Hydrogen is being considered as a future energy source for shipping, among traditional fuels and renewable energy sources.[23] Currently, research is limited to a small number of vessels and academic studies.[24]

Another use for hydrogen is its ability to be a substitute for coking coal in the making of steel.[25] If global moves towards decarbonisation continue, steelmaking is likely to make increasing use of the hydrogen direct-reduction process, which produces only 2.8% of the carbon of traditional manufacturing.[26]

1.2 Australian context

Exports and natural resources are the foundations of the Australian economy. Our economic welfare and growth reply on export demands. Australia is one of the top exporters of natural resources globally as we have an abundance of natural resources. Half of our exports are from resources with our three biggest exports being coal, iron ore and natural gas.[27] A large portion of these resource exports are exported to Australia's largest trading partners – China, Japan, South Korea, United States and India.[28]

Countries are diversifying their energy mix. Consumer empowerment and environmental objectives are driving a new wave of energy sources. Renewables, such as wind, solar and hydro, are growing and are increasingly becoming lower cost compared to more traditional sources of energy (coal, diesel and natural gas).

Hydrogen provides a large unique opportunity to grow our economy. The changing global demand and mix of demand for natural resources creates the potential for new opportunities to complement our top exports like coal, iron ore and natural gas. Australia has world-class capabilities as an explorer, developer, producer and supplier of energy.
It remains unclear, however, exactly how these attributes are best leveraged to become and remain a dominant player in the emerging hydrogen value chain. We are aware that many governments and industry players are currently reviewing their options for participation in this market and 2020 is shaping to be a critical year for major steps to be taken.

The value proposition hydrogen presents is enormous. What size will actually materialise depends on countless factors. Economic factors domestically and globally, government policy, technology costs and learning rates present a plethora of uncertainties which will all shape the growth and design on the hydrogen industry over time.

Australia has made some preliminary moves in order to position itself in the developing hydrogen industry. This includes the Hydrogen Energy Supply Chain project which is a trial project to demonstrate hydrogen production from brown coal and transport to Japan.[29] Yara Pilbara has indicated it intends to construct a renewable hydrogen plant as its ammonia production facility on the Burrup Peninsular.[30] Further, CSIRO is investing in various research, development and trial projects aimed at hydrogen development.[31]

1.3 Scope of this report

Deloitte was commissioned by the National Hydrogen Taskforce, established by the COAG Energy Council to undertake an Australian and Global Growth Scenario Analysis. Deloitte analysed the current global hydrogen industry, its development and growth potential, and how Australia can position itself to best capitalise on the newly forming industry.

To conceptualise the possibilities for Australia, Deloitte created scenarios to model the realm of possibilities for Australia out to 2050, focusing on identifying the scope and distribution of economic and environmental costs and benefits from Australian hydrogen industry development. This work will aid in analysing the opportunities and challenges to hydrogen industry development in Australia and the actions needed to overcome barriers to industry growth, manage risks and best drive industry development.

1.3.1 Our Approach

This report discusses four scenarios.

a. **Hydrogen: Energy of the future –** This scenario provides information on the impact that hydrogen demand can have for Australia where all aspects of industry development are favourable for hydrogen.

b. **Hydrogen: Targeted deployment –** Under this scenario, countries adopt a targeted approach that aims to maximise economic value and benefits for effort in the deployment of hydrogen.

c. **Business as usual –** This scenario assumes that Australia follows a path in which social economic and technological trends do not shift markedly from historical patterns. However, there are shifts in global markets for hydrogen.

d. **Electric breakthrough –** Under this scenario, there is rapid technological development in electrification.

These four futures are a tool to navigate the significant uncertainty intrinsic to the energy and export markets currently faced by policy makers. These four future narratives are alternative, sometimes extreme or dramatic, that identify the risks and rewards of both action and inaction on the part of consumers, industry and government. These scenarios give governments an opportunity to consider not only the ‘most likely’ view of the future but also the range of ‘plausible outcomes’.

1.4 This report

This report outlines the findings of our review, analysing the scenarios of the expected growth of Australian hydrogen value chains and hydrogen demand, economic impacts of an Australia hydrogen industry and the environmental impacts from domestic hydrogen production.

The remainder of this report is structured as follows

- Chapter 2: **Policy Settings and Demand Forecasts –** Provides a view of key policy announcements across the globe to help understand the activity in the market and who the key players are. This chapter also provides projections for future hydrogen demand and market growth.
- Chapter 3: **Global Supply Competition –** Provides a competitive analysis on Australia and its key competitors in the market, looking particularly at economic, political, environmental and technical factors.
- Chapter 4: **Market Growth Scenarios –** Draws attention to the detailed thinking behind the four scenarios modelled by Deloitte in this report. This includes key assumptions around how quickly Australia's economy is going to grow; how established technologies are going to incrementally improve; what the price of electricity is going to be, and where it's going to be coming from.
- Chapter 5: **Modelling inputs and assumptions –** Looks into the key modelling inputs and assumptions used in developing global market demand, Australian market demand, economic impact analysis and environmental impact analysis.
- Chapter 6: **Modelling Outputs –** Addresses the key implications of each scenario. Areas of specific focus are:
  - Global demand growth – size of the global demand for hydrogen;
  - Australian demand growth – size of the domestic demand for hydrogen;
  - Economic impact analysis – how key indicators in the economy respond to an Australian hydrogen industry; and,
  - Environmental impact analysis – how an Australian hydrogen industry impacts environmental indicators like water use and availability and carbon emissions.
- Chapter 7: **Further Analysis –** Considers the policy options available, signals and pathway development.
- Chapter 8: **Conclusion –** Provides concluding remarks about Australia's position, additional research and final thoughts.
- Appendix A: Detail Multi-criteria analysis
- Appendix B: SSP Scenarios
- Appendix C: CGE Modelling
- Appendix D: Signals and signposts
- Appendix E: Modelling input sources

2 Policy Settings and Demand Forecasts

In recent history, the conversation around energy has been dominated by energy sources such as coal, natural gas and more recently renewables and biofuels or biomass. While hydrogen has not previously made it to the forefront of the energy debate, government, industry and communities across the globe are now turning their attention to hydrogen deployment, as the market is seeing an increasing effort by key players to remove barriers and position themselves to benefit from the development of the hydrogen opportunity.

There are several drivers to the development of the hydrogen industry and the increased interest by governments and industry:

1. **Technologies are evolving:** making hydrogen production and use cheaper than ever before and allowing it to be competitive with other energy sources.
2. **Increasing focus on emissions reductions, particularly beyond the electricity sector:** aligning decarbonisation policies to the Paris Agreement creates the potential for green hydrogen to be a key player in countries' decarbonisation strategies.
3. **Continuous focus on energy security:** with countries increasing their focus on energy innovation to ensure access to energy and that the system is able to meet demand at the times when it is needed.

These drivers of growth have increased investment in production and downstream applications of hydrogen globally, which, coupled with forecast growth provides significant opportunity in the global market for countries and companies capable of partaking in the hydrogen supply chain.

2.1 Policy settings

Clear policy targets and specific hydrogen targets are important for a countries development of their domestic hydrogen economy as it gives stakeholders and investors insight into the government's direction. From an international perspective, announcing policy and targets puts the domestic economy on the radar of the key players in the global industry indicating to potential importers/exporters of their position and appetite.

With a large number of hydrogen specific government announcements since early 2018, it is clear that a number of countries are beginning to position themselves in the international hydrogen market. These announcements include introducing a variety of policies aimed at removing barriers to the development and commercialisation of hydrogen as well as incentives aimed to encourage investment and growth in the hydrogen industry.

Policy measures introduced have included: funding mechanisms; targets for hydrogen applications; new regulation subsidy mechanisms; creation of investment funds; and tax credit schemes. Generally, these measures are being pursued for a combination of decarbonisation goals and for energy security. Following is a summary of recent policy measures adopted or being assessed internationally.

Table 2.1 Hydrogen policy announcements since 2018

Country	Announcements and developments since 2018	Transport	Power systems	Hydrogen strategy development	Policy measure
Austria	Announced that a hydrogen strategy based on renewable electricity would be developed in 2019 as part of the Austrian Climate and Energy Strategy for 2030.			✓	
Belgium	Published a government-approved hydrogen roadmap in 2018, with specific targets set for 2030 and 2050 and an associated EUR 50 million regional investment plan for power-to-gas.			✓	Target focussed
Brazil	Included hydrogen in the Science, Technology and Innovation Plan for Renewables and Biofuels. Hosted and supported the 22nd World Hydrogen Energy Conference in 2018.			✓	
China	Announced that the Ten Cities programme that launched battery electric vehicles in the People's Republic of China ("China") would be replicated for hydrogen transport in Beijing, Shanghai and Chengdu, among others. Announced that Wuhan will become the first Chinese Hydrogen City, with up to 100 fuel cell automakers and related enterprises and up to 300 filling stations by 2025. Announced targets of 5,000 fuel cell electric vehicles (FCEVs) by 2020 and recommitted to a 2015 target of 1 million FCEVs by 2030, plus 1,000 refuelling stations. Exempted FCEVs (and battery electric vehicles) from vehicle and vessel tax.	✓			
Chile	Government has a stated goal of reducing up to 30 per cent of carbon emissions by 2030 and switching increasingly to renewable energy. The Department of Energy is focusing on hydrogen production from alternative sources for use in fuel cells and hybrid-powered trucks.	✓			Funding program
The Netherlands	Published a hydrogen roadmap, including a chapter on hydrogen in the Dutch Climate Agreement and spearheaded the first meeting of the Pentalateral Energy Forum of Belgium, the Netherlands, Luxembourg, France, Germany and Austria in support of co-operation on hydrogen in north west Europe. The Dutch provinces of Groningen and Drenthe have drawn up a 2.8 billion (Euro) plan that is supported by over 50 partners around the world to be a springboard for hydrogen industry. The project is to bring hydrogen production to scale and includes projects related to production, pipelines, storage sites, hydrogen refuelling stations and residential heating. Further, Amsterdam has banned gasoline and diesel fuelled cars and motorcycles from 2030.	✓	✓	✓	Direct initiative through ban

Country	Announcements and developments since 2018	Transport	Power systems	Hydrogen strategy development	Policy measure
New Zealand	Signed a memorandum of co-operation with Japan to work on joint hydrogen projects. Further, began preparing a New Zealand Green Hydrogen Paper and Hydrogen Strategy. As part of these development has set up a Green Investment Fund to invest in business, including those commercialising hydrogen.			✓	Investment fund
Norway	Awarded funding for development of a hydrogen-powered ferry and a coastal route vessel. Norway has made commitments to decarbonise fossil fuel cars and light vans by 2025 and has sales targets for zero-emission vehicles of 100 percent heavy duty vehicles, 75 per cent long distance coaches, 50 per cent new trucks by 2030 – however, it should be noted that these vehicles could be either electric or hydrogen. There is also progress being made on a National Hydrogen Strategy.	✓		✓	Funding mechanism; tax mechanism
France	Unveiled a Hydrogen Deployment Plan, EUR 100 million funding and 2023 and 2028 targets for low-carbon hydrogen in industry, transport and in relation to the power system through renewable energy storage, including for islands.	✓	✓	✓	Target focused, funding mechanism
Germany	Approved the National Innovation Programme for Hydrogen and Fuel Cell Technologies for another ten years with EUR 1.4 billion of funding, including subsidies for publicly accessible hydrogen refuelling stations, fuel cell vehicles and micro co-generation purchases, to be complemented by EUR 2 billion of private investment. Supported the first commercial operation of a hydrogen-powered train, and the largest annual increase in refuelling stations in the country, though the H2mobility programme. There is additional work that is being assessed such as power-to-gas and gas blending projects. It also appears that Germany will be releasing a Hydrogen Strategy sometime in 2019.	✓	✓		Subsidy mechanism, funding mechanism
India	The Supreme Court asked Delhi to explore use of fuel cell buses in the city to counter air pollution, and the government published an INR 60 million call for research proposals on hydrogen and fuel cells.	✓			
Italy	Issued regulations to overcome barriers to the deployment of hydrogen refuelling stations by raising the allowable pressure for hydrogen distribution and enhancing safety, economic and social aspects of hydrogen deployment.	✓			New regulations

Country	Announcements and developments since 2018	Transport	Power systems	Hydrogen strategy development	Policy measure
Japan	Hosted the first Hydrogen Energy Ministerial Meeting of representatives from 21 countries, plus companies, resulting in a joint Tokyo Statement on international co-ordination. Updated its Strategic Roadmap to implement the Basic Hydrogen Strategy, including new targets for hydrogen and fuel cell costs and deployment, and firing hydrogen carriers in power plants. The Development Bank of Japan joined a consortium of companies to launch Japan H2 Mobility with a target to build 80 hydrogen refuelling stations by 2021 under the guidance of the Japanese central government's Ministerial Council on Renewable Energy, Hydrogen and Related Issues. The Cross-Ministerial Strategic Innovation Promotion Program (SIP) Energy Carriers initiative concluded its 2014–18 work programme and a Green Ammonia Consortium was launched to help support the next phase.	✓	✓	✓	Target focused
Korea	Published a hydrogen economy roadmap with 2022 and 2040 targets for buses, FCEVs and refuelling stations, and expressed a vision to shift all commercial vehicles to hydrogen by 2025. Provided financial support for refuelling stations and eased permitting. Announced that it would work on a technological roadmap for the hydrogen economy. There is also work being undertaken in relation to hydrogen gas pipeline development to 2030 and beyond.	✓		✓	Funding mechanism
Saudi Arabia	Saudi Aramco and Air Products announced they are to build Saudi Arabia's first hydrogen refuelling station.	✓			
South Africa	Included fuel cell vehicles as part of Green Transport Strategy to promote the use of fuel cell public buses in metropolitan and peri-urban areas of the country, as well as deployment of hydrogen fuelled vehicles on mine sites.	✓			

Country	Announcements and developments since 2018	Transport	Power systems	Hydrogen strategy development	Policy measure
United Kingdom	Set up two GBP 20 million funds for innovation in low-carbon hydrogen supply and innovation in storage at scale including Power-to-X. Published a review of evidence on options for achieving long-term heat decarbonisation, including hydrogen for buildings. They are testing blending up to 20% hydrogen in part of the UK natural gas network. Further, announced decarbonising Industrial Clusters Mission supported by GBP 170 million of public investment from the Industrial Strategy Challenge Fund.		✓	✓	Investment fund
United States	Extended and enhanced the 45Q tax credit that rewards the storage of carbon emissions in geological storage sites, and added provisions to reward the conversion of carbon emissions to other products, including through combination with hydrogen. California amended the Low Carbon Fuel Standard to require a more stringent reduction in carbon intensity by 2030, incentivise development of refuelling stations and enable CCUS operators to participate in generating credits from low-carbon hydrogen. California Fuel Cell Partnership outlined targets for 1,000 hydrogen refuelling stations and 1,000,000 FCEVs by 2030, matching China's targets.	✓			Tax credit, target focused

Source: IEA (2019), The Future of Hydrogen; FuelCell Works; Reuters; Foresight Climate & Energy; Clean Energy Wire

Note: Power system refers to the electricity network, gas network or both.

Further, the global shift toward decarbonisation ambitions means that a large majority of countries have established general renewable energy targets in some way. As hydrogen can be a zero emissions source of energy when it is produced from renewable energy, it does have the potential to play a key role in countries' decarbonisation strategies. Further, there are approximately 50 policies, which include incentives, targets and/or mandates – targeting hydrogen development specifically.

Currently, a significant number of these policies focus on hydrogen development for the transport sector, and are particularly targeted to support fuel-cell vehicles and hydrogen refuelling stations (HRS). Many governments have determined to pursue transport sector initiatives being underpinned by air quality and climate change commitments. Currently in transport there are several commercial enterprises for hydrogen and fuel cell vehicles which provides a platform for wider deployment. Furthermore, it is thought that once transport is at scale in a given region, hydrogen infrastructure built for the transport sector can be a stepping stone to using hydrogen for other uses.[32]

Further transportation initiatives are seen as politically acceptable and can be pursued at all levels of government – federal, state and local. Although, this may be an important component in hydrogen uptake, other diverse applications should also be considered in developing policy frameworks.

Table 2.2 Country-specific renewable energy and hydrogen targets

Country	Renewable Energy Targets	Hydrogen-specific targets			
		FCEV Targets	Hydrogen refuelling station (HRS) Targets	Hydrogen flow (MtH2/yr)	Other
United States – Federal	20% (2020)	40,000 (2023)	100 (2023)	-	-
United States – California	100% (2045)	1 million (2030)	1,000 (2030)	-	33% green hydrogen
Germany	18% (2020)	500	100 (2019)	-	-
France	32% (2020)	50,000 (2023)	100 (2023)	-	20-40% green hydrogen
Netherlands	14.5% (2020)	2,000 (2020)	5	-	-
Norway	67.5% (2020)	50,000	200	-	-
Denmark	30% (2020)	75	10	-	-
China	770 GW (2020)	1 million (2030)	500 (2030)	0.2 (2030)	-
South Korea	11% (2030)	630,000 (2030)	520 (2030)	-	-
Japan	22-24% (2030)	800,000 (2030) and 1,200 buses (2030	320 (2030)	0.3 (2030)	-
India	175 GW (2022)	1 million (2020)	-	-	-
Australia	33,000 GWh (2020)	-	-	0.5 (2030)	-
New Zealand	100% (2035)	-	-	0.7 (Taranaki only, 2030)	Taranaki proposes exporting around 0.5–1 GW, or 40% of production

Source: Deloitte Research and IEA Report

The key players in the market, who have been identified in various desktop forecasts as likely to demand the largest amount of hydrogen in the future, include Japan, South Korea, China and Singapore. These countries have underpinned their demand by incentives, policy, research and development, which has supported and encouraged hydrogen uptake. Brief case study examples of recent announcements and initiatives are listed below:

Japan

Key driver: Energy Security and Reliability

Significance for Australia: Potential off-taker and project developer

- In December 2017, Japan released its Basic Hydrogen Strategy[33] with the vision of being a world-leader in hydrogen and developing commercial-scale international integrated hydrogen supply chains around 2030. The Strategy includes an aim of importing 300,000 tonnes of hydrogen annually by 2030 at AUD$33/GJ and a longer-term goal of 10Mt/yr.
- The 2020 Tokyo Olympics will be fuelled by hydrogen, with the governor of the Tokyo Metropolitan Government reserving US$350 million in a special fund to subsidise hydrogen fuel cell cars and refuelling stations in the lead-up to the Olympics[34].
- From 2030 it will shift to expand demand in the mobility sector and introduce hydrogen power generation to consume national scale amounts of hydrogen[35].
- Hosted the first Hydrogen Energy Ministerial Meeting of representatives from 21 countries, plus companies, resulting in a joint Tokyo Statement on international co-ordination.
- Updated its Strategic Roadmap to implement the Basic Hydrogen Strategy, including new targets for hydrogen and fuel cell costs and deployment, and firing hydrogen carriers in power plants.
- The Development Bank of Japan joined a consortium of companies to launch Japan H2 Mobility with a target to build 80 hydrogen refuelling stations by 2021 under the guidance.

South Korea

Key driver: Energy Security and Reliability

Significance for Australia: Potential off-taker and project developer

- South Korea's National Basic Plan for New and Renewable Energies (2014) aims to invest over US$2bn on hydrogen infrastructure, manufacturing and technology[36].
- South Korea is expected to require 170,000 tonnes of hydrogen annually by 2030 and 500,000 tonnes by 2040.
- In 2019, South Korea announced a new road map, which would aim to have 80,000 FCEVs on the road by 2022[37].
- Published a hydrogen economy roadmap with 2022 and 2040 targets for buses, FCEVs and refuelling stations, and expressed a vision to shift all commercial vehicles to hydrogen by 2025. Provided financial support for refuelling stations and eased permitting. Announced that it would work on a technological roadmap for the hydrogen economy (Korea).

China

Key driver: Decarbonisation and Air Quality

Significance for Australia: Potential off-taker and project developer

- China's 13th National Five-Year Plan highlights "new energy vehicles" as an important emerging technology, with 5 million to be delivered across the country by 2020. China plans to have the capacity to produce 170,000 FCEVs annually. It is estimated that China is investing A$20 billion in hydrogen energy R&D.
- Announced that the Ten Cities programme that launched battery electric vehicles in the People's Republic of China ("China") would be replicated for hydrogen transport in Beijing, Shanghai and Chengdu, among others.
- Announced that Wuhan will become the first Chinese Hydrogen City, with up to 100 fuel cell automakers and related enterprises and up to 300 filling stations by 2025.
- Announced targets of 5,000 fuel cell electric vehicles (FCEVs) by 2020 and recommitted to the 2015 target of 1 million FCEVs by 2030, plus 1,000 refuelling stations. Exempted FCEVs (and battery electric vehicles) from vehicle and vessel tax.

Singapore

Key driver: Economic Development

Significance for Australia: Potential off-taker and project developer

- Singapore has an active R&D program in fuel cell and hydrogen technologies, specifically targeting methods of reducing the cost of water electrolysis (green hydrogen). Planned increases to the carbon tax support the transition toward hydrogen; however its most likely prospect is as fuel for FCEVs.
- Despite the lack of underpinning resources, Singapore's government has taken a proactive approach in developing a hydrogen industry – with a feasibility study on hydrogen imports and downstream applications being awarded to KBR and Argus in September 2019.
- Announced in 2019, Linde aims to invest US$1.4bn to expand hydrogen production in Singapore's Jurong Island with the aim of starting up in 2023.
- In 2017, Engie was involved in developing a microgrid-based hydrogen storage system for Semakau Island.

In addition, countries like Taiwan may become major markets for Australian produced hydrogen. Taiwan has made commitments to address energy security, air pollution and climate change which is resulting in a significant energy transition. The goals associated with this energy transition is to increase the share of renewable energy and LNG. As Taiwan continues down its path of transitioning its energy system, hydrogen may have a substantial role in its efforts. This could provide an opportunity for Australia as it is currently a major supplier of energy to Taiwan.

2.2 Demand forecasts

2.2.1 Desktop review of demand forecasts

Currently, hydrogen is largely demanded as an input for refining and ammonia, with the use of hydrogen for energy purposes estimated to be only 1-2% of total consumption.[38]

Ammonia is widely seen as a viable method of storing and transporting hydrogen due to its high energy density, safety and cost effectiveness.[39] As ammonia is already widely produced, transported and stored around the world as a key input for fertilisers and explosives production, many companies already have the infrastructure and expertise required to handle additional ammonia demand that might be driven by a rapidly growing hydrogen industry in Australia. Therefore, ammonia provides an early pathway for hydrogen industry development and can be leveraged to develop infrastructure and demand for other use cases.

Ammonia production facilities are projected to use hydrogen (in part) derived from electrolysis powered by green electricity sources[40] and can therefore function as energy storage units or back-up for energy producers using excess renewable energy. Ammonia production facilities can be built in the areas where solar, wind or other forms of green energy are abundantly available.

The agricultural sector constitutes 80% of the global ammonia market in 2018.[41] Demand for fertilizer is increasing marginally as a result of improving economic prospects in developing economies such as Russia, Brazil and Sub-Saharan Africa. Further, the global ammonia market is expected to record a compound annual growth rate (CAGR) of over 5% during the forecast period of 2019-2024,[42] with demand centred on Asia Pacific.

Ammonia is also under consideration as a maritime transport fuel. Gaseous hydrogen requires a high volume of space to transport safely and therefore is not likely to be widely deployed without technological advances, unlike ammonia which can be used as a liquid bunker fuel[43] or in fuel cells.

The global ammonia market is consolidated, with a small number of significant manufacturers and suppliers. Australia is not a major player in the production of ammonia at this time.

Table 2.3 Global ammonia producers (2018)

	Country	Production (million tonnes)
1	China	44
2	Russia	14
3	United States	13
4	India	11
5	Indonesia	6
6	Trinidad & Tobago	4
7	Saudi Arabia	4
8	Canada	4
9	Pakistan	4
10	Qatar	3
18	Australia	1

Source: US Geological Survey, Mineral Commodity Summaries (February 2019)

Hydrogen has various positive attributes that has led to growing interest from policymakers around the world, including Japan with its Basic Hydrogen Strategy that aims to ramp up the use of clean hydrogen throughout the value chain. These positive attributes include:

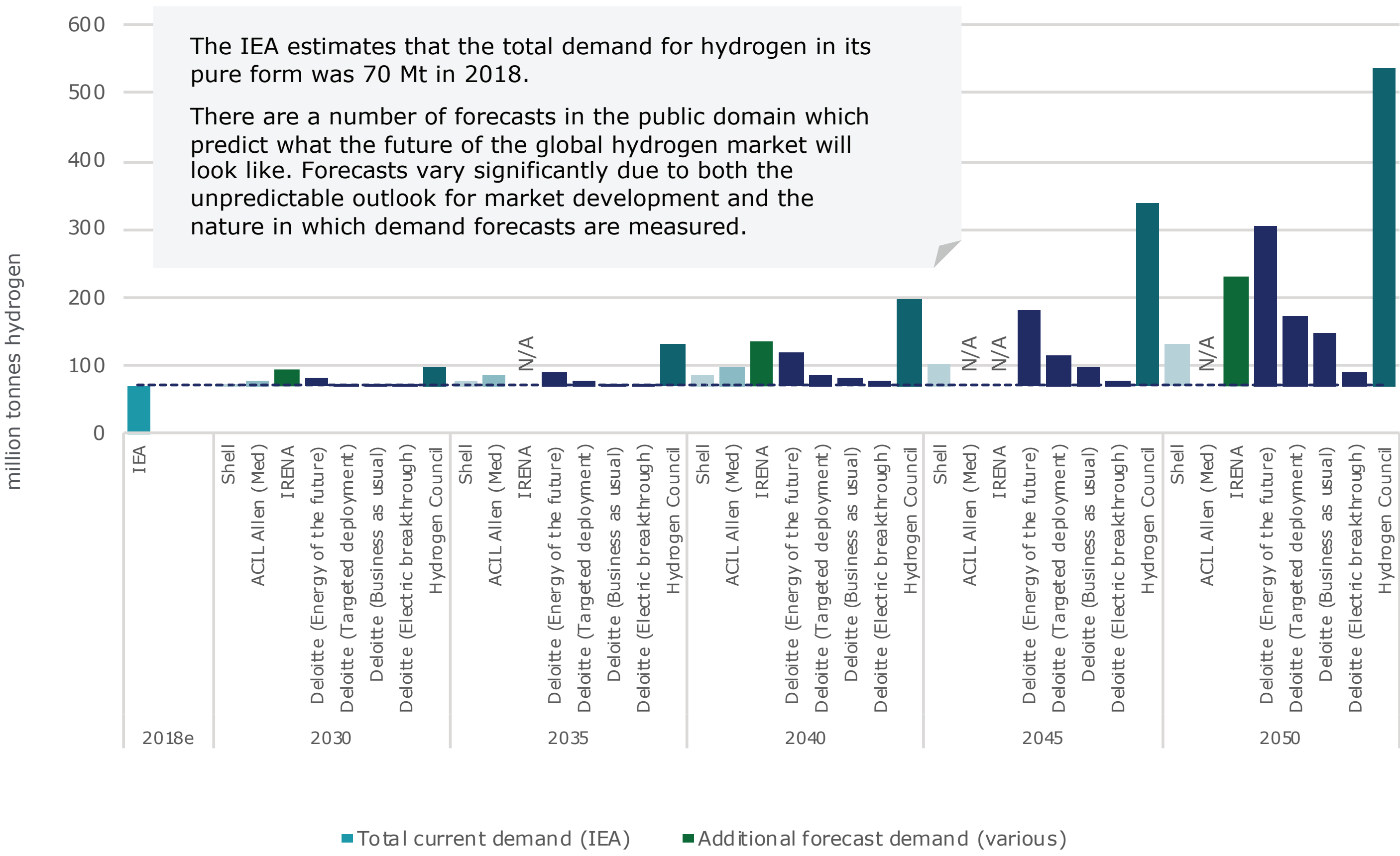
- high energy density to weight ratio;
- ability to be readily produced at industrial scale with low-carbon energy inputs such as renewables-driven electricity; and,
- wide range of end-use applications such as transport, heating and steelmaking.

As part of the international review, Deloitte reviewed numerous public documents on the hydrogen industry to understand both the purpose of the report and its possible use in examining the hydrogen market:

- *Hydrogen Scaling Up.*[44] This report presents a vision of the long-term potential for hydrogen and a roadmap for deployment. This report presents an ambitious vision for hydrogen deployment which would include an aggressive push for scaling new technologies throughout the value chain and cross sector. This would require a high level of coordination and dialogue between investors, policy makers and industry.
- *Opportunities for Australia from Hydrogen Exports.*[45] This report was prepared for the Australian Renewable Energy Agency with the aim to identify the opportunities for Australia to export hydrogen as an energy source. The report is focused on production and export opportunity, specifically relating to 'clean hydrogen' which includes zero emissions hydrogen produced from renewable energy and low emissions hydrogen produced from fossil fuels. However, especially in the short to mid-term, hydrogen development, domestically and in the export market, is also going to be driven through brown and blue production methods.
- *National Hydrogen Roadmap.*[46] This report was prepared by CSIRO with support from industry, government and consulting participants with an aim to provide a blueprint for the development of a hydrogen industry in Australia. The Roadmap only included "Base case" cost figures which presents an ambitious vision of the future hydrogen sector. As the report aims to inform and support industry it does not always take into account the same considerations that drive policy makers domestically and internationally.
- *Strategy for Energy Transition.*[47] This report was prepared by Shell and sees the growth of hydrogen use in final energy consumption as a high-density and storage energy source in transport and industry. Further, it explores hydrogen refuelling for vehicles. This report was prepared to allow Shell to develop its strategy going forward and includes the case for green hydrogen as part of Shell's strategy.
- *Hydrogen from Renewable Power.*[48] This report was prepared by IRENA to look at the transition that is occurring in the global energy system to achieve the targets in the Paris Agreement. The report acknowledges that electrification of some industries such as transport, industry and uses that require high-grade heat may be difficult and that hydrogen can potentially provide a pathway for those industries. This report provides valuable insights but predominately examines the role of hydrogen produced through renewable electricity.
- *Hydrogen Generation Market Analysis and Segment Forecast to 2025.*[49] The purpose of this report was to attract industry buyers by segmenting the market and providing a positive view on the possible growth potential for hydrogen. While the research paper notes the potential for hydrogen for energy storage and transport, it seems the forecasts are based on markets where hydrogen is supplied domestically.
- *Future of Hydrogen G20 Japan.*[50] This report presents a reasonable forecast of options at the request of the government of Japan under its G20 presidency. The report aims to analyse the current state of play for hydrogen and to offer guidance on its future development. This report provides good, recent information on what is happening in the market globally and the types of targets, policies and incentives that are being considered. However, the report does not provide forecasts of future demand for hydrogen or how that demand will be met.

While the forecasts for the demand of hydrogen vary due to both the unpredictable outlook for market development and the nature in which demand forecasts are measured, it is clear that the level of interest and support across both industry and government is leading to an increase in forecasted hydrogen demand.

Figure 2.1 Forecasted global hydrogen demand (million tonnes hydrogen)



Source: IEA, ACIL Allen, IRENA, Hydrogen Council, Deloitte Analysis

Note:
a) IEA current demand is treated as a universal baseline for all additional demand
b) Where possible, raw inputs have been converted from J to Mt using an assumed energy density of 120 MJ/kg
c) N/A indicates that the data was not available for the given year. ACIL Allen only provided a forecast until 2040
d) The Shell demand forecasts relate only to additional demand for energy use and does not include any additional demand for feedstock.

The figure shows that total demand for hydrogen in 2018 in its pure form is estimated to be around 70 million tonnes of hydrogen per year. The primary use for this hydrogen is refining and ammonia production and is almost entirely supplied from fossil fuels. Beyond the use of hydrogen in its pure form, a further 45 MtH2/yr is estimated to be used in industry without prior separation from other gases.

Table 2.4 Examples of various projections for the growth of hydrogen demand (non-exhaustive)

Source	Period to projection	CAGR
Persistence Market Research[51]	2017 to 2025	6.1%
Zion Market Research[52]	2017 to 2023	6%
Shell's Sky Scenario[53]	2020 to 2040	23%
Hydrogen Council Scaling Up[54]	2020 to 2050	35% to 2040 28% to 2050

From 2025 to 2050 there is a vast difference in projections, with the Hydrogen Council forecasts being significantly higher than any other projection. The Hydrogen Council forecasts that by 2050, hydrogen could power more than 400 million cars, 15 to 20 million trucks, and around 5 million buses, which constitute on average 20-25% of their respective transportation segments. The numbers by the Hydrogen Council present an ambitious vision for hydrogen deployment, which would include a strong push for scaling new technologies throughout the value chain and cross sectors internationally.

The ACIL Allen Report provided forecasts for 2025, 2030 and 2040. The report examines the potential demand for low emissions hydrogen for energy use, including hydrogen produced through electrolysis or using fossil fuels combined with CCS.

Therefore, it does not take into account the potential that, in the short-term and potentially the mid-term, hydrogen will be produced most cost-effectively through blue or brown hydrogen methods. These forecasts, while sitting significantly below the forecasts for demand from the Hydrogen Council, are higher than the projections from Shell's Sky Scenario.

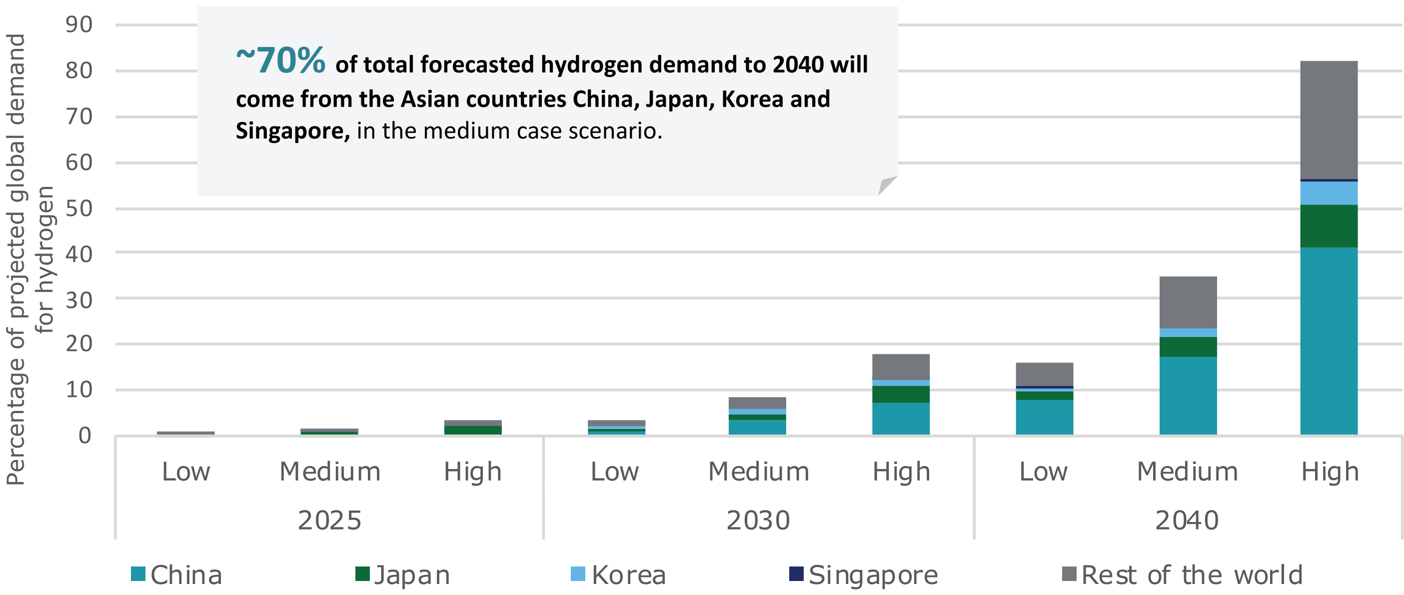
Deloitte provides a range of possible hydrogen demand figures across four scenarios for all years between 2019 and 2050. In 2050, Deloitte's most optimistic view of hydrogen, *Energy of the future* – is just over 300 MtH2/yr, which is more than Shell's and IRENA's estimates, but significantly less than the Hydrogen Council's forecasts. Further information about Deloitte's views on global hydrogen demand can be found in Chapter 6.

Table 2.4 provides examples of various projections for the growth of hydrogen demand. The CAGR from Persistence Market Research and Zion Market Research are similar at 6.1% and 6% respectively and both are projections for the total hydrogen demand. Shell's Sky Scenario and the Hydrogen Council's CAGR projections are significantly higher. Shell's projection was an output of a future scenario designed to reach the Paris Agreement's goal in a technically possible way. The Hydrogen Council report is, in their view, an ambitious yet realistic approach which would deliver deep decarbonisation of transport, industry, and buildings, including up to 10 to 15 million tonnes of chemicals that could be produced using hydrogen as feedstock[55] and enable a renewable energy production and distribution system.

2.2.2 Key demand markets

Various desktop forecasts predict the Asia Pacific region to be the largest hydrogen market in the world, driven by the demand from Japan, China, South Korea and Singapore. They key factors driving hydrogen demand in Asia include the view that hydrogen is a viable fuel option to reduce dependency on nuclear power and imported traditional fuels and as a pathway to move towards a greener economy. Figure 2.2 presents the hydrogen demand in Asia and the rest of the world.

Figure 2.2 Hydrogen demand in Asia and the rest of the world



Source: ACIL Allen Consulting, 2018, Opportunities for Australia from Hydrogen Exports

2.3 Challenges for market development

There are a number of challenges that must be addressed in order for the hydrogen industry to achieve market activation. Firstly, the ability of hydrogen to replace other technologies and processes will be dependent on its **cost effectiveness.**

Table 2.5 Hydrogen production cost forecast by 2025

Production method	2025 (AUD/GJ)	2025 (AUD/kg)
Proton exchange membrane (PEM) electrolysis	~$40	~$5
Alkaline electrolysis	~$35	~$4
SMR with CCS	~$13	~$2
Coal gasification with CCS	~$26	~$3

Source: Deloitte modelling

Note: $/GJ figures have been converted using a conversion rate of 120GJ/tonne.

The total levelised costs shown in Table 2.6 indicate that by 2035 hydrogen produced through alkaline electrolysis and SMR are more cost effective than diesel (used in vehicles), with PEM electrolysis approaching cost parity. This is not surprising given the improved efficiency of fuel cells versus internal combustion engines as fuel cells are generally significantly more efficient in converting delivered energy. However, hydrogen remains behind natural gas (industrial use) even out to 2050 in terms of cost. It should be noted however, that these total levelised costs are fuel costs only and do not include equipment costs associated with the use of that fuel. These costs have been determined based on the modelling undertaken by Deloitte recognising there may be various estimates in the market given the work being undertaken on hydrogen at the moment. These estimates are based on various assumptions and need to be considered based on the underlying reasoning for the modelling being done.

Table 2.6 Total levelised cost (AUD/GJ)

Production method	2025	2035	2050
Hydrogen – PEM electrolysis	~$40	~$36	~$30
Hydrogen – Alkaline electrolysis	~$35	~$33	~$29
Hydrogen – SMR	~$13	~$11	~$9
Diesel (Comparison)	~$31	~$35	~$35
Natural Gas (Comparison)	~$6	~$7	~$8

Source: Deloitte modelling, IEA (2019)

Policy and technology uncertainty is another challenge and requires government and policy support. This support will assist in creating an environment for low-carbon hydrogen application to become competitive with other technologies and energy sources. Policy is only one side of the equation however, as technology development will be a key to the hydrogen industry becoming commercial. For example, CCS is currently required in order to produce blue hydrogen unless offsets are utilised. At this time, CCS is not cost competitive and there are questions about whether CCS facilities can be located where significant transport costs are not also required. That said, there is activity occurring in Australia (CarbonNet, GCCI and CRC CO2) exploring CCS technology which may result in cost reductions for this technology and allow for widespread deployment of this technology for the use in producing blue hydrogen. Fossil fuel based hydrogen producers are assumed to use the cheaper of CCS technology or carbon offsets. Other sequestration technologies may need to be developed to allow for the use of natural gas as a feedstock in the longer term. It is viewed by some stakeholders that, for the hydrogen market to reach its full potential, advances in CCS technology will need to be made in order to allow production and end-uses to be scaled up and become cost competitive.

Hydrogen also has a complex value chain and for it to be successfully deployed to end users, investments and policies need to be synchronised in scale and time. In addition, the hydrogen value chain must be enabled through supporting infrastructure such as distribution pipelines, or in the case of road transport, a widespread network of refuelling stations. A shift in the pace of development will be required to remove barriers to adoption throughout the entire value chain.

Regulations, standards and acceptance will also be a hurdle for the industry as they are generally currently in their infancy. Around the world, regulations and standards do not yet fully support hydrogen uptake or new uses of hydrogen, as a result limiting the benefits that it can provide. In addition, key standards have not yet been agreed, including standards for hydrogen vehicle refuelling, gas composition for cross-border sales, safety measures, permitting, materials and how to measure lifecycle environmental impacts. Furthermore, hydrogen poses safety risks, due to its extended ignition range compared to traditional fuels that will need to be addressed through specific regulations or standards. It is unclear what acceptance will look like for this aspect of hydrogen. However, work is being undertaken to set standards related to hydrogen. The International Organisation for Standardization (ISO) is working on developing standards related to systems and devices for the production, storage, transport, measurement and use of hydrogen. Currently there are twenty published standards and an additional 6 that are under development.[56] Standards Australia is working with CSIRO and Hydrogen Mobility Australia to examine how standards can assist in the development of the hydrogen industry in Australia.[57]

3 Global Supply Competition

There is emerging global interest in hydrogen as an energy carrier as countries, such as Japan and South Korea, establish hydrogen as a cornerstone in their long-term energy strategies. This is driving the potential for significant hydrogen demand internationally. Australia is well positioned to capture these export opportunities due to its abundant natural resources, substantial experience in exporting energy, geographic location and relationships to key potential trading partners. The World Energy Outlook 2018 highlights Australia as a case study for the potential of hydrogen and the world-role Australia can play.[58]

However, other countries are also positioning themselves to meet the projected significant increase in the global hydrogen demand.

Latest forecasts expect the global market to expand at a CAGR of 5.8% to USD $180.2 billion by 2025.[59] Steam methane or naphtha reforming account for nearly 80% of hydrogen produced, followed by coal gasification. Electrolysis supplies 4% of global hydrogen supply.[60] Table 3.1 shows Grand View Research's estimated and forecast hydrogen production by region in terms of volume and revenue.

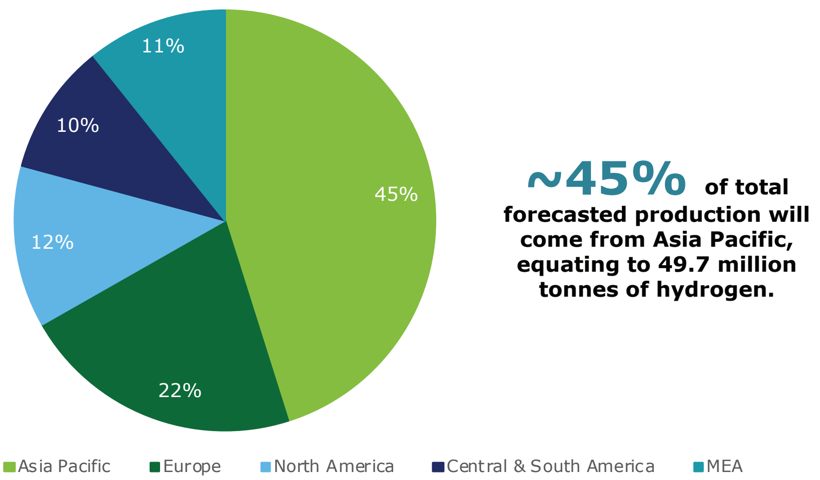
Table 3.1 shows the Asia-Pacific emerging as the leading regional market for hydrogen where it accounted for 38% of the overall volume generated in 2016. The region is expected to witness a strong revenue growth rate from the production of hydrogen of 4.7% from 2016 to 2025. Figure 3.1 provides a clearer view from a regional perspective on where the forecast production will come from in 2025.

Table 3.1 Hydrogen production by region in terms of volume and revenue

Region	Europe	North America	Central and South America	Middle East and Africa (MEA)	Asia-Pacific
Revenue 2016 (USD)	$29 Bn	$24 Bn	$9 Bn	$10 Bn	$36 Bn
Revenue 2025 (USD)	$49 Bn	$33 Bn	$21 Bn	$24 Bn	$55 Bn
Revenue CAGR	6%	3%	9%	10%	5%
Volume 2016 (tonnes)	15 m	7 m	4 m	6 m	20 m
Volume 2025 (tonnes)	24 m	14 m	11 m	12 m	50 m
Volume CAGR	5 %	8%	11%	19%	11%
Notable markets	Russia, UK	US (particularly California)	Brazil	UAE, Saudi Arabia	China, India

Source: Grand View Research, 2018, Hydrogen Generation Market Analysis and Segment Forecasts to 2025

Figure 3.1 Forecasted regional hydrogen production volume in 2025 (million tonnes hydrogen)



Source: Grand View Research, 2018, Hydrogen Generation Market Analysis and Segment Forecast to 2025

Asia-Pacific is expected to become a large player in the hydrogen market. This is primarily driven by China where robust economic performance and high growth rates, together with large R&D spending will increase hydrogen production. The European market is also expected to grow in hydrogen production in countries like Spain, the UK, Italy, Germany and Russia as a result of growing demand for superior quality and reliable supply for various end-uses of hydrogen.[61]

There is a large opportunity for countries exporting hydrogen to meet the needs of those countries that cannot cost competitively produce it themselves. In examining the potential for Australia to capture a fair share of this market it is essential to examine how Australia compares against other countries also looking to export hydrogen.

Globally, very few countries are responsible for the vast majority of hydrogen exports. Table 3.2 lists the largest exporters of hydrogen globally as of 2017, and shows that only a few countries are producing hydrogen and many of those countries are not producing significant amounts. The United States as the top exporter, exporting approximately $2,200 million USD of hydrogen. Australia is currently exporting approximately $130 million USD.

Table 3.2 Top exporters of hydrogen globally

	Country	% of global exports by economic value[62]
1.	United States	19%
2.	China	15%
3.	South Korea	11%
4.	Germany	11%
5.	Norway	5%
6.	Japan	5%
7.	France	3%
8.	Brazil	3%
9.	Qatar	3%
10.	Vietnam	2%
11.	Netherlands	2%
12.	Kazakhstan	2%
13.	Belgium/Luxembourg	2%
14.	Malaysia	2%
15.	Australia	1%

Source: The Observatory of Economic Complexity, MIT.edu

To understand Australia's competitive position relative to its global competitors in relation to the opportunity to capture a key segment of hydrogen export industry, a multi-criteria assessment has been developed which allows the current key hydrogen exporters to be examined.

The multi criteria framework summarised is in the Figures below and has been developed to assess Australia's competitiveness in a future global clean hydrogen marketplace by examining how it performs relative to the top seven hydrogen exporters (excluding Japan and South Korea given their recent announcements on their import targets).

Australia is currently ranked 15th in the top global hydrogen exporters by export value. Singapore and Saudi Arabia have been included in the analysis due to recent announcements made regarding efforts to export hydrogen.[63, 64] These countries were then assessed across economic, environmental, political and technical criteria points.

Table 3.3 Multi criteria framework summaries

Criteria	Description
1. Economic	
1.1 Trade relations	Any potential hydrogen exporter will need trade relationships with potential importers. These relationships may be developed over time, but existing trade relationships will smooth the path for hydrogen exports. Relationships considered in the MCA will be with the 2017 main hydrogen importers: China, Japan, Germany, South Korea and the United States.
1.2 Access to finances	Companies seeking to participate in the clean hydrogen value chain in their respective countries will need a source of finance or funding. In countries with relatively liberal economies, or countries where the government agenda aligns with the pursuit of hydrogen, this is likely to be easier. The World Bank ranks economies on the ability to get credit from 1 to 190. It is also necessary to look beyond the World Bank rankings for those countries that have access to high-levels of sovereign funds.
1.3 Ease of doing business	This relates to the ability of a local firm to start and operate within the broad regulatory, political and economic conditions present in the country. The World Bank ranks economies on the ease of doing business from 1 to 190.
2. Environmental	
2.1 Extent of existing hydrogen applications in-country	We envisage that most countries would only become hydrogen exporters if exports are supported by domestic hydrogen applications.
2.2 Ports and other infrastructure	Maritime infrastructure is likely to be necessary for countries to export and import large volumes of hydrogen. Countries with trading partners accessible by land may be able to use existing or new natural gas pipelines to export hydrogen. Experience and capability in exporting fuels is seen as an advantage.
2.3 Feedstock for generation	Countries generating hydrogen will need an input energy source to do so. This is likely to be natural gas or renewable resources, such as solar and wind energy, combined with water for electrolysis.
2.4 Delivery times and distances	Distance from trade partners can have an effect where hydrogen delivery is time-dependent. Significantly, distance can increase shipping costs and therefore cost-competitiveness – although for large scale imports this is a relatively minor component of the costs. Delivery times and distance considered in the MCA will be to the 2017 main hydrogen importers: China, Japan, Germany, South Korea and the United States. It is acknowledged that some of these countries are also major exporters of hydrogen – including China, United States and Germany. However, it must be acknowledged that imports and exports could relate to different use cases.
2.5 Access to electricity for hydrogen production	The consistent supply of electricity and/or gas is necessary for a hydrogen supply chain to function successfully. This requires mature and reliable energy networks. This is based on the World Bank ratings and Ease of Doing Business Score relating to access to electricity.

Criteria	Description
3. Political	
3.1 Government stability and support	Given the multiple components of a hydrogen supply chain, it is unlikely that one can come to fruition without a relatively stable government. It will also be helpful for hydrogen if the government is generally supportive of hydrogen or new/related technologies, and has a declared hydrogen policy. Governments with long-term policy stability are seen favourably.
3.2 Regulatory settings	Governments may seek to actively encourage a hydrogen industry through regulatory settings, including incentives for third parties to invest in hydrogen or support for hydrogen research. This includes ability to obtain necessary licensing and approvals required to operate the business.
3.3 Government transparency	The ability to understand the process followed by or adopted by a government may allow proponents of new technology or projects to understand what is necessary for development or deployment within the governmental programs or policies. This level of transparency and lack of corruption also provides an understandable and predictable environment that enables investment.
4. Technical	
4.1 Experience in delivering similar technologies or resources/parallel industries	A country with an existing supply chain and/or experience in delivering similar products to hydrogen (e.g. natural gas) is likely to have a competitive advantage in delivering hydrogen.
4.2 Availability of human and technological resources	The ability to staff the entire value chain of the hydrogen process will be vital for effective competition in the global market. Presence of high-quality higher education or other similar high technology sectors may indicate the presence of useful human and technological resources.
4.3 Adaptability in a changing environment	Hydrogen processes and value chains, as well as drivers such as the energy market, are unlikely to remain static in the coming 30 years. The ability to respond to such changes is vital, and may be demonstrated through responses to past changes in technology or circumstances. Generally, a country will rate strongly in this criterion when it has a history of embracing new technologies and implementing changes in the energy market. This is in comparison to those that rate unfavourably where there is limited evidence of adopting changes in the energy market or deploying new technologies.

Publicly available information and our expert market opinions were used to assess and rate the countries in scope against the multi-criteria framework, noting the judgements are qualitative and/or subjective.

Strong competitors are those countries that score 15 or above on the assessment and competitors those that score 14 or less. An assessment was undertaken in relation to the criteria itself and then relative to the other countries being examined. See Appendix A for the detailed assessment.

Although some countries have not scored relatively high in the multi-criteria assessment in comparison to other countries, their relative strength against other competitors may change depending on how the future unfolds. For example, Brazil scores relatively low on the criteria due in large part to the instability of its governments and the issues with ease of doing business, access to finance and government stability and support which flows from the current political environment. Qatar also faces issues related to its political environment, impacting on the criteria related to government transparency, ease of doing business and government stability and support. However unlike Brazil, Qatar has the ability to access sovereign funding that can easily be used to kick-start major development in the hydrogen industry.

Generally, the countries selected for the MCA are those countries that already are involved in the hydrogen export market. However, given the early stage of this market, there is the possibility for numerous countries to pursue policies or projects that will change its position in the hydrogen export market. For example, Russia, New Zealand or Chile which have not been examined but could become major players in the export market given their current role in the energy or natural resource export markets or ambitions related to hydrogen industry development. These countries, as well as others should be kept in mind while the hydrogen market develops to allow the position of Australia to be continually reviewed and assessed.

It is also important to understand that the demand for hydrogen is changing and is set to continue to change significantly over the next decade. The hydrogen activities and government support of countries will have a profound effect on whether, and to what extent, a country captures some of the hydrogen export opportunities. Countries who are not currently exporting hydrogen may decide that the demand for hydrogen aligns with their competitive advantages. For example, in Canada, ITM Power recently announced the completion of a government supported 300 MW renewable energy produced hydrogen feasibility study, which has the potential to be the largest of its kind globally with Japan as a key target location for the hydrogen.

Australia may want to monitor announcements made by other countries related to hydrogen over the coming years to continually assess its global competitiveness and who are its strongest competitors. Importing countries are setting clear expectations for the delivery costs and the type of hydrogen they will accept, both in the short and longer term, and how countries meet the key trading partners’ expectations will affect who is ultimately successful in capturing these markets.

Figure 3.2 provides the summary of the competitive analysis assessment, with the assessment key attached.

Figure 3.2 Competitive analysis assessment

	USA	China	Germany	Norway
1. Economic				
1.1 Trade relations	1	0	1	2
1.2 Access to finances	2	0	1	0
1.3 Ease of doing business	2	0	1	2
2. Environmental				
2.1 Other hydrogen applications in –country	1	1	1	0
2.2 Ports and other infrastructure	2	2	1	1
2.3 Feedstock for generation	2	1	1	2
2.4 Delivery times and distance	0	1	0	0
2.5 Access to electricity for hydrogen production	0	2	2	2
3. Political				
3.1 Government stability and support	1	2	1	1
3.2 Regulatory settings	1	1	2	0
3.3 Government transparency	1	-1	1	2
4. Technical				
4.1 Experience in delivering similar technologies or resources	2	2	1	2
4.2 Availability of human and technological resources	2	2	2	1
4.3 Adaptability in a changing environment	1	1	0	0
Overall rating	**Strong competitor**	**Competitor**	**Strong competitor**	**Strong competitor**

2	Favourable to hydrogen exports
1	Mildly favourable
0	Neutral to hydrogen exports
-1	Mildly unfavourable to hydrogen exports
-2	Unfavourable to hydrogen exports

France	Brazil	Qatar	Australia	Singapore	Saudi Arabia
1	0	0	2	2	2
-1	-1	0	2	2	0
1	-1	-1	2	2	-1
1	0	0	1	0	1
1	2	2	2	2	2
1	1	2	2	-1	1
0	1	1	1	1	1
2	1	0	0	2	0
1	0	1	1	1	0
0	0	1	0	0	1
1	-1	0	2	1	0
1	1	2	2	1	2
1	0	1	2	2	1
0	-1	0	0	0	0
Competitor	**Competitor**	**Competitor**	**Strong competitor**	**Strong competitor**	**Competitor**

The purpose of the multi-criteria assessment is to understand Australia's competitiveness against current hydrogen exporters. The particular criteria were chosen as we believe they are the components that a country should have to support a hydrogen export market. Although the rankings were not weighted, in practice it is likely that some of the criteria will prove to be more important – such as feedstock for generation, access to electricity for hydrogen production, the ability to drive investment (captured under the economic section) and innovation abilities (captured under the technical section).

Based on the multi-criteria assessment, strong competitors in the hydrogen export market are the US, Germany, Singapore, Norway and Australia. It is expected that going forward it is expected that the hydrogen industry will be global in nature. Further, hydrogen will generally be shipped and there will be costs associated with shipping. However, shipping costs are marginal and the additional costs of shipping longer distances required to obtain hydrogen from various countries that we examined are not expected to prohibit supply from any given country.

Australia performs very well in the economic criteria as it has high ratings with the World Bank in terms of access to finance and ease of doing business. Australia also has strong trade relationships with China, Japan and South Korea – expected major importers. Further, Australia is heavily involved in the export of natural resources and energy resources, which can be leveraged for use in the hydrogen export market.

From an environment perspective, Australia, both at the federal and state level, is examining the role of hydrogen. State strategies for hydrogen have been published by South Australia, Queensland and Western Australia, and Victoria is expected to release theirs in 2019. States have earmarked funds to help with the implementation of these strategies and the Australian Renewable Energy Agency (ARENA) has made substantial investments in funding hydrogen research projects. Australia is in a good position to leverage strong maritime infrastructure and experience in developing LNG infrastructure and its experience in exporting fuels. Further, given its large tracts of land, together with its ample natural gas, sun, wind and general water access Australia is well poised to be able to produce hydrogen at scale. Australia also has an advantage in relation to competitors in relation to delivery times and distance due to its location in the Asia-Pacific; however, it is noted that this is a relatively minor advantage in the longer term and this advantage does not extend to other possible import markets

Australia is incredibly competitive in key areas such as experience in delivering similar technologies, feedstock for generation and ports and infrastructure. Access to electricity for hydrogen production is one area where Australia rates neutral; however, several energy market reforms are currently underway which is likely to increase the reliability of Australia's energy supply. As a global leader in energy exporting, and the largest exporter of LNG in 2018, Australia is able to leverage its experience and reputation to enable the country to more easily pivot to exporting hydrogen than other countries will be able to do. As reflected in the Issues Paper series published by the National Hydrogen Taskforce, there are substantial learnings flowing from Australia's LNG experience that can be applied directly to how Australia can most effectively and efficiently scaleup hydrogen production. This in turn can provide a competitive advantage by having a more coordinated and considered approach to the scaling of hydrogen production.

Further, Australia has shown an ability to innovate and develop new technologies and the workforce is generally highly skilled. However, while there is some evidence of its ability to adapt to changes in the energy market or embrace new technologies, the timing and ability to embrace both changes in the energy market and new technologies is not as well established.

There is currently broad government support for the development of settings that will be needed for Australia to capture a portion of any future hydrogen export market. There is a wide-range of current activities occurring across Australia, such as state-led hydrogen roadmaps, strategies and industry development plans backed with funding programs, CSIRO's National Hydrogen Roadmap and soon to be released Research, Development and Demonstration report. This activity is the starting place for the support required for the hydrogen industry to flourish.

Energy security is a critical aspect of a country's energy importing strategy. Importing countries will want to diversify to ensure secure fuel supply by diversifying suppliers and fuel types. Energy security in this context refers to an ability of an importing nation to have sufficient fuel sources to meet its demand. It is therefore, unlikely that any one country will capture an entire importing country's demand. As energy forms an integral aspect of the overall economy, importing countries will also want to have trusted trading partners. Australia has proven itself a trusted energy trading partner and that reputation will be able to be leveraged in a hydrogen export marketplace. Australia's strong trade relationships with many of the Asian countries who are likely to be major importers of hydrogen, including China, Japan and South Korea.

The US is currently the number one hydrogen exporter, and has ranked high in the technical, environment and economic areas of the multi-criteria assessment. The World Bank Ratings for access to finance, ease of doing business, and high-levels of skilled labour, coupled with its current market power, provide an initially very strong position for the US. Domestic use for hydrogen is primarily limited to historic industrial uses, aside from some hydrogen transportation initiatives federally and in California (which has a target of 200 hydrogen refuelling stations across the state by 2025). Whether these types of policies will be rolled out to other states remains a question. A key challenge for the US arises from the nature of its trade relationships. The US is currently in challenging trade negotiations with key potential trading partners. The outcomes of those negotiations and ongoing trade relations under the current and future administrations coupled with the future domestic hydrogen policy settings are likely to be key factors of consideration in whether, and to what extent, the US is able to capture new export market opportunities.

Germany has a number of hydrogen demonstration and commercial projects underway, including hydrogen injections in the gas network and renewable gas incentives and hydrogen mobility applications (including the first hydrogen-powered train). Germany is known as a leader in technology and innovation with a highly skilled workforce, and is currently one of the larger hydrogen exporters. However, Germany does not have access to the same degree of land, sun or wind resources as other competitors, especially Australia. This may prove particularly challenging if Germany was to want a significant stake in the export opportunity with key markets indicating a preference for clean hydrogen.

Singapore also has the same challenge as Germany with respect to the natural resources, only exacerbated. However, like several of the competitor countries, Singapore does provide strong economic stability to drive investment and has good port infrastructure. Singapore is a major trading partner to several of the countries that will be strong importers of hydrogen and has existing port infrastructure and is a major shipping hub which can be leveraged to become a major player in the hydrogen export market. Further, Singapore has a stable government with the ability to rally significant resources to pursue new government policies and strategies. It is acknowledged that Singapore will have to carefully consider some aspects of the hydrogen production value chain – particularly related to production with either renewable resources or blue hydrogen where CCS is pursued given its limited access to these types of resources. However, given these only form one part of the picture and Singapore may pursue a strategy where it is both a major importer and exporter, Singapore's role in the export market going forward was considered as part of the analysis.

Norway has signalled its interest in exporting hydrogen to key trading partners like Japan, with Norway and Japan looking to demonstrate the transportation of liquid hydrogen produced from renewable energy. Norway's experience with exporting energy coupled with the large amounts of natural gas and renewable energy provide a solid base from which it could increase its hydrogen production. Compared to other countries, such as Australia, it may not be as well positioned geographically with respect to key Asian trading partners.

All countries examined are likely to be at least a competitor with Australia due to the country already having an established hydrogen export market. A key differentiating factor between countries who are strong competitors is the ability to drive investment shown through the economic rankings. China, Brazil, France, Qatar, Saudi Arabia are ranked as competitors and clearly suffered due to their access to finance or ease of doing business and government transparency.

China did perform strongly in some areas, including government stability and experience delivering similar technologies; however, this is offset by unfavourable conditions relating to government transparency.

Brazil and Qatar do have strengths in relation to experience in similar industries, access to electricity for hydrogen production and access to feedstock that can be leveraged to increase their competitive position. Implementation of government policies aimed at promoting hydrogen development may overcome some of the weaknesses present at this time.

Saudi Arabia is not currently ranked as a strong competitor. However, it is currently building relationships with Japan that may move them towards becoming a strong competitor in the export market. These countries are investigating the potential to extract hydrogen from crude oil that can then be transported via ammonia. Saudi Arabia is the 9^{th} largest producer of ammonia, has good port infrastructure, and ranked highly for feedstock for generation. Further, given access to sovereign funding, similar to Qatar, if the country decides to put its efforts into the development of a hydrogen market, its relative competitive position may change quickly.

4 Market Growth Scenarios

4.1 What are scenarios?

Scenarios are rich, data-driven stories about possible tomorrows that can help organisations make better decisions today. Scenarios provide us with a structured way of thinking through and making strategic choices in the midst of uncertainty. In particular, they serve to test important questions to inform strategic decisions and possible pathways for the future and can provide signals and signposts about how the industry is developing.

Most importantly, scenarios are not forecasts or predictions about the future, but rather hypotheses that describe a range of possibilities for the future.

4.2 Scenario processes

Best practice scenario development creates scenarios that are plausible, distinctly different and internally consistent.

In determining the scenario framework, a 6-step process is followed:

1. Determine the focal question;
2. Identify the key drivers with potential to impact the future;
3. Determine the key uncertainties and then prioritise and cluster these;
4. Combine critical uncertainties into a scenario frame, forming the axis;
5. Define framing conditions for each scenario; and,
6. Test the hypothesis against each scenario, to determine the implications for strategic direction.

The developed scenarios test what international demand for hydrogen at all levels of the value chain may look like and the opportunities for Australia in the export market. When designing the scenarios, our approach was to start with drivers that will likely affect outcomes in a specific market.

As per the 6-step process, the focal question and sub-question where determined. In this case the focal question is: what does international demand for hydrogen at all levels of the value chain look like. The sub-question for the purpose of the analysis is: what export opportunities exist for Australia to capitalise on international demand.

In examining how to answer these questions it is necessary to determine what key drivers will impact on the development of the hydrogen industry. The key drivers were determined to be:

- levels of domestic and international demand for hydrogen;
- the position of Australia relative to other potential exporters of hydrogen; and,
- the speed of technological development.

The key uncertainties were then examined, recognising that how these factors play out will have a significant impact on the pathway that the hydrogen industry progresses along. These uncertainties include:

- government policies both domestically and internationally in relation to hydrogen, decarbonisation goals and other industry policies;
- the relative hydrogen technological change and adoption domestically and internationally;
- Australia's ability to develop its domestic hydrogen market to leverage technology, infrastructure and skilled workforce in meeting international demand;
- the proliferation of a substitute technology which displaces the role of hydrogen; and,
- level of global cooperation and trade.

These drivers and uncertainties formed the basis of developing four scenarios to allow for scenarios that were tied by the same factors but with variable outcomes that drive demand and Australia's share of international demand.

4.3 What do we see?

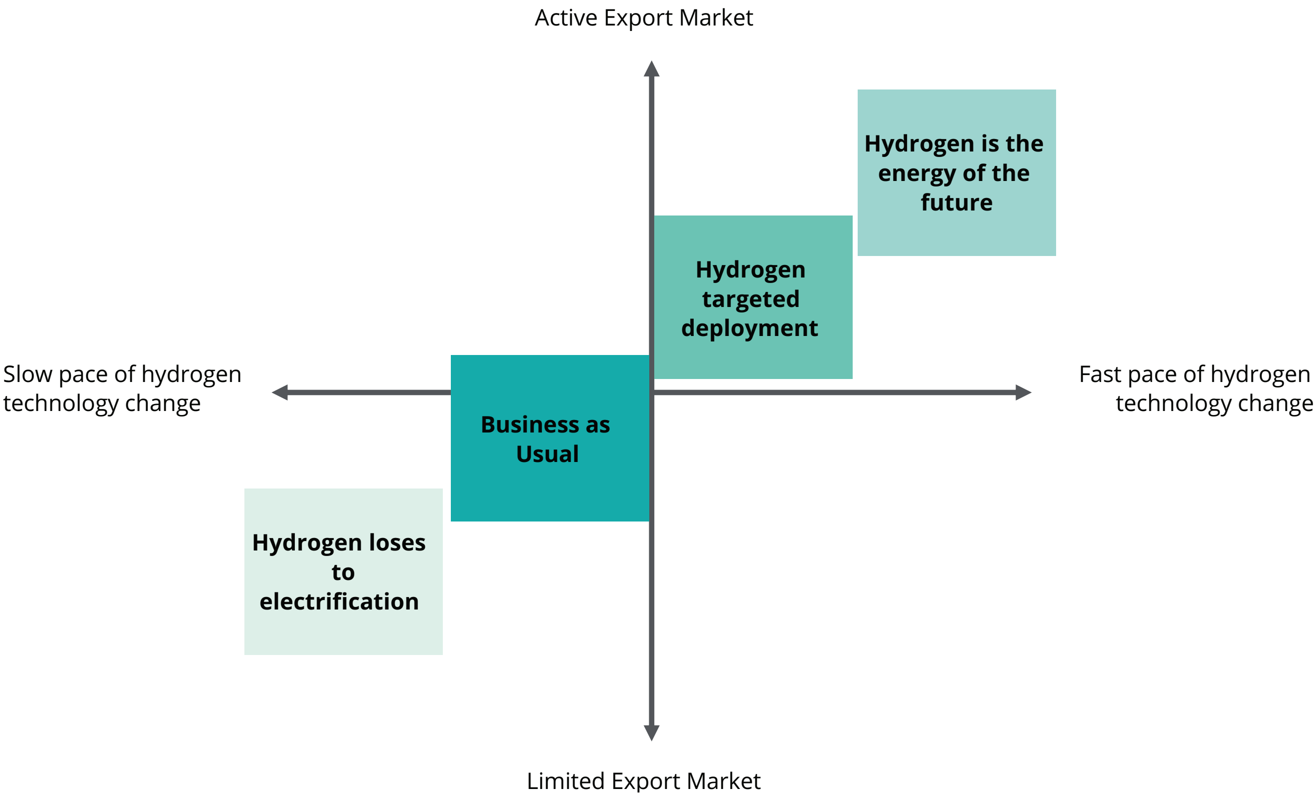
Deloitte has used two key drivers of change around which we have constructed the scenarios: Policy – both international and domestic; and, Technology – technology readiness level and commercial readiness level.

Policy refers to the extent that international and domestic policies target the removal of barriers and enable access for a hydrogen export market. That is, an active export market will constitute a large interconnected market with high export demand and a large number of participants enabled by supportive policy. While a limited export market will be a small market with low demand and a small number of participants with little to no policy implemented to remove barriers for hydrogen uptake.

In reality, the growth and competitiveness of the Australia hydrogen industry will likely be driven by a combination of new international and domestic policy supportive of hydrogen and hydrogen technology advancements. The new hydrogen industry is also likely to be driven by the cost of technologies and their relative cost-competitiveness to substitute energy sources. Policy is likely to be driven by a range of factors, including availability of technology and its attractiveness, environmental concerns, social concerns and price. Of these factors, historically, price has been the dominating factor driving change.

This is summarised in Figure 4.1 below.

Figure 4.1 Scenario map



The four scenarios modelled by Deloitte integrate both external and internal forces. External forces include policy – both international and domestic, technological advances and consumer acceptance. Internal forces include domestic and international outlook for hydrogen development, supply – including the costs of natural resources to produce hydrogen, substitutes, new entrants to the market and international competitiveness. Four plausible futures that could eventuate for Australia were developed through this process.

4.3.2 Hydrogen: *Energy of the future*

- Positive outlook
- Deep and early decarbonisation
- Hydrogen as fuel of choice
- Australia is a strong competitor in the export market
- Global and domestic views match
- Hydrogen deployed across all sectors
- Hydrogen across all areas of transport

The first scenario is ***Hydrogen: Energy of the future***. This scenario is the most optimistic in terms of both global and domestic demand potential. Demand is driven by supportive policy globally, to remove the barriers and enable access to uptake of hydrogen. Deep and early decarbonisation policies have not been aimed at a particular emissions reduction targets, nonetheless result in decarbonisation that goes well beyond countries current Paris commitments. Following are the key drivers and detailed parameters associated with this scenario:

Table 4.1 Key drivers and detailed parameters for Hydrogen: *Energy of the future* scenario

Key Drivers	Detailed Parameters
Highly positive future outlook for hydrogen uptake.	• Globally, stakeholders, governments and shareholders, see the role of hydrogen as important and it will continue to grow. • Investment potential and returns in the hydrogen sector are high for production, storage and transport facilities. • The useful cost of the use of hydrogen throughout the value chain is comparatively less expensive than alternatives.
Australian supply chain costs decrease rapidly.	• Production technology improves so that there are rapid declines in renewable energy, CCS and shipping and handling cost. • Utilisation technology improves and Australia industry rapidly changes, thereby driving quick technology learning rates, with the cost of new hydrogen production, transport and storage technologies decreasing. • The Australian hydrogen industry capitalises on the experience gained through the development of the existing LNG export industry. • There are no barriers to the use of hydrogen in distribution pipeline infrastructure as the maximum amount of hydrogen that can be mixed with natural gas is addressed through low-cost processes. • Piloting and trials of hydrogen deployment happen immediately with widespread deployment occurring several years prior to 2030.
Domestic government policies stimulate hydrogen uptake in all possible sectors of the economy including transport, industrial processes, and power generation and hard to abate industries (resources, chemical and steel manufacturing and agriculture sectors).	• Domestic policy removes barriers and streamlines processes, allowing for timely infrastructure investment and coordinating hydrogen generation with network resources. • Energy policies encourage coordination between the location of hydrogen facilities with generation and network resources.

Key Drivers	Detailed Parameters
Most foreign governments that cannot cost competitively produce hydrogen choose to import it as it is cost effective to do so. Government policies aim for early and deep decarbonisation which promotes finding alternatives to traditional fossil fuels throughout the value chain, hydrogen being only one aspect of the overall strategy.	• Countries import hydrogen where they have insufficient land, CCS sites, water resources and renewable resources to enable clean hydrogen production. • Hydrogen is deployed to aid in meeting the objectives of government policies enacted for early and deep decarbonisation. • As a result of policy drivers, there is a change in energy mix that results in a decoupling between energy and economic growth. • Countries use hydrogen to decarbonise hard to abate sectors like resources, chemical and steel manufacturing.
Australia builds and maintains a strong competitive position relative to other exporting countries.	• Hydrogen infrastructure is built upon the experience gained in developing the LNG export industry. • Governments encourage investment throughout the value chain but particularly in relation to production. • Australia leads technological innovation and adoption providing a cost advantage relative to other countries.
Proliferation of hydrogen use internationally in transport including long-haul transport, municipal fleets and public transportation as well as industrial processes, power and heat.	• Passenger and long-haul vehicles (new) are almost all hydrogen powered. • Government policies in developed countries require all fleet vehicles purchased to be hydrogen-fuelled and governments actively invest in supporting infrastructure (i.e. fuelling stations). • In countries where solar and wind resources are abundant, hydrogen is used for domestic and commercial heating to replace natural gas. • Where solar and wind resources are not plentiful and the country imports hydrogen, hydrogen is used as the fuel for generators to produce electricity as well as for domestic and commercial heating. • Steelmaking processes are adapted in all countries that make steel to use hydrogen direct-reduction processing.
High-levels of consumer acceptance of hydrogen use.	• Hydrogen becomes the fuel of choice for consumers. • The majority of consumers (stages 1 through 4) adopt some form of hydrogen use. This is based on the 5 stages of technology adoption: are innovators (stage 1), early adopters (stage 2), early majority (stage 3), late majority (stage 4) and laggards (stage 5). • The laggard group of technology adopters (stage 5) is adopting the most mature hydrogen technologies, including transport. • As a result of successful trials and community engagement both overseas and domestically, consumers are supportive of hydrogen use and no longer differentiate between hydrogen and other energy sources in terms of safety and technology acceptance. • Hydrogen production facilities can readily access suitable water resources.

4.3.3 Hydrogen: *Targeted deployment*

Moderate outlook

Decarbonisation policies in addition to those previously announced

Consumers understand the importance of hydrogen and electrification

Targeted Electrification deployment

Global and domestic views match

Targeted Hydrogen deployment

Australia has a share in the export market

The second scenario is ***Hydrogen: Targeted deployment.*** This scenario envisages an active export market but one where countries adopt a targeted approach to developing hydrogen in sectors where there is maximum economic value and benefits, creating investment opportunities in these areas. Iron ore exports from Australia are expected to be approximately $61 billion for 2018-2019 thereby being an important export.[65] The role of iron ore in steelmaking combined with the potential use of hydrogen in the process provides an opportunity for Australia to maintain or grow existing and new exports. Therefore, under the modelling, the steelmaking sector was targeted. Steelmaking was selected as it has the potential to create more value from hydrogen than straight fuel substitution and provides an opportunity to deploy a cost-effective low-emissions alternative process going forward.

Following are the key drivers and detailed parameters associated with this scenario:

Table 4.2 Key drivers and detailed parameters for Hydrogen: *Targeted deployment* scenario

Key Drivers	Detailed Parameters
Moderately positive future outlook for hydrogen uptake.	• Globally, stakeholders, governments and shareholders view the role of hydrogen as important in targeted sectors. • Investment potential and returns for hydrogen in the targeted sectors are considered moderate with potential for growth. • The useful cost of the use of hydrogen for end-use in the targeted sectors is comparatively less expensive than alternatives.
Australian supply chain costs drop quickly for targeted sectors with cost decreases in related sectors occurring at a more moderate pace.	• Production technology improves so that there are moderate declines in renewable energy, CCS and shipping and handling costs. • Utilisation technology improves so that there are moderate declines in costs. • Uptake in targeted sectors resulting in rapid decline in supply chain costs. • There are improvements in the efficiency of balance of plant technology in mature production technologies. • Piloting and trials of hydrogen deployment happen immediately in the targeted sectors with widespread deployment in these sectors occurring several years prior to 2030. • Remaining sector deployment is more moderate and occurs after 2030.
Domestic government policies stimulate uptake in targeted sectors of the value chain and reduce non-price barriers to uptake in targeted sectors of the economy.	• Australian governments adopt policies to enable access for hydrogen deployment in targeted sectors. • Licensing and approval processes related to the target sectors are streamlined, allowing for greater ease in deploying hydrogen.

Key Drivers	Detailed Parameters
Most foreign governments that cannot cost competitively produce hydrogen choose to import it and set policies to incentivise hydrogen in particular sectors of the value chain where it is cost effective to do so. Governments adopt decarbonisation policies in addition to those previously announced with hydrogen deployment being one aspect of the strategy.	• Several developed countries, including Japan, South Korea, China and the United States adopt policies specifically targeting deployment of hydrogen in selected sectors. • The policies adopted by these nations support hydrogen uptake in selected sectors but at different levels of ambition, incentives and targets. • Countries import hydrogen where they have insufficient land, CCS sites, water resources and renewable resources to enable clean hydrogen production. • Hydrogen is deployed as one of the means to achieving decarbonisation objectives.
Australia can build new relationships or has trade relationships with those foreign governments that have set hydrogen targets.	• Australia already has strong trade relationships with early movers in the hydrogen import market – Japan, South Korea and China. • The Commonwealth Government actively pursues trade relationships with countries that have set hydrogen targets or are expected to set hydrogen targets. • Australian government agencies collaborate with industry participants to quickly build markets through the leveraging of existing relationships between those industry participants and stakeholders in international markets.
Australia faces competition in the export market including from other countries with similar competitive advantage.	• Australia's main competitors in the export market – the United States, Germany and Norway – adopt government policies that provide certainty for investors, reducing the risk of investment in these countries and increasing their attractiveness to international investors. • Australia's policies provide similar signals for international investment in the hydrogen sectors as its competitors. • Australia has a moderate share of the export market.
Proliferation of electrification technologies in relation to end-user applications in non-targeted hydrogen sectors.	• At the same time as hydrogen deployment in the targeted sector, electricity costs decrease globally given technological advancements. • Electrification, and other decarbonisation technologies, fulfil the decarbonisation challenge in the sectors where hydrogen is not deployed as these technologies are more compelling.
Moderate levels of consumer acceptance of hydrogen use.	• Consumers accept the use of hydrogen in targeted sectors of the value chain and the use of electrification technologies in non-targeted sectors. • A small segment of consumers, or innovators, accept and deploy hydrogen use in all sectors. • Early majority (stage 3) moving into late majority (stage 4) of consumers (based on the 5 stages of technology development) accept the use of hydrogen in the targeted sectors of the value chain. • In non-targeted sectors, consumer deployment remains with innovators (stage 1) and early adopters (stage 2) of technology. • Successful trials in the targeted sector and community engagement results in change in perception and community acceptance of hydrogen use. • Hydrogen production facilities can readily access suitable water resources.

4.3.4 *Business as usual*

Minimal outlook

Decarbonisation polices align with those currently announced

Export market share is small

Global and domestic views do not match

Consumers understand the importance of hydrogen and electrification

The third scenario is ***Business as usual***. In this scenario, global and domestic views on the importance of hydrogen are in disconnect. Hydrogen is important internationally and deployed across targeted sectors. In this scenario, there is minimal future outlook for hydrogen uptake domestically.

Following are the key drivers and detailed parameters associated with this scenario:

Table 4.3 Key drivers and detailed parameters for *Business as usual* scenario

Key Drivers	Detailed Parameters
Minimal future outlook for hydrogen uptake.	• Domestic stakeholders, governments and shareholders view the role of hydrogen as on possible pathway forward and continue to explore the various pathways. • International stakeholders, governments and shareholders view the role of hydrogen as important especially in targeted sectors, resulting in moderate growth over time. • Investment potential and returns in the hydrogen sector exist and are moderate in the targeted sectors. • The useful cost of the use of hydrogen for end-use in the targeted sectors is comparatively less expensive than alternatives internationally but there is minimal impacts domestically.
Australian supply chain comparative costs decrease only marginally.	• Production technology improves moderately so that there are some declines in renewable energy, CCS and shipping and handling costs. • There are some improvements in hydrogen utilisation technology with some decline in costs. • Selected domestic deployment results in marginal reduction in supply chain costs. • Piloting and trials of hydrogen deployment occur slowly between now and 2030 with deployment only starting to occur slowly after 2030.
Limited domestic policies and programs encourage hydrogen uptake. Policies reduce non-price barriers to uptake of decarbonisation technologies.	• Domestic policy reforms focus on decarbonisation through the most efficient means. • Policies address non-price barriers associated with any specific technology or deployment in any sector of the value chain.
Several foreign governments that cannot cost competitively produce hydrogen choose to import it and set policies to incentivise hydrogen in particular sectors of the value chain as it is cost effective to do so. Government policies are set to meet currently announced 2030 and longer-term Paris commitments with hydrogen only forming one small part of the strategy.	• Several developed countries, including Japan, South Korea, China and the United States adopt policies specifically targeting deployment of hydrogen in selected sectors. • The policies adopted by these nations target selected sectors but have different levels of incentives, targets and effectiveness. • Countries import hydrogen where they have insufficient land, CCS sites, water resources and renewable resources to enable clean hydrogen production. • The decarbonisation policies generally focus on the major sectors of the economy for emissions – energy, with minimal impact on hard to abate sectors, including resources, chemical and steel manufacturing and agriculture sectors. This results in less proliferation of hydrogen throughout the value chain.

Key Drivers	Detailed Parameters
Australia can build new relationships or has trade relationships with those foreign governments that have set hydrogen targets.	• Australia already has strong trade relationships with early movers in the hydrogen import market – Japan, South Korea and China. • Governments actively pursues trade relationships with countries that have set hydrogen targets or who are expected to set hydrogen targets. • Australian government agencies collaborate with industry participants to quickly build markets through the leveraging of existing relationships between those industry participants and stakeholders in international markets.
Australia faces significant competition in the export market including from other countries with similar competitive positions.	• Without policies to encourage hydrogen uptake, Australia captures a smaller share of global hydrogen demand. • Strong competitors – like the United States, Germany and Norway – adopt government policies, providing certainty to investors and increasing their international competitiveness. • The resulting investment leads to major overseas innovations, with Australia quickly adopting hydrogen technology upon it being trialled and tested.
Proliferation of electrification technologies in relation to end-user applications in most sectors of the value chain.	• At the same time as hydrogen deployment in the targeted sector internationally, electricity costs decrease globally given technological advancements. • In sectors where hydrogen's role is not as compelling, electricity is deployed. • Australia focuses efforts on further developing the individual roles that both hydrogen and electrification possess across the value chain.
Minimal levels of consumer acceptance of hydrogen use in Australia with moderate levels of consumer acceptance in importing countries.	• Consumers understand the roles both hydrogen and electrification technologies play in the decarbonisation challenge. • Domestically, consumer deployment remains with innovators (stage 1) and early adopters (stage 2) of technology. • Internationally, early stage majority (stage 3) consumers adopt hydrogen technologies. • Limited successful trials and minimal international or Australian public outreach related to hydrogen means that only innovators and early adopters embrace hydrogen technologies. • Internationally, countries that import hydrogen deploy domestic hydrogen education programs and outreach programs to allow for more wide-spread acceptance of hydrogen. • Hydrogen production facilities can readily access suitable water resources.

4.3.5 *Electric breakthrough*

- Minimal outlook
- Decarbonisation policies in addition to those previously announced
- Electrification as fuel of choice
- Electric vehicles across all areas of transport
- Global and domestic views match
- Electrification deployed across all sectors
- Hydrogen export market share is small
- Battery innovation high

The last scenario is ***Electric breakthrough***. In this scenario the electrification wins as the technology of choice. There is minimal future outlook for hydrogen uptake due to cost breakthroughs on electrification technologies. The key drivers and detailed parameters of this scenario follow:

Table 4.4 Key drivers and detailed parameters for *Electric breakthrough* scenario

Key Drivers	**Detailed Parameters**
Minimal future outlook for hydrogen uptake	• Other decarbonisation technologies, i.e. electrification, become more compelling. • Hydrogen uptake interest shifts to positive future outlook for electrification.
Australian supply chain comparative costs decrease slowly and marginally.	• Policies focus on removing barriers for electrification technologies. • This alternate focus means mature hydrogen production technologies only marginally improve. • Advances in battery and charging technology for electric vehicles creates strong competition for the deployment of hydrogen vehicles and refuelling infrastructure. • Hydrogen's role in industrial processes and heat faces barriers as the case for other technologies becomes more compelling.
Domestic and international government policies and programs achieve decarbonisation at lowest cost and do not specifically target or promote hydrogen development.	• Policies focus on enabling the adoption of electrification. • This alternate focus means mature hydrogen production technologies only marginally improve and development, testing or use of new technologies is driven by innovators only. • Minimal hydrogen vehicle deployment and associated refuelling stations – selected deployment generally to long-haul vehicles. • Hydrogen's role is reserved for used in industrial processes and heat, as there is minimal improvement in costs and infrastructure investment. • Domestically and internationally, policy reforms are about decarbonisation through the most efficient means. • Policies do not specifically address non-price barriers associated with hydrogen development or deployment in any sector of the value chain.
Most foreign governments that previously explored the role of hydrogen have shifted to different technologies and solutions to meet their decarbonisation goals consistent with scenario 2 above, as they present the most efficient means to decarbonise.	• Several developed countries, including Japan, South Korea and China move away from their hydrogen commitments as other technologies become more compelling. • These same countries implement new policies that support electrification. • Countries use electricity to decarbonise hard to abate sectors, for example, resources, chemical and steel manufacturing and agriculture sectors.

Key Drivers	Detailed Parameters
Australia can build new relationships or has trade relationships	• Australia already has strong trade relationships with earlier movers in the hydrogen import market – Japan, South Korea and China. • Governments actively pursues trade relationships with countries that have set hydrogen targets or who are expected to set hydrogen targets. • Australian government agencies collaborate with industry participants to build markets through the leveraging of existing relationships between those industry participants and stakeholders in international markets.
Australia's competitive position relative to other exporters is not a factor.	• Australia is a strong competitor in the export market but faces competition from other exporters to meet the low levels of demand internationally.
Proliferation of electrification technologies in all sectors of the value chain as battery and charging technology progresses rapidly.	• Electricity costs decrease globally. • Technological advancements significantly increase the capacity factor of renewable energy resources providing increased energy output with the same input. • Electricity is deployed across all sectors of the value chain. • Technological advances allow easy and inexpensive ways to firm intermittent generation. • Battery charging times decrease significantly and battery life is extended.
There is wide-spread acceptance of the use of electrification in all sectors by stakeholders.	• Electricity becomes the fuel of choice and alternative of consumers. • The majority of consumers (stages 1 through 4) adopt new electrification technologies and uses, based on the 5 stages of technology adoption. • The laggard group of technology adopters (stage 5) has adopting the most mature electrification technologies. • Due to unsuccessful trials or trials that resulted in the identification or perception of safety risks, hydrogen use is not widely accepted. • On the other hand, people are generally comfortable with the use of electricity and willing to accept its wider use. • Hydrogen production facilities can readily access suitable water resources.

4.3.6 Impact of decarbonisation aspirations on modelling

In developing the scenarios, decarbonisation aspirations include the use of Shared Socio-economic Pathways (SSPs) which were developed as part of the Integrated Assessment Model (IAM) project which flows from the Intergovernmental Panel on Climate Change's (IPCC) reports.

The SSPs form a set of narratives to describe five internally consistent, distinctly different and plausible futures for the world. The narratives enable the exploration and examination of climate change impacts, vulnerabilities, adaptation and mitigation. The scenarios are designed to address two challenges – the level of mitigation and adaptation achieved globally:

- challenges to mitigation – this explores climate forcing (which is a variable connecting the emissions trajectory to a future degree of warming); and,
- challenges to adaptation – explores socio-economic conditions present to describe the future ability to adapt to climate change.

The descriptions of the SSP scenarios are contained in Appendix B.

The framework is used as one input in relation to the modelling to examine impacts on the technology mix of hydrogen production technologies and the rate of decarbonisation of the electricity grid. This results in the modelling not being targeted to any particular emissions reduction target but rather it is about the speed with which government policies aim to decarbonise parts of their economy.

5 Modelling inputs and assumptions

This section provides the key modelling inputs and assumptions used in developing the global market demand, Australian market demand, economic impact analysis and environmental impact analysis across the four scenarios. The inputs used in the model are a combination of publicly available information and Deloitte analysis based on multiple public sources, industry knowledge and current projects. Appendix E contains inputs that were sources from a single publically available source. All other inputs are proprietary information of Deloitte and are not released publicly.

5.1 Overriding assumption inputs

Some assumptions override any scenario, including the following:

Overriding Assumption	Description
Cost elasticity function	A model assumption that increases demand for hydrogen for every percentage decrease in price.
Cost of shipping to key export markets	A model assumption that determines the total cost of moving hydrogen from Australia to key export markets.

The cost elasticity function relates to how much additional demand there would be for hydrogen for a certain application for every percentage decrease in the cost of delivered hydrogen, with demand accelerating when delivered hydrogen becomes more cost competitive than its alternatives.

For the cost of shipping assumption, hydrogen is assumed to be exported from Port Hedland in Western Australia to import terminals in key markets like Tianjin (China), Tokyo (Japan), Incheon (Korea) and Singapore (Rest of the World). It is noted that there several potential methods of shipping hydrogen with the more mature options including liquefied hydrogen, ammonia and methylcyclohexane.
The shipping costs, and overall end-to-end delivery efficiencies, using these different carriers is highly uncertain and generic shipping costs sourced from CSIRO have been used instead. The most economic carrier will eventually be used and there is not yet any indication on which this will be. Detailed technical assessment and modelling has not been completed as part of the scope for this report.

5.2 Technology specific assumptions

Technology specific assumptions change for each of the four scenarios. There are three model assumptions that fall into this category:

Technology Specific Assumption	Description
Technology learning rate	Relates to the rate of decrease in the cost of producing hydrogen throughout the value chain.
Electrolyser proportion by technology	Relates to the proportion of technology type for hydrogen production through the forecast period.
Carbon intensity of the Australian electricity grid	Affects the carbon emissions related to the production of hydrogen from electrolysis.

Table 5.1 Model inputs across scenarios

Scenario	Technology Learning Rate	Electrolyser Proportions by Technology	Carbon intensity of the Australian	Sensitivity analysis for carbon intensity of the Australian electricity grid
1. Energy of the future	The costs of producing hydrogen reduce aggressively making hydrogen much cheaper in the long-run than in the other scenarios.	Aggressive transition away from fossil-fuel based hydrogen production technologies to electrolyser technologies to 90% by 2050.	Net zero by 2050	Net zero by 2050
2. Targeted deployment	As Scenario 1.	A moderate transition to electrolysers with 50% penetration by 2050.	Consistent with a linear extrapolation to 0.2kg CO2/kWh produced in in 2050	Consistent with a linear extrapolation to 0.4kg CO2/kWh produced in in 2050
3. Business as usual	Slow reduction in technology costs.	A slow transition to electrolysers with only 5% penetration by 2050.	Consistent with a linear extrapolation to 0.4kg CO2/kWh produced in 2050	Consistent with a linear extrapolation to 0.4kg CO2/kWh produced in 2050
4. Electric breakthrough	Moderate reductions in technology costs.	As Scenario 1	Consistent with a linear extrapolation to 0.2kg CO2/kWh produced in in 2050	Consistent with a linear extrapolation to 0.4kg CO2/kWh produced in in 2050

Technology learning rates
Under the *Energy of the future* and the *Targeted deployment* scenarios, costs of producing hydrogen under all technologies experience aggressive reductions in technology costs, making hydrogen much cheaper in the long-run than in the other scenarios. Technology costs fall slowest under the Business As usual scenario as limited investment in hydrogen production in Australia sees limited improvements made in hydrogen technology. The *Electric breakthrough* scenario sees low-moderate reductions in technology costs.

Electrolyser proportions by technology
Under the *Energy of the future* and the *Electric breakthrough* scenarios, hydrogen production transitions aggressively away from fossil-fuel based hydrogen production technologies like coal gasification and steam methane reforming to electrolyser technologies like PEM. Under these scenarios, electrolysers produce 90% of all hydrogen production by 2050.

Under the *Targeted deployment* and *Business as usual* scenarios, the transition to electrolyser is slower, with electrolysers making up 20% of total hydrogen production in *Targeted deployment* and only 5% of total hydrogen production in the *Business as usual* scenario by 2050. A slower transition to electrolyser technology may be due in part to a relatively slower reduction in electrolyser costs.

Carbon intensity of the Australian electricity grid
This model assumption looks into the degree of decarbonisation within Australia's electricity grid, and has a significant impact on the carbon intensity of electrolysis-produced hydrogen. In scenarios heavily dependent on electrolysis technology, such as *Energy of the future* and *Electric breakthrough*, carbon intensity has a significant impact on total carbon emissions from Australian-produced hydrogen.

The *Energy of the future* scenario has Australia's electricity grid decarbonising at the fastest rate of all four scenarios. The *Targeted deployment* and *Electric breakthrough* has moderate rates of decarbonisation of Australia's electricity grid. The *Business as usual* scenario aims to achieve the current rate of decarbonisation of Australia's electricity grid. The graph below shows the emissions avoided in all scenarios.

Sensitivity analysis for carbon intensity of the Australian electricity grid
Sensitivity analysis was also conducted, where in scenarios *Targeted deployment* and *Electric breakthrough*, the carbon intensity of the electrical grid followed the same pathway as the *Business as usual* scenario. This was done to assess the impact of grid decarbonisation rates on overall emissions from Australian hydrogen production across different scenarios.

5.3 Market specific assumptions

Market specific assumptions also change for each of the four scenarios with numerous model input assumptions driving the model outputs:

Proportion of market captured	A model assumption that refers to the proportion of an end-use application like steelmaking operations being captured by hydrogen. These are different for the Australian market and the generic international market.
Basic cost of competing fuels	A model assumption that refers to the cost of delivering competing fuels such as metallurgical coal and diesel. This impacts the overall cost competitiveness and hence impacts the Proportion of Market Captured.
Implied international cost of decarbonisation	An implied international cost of decarbonisation that could make carbon-intensive competing fuels more expensive compared to hydrogen. This impacts the mix of hydrogen technologies.
Implied Australian cost of decarbonisation	The price of carbon offsets that fossil-fuel-based hydrogen producers would purchase to ensure hydrogen production was carbon neutral. This impacts the mix of technologies and the carbon impacts from hydrogen growth. If CCS technology is cheaper than carbon offsets, fossil fuel producers will switch to CCS technology instead.
Australia's market share	Refers to the proportion of key export markets for hydrogen that Australia secures.

How these model inputs vary across the scenarios is summarised below.

Table 5.2 Proportion of market captured by scenarios by 2050

%	**Proportion of Domestic Market Captured by 2050**					**Proportion of International Market Captured by 2050**				
Scenario	**Pipeline Gas**	**Industrial Heat**	**Steel**	**Transport Fuels**	**Feedstock**	**Pipeline Gas**	**Industrial Heat**	**Steel**	**Transport Fuels**	**Feedstock**
1. Energy of the future	40	50	100	50	50	25	30	100	50	50
2. Targeted deployment	10	15	100	10	25	10	15	100	10	25
3. Business as usual	5	8	15	3	13	10	15	30	5	13
4. Electric breakthrough	1	4	0	0	25	1	4	10	0	25

Source: Deloitte Analysis

Proportion of market captured

This model assumption looks into what proportion of end-use applications might be captured for hydrogen use under each scenario. These proportions are determined by factors such as hydrogen cost reductions, government support in various markets and global drive towards decarbonisation. The proportions of use-case markets captured by hydrogen have a significant impact on the final demand figures resulting from the model. The assumptions above have been designed to reflect a range of possible future worlds. The assumed values are highly debateable and are not intended to be accurate forecasts of the future but rather a range of possible outcomes to provide guidance on how the sector may grow over time. There is a clear logic between the relative differences across the scenarios but the actual proportions have the potential to differ materially.

The demand component for industrial feedstock looks at the demand for clean hydrogen for the production of industrial feedstock such as ammonia.

The proportion of industrial feedstock market captured in the model refers to the proportion that is captured by green hydrogen. The proportions captured differ by scenario.

Under the *Energy of the future* scenario, hydrogen penetration rates are the highest. In this scenario, 40% of all domestic gas needs are met by hydrogen, 50% of domestic industrial heating operations use hydrogen, 100% of domestic steelmaking operations use hydrogen, 50% of all domestic transport fuels and all industrial feedstock for ammonia and other chemicals use hydrogen. Internationally, 25% of all gas needs, 30% of all industrial heating, 100% of steelmaking and 50% of transport fuels and feedstock use hydrogen.

The *Targeted deployment* scenario sees a strong focus on hydrogen for steelmaking purposes and transport fuels, with relatively lower penetration rates in other sectors. 10% of both domestic and international gas needs are met by hydrogen, 15% of industrial heat, 100% of steelmaking and 10% of transport fuels use hydrogen. The feedstock proportion also remains relatively high at 25% due a lack of alternative options.

The *Business as usual* scenario sees smaller penetration rates across the economy for hydrogen although the international demand is seen to increase more than the Australian demand as signalled by current global policy initiatives. In Australia 5% of pipeline gas, 7.5% of industrial heat, 15% of steelmaking, 2.5% of transport fuels and 12.5% of industrial feedstock are assumed to use hydrogen. Internationally, 10% of pipeline gas needs, 15% of industrial heat, 30% of steelmaking, 5% of transport fuels and 12.5% of industrial feedstock are assumed to use hydrogen.

The *Electric breakthrough* scenario sees the smallest penetration rate for most use cases as electrification provides solutions wherever possible. Hydrogen is assumed to be only used in 1.3% as the remnant of local and international pipeline gas sector, 3.8% of industrial heating loads and 10% of the international steel sector with no use across transport fuels. Because of the rapid decarbonisation under this scenario, industrial feedstock demand is still resilient with 25% market share assumed.

Table 5.3 Model assumptions across scenarios

Scenario	Cost of competing fuels	Implied international cost of decarbonisation	Implied Australian cost of decarbonisation	Australia's Market Share by 2050
1. Energy of the future	25% above base-case forecasted prices	Increases aggressively from AU$16.84/tCO2 to AU$145.73/tCO2 in 2050	Rapid increase from 2019's ACCU prices of AU$16.50/tCO2 to $74.88/tCO2 in 2050	Using current LNG market proxy: China – 14% Japan – 29% Korea – 14% RoW – 3%
2. Targeted deployment	25% above base-case forecasted prices	Moderate increase from AU$16.84/tCO2 to AU$39.89/tCO2 in 2050	Moderate increase from AU$16.50/tCO2 to AU$41.25/tCO2 in 2050	As Scenario 1
3. Business as usual	Base-case forecasted prices	No implied international cost of carbon	No implied Australian cost of carbon	Australia lags – 25% of current LNG proportion: China – 3% Japan – 7% Korea – 4% RoW – 1%
4. Electric breakthrough	Base-case forecasted prices	As Scenario 2	As Scenario 2	As Scenario 1

Source: Deloitte Analysis

Basic cost of competing fuels
This model assumption looks into base costs of fuels like natural gas, diesel, metallurgical coal and thermal coal. Some of these fuels are used in the production of hydrogen (thermal coal for coal gasification technologies and natural gas for SMR), so increases in these costs affect the cost-competitiveness of fossil-fuel driven hydrogen production.

Under the *Energy of the future* and *Targeted deployment* scenarios, hydrogen's pathway is made more competitive with competing fuels and this is achieved, in part, by applied a 25% uplift to forecast prices of those competing fuels. Under the *Business as usual* and *Electric breakthrough* scenario, all competing fuels use the base-case forecasted prices.

Implied international cost of decarbonisation
This model assumption is intended to be representative of the effects of various decarbonisation policies that could be adopted internationally to deliver the climate goals of various countries. It acts to add an implied cost of decarbonisation to competing carbon emitting fuels. As with all scenario assumptions, these are not a forecast of a likely transparent global price necessary for hydrogen uptake.

Under the *Energy of the future* and *Electric breakthrough* scenarios, the implied international cost of decarbonisation grows aggressively from AU$16.84/tCO2 to AU$145.73/tCO2 in 2050. In the *Targeted deployment* scenario, the implied international cost of decarbonisation grows more slowly from AU$16.84/tCO2 to AU$39.89/tCO2. Under *Business as usual*, no implied international cost of decarbonisation is active at all.

Implied Australian cost of decarbonisation
This model assumption looks into the cost of carbon offsets that fossil-fuel-based hydrogen producers could purchase to ensure hydrogen production was carbon neutral. Australian Carbon Credit Units (ACCUs) are used as a proxy for the offset price as this is the current market mechanism for providers that wish to offset emissions. Companies may also choose to invest in projects directly rather than buy credits from a market. This pricing is also taken as a proxy for any CCS that may be achieved over time in specific locations.

Under the *Energy of the future* and *Electric breakthrough* scenarios, carbon offset costs rise from the most recent ACCU auction prices of AU$16.50/tCO2 increasing up to $74.88/tCO2 in 2050. In the *Targeted deployment* scenario, carbon offset costs rise from AU$16.50/tCO2 to AU$41.25/tCO2.

Hydrogen producers who are dependent on fossil fuel feedstock, such as those using coal gasification or SMR technology, have the option of choosing between using these ACCU carbon offsets or using CCS technology to abate the carbon emissions from hydrogen production. The model assumes that producers will choose the cheaper of these two options. Because of the relatively rapid increase in ACCU prices under the *Energy of the future* scenario, CCS becomes price competitive with ACCUs in 2039. In *Targeted deployment* and *Electric breakthrough*, CCS becomes price competitive with ACCUs in 2041. In the *Business as usual* scenario, hydrogen producers do not use either offsets or CCS technology.

Table 5.4 Comparison between ACCU and CCS prices across scenarios in selected years

AU$/tonne	2019		2030		2050	
	ACCU	CCS	ACCU	CCS	ACCU	CCS
Scenario 1	$16.50	$121.68	$28.22	$99.91	$74.88	$67.63
Scenarios 2,4	$16.50	$121.68	$22.84	$90.19	$41.25	$45.09
Scenario 3	$0.00	$121.68	$0.00	$109.64	$0.00	$90.18

Source: Deloitte Analysis

In our modelling, CCS technology costs have been assumed to fall at different rates across the four scenarios, with costs reductions most rapid in the *Targeted deployment* and *Electric breakthrough* scenarios, followed by *Energy of the future* and finally *Business as usual*.

Under the *Targeted deployment* scenario, factors driving CCS cost reductions have been assumed to include the high proportion of hydrogen producers that continue using fossil-fuel as part of its production process. This relatively high demand for CCS technology should see greater investments made to make the technology increasingly more price competitive as time progresses.

Under the *Electric breakthrough* scenario, CCS technology costs fall because of broader strong decarbonisation initiatives in non-hydrogen related sectors of the economy. These decarbonisation initiatives see CCS costs fall rapidly, which benefits what little fossil-fuel based hydrogen producers that exist under this scenario.

CCS technology costs do not fall rapidly in *Energy of the future* because of the rapid uptake in electrolyser technology that does not necessitate deployment of CCS technology for hydrogen production. Finally, in *Business as usual*, there is limited incentive to invest in CCS technology, as fossil-fuel driven hydrogen producers are free to produce emissions without offsets.

Carbon offset assumptions

The hydrogen produced from fossil fuels has an increasing proportion of its production being offset using the forecast ACCU pricing for each scenario.

Under the *Energy of the future* scenario, 10% of all the production from fossil fuels is assumed to be offset from 2020 with this proportion increasing linearly to 100% by 2030.

Under the *Targeted deployment* and the *Electric breakthrough* scenarios, 5% of all the production from fossil fuels is assumed to be offset from 2020 with this proportion increasing linearly to 100% by 2035.

Under the *Business as usual* scenario, 5% of all the production from fossil fuels is assumed to be offset from 2025 with this proportion increasing linearly towards reaching 100% by 2070.

Australia's market share

This model assumption refers to the total hypothetical demand for hydrogen of a key export market that could be met by Australian production. The percentages represent the portion of a given market's (e.g. China) total energy consumption that would be met by Australian hydrogen exports. For example, in *Energy of the future*, *Targeted deployment* and *Electric breakthrough*, Australia supplies 5% of China's total energy demand in 2030 through hydrogen exports.

Table 5.5 Australia's market share by scenario

Scenario	Australia's Global Market Share 2030				Australia's Global Market Share 2050			
	China	Japan	Korea	RoW	China	Japan	Korea	RoW
Scenarios 1, 2 & 4 (LNG proportions by 2050)	5%	10%	5%	1%	14%	29%	14%	3%
Scenario 3 (25% of LNG proportions by 2050)	1%	3%	1%	0%	3%	7%	4%	1%

Source: Deloitte Analysis

Under the *Energy of the future*, *Targeted deployment* and *Electric breakthrough* scenarios, Australia is assumed to be able to capture 14% of China's total hydrogen demand, 29% of Japan's total hydrogen demand, 14% of Korea's total hydrogen demand and 3% of the rest of the world. These assumptions are taken from Australia's current LNG export percentages in these markets and are assumed to grow linearly to achieve these proportions by 2050. There is an argument that the final proportions should be applied to total global market across the forecast period but this approach was not used due to the nascent state of the current Australian sector.

The *Business as usual* scenario differs in that Australia lags behind the rest of the world and Australian hydrogen production is significantly reduced due to higher technology costs relative to the rest of the world. Under this scenario, Australia is only able to ultimately capture 25% of the proportions currently captured in the LNG market.

5.4 Economic impact modelling assumptions

The economic impacts of a hydrogen sector are assessed by comparing three distinct scenarios:

- The *Business as usual* scenario — which describes a world in which the global market for hydrogen expands gradually;
- The *Targeted deployment* scenario – in which countries adopt targeted approaches to maximise economic value and benefits for effort in the deployment of hydrogen; and
- The *Energy of the future* scenario — in which growth of the Australian hydrogen sector is supported by rapid expansion in international demand.

The main assumptions used to inform these scenarios are global hydrogen demand and supply as detailed in the outputs section of this report. These inputs, in terms of financial impacts to capital expenditure, operational expenditure and export revenues, are used as the 'shocks' imposed on the Computable General Equilibrium (CGE) Model analysis. Table 5.6 sets out the high level inputs to the analysis.

Table 5.6 Global hydrogen production in selected years across different scenarios

Scenario 1: Hydrogen: *Energy of the future*	2019 Production (Mt)	2050 Production (Mt)	CAGR
Domestic	0.1	6.1	15%
China	0.8	42.1	14%
Japan	0.1	8.6	14%
Korea	0.1	7.2	15%
RoW	0.6	169.7	20%
Total	1.6	233.7	17%

Scenario 2: Hydrogen: *Targeted deployment*	2019 Production (Mt)	2050 Production (Mt)	CAGR
Domestic	0.1	1.6	10%
China	0.8	21.1	11%
Japan	0.1	3.0	10%
Korea	0.1	2.8	11%
RoW	0.6	74.1	17%
Total	1.6	102.6	14%

Scenario 3: *Business as usual*	2019 Production (Mt)	2050 Production (Mt)	CAGR
Domestic	0.1	0.7	7%
China	0.7	13.0	10%
Japan	0.1	2.1	9%
Korea	0.1	2.0	10%
RoW	0.5	50.2	16%
Total	1.5	78.0	14%

Source: Deloitte Analysis

Further details of how the CGE operates are provided in Appendix C with a brief summary provided below.

A change in any part of the economy has impacts that reverberate throughout the economy. For example, the doubling of government expenditure on disability support services will involve increased economic activity in the disability services industry but it will also have a range of impacts in other parts of the economy:

- As the sector expands, it will draw in an increased volume of primary factors as well as intermediate inputs from related service, manufacturing and mechanical repair sectors.
- The additional taxation associated with funding the scheme may have an impact on peoples' labour supply (given it is partly funded by the Medicare levy) as well as other firm and household decisions (given it is also funded from consolidated revenue and thus company tax and a collection of indirect taxes).
- Apart from the direct effects of expanding services and taxation, the rollout will result in changed consumer spending by households whose income and employment have changed with the change in economic activity. This could mean a change in investment flows and consequently a changed capital stock.
- Importantly, increased activity will be recorded in the regions where this transformation is concentrated but there will also be altered activity levels in other areas which export to those more directly affected.

6 Modelling outputs

This section presents the results of the scenario modelling and provides scenario outputs for global market demand, Australian market demand, economic impact analysis and environmental impact analysis.

6.1 Global market demand

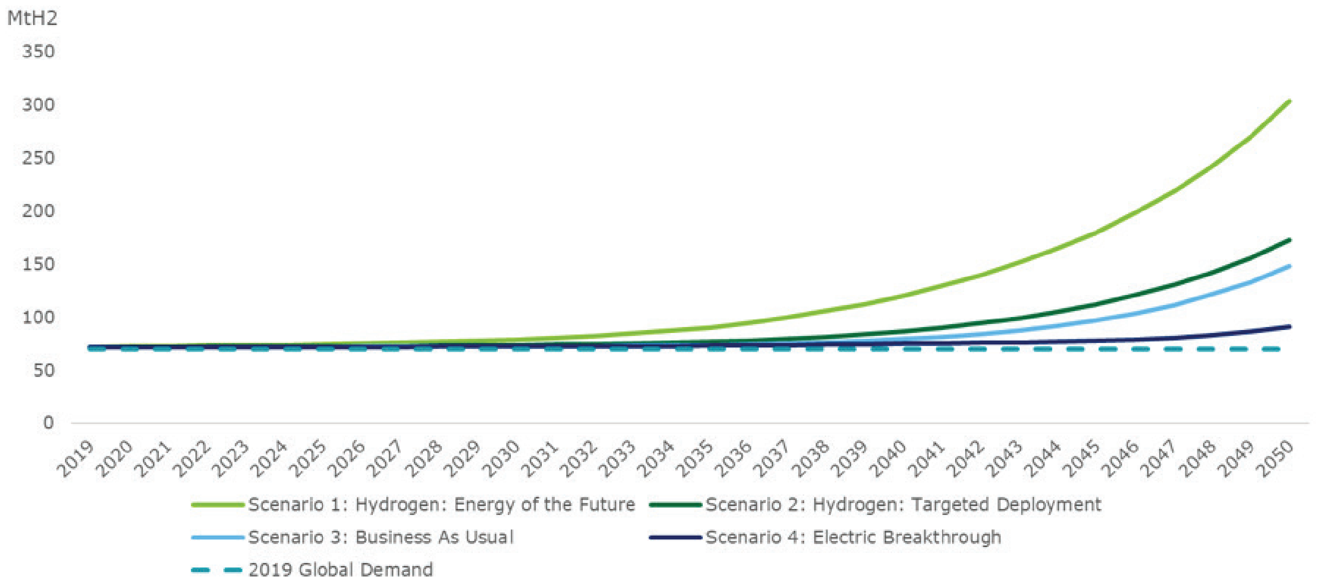
With all new industries, immediate changes to markets take time to develop and build a foundation for industry growth. Given hydrogen's versatility to act as both a carrier of energy and an industrial feedstock creates additional uncertainty regarding its exact future role in any given application. There are a number of pathways to different markets providing different opportunities, all with their own individual and unique barriers. As pathways are developed, connections between use cases build potential for sector coupling opportunities, also referred to as the compounding effect. All of this contributes to an uncertain image of what the hydrogen industry could look like in the future. A key outcome from all four scenarios however is that global market for hydrogen grows into the future. The final size, composition and rate of uptake differ significantly between each of the scenarios but all see some level of growth.

The scenario analysis maps a range of possible futures as to what an alternative and diverse hydrogen industry could look like internationally. The scenarios are not intended to represent forecasts but rather present a range of many possible futures to allow a current strategy to be developed cognisant of the wide range of futures which may need to be negotiated. This understanding of how the different drivers affect the timing, scale, composition and growth of the industry is important for setting realistic expectations for the future.

Current annual global demand for hydrogen is forecast to be approximately 70 Megatonnes per annum (Mtpa). The 2030 figures range from an additional 2.1 Mtpa to 8.8 Mtpa. This is consistent with the global demand forecasts from governments such as Japan targeting a 2030 additional hydrogen use of 0.3 Mtpa. Going forward, the global demand for hydrogen differs significantly across all four scenarios, with demand ranging from a high of 304 Mtpa of hydrogen by 2050 in the *Energy of the future* scenario to just over 90 Mtpa by 2050 in the *Electric breakthrough* scenario (Figure 6.1).

Demand is strongest in the *Energy of the future* and *Targeted deployment* scenarios, where global policies and rapid technological improvements encourage global uptake of hydrogen use across all sectors – including industrial and transportation. These two scenarios both assume the implied costs of action taken to decarbonise, at both an international and national level, raising the cost of competing carbon-intensive fuels like natural gas and metallurgical coal, making hydrogen relatively cheaper for end-users. Assumed aggressive reductions in hydrogen technology costs over time see the delivered cost of hydrogen reduce dramatically. The *Energy of the future* and *Targeted deployment* scenarios also assume a greater proportion of end-use applications are captured by hydrogen instead of competing fuels – such as pipeline gas and steelmaking operations that are largely driven by hydrogen use by 2050 under these scenarios.

Figure 6.1 Global forecasted hydrogen demand



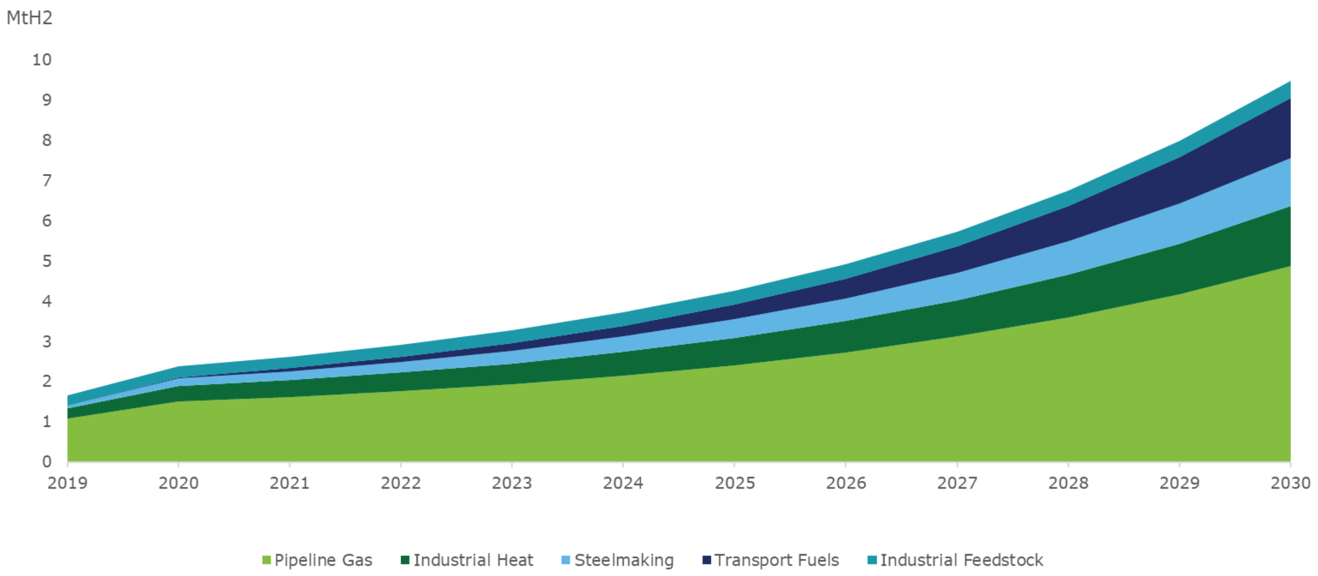
Source: Deloitte Analysis

In contrast, demand is relatively weak in the *Business as usual* and *Electric breakthrough* scenarios, where technological improvements in hydrogen production are relatively slow in Australia or globally when compared to other technologies. This results in hydrogen only capturing minimal proportions of end-use applications.

In the *Business as usual*, technological are relatively slow in Australia when compared to other technologies and other countries and there are no policies to promote hydrogen production activity at a national level. The relatively slow technological progress means hydrogen costs remain high, especially when compared to its alternative fuels, making it significantly less cost-competitive. Technology cost reductions are significantly less, meaning the delivered cost of hydrogen remains high. These factors mean that hydrogen is only able to capture small portions of end-use applications across the global economy.

In *Electric breakthrough*, technological improvements in hydrogen production are relatively slow globally when compared to both other technologies and hydrogen captures the bare minimum of end-use applications across the economy, with some segments like transport and steelmaking seeing no market penetration at all. Under this scenario, electrification technologies advance much more rapidly than hydrogen technology and end-use applications that can be electrified, are electrified. In this scenario, even with implied costs of taking decarbonisation action at a national and international level, hydrogen only has relatively minor technological improvements, due to more rapid progression in electrification technology.

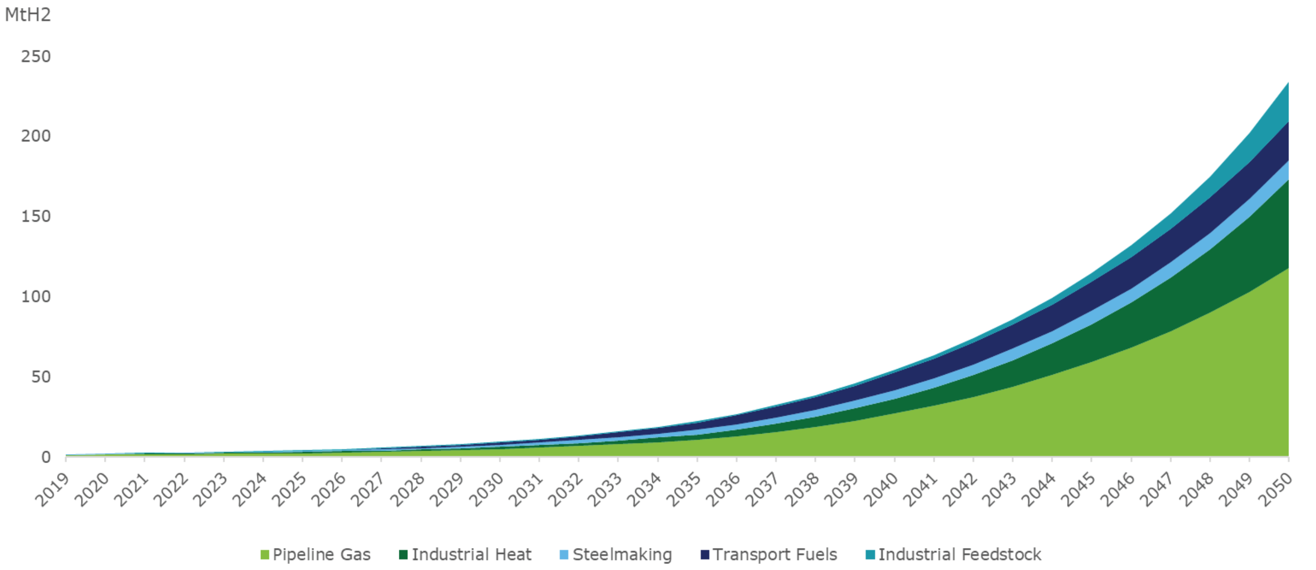
Figure 6.2 Global additional forecasted hydrogen demand by application – Scenario 1 (2019-2030)



Source: Deloitte Analysis

The above figure shows a snapshot of additional global hydrogen demand under the *Energy of the future* scenario to 2030, instead of the full forecast horizon to 2050, in order to provide a more granular view of trends in hydrogen demand by application until 2030. In this scenario, 55% of the 8.8 Mtpa of global hydrogen use in 2030 is used in pipeline gas. In this scenario, the large-scale construction of hydrogen-capable pipelines allows for hydrogen to be used extensively in pipeline gas applications globally.

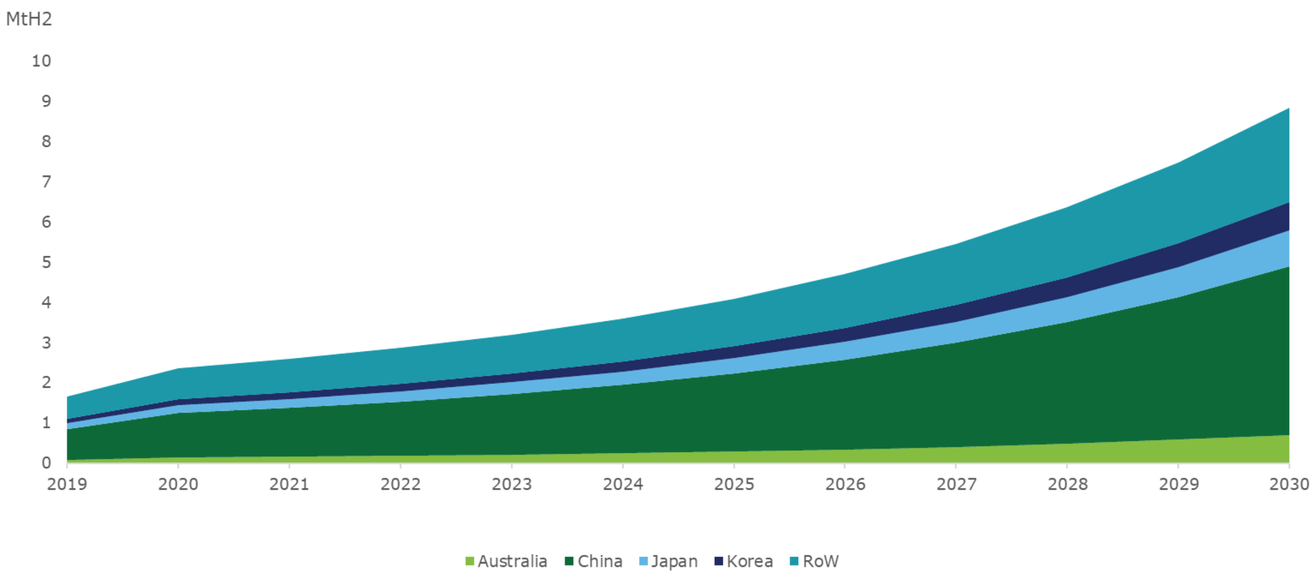
Figure 6.3 Global additional forecasted hydrogen demand by application – Scenario 1 (2019-2050)



Source: Deloitte Analysis

The above figure shows additional global hydrogen demand under the *Energy of the future* scenario for the full period to 2050. By 2050, global hydrogen demand is largely driven by pipeline gas and industrial heating, which make up 74% of total global hydrogen use in 2050 (Figure 6.3). By 2050, there is widespread development and utilisation of hydrogen-capable pipelines which allow hydrogen to be used extensively in pipeline gas applications globally. Hydrogen is also able to capture the entire market for steelmaking fuel requirements at a national and global level, and is able to capture half of the total alternative-drive vehicle fleet and industrial feedstock by 2050 under this scenario. Growth in hydrogen demand in these sectors is largely driven by steep reductions in hydrogen production technology costs that make hydrogen increasingly cost competitive against its alternative fuels such as natural gas, metallurgical coal and diesel. Under this scenario, strong international decarbonisation policies increase the viability of clean technologies like hydrogen.

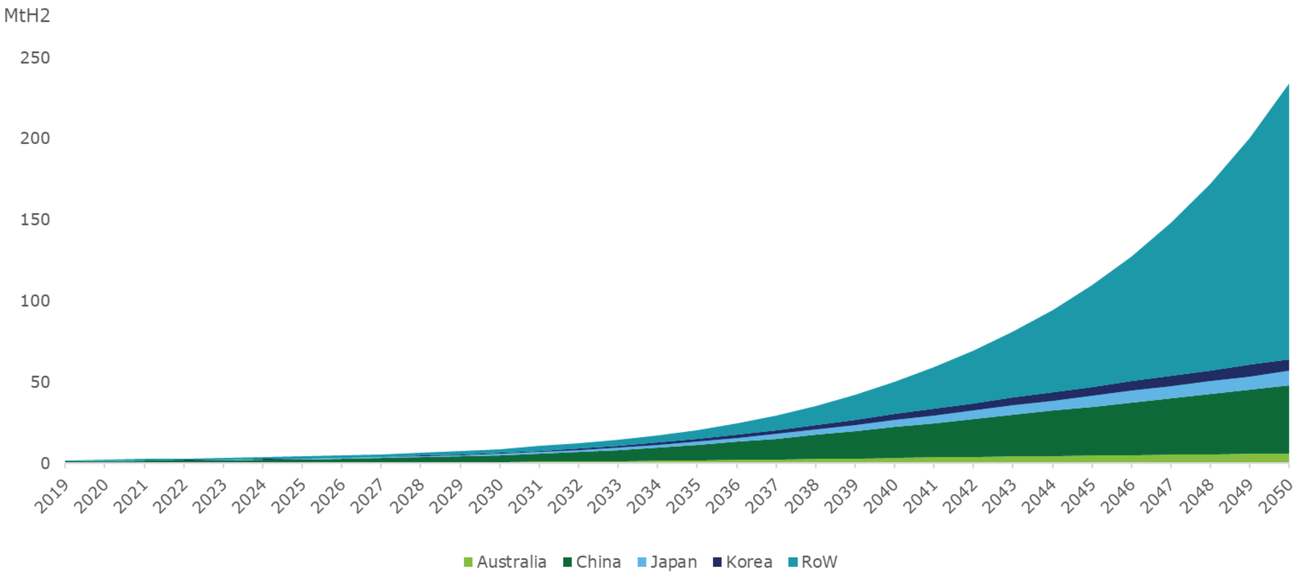
Figure 6.4 Global additional forecasted hydrogen demand by region – Scenario 1 (2019-2030)



Source: Deloitte Analysis

The above figure depicts the additional demand of hydrogen globally under the *Energy of the future* scenario to 2030, which is predominantly driven by Chinese demand. Compared to the broader 2050 view, China plays a more dominant role in hydrogen demand. Hydrogen demand is expected to be largely centred around the key Asian markets of China, Japan and Korea as these countries have strong policies around hydrogen development and use that encourage early demand, at least until the Rest of the World begins to catch up.

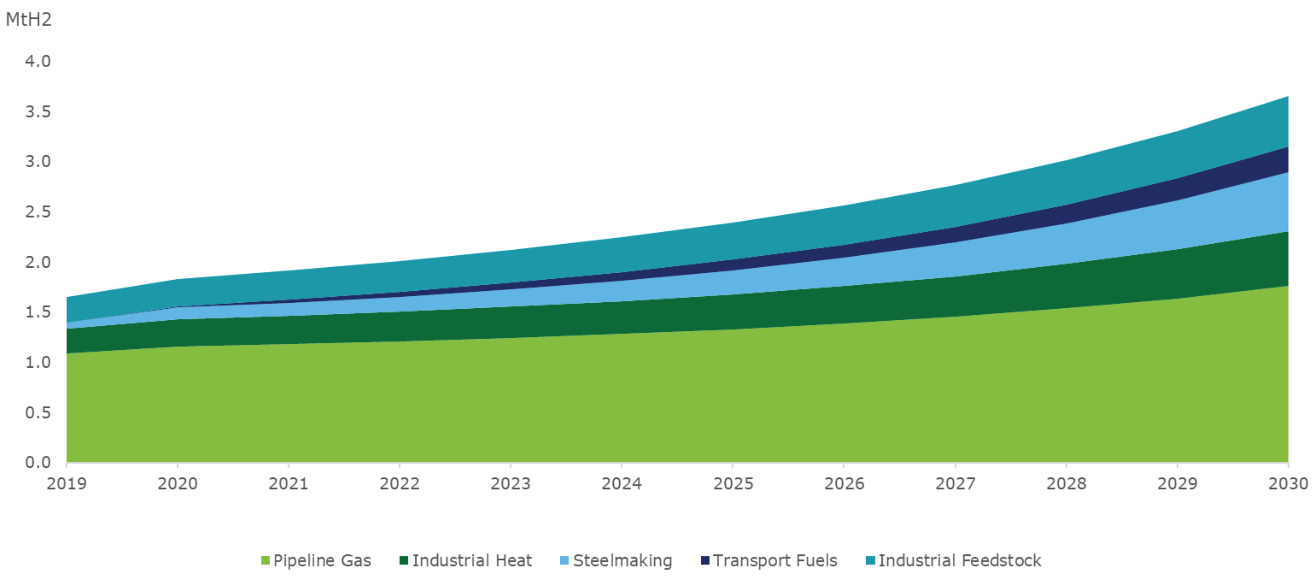
Figure 6.5 Global additional forecasted hydrogen demand by region – Scenario 1 (2019-2050)



Source: Deloitte Analysis

The above figure depicts the additional demand of hydrogen globally under the *Energy of the future* scenario for the full period to 2050 in regions key for Australian produced hydrogen, notably the domestic market, China, Japan and Korea, as well as the rest of the world. Total additional hydrogen demand in the key Asian export markets under the assumptions used for this scenario is approximately 58 Mtpa by 2050, representing over 25% of global hydrogen demand at that time. From the mid 2030s onward, the Rest of the World begins to play a more dominant role in hydrogen demand, and the combined demand of key hydrogen consumers in Europe and the Americas quickly displaces the three key Asian economies.

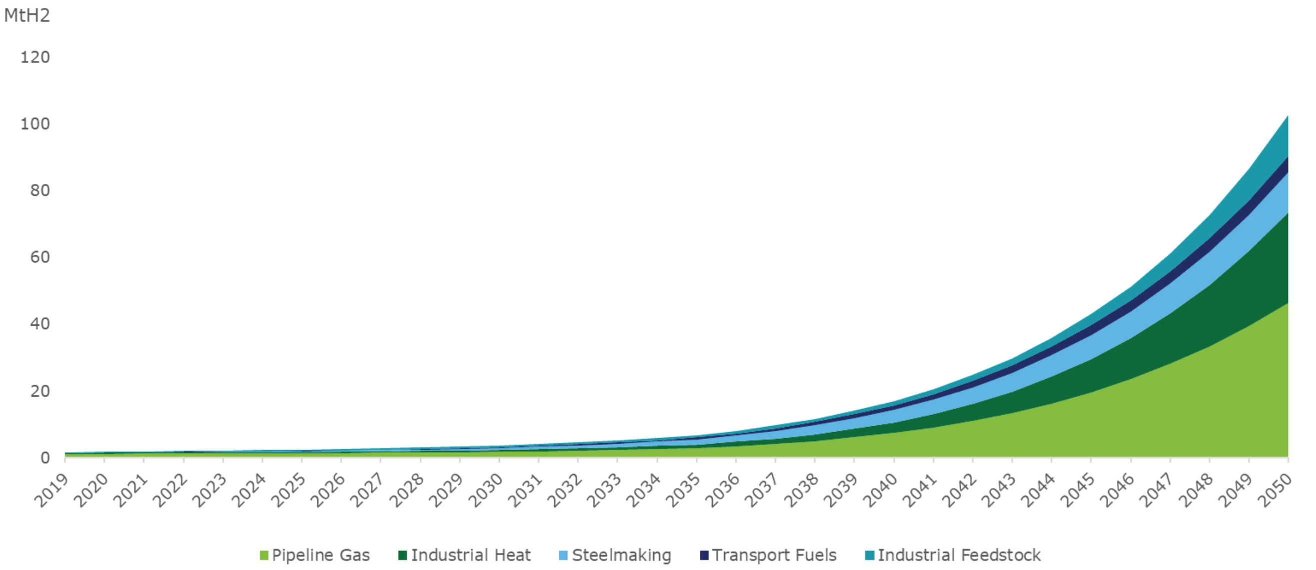
Figure 6.6 Global additional forecasted hydrogen demand by application – Scenario 2 (2019-2030)



Source: Deloitte Analysis

The above figure shows a snapshot of additional global hydrogen demand in the *Targeted deployment* scenario to 2030. In this scenario, hydrogen demand continues to be largely driven by pipeline gas, which makes up roughly 50% of the global hydrogen demand of 3.5 Mtpa. This trend continues in the full period to 2050.

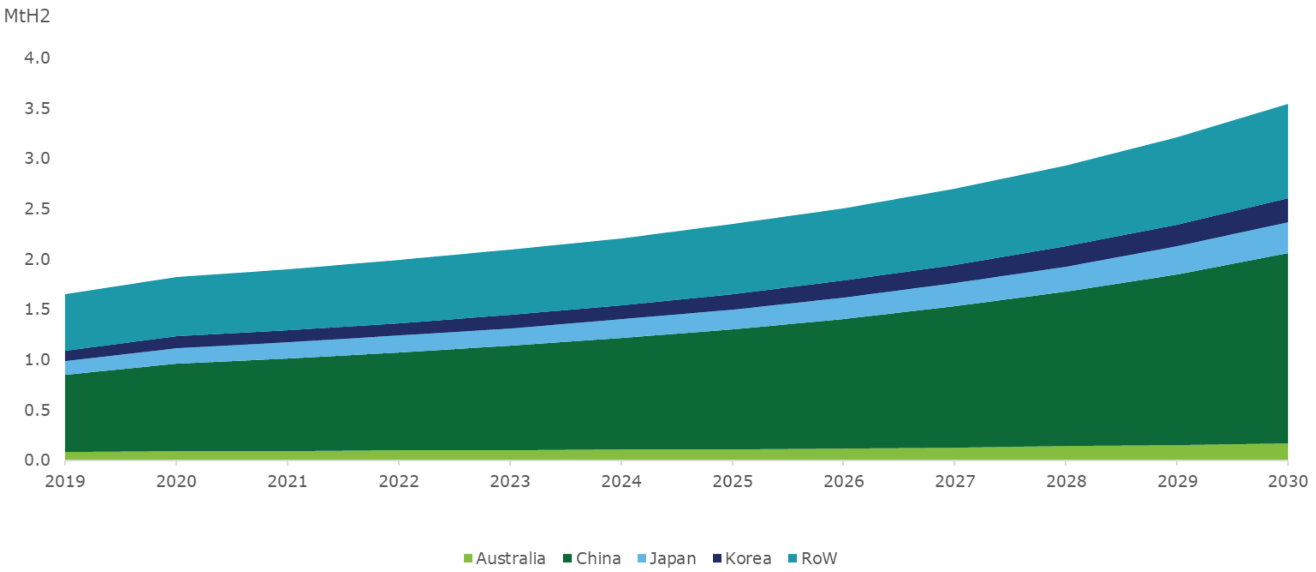
Figure 6.7 Global additional forecasted hydrogen demand by application – Scenario 2 (2019-2050)



Source: Deloitte Analysis

Additional global hydrogen demand under the *Targeted deployment* scenario to 2050 continues to be driven by pipeline gas and industrial heat, which together make up 72% of total global hydrogen use in 2050. Hydrogen for steelmaking purposes makes up 11.6% with 12.0% used for industrial feedstock. Hydrogen is not able to capture the same market share of the domestic and international pipeline gas under *Targeted deployment*, which has a material impact on the total demand for hydrogen by 2050.

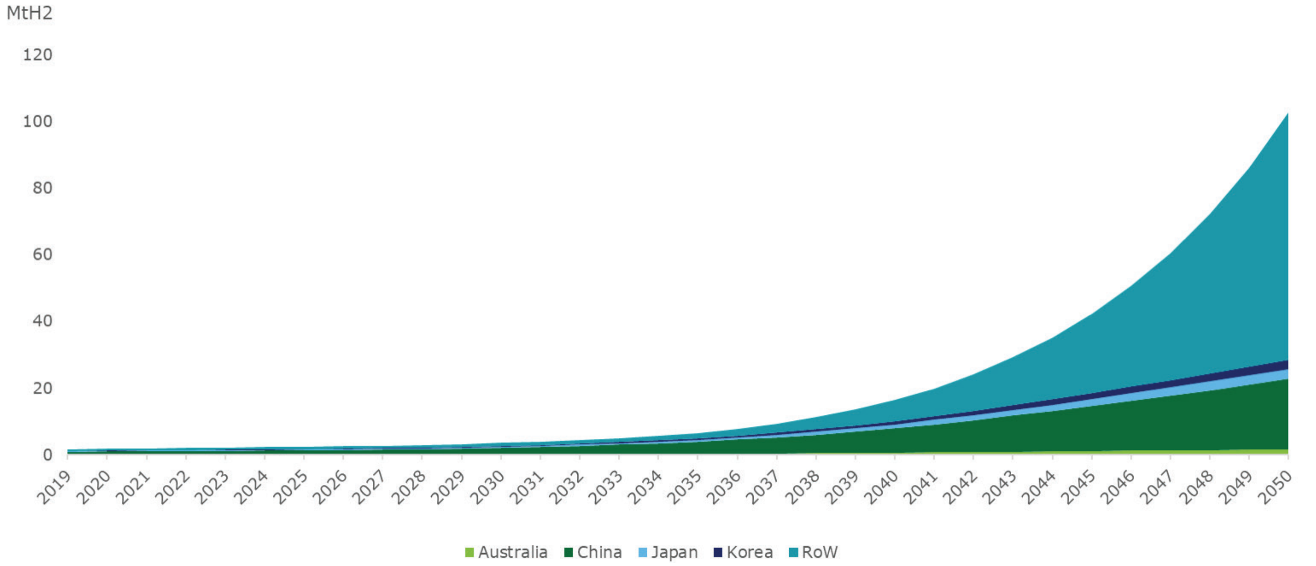
Figure 6.8 Global additional forecasted hydrogen demand by region – Scenario 2 (2019-2030)



Source: Deloitte Analysis

The above figure depicts the additional demand of hydrogen globally under the *Targeted deployment* scenario to 2030, which is predominantly driven by Chinese demand. Compared to the broader 2050 view, China plays a more dominant role in hydrogen demand. Hydrogen demand is expected to be largely centred around the key Asian markets of China, Japan and Korea as these countries have strong policies around hydrogen development and use that encourage early demand, at least until the Rest of the World begins to catch up.

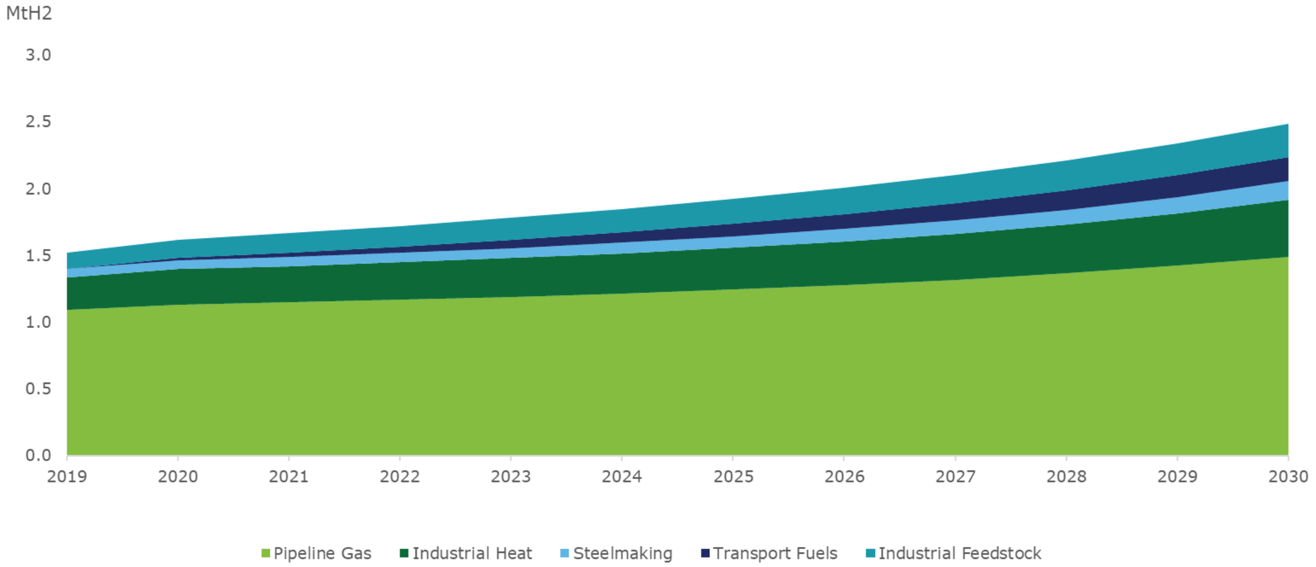
Figure 6.9 Global additional forecasted hydrogen demand by region – Scenario 2 (2019-2050)



Source: Deloitte Analysis

The above figure depicts the additional demand of hydrogen globally under the *Targeted deployment* scenario by region. Targeted Asian hydrogen market additional demand is approximately 26.8 Mtpa by 2050, with China dominating at 21.1 Mtpa. Global demand for hydrogen by 2050 is 102.5 Mtpa, with the Rest of the World beginning to play a more dominant role from the mid 2030s onwards.

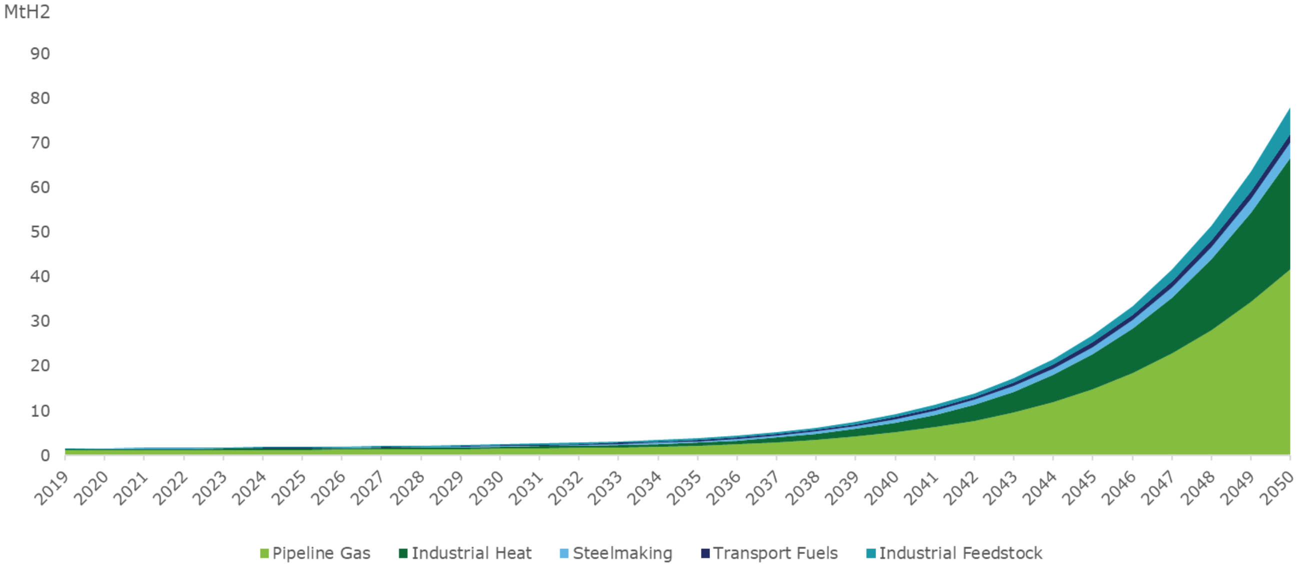
Figure 6.10 Global additional forecasted hydrogen demand by application – Scenario 3 (2019-2030)



Source: Deloitte Analysis

The above figure shows a snapshot of additional global hydrogen demand in the *Business as usual* scenario to 2030. In this scenario, global growth in hydrogen demand is more subdued than other scenarios, and continues to be dominated by pipeline gas usage, which makes up roughly 62% of the global hydrogen demand of 2.4 Mtpa. This trend continues in the full period to 2050.

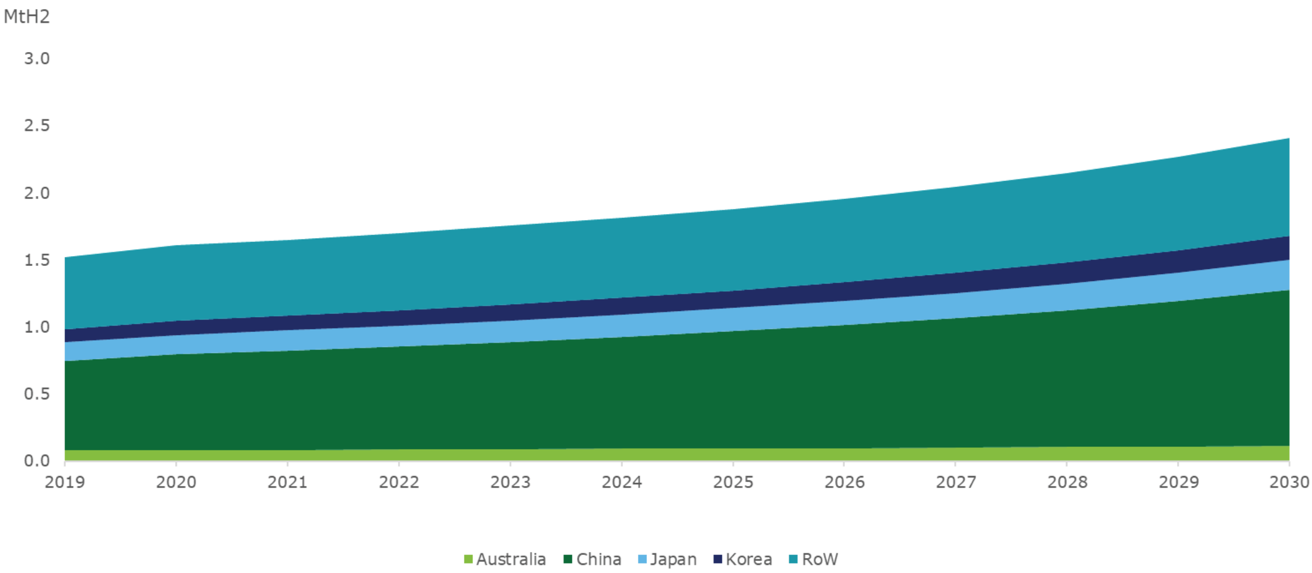
Figure 6.11 Global additional forecasted hydrogen demand by application – Scenario 3 (2019-2050)



Source: Deloitte Analysis

In the *Business as usual* scenario to 2050, additional hydrogen demand around the world continues to grow to some extent whilst hydrogen technological developments in Australia remain slower. This scenario sees hydrogen demand being increasingly driven by pipeline gas and industrial heating requirements, which make up over 85% of total additional hydrogen use in 2050. Hydrogen captures small proportions of end-use applications in this scenario, with only 30% of the international steelmaking heat market and 5% of alternative-drive vehicles using hydrogen fuel. Under this scenario, global hydrogen demand, whilst not insignificant, is not buoyed by the aggressive implied international cost of decarbonisation that are active in other scenarios.

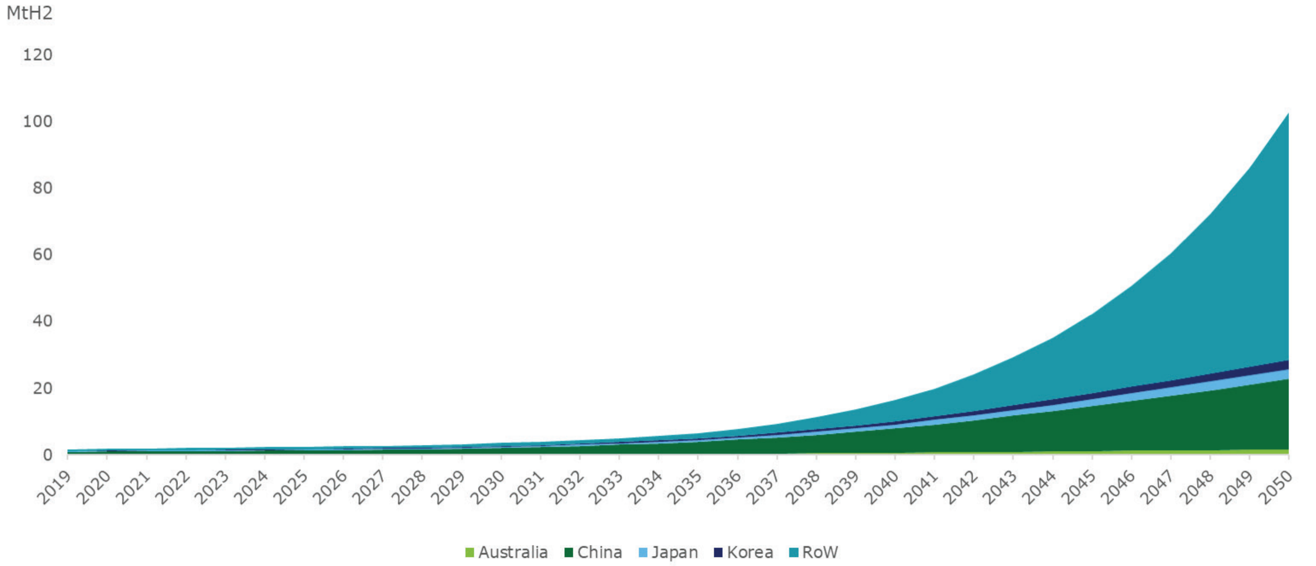
Figure 6.12 Global additional forecasted hydrogen demand by region – Scenario 3 (2019-2030)



Source: Deloitte Analysis

The above figure depicts the additional demand of hydrogen globally under the *Business as usual* scenario to 2030, which is predominantly driven by Chinese demand. Compared to the broader 2050 view, China plays a more dominant role in hydrogen demand. Hydrogen demand is expected to be largely centred around the key Asian markets of China, Japan and Korea as these countries have strong policies around hydrogen development and use that encourage early demand; at least until the Rest of the World begins to catch up.

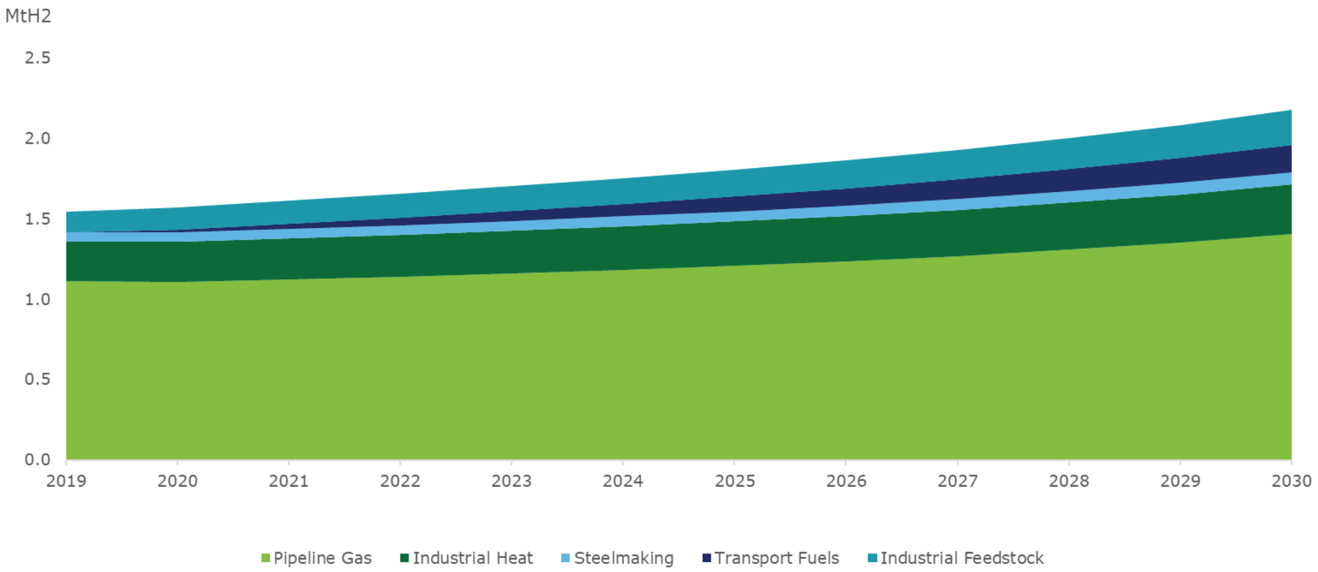
Figure 6.13 Global additional forecasted hydrogen demand by region – Scenario 3 (2019-2050)



Source: Deloitte Analysis

The above figure depicts the additional demand of hydrogen globally under the *Business as usual* scenario by region. Targeted Asian hydrogen additional market demand is approximately 17.0 Mtpa by 2050, with China dominating at 13.0 Mtpa. Global demand for hydrogen by 2050 in this scenario is approximately 78 Mtpa, with the Rest of the World beginning to play a more dominant role from the mid 2030s onwards.

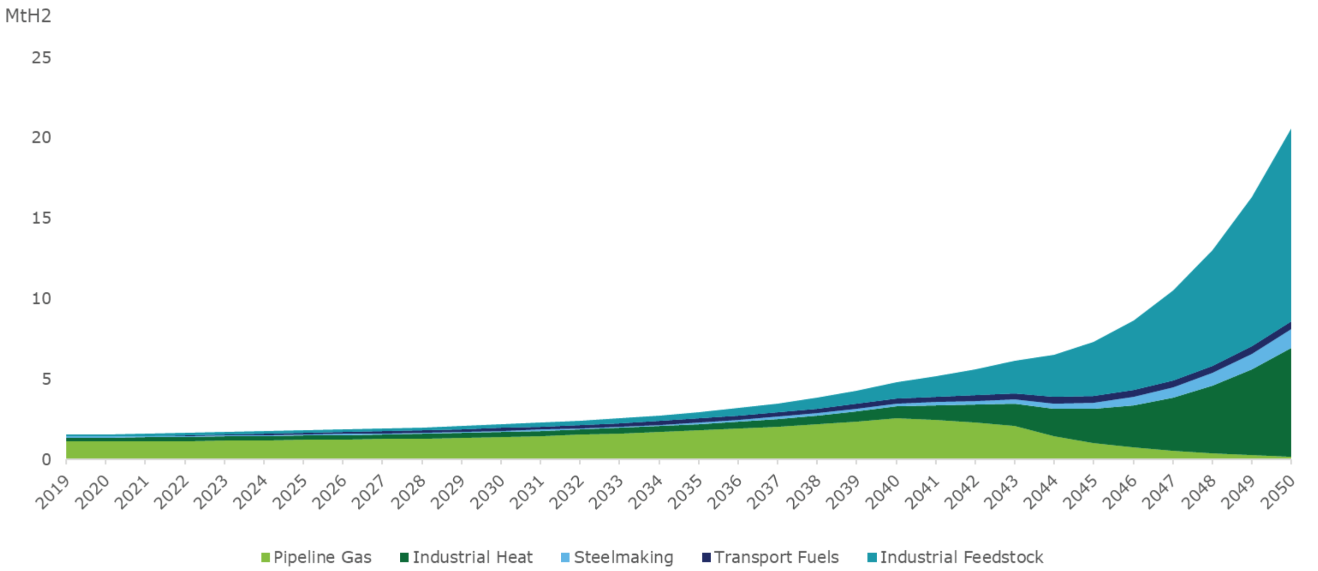
Figure 6.14 Global additional forecasted hydrogen demand by application – Scenario 4 (2019-2030)



Source: Deloitte Analysis

The above figure shows a snapshot of global hydrogen demand in the *Electric breakthrough* scenario to 2030. In this scenario, hydrogen demand is driven by pipeline gas, which makes up roughly 67% of the global hydrogen demand of 2.1 Mtpa. This trend does not continue to 2050 as hydrogen usage in pipeline gas application drops to negligible levels as technological advancements allow for these applications to be completely electrified.

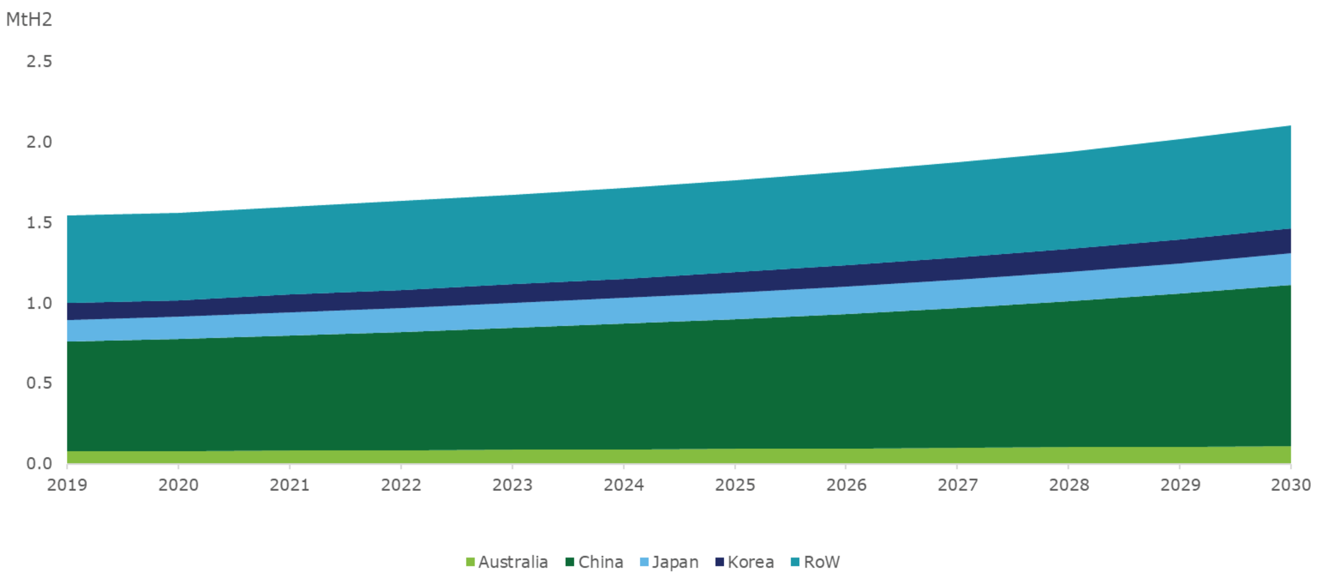
Figure 6.15 Global additional forecasted hydrogen demand by application – Scenario 4 (2019-2050)



Source: Deloitte Analysis

The *Electric breakthrough* scenario to 2050 sees additional hydrogen demand being initially driven by pipeline gas usage but then, as electrification takes over, demand is limited to only the sectors where electricity cannot fully compete such as industrial heat and feedstock take over the only remaining use cases by 2050. Under this scenario, hydrogen is unable to capture any additional market share on a national or international basis for the steelmaking or transportation sectors. Whilst this scenario sees hydrogen become cost competitive with carbon-intensive alternative fuels like natural gas, metallurgical coal and diesel through aggressive international carbon pricing, faster technological advancements in electrical applications means that global hydrogen demand by 2050 is relatively small compared to other scenarios.

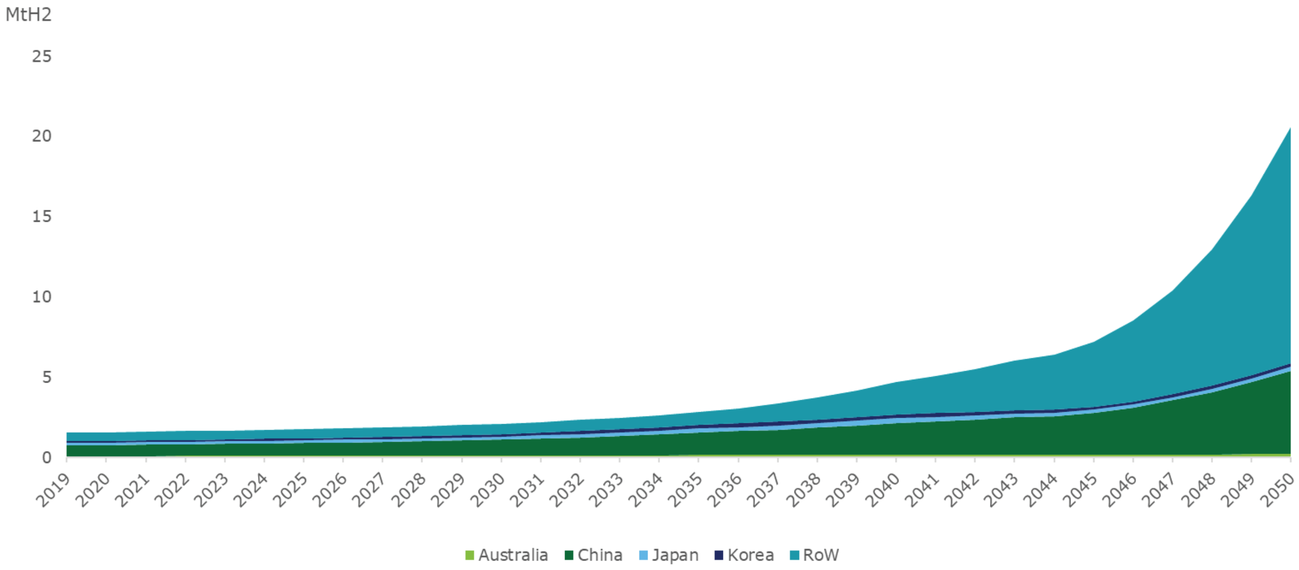
Figure 6.16 Global additional forecasted hydrogen demand by region – Scenario 4 (2019-2030)



Source: Deloitte Analysis

The above figure depicts the additional demand of hydrogen globally under the *Electric breakthrough* scenario to 2030, which is predominantly driven by Chinese demand. Compared to the broader 2050 view, China plays a more dominant role in hydrogen demand. Hydrogen demand is expected to be largely centred around the key Asian markets of China, Japan and Korea as these countries have strong policies around hydrogen development and use that encourage early demand, at least until the Rest of the World begins to catch up.

Figure 6.17 Global additional forecasted hydrogen demand by region – Scenario 4 (2019-2050)



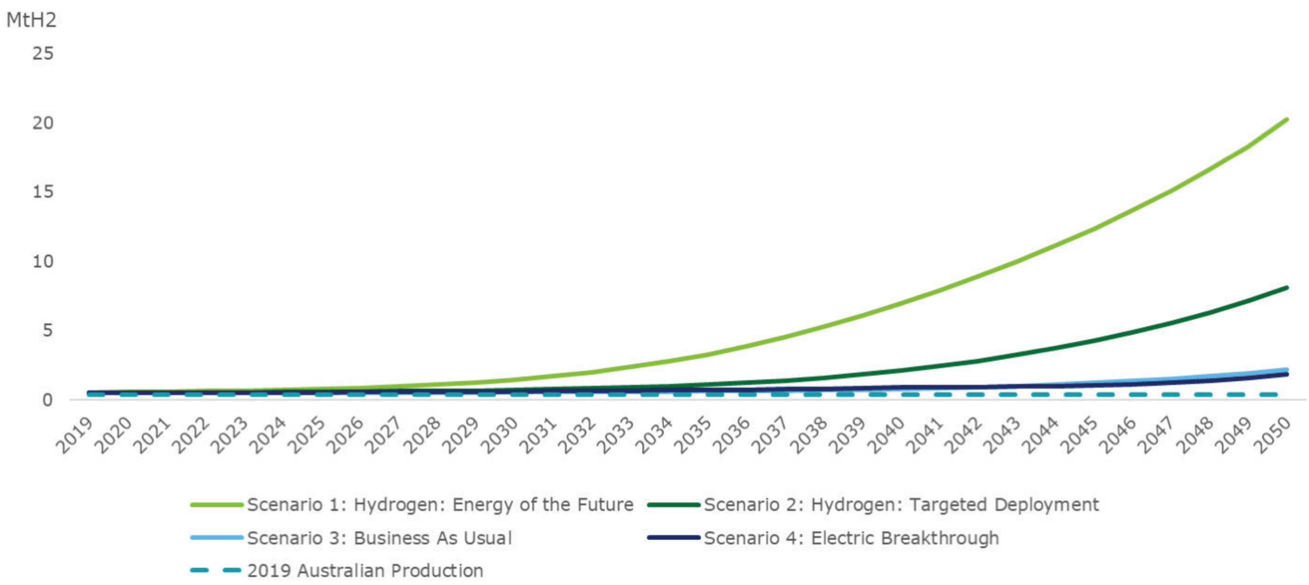
Source: Deloitte Analysis

The above figure depicts the additional demand of hydrogen globally under the *Electric breakthrough* scenario to 2050. Total hydrogen demand is the lowest of all four scenarios due to the competitiveness of electrification in all end-use categories. Targeted Asian hydrogen market demand is approximately 5.6 Mtpa by 2050, with China dominating at 5.2 Mtpa. Global demand for hydrogen by 2050 is 20.6 Mtpa, with the Rest of the World beginning to play a more dominant role from the mid 2030s onwards.

6.2 Australian market demand

This figure depicts the range of additional hydrogen production in Australia under each of the four scenarios. Domestic production of hydrogen could range from as high as 19.8 Mt by 2050 in the *Energy of the future* scenario, to as low as 1.4 Mt in the *Electric breakthrough* scenario (Figure 6.18).

Figure 6.18 Forecasted hydrogen production from Australia



Source: Deloitte Analysis

Based partly on the assumptions around Australia's market share, hydrogen production is highest in the *Energy of the future* and *Targeted deployment* scenarios, where high international and domestic policies to remove barriers and enable access to hydrogen translate to aggressive costs reductions for hydrogen production, improving hydrogen's cost-competitiveness with alternative fuels. This effectively leads to high proportions of end-use markets captured for hydrogen, leading to further increases in demand for Australian-produced hydrogen.

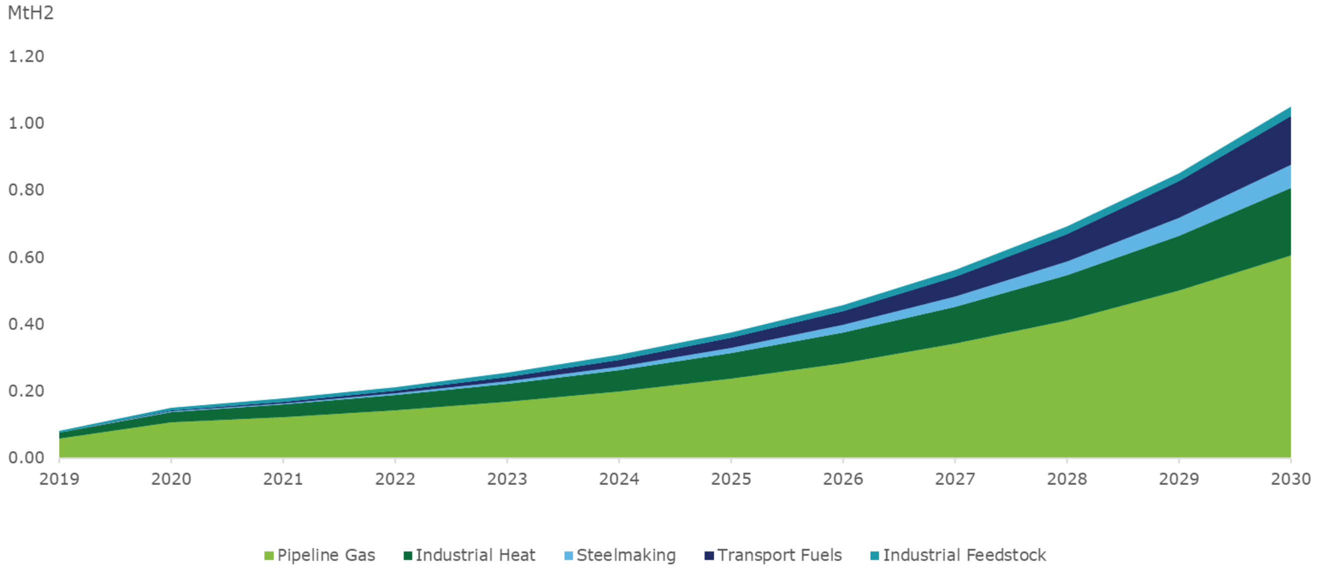
In contrast, the *Business as usual* sees global demand being relatively strong but that Australia's market share declines significantly. The *Electric breakthrough* scenario has a stronger market share but sees subdued global demand for Australian-produced hydrogen due to slower improvements in hydrogen technological learning rates and an inability for hydrogen to compete against its alternatives.

The cost of delivering to these regions is based on the cost of shipping hydrogen from Australia's Port Hedland region in Western Australia to key ports in China (Tianjin), Japan (Tokyo), Korea (Incheon) and the Rest of the World (Singapore). The current cost of shipping hydrogen to these locations is assumed to range from A$0.45/kg – $0.89/kg[66] based on FY19 dollars but this does not include the cost of transformation of the hydrogen into its carrier state, such as liquefied hydrogen, ammonia or MHC, at either the export or import ports.

There is an argument to vary these shares more significantly under each scenario, but in the modelling development process, this was considered and dismissed. The reason for this was that it introduces an additional level of assumptions and variations between the scenarios, which is not believed to add any additional insights into the overall conclusions, noting that these are a range of scenarios rather than intended to be market forecasts.

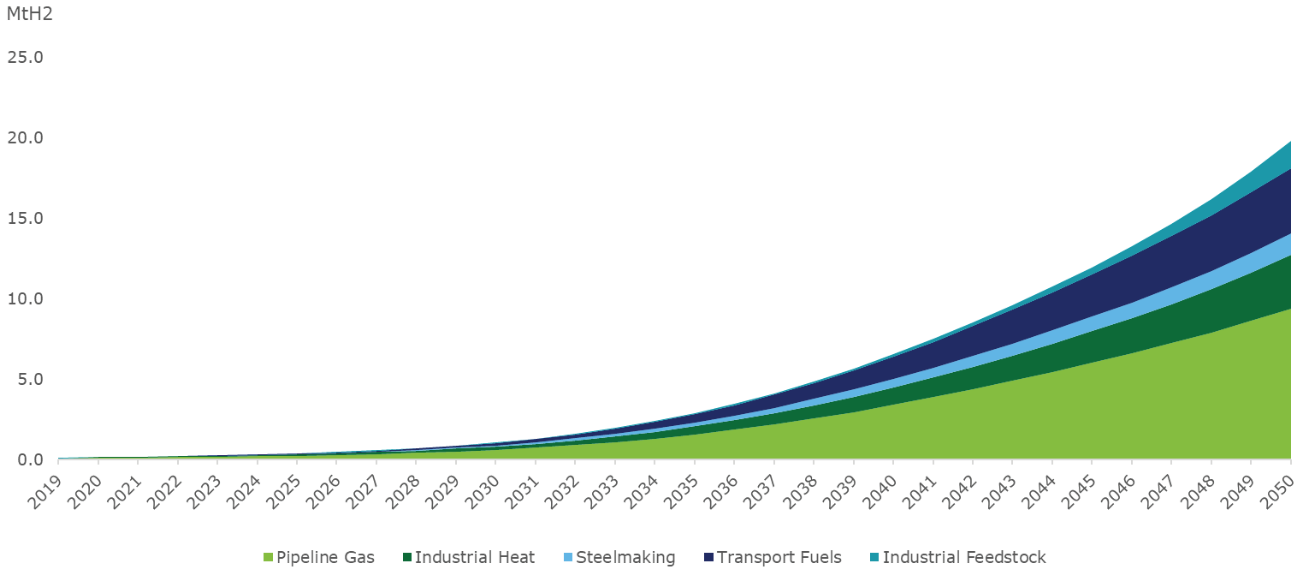
The below figure shows a snapshot of additional demand for Australian-produced hydrogen under the *Energy of the future* scenario to 2030 instead of the full forecast horizon to 2050 for a more granular view of trends in hydrogen demand by application until 2030. By 2030, demand for Australian-produced hydrogen is being largely driven by pipeline gas, industrial heating and transportation. Total additional hydrogen production by Australia reaches 1 Mtpa by 2030, under policy settings that encourage additional hydrogen demand. These include the removal of price barriers and enabling of access to lower cost production, both internationally and domestically – through the implied cost of action taken to decarbonise. Steep reductions in technology costs associated with hydrogen production improve the cost-competitiveness of hydrogen compared to alternative fuels.

Figure 6.19 Additional Australian-produced hydrogen demand by application – Scenario 1 (2019-2030)



Source: Deloitte Analysis

Figure 6.20 Additional Australian-produced hydrogen demand by application – Scenario 1 (2019-2050)

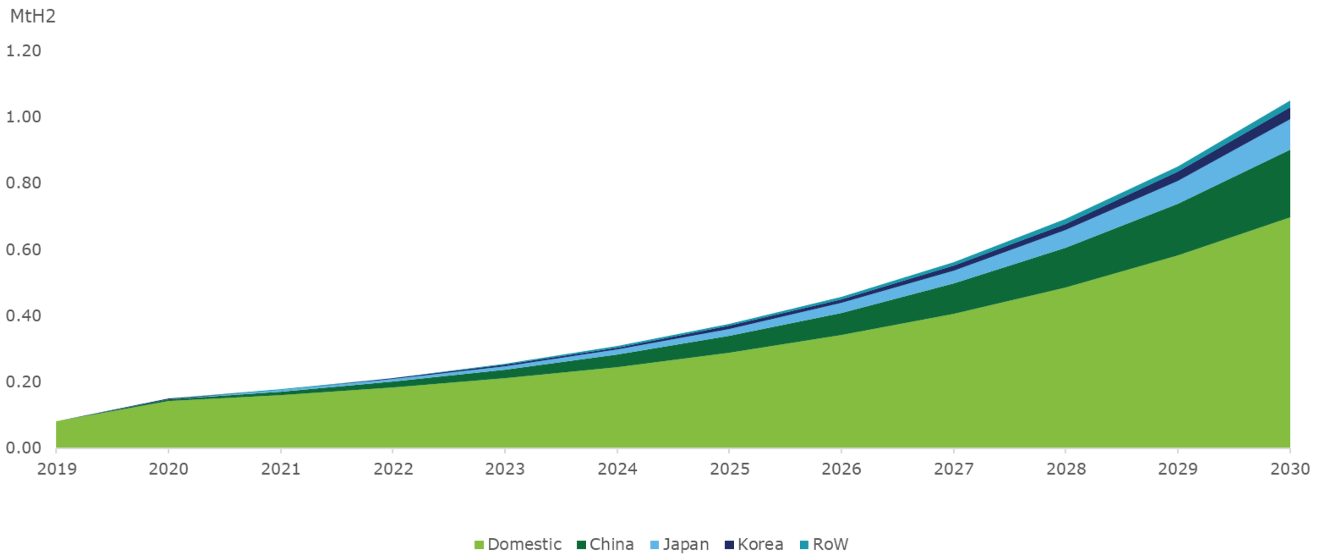


Source: Deloitte Analysis

The above figure shows additional demand for Australian-produced hydrogen under the *Energy of the future* scenario for the full period to 2050. By 2050, pipeline gas and transportation requirements drive the demand for Australian-produced hydrogen, constituting 47% and 21% respectively of total hydrogen demand by 2050 (Figure 6.20). Alternative-drive vehicles utilising hydrogen drive become popular at both an international and national level, driving the significant demand for hydrogen in transport use. Total additional hydrogen production by Australia reaches 20 Mtpa by 2050, under policy settings that encourage additional hydrogen demand.

Under the *Energy of the future* scenario, hydrogen demand rapidly grows worldwide as hydrogen becomes cost competitive with alternative fuels such as diesel for vehicles and metallurgical coal for steelmaking operations. Pipeline gas demand grows significantly as infrastructure is developed to allow injected hydrogen to make up 100% of distribution pipeline gas.

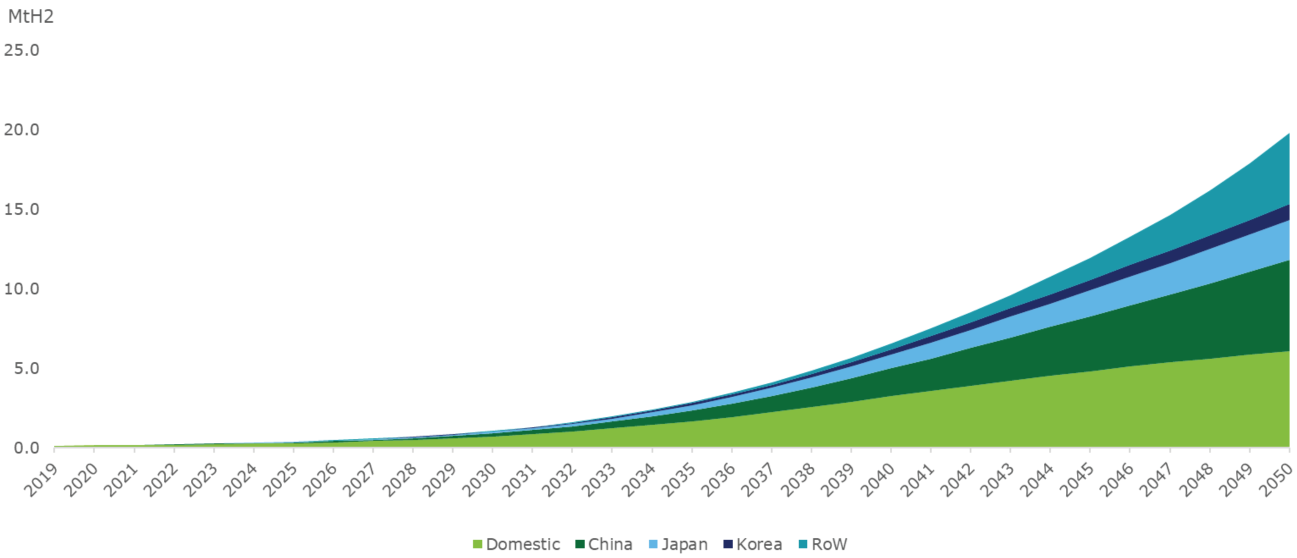
Figure 6.21 Additional Australian-produced hydrogen production by region – Scenario 1 (2019-2030)



Source: Deloitte Analysis

In the *Energy of the future* scenario to 2030, Australia's hydrogen production reaches 1 Mtpa. Additional demand for Australian hydrogen is largely driven by domestic demand as Australia is still at the early stages of capturing international demand for hydrogen in key export markets like China, Japan and Korea.

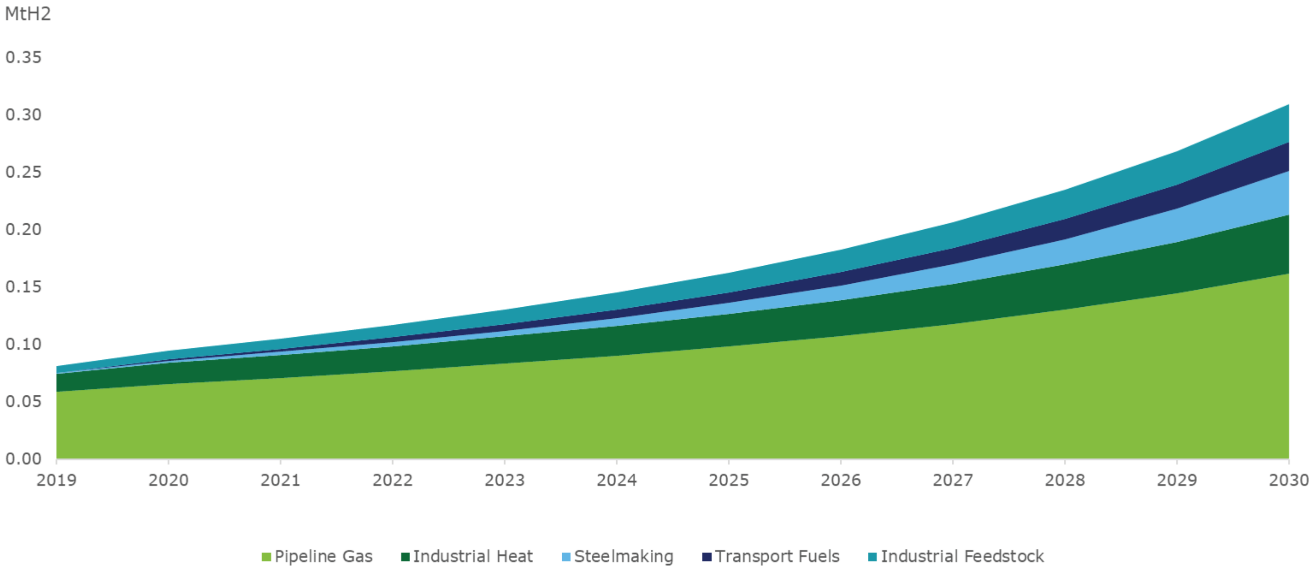
Figure 6.22 Additional Australian-produced hydrogen production by region – Scenario 1 (2019 – 2050)



Source: Deloitte Analysis

In the *Energy of the future* scenario to 2050, Australia's hydrogen production reaches 20 Mtpa in 2050. Removing barriers for hydrogen domestically drives uptake resulting in domestic consumption of 6 Mtpa in 2050. This equates to 31.3% of Australia's total production of hydrogen. Under the assumptions used in this scenario, China is the largest export consumer of Australian hydrogen – consuming 6 Mtpa, followed by Japan at 3 Mtpa and then Korea at 1 Mtpa.

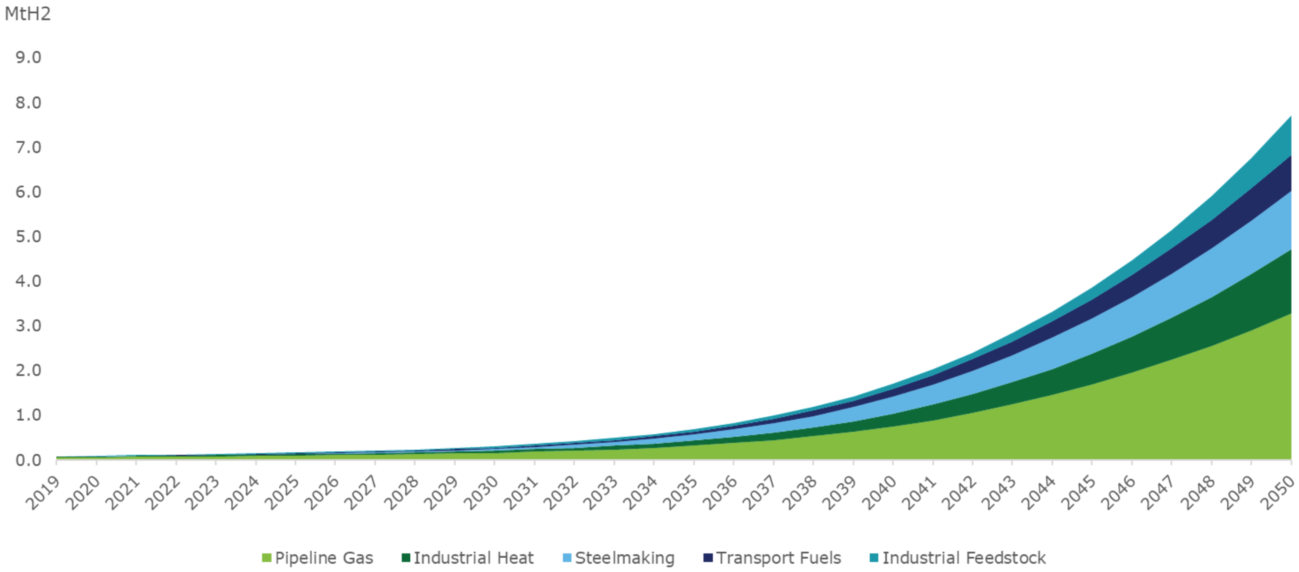
Figure 6.23 Additional Australian-produced hydrogen demand by application – Scenario 2 (2019-2030)



Source: Deloitte Analysis

Demand for Australian-produced hydrogen under the *Targeted deployment* scenario to 2030 is largely driven by pipeline gas, which makes up 52% of Australia's total hydrogen production by 2030. Hydrogen production by Australia in this scenario is lower, reaching <1 Mtpa by 2030.

Figure 6.24 Additional Australian-produced hydrogen demand by application – Scenario 2 (2019-2050)

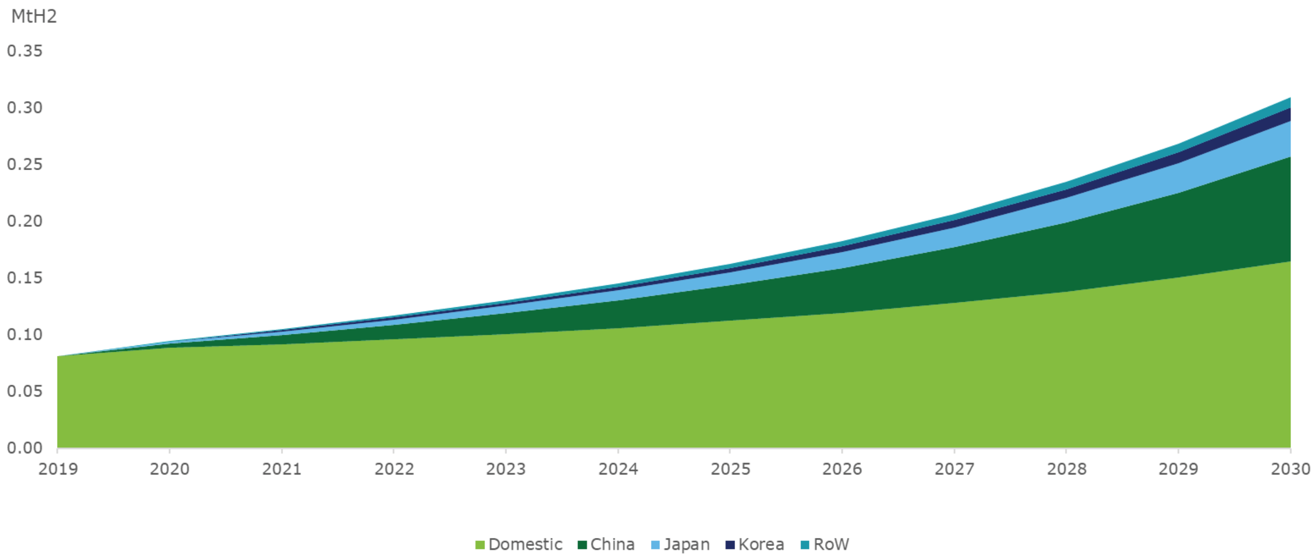


Source: Deloitte Analysis

Demand for Australian-produced hydrogen under the *Targeted deployment* scenario to 2050 is driven by pipeline gas, industrial heating and steelmaking requirements – which cumulatively make up 78% of Australia's total hydrogen production. Total hydrogen production by Australia in this scenario is lower, reaching 8 Mtpa by 2050. Hydrogen produced in Australia in this scenario is one third of the quantity produced in the *Energy of the future* scenario, as hydrogen is generally unable to capture significant portions of end-use markets compared to the *Energy of the future* scenario, with the exception of steelmaking operations.

In the *Targeted deployment* scenario, efforts in encouraging hydrogen demand is focused on steelmaking operations, with 100% of global steelmakers utilising hydrogen by 2050. In contrast with the *Energy of the future* scenario, hydrogen does not make the same inroads in other applications like pipeline gas, industrial heating or alternative vehicles, due to the costs associated with revamping pipeline infrastructure, and the cost competitiveness of alternative fuels such as natural gas for heating and electric vehicles or diesel for vehicles, other than for heavy vehicles.

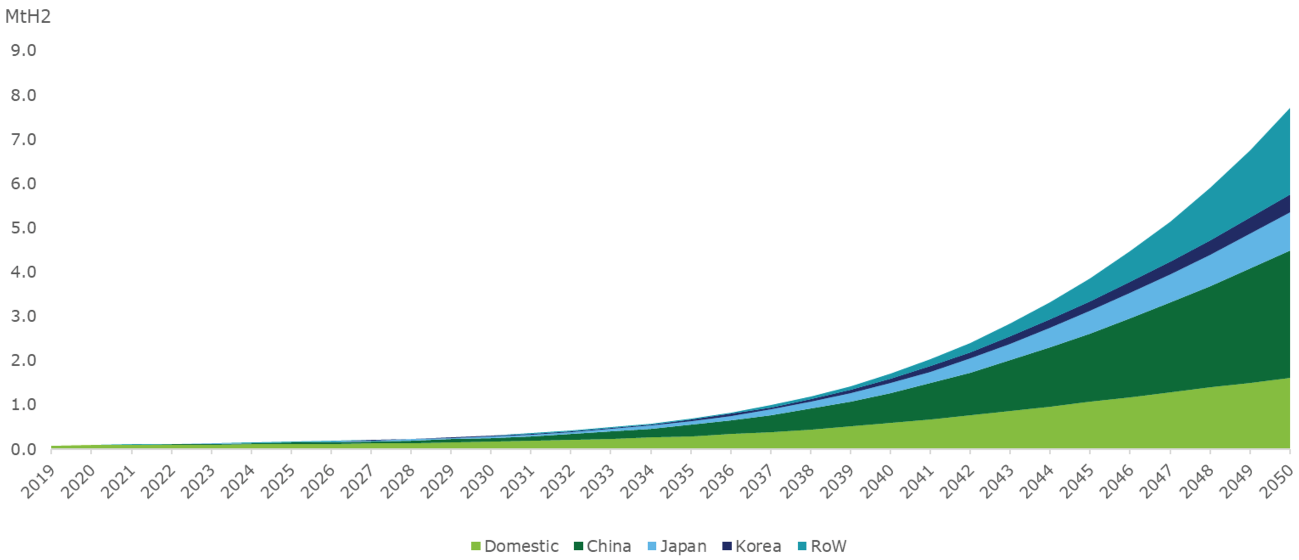
Figure 6.25 Additional Australian-produced hydrogen production by region – Scenario 2 (2019-2030)



Source: Deloitte Analysis

In the *Targeted deployment* scenario to 2030, Australia's additional hydrogen production reaches 0.3 Mtpa. Additional demand for Australian hydrogen is largely driven by domestic demand as Australia is still at the early stages of capturing international demand for hydrogen in key export markets like China, Japan and Korea.

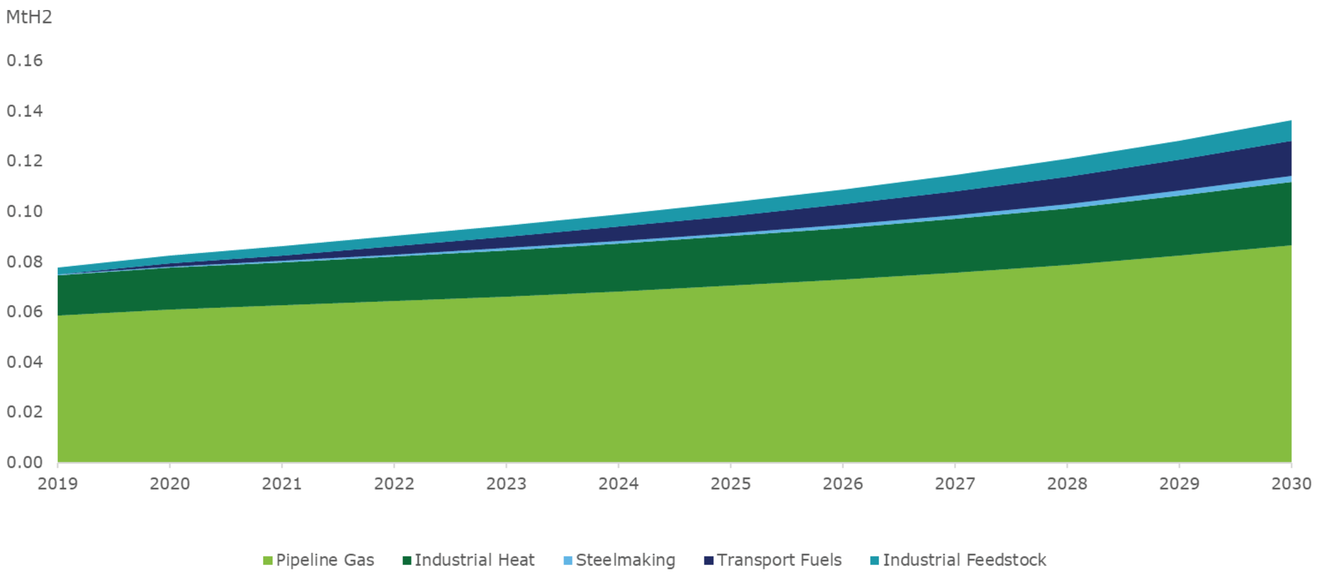
Figure 6.26 Additional Australian-produced hydrogen production by region – Scenario 2 (2019-2050)



Source: Deloitte Analysis

In the *Targeted deployment* scenario to 2050, China consumes the greatest proportion of Australian hydrogen, which is even more than the domestic market. Domestically, only 2 Mtpa of hydrogen is utilised by 2050 as deployment is targeted to specific sectors.

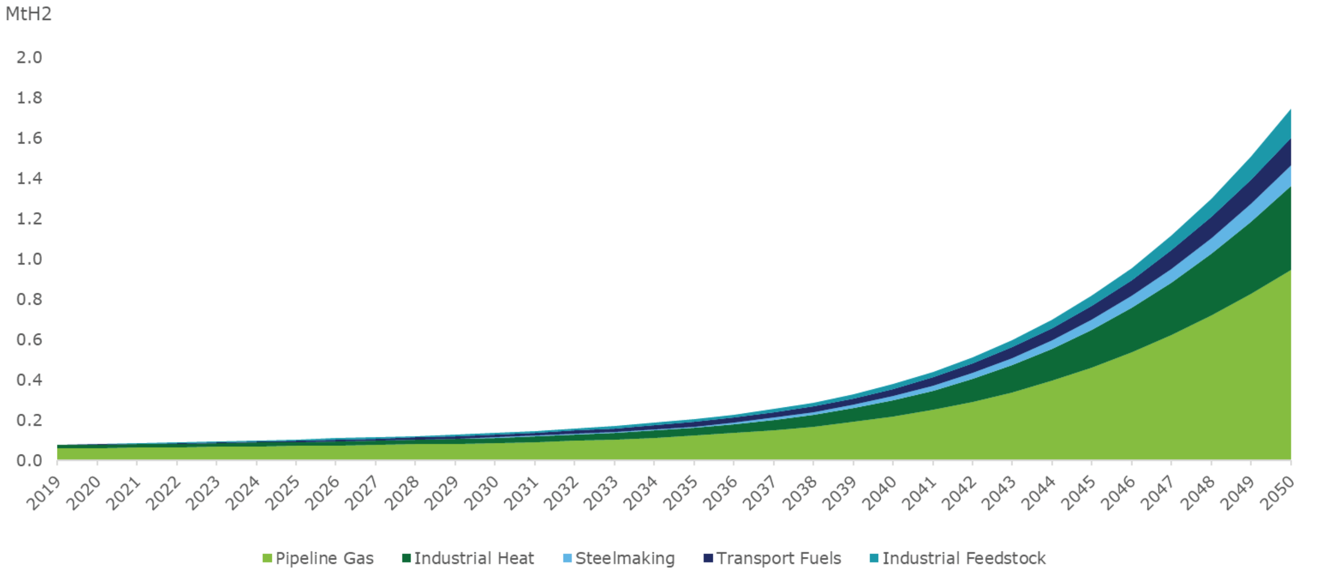
Figure 6.27 Additional Australian-produced hydrogen demand by application – Scenario 3 (2019-2030)



Source: Deloitte Analysis

Under the *Business as usual* scenario to 2030, additional hydrogen production in Australia is limited despite faster growth overseas due to lack of technological progress in hydrogen production, storage and transportation and policy support in Australia. Additional hydrogen production in Australia is <1 Mtpa in 2030, and is mostly used for pipeline gas.

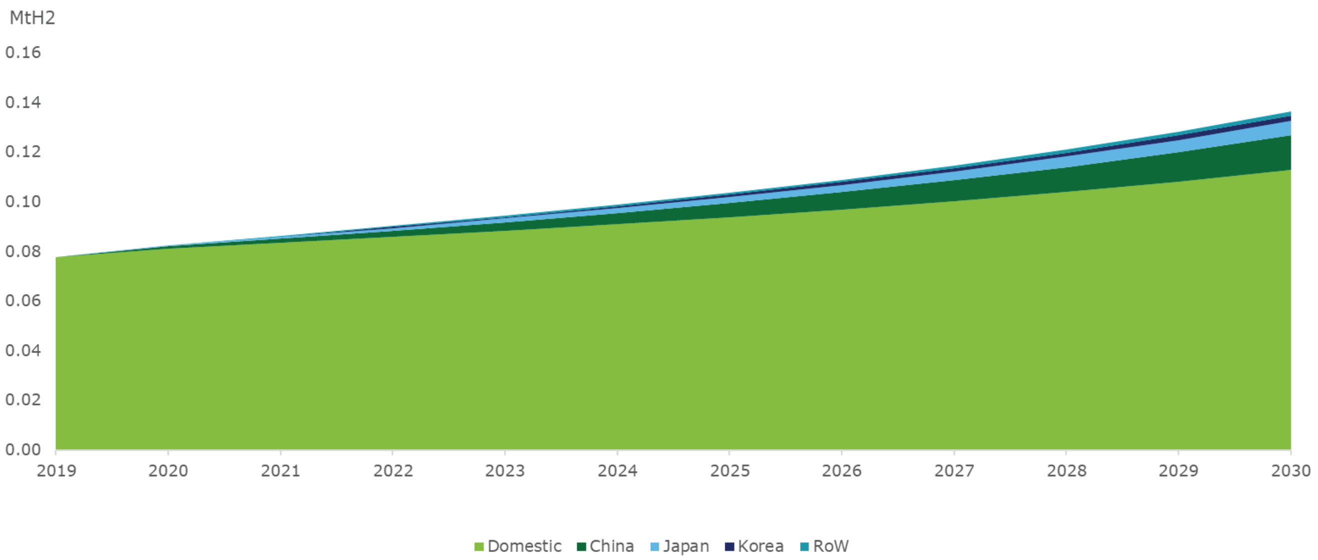
Figure 6.28 Additional Australian-produced hydrogen demand by application – Scenario 3 (2019-2050)



Source: Deloitte Analysis

Under the *Business as usual* scenario to 2050, hydrogen continues to be utilised largely for pipeline gas and industrial heating processes, making up 78% of Australia's total hydrogen production by 2050. Total additional hydrogen production by Australia is low, reaching only 2 Mtpa by 2050 as hydrogen makes minimal inroads into any end-use market, particularly in key export markets and no direct policies are enacted to remove barriers domestically. This makes hydrogen much more expensive than its alternatives. Limited decarbonisation policies at an international level mean that alternative fuels retain their price competitiveness compared to hydrogen for much longer than in other scenarios.

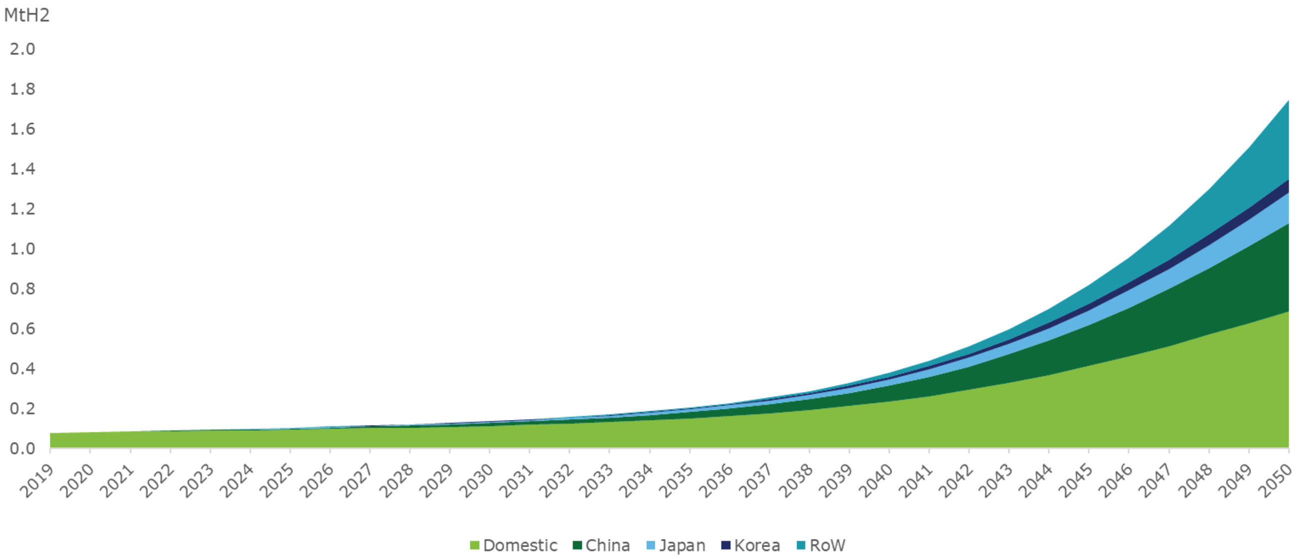
Figure 6.29 Additional Australian-produced hydrogen production by region – Scenario 3 (2019-2030)



Source: Deloitte Analysis

In the *Business as usual* scenario to 2030, Australia's hydrogen production is <1 Mtpa. Additional demand for Australian hydrogen is largely driven by domestic demand as Australia is still at the early stages of capturing international demand for hydrogen in key export markets like China, Japan and Korea.

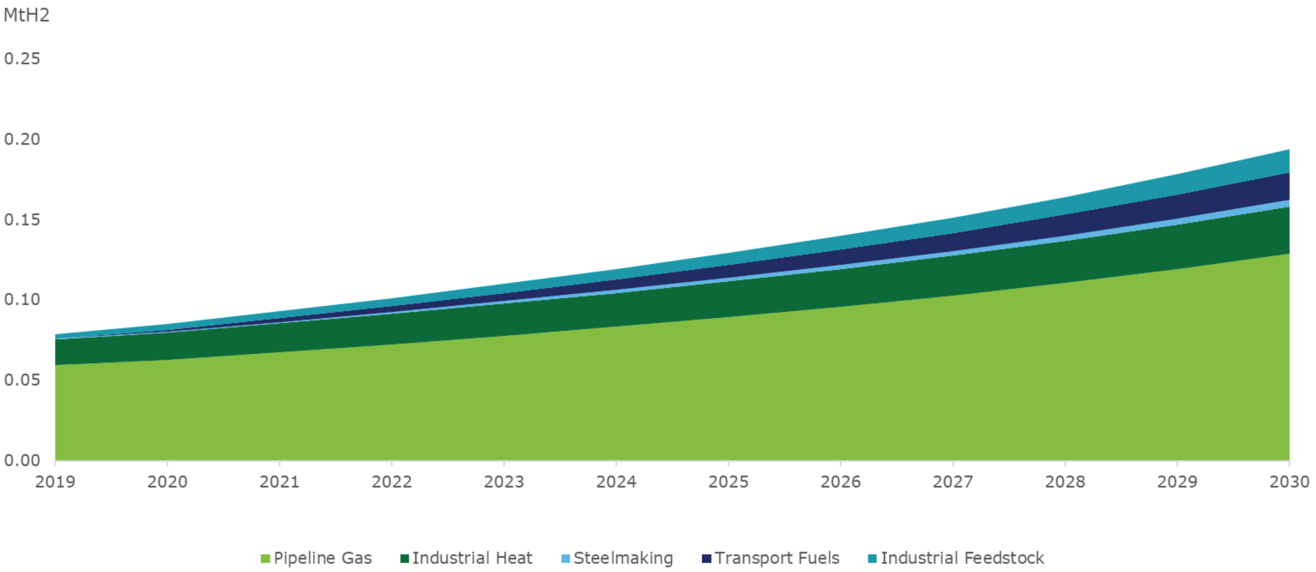
Figure 6.30 Additional Australian-produced hydrogen production by region – Scenario 3 (2019-2050)



Source: Deloitte Analysis

In this scenario to 2050, Australia consumes <1 Mtpa of hydrogen, equating to 39% of the total Australian production of hydrogen of 2 Mtpa. Domestic policies support decarbonisation through the most efficient means, so policies remove barriers and enable access to any technologies deployed across the value chain. In contrast, hydrogen is relatively more important internationally and deployed across targeted sectors. In this limited market, China remains the largest consumer of Australian produced hydrogen followed by Japan then Korea.

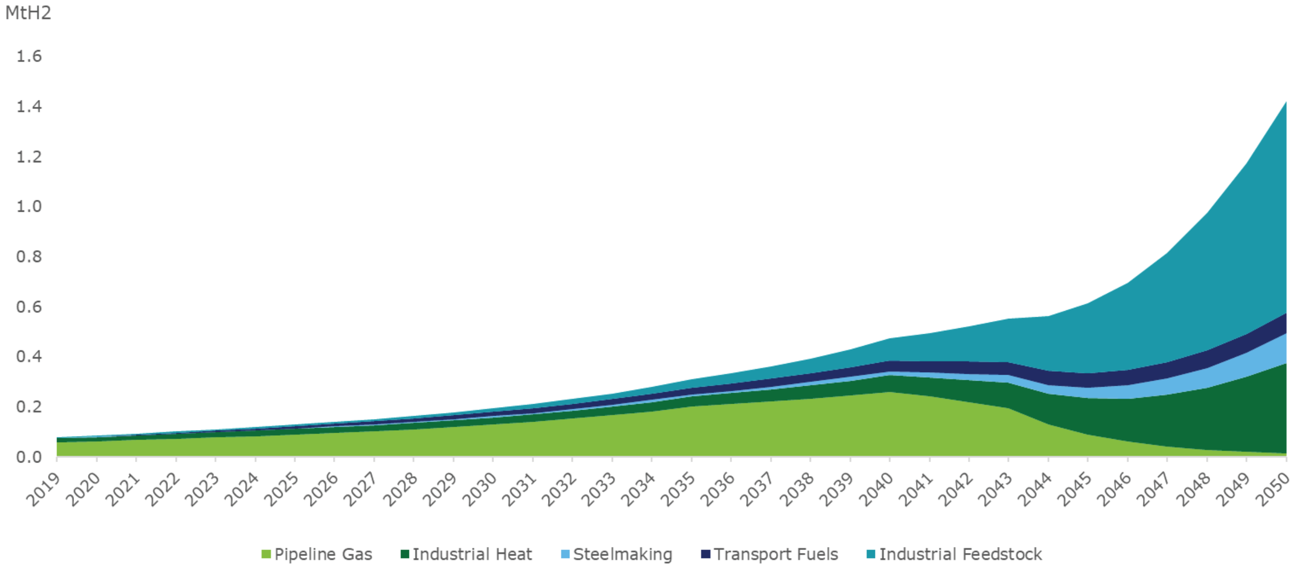
Figure 6.31 Additional Australian-produced hydrogen demand by application – Scenario 4 (2019-2030)



Source: Deloitte Analysis

Under the *Electric breakthrough* scenario to 2030, additional Australian-produced hydrogen is driven by pipeline gas, which makes up 66% of Australia's hydrogen production of <1 Mtpa by 2030.

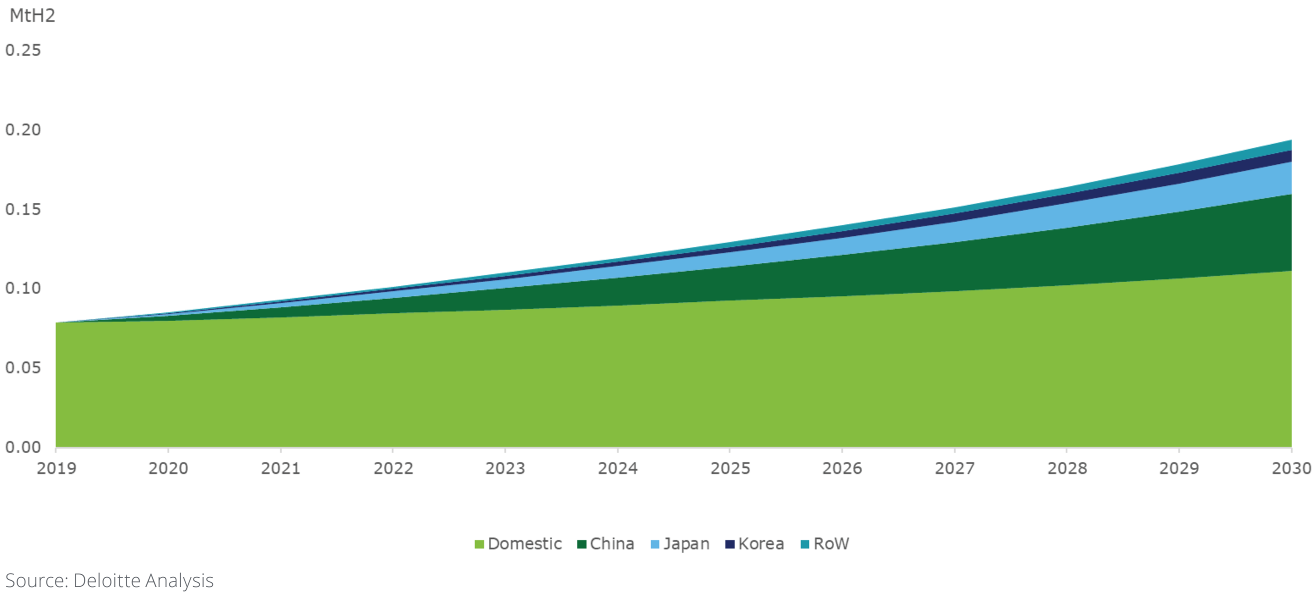
Figure 6.32 Additional Australian-produced hydrogen demand by application – Scenario 4 (2019-2050)



Source: Deloitte Analysis

Under the *Electric breakthrough* scenario to 2050, additional Australian-produced hydrogen is initially driven by demand for pipeline gas until this sector goes into decline beyond 2040. Beyond this time the demand from hard-to-abate industrial sectors become dominant users. Total additional hydrogen production in Australia is the lowest of all scenarios, with only 1 Mtpa produced by 2050. Hydrogen penetration rates into end-use markets are either minimal or non-existent, as reductions in hydrogen technology costs are insignificant and applications are largely electrified instead.

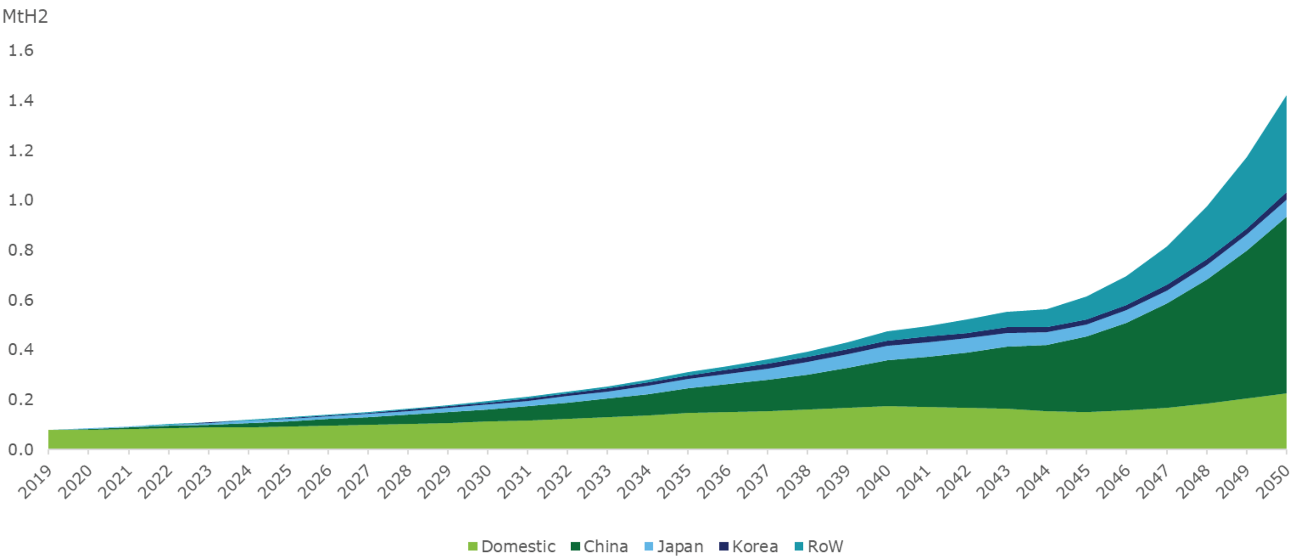
Figure 6.33 Additional Australian-produced hydrogen production by region – Scenario 4 (2019-2030)



Source: Deloitte Analysis

In the *Electric breakthrough* scenario to 2030, Australia's hydrogen production is <1 Mtpa. Demand for Australian hydrogen is largely driven by domestic demand as Australia is still at the early stages of capturing international demand for hydrogen in key export markets like China, Japan and Korea.

Figure 6.34 Additional Australian-produced hydrogen production by region – Scenario 4 (2019-2050)



Source: Deloitte Analysis

In this scenario to 2050, Australia consumes <1 Mtpa of hydrogen, equating to 16% of the total Australian production of hydrogen of 1 Mtpa. Overall, hydrogen is not the fuel of choice for decarbonisation. Instead global and domestic action for decarbonisation focuses on electrification. In this small export market, China remains the largest consumer of Australian-produced hydrogen.

6.3 Economic impact analysis

This section presents the results of the economic impact analysis. Here the *Hydrogen of the future* and *Targeted deployment* scenarios— are compared with the *Business as usual* scenario.

In the *Business as usual, Energy of the future* and *Targeted deployment* scenarios, the supply of capital and labour — the primary productive resources used by the Hydrogen sector — is projected to grow in line with historical rates. Introduction of an expanding hydrogen sector creates additional demand for these scarce inputs to production. Returns to capital and labour consequently rise and those sectors that are able to accommodate higher input prices are able to expand as input use increases. Those sectors that cannot accommodate the higher returns to capital and labour are effectively crowded out, with fewer inputs available growth slows in these industries.

In the *Energy of the future (without constraints)* scenario, the restrictions that cause crowding out are relaxed. Here, industries do not face rising costs for capital and labour, with these inputs assumed to grow at a rate that accommodates demand from each sector. In this scenario, the introduction of a rapidly expanding hydrogen sector does not impact the availability of inputs for other sectors. As a consequence, growth in all other sectors of the economy is not constrained by the introduction of a hydrogen sector.

Relaxing capital and labour constraints in the *Energy of the future (without constraints)* scenario is an extreme assumption. The results of this scenario should be contrasted with that in the *Energy of the future* scenario.

6.3.1 Economic impact modelling results

This section describes the results of the economic impact modelling. Deloitte's in-house CGE model, DAE-RGEM, is used to compare the policy scenarios, against the *Business as usual* scenario. For more information on Deloitte's in-house CGE model please see Appendix C. Here, headline economic impacts — GDP and employment — are discussed as well as the impact on specific sectors.

6.3.1.1 GDP impacts

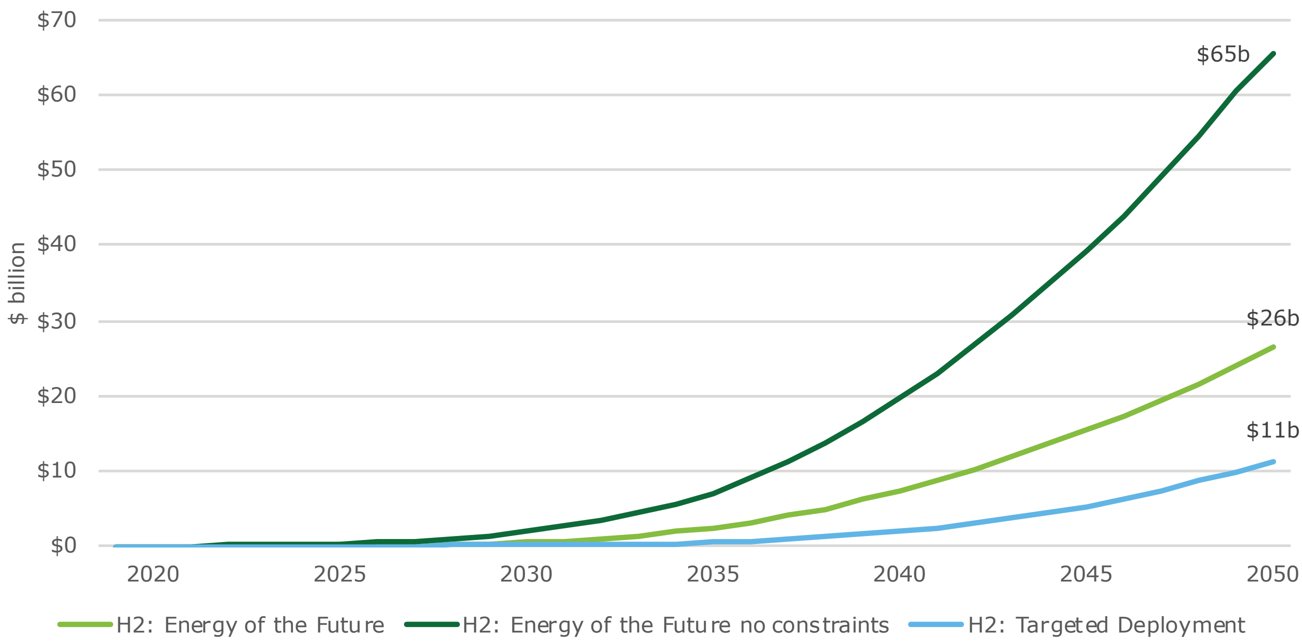
The development of the Hydrogen sector has a positive impact on Australian GDP under all three Policy Scenarios compared to the *Business as usual* scenario. In the *Energy of the future* scenario, GDP is projected to be around $26 billion higher by 2050 (Figure 6.35),[67] reflecting the speed with which the Hydrogen sector is assumed to scale compared with to the *Business as usual* scenario. Similarly, under a *Targeted deployment* scenario, Australian GDP is projected to be around $11 billion higher.

Relaxing constraints around the mobility of labour and capital has a significantly large impact on the impact of the *Energy of the future* scenario. Australian GDP is projected to be around $65 billion higher than in the *Business as usual* scenario and compared to the *Energy of the future* scenario, *Energy of the future* (without constraints) results in GDP being around $39 billion higher in 2050. This is due to the improved performance of sectors other than hydrogen (discussed more detail below in Section 6.3.1.2) as the crowding out of these other sectors does not occur.

The *Business as usual* scenario depicts a world where the world moves ahead with hydrogen technology, but Australia lags behind due to policy or other constraints. While this could mean Australia misses out on the hypothetical upsides from exporting hydrogen, this scenario could also see demand for Australia's traditional energy sources like coal and gas decline. This has not been modelled as part of this project.

While the introduction of the hydrogen sector drives a large dollar increase in Australia's GDP, in relative terms the increase is modest. In the *Energy of the future* scenario, Australian GDP is projected to be just 0.8% higher compared to *Business as usual*, and just 0.34% higher under the *Targeted deployment scenario.* This reflects, in part the offsetting impacts Hydrogen has on other sectors in Australia, but also relative size of the industry compared to Australia's established resource sectors.

Figure 6.35 Projected deviation in Australian GDP from *Business as usual* scenario, selected policy scenarios



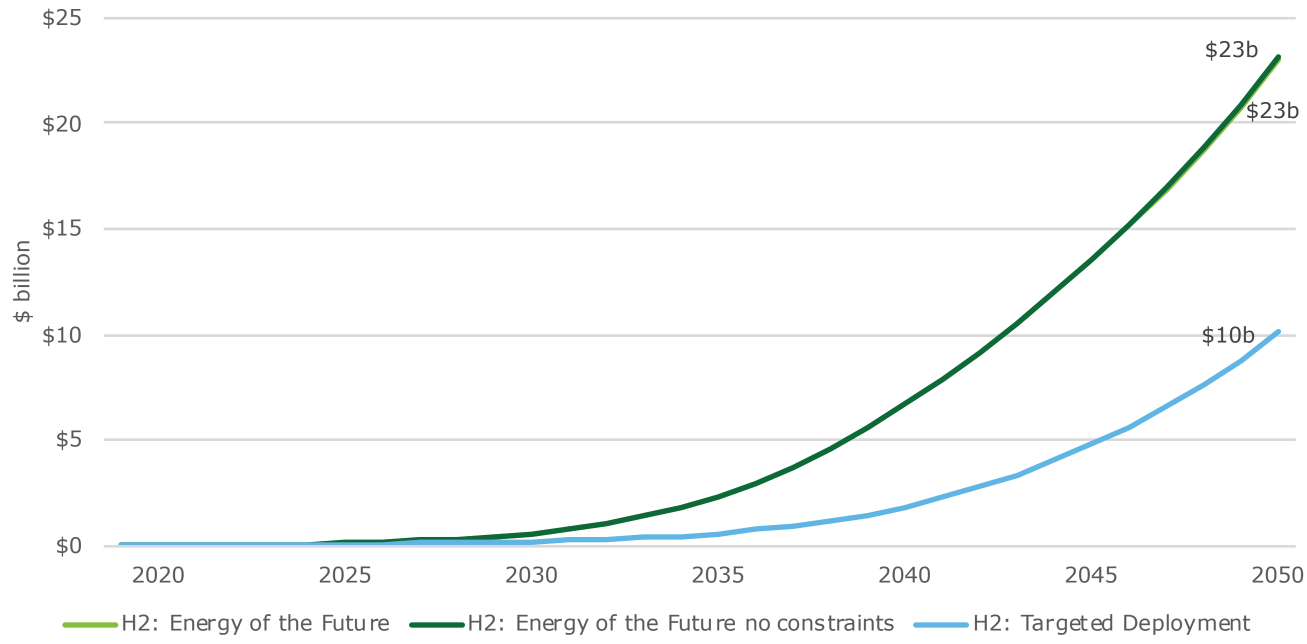
Source: DAE-RGEM

Impacts to GDP are also positive in other modelled regions, although compared to Australia, these impacts are small. The largest increase is in Korea, where GDP is 0.04% higher in the *Energy of the future* scenario. Across all modelled regions, the impacts to GDP are larger in the *Energy of the future scenario* than in the *Targeted deployment* scenario.

6.3.1.2 Sectoral impacts

The increase in Australia's GDP is driven largely by the expansion of hydrogen production. By 2050 the value of the hydrogen sector in the *Energy of the future* scenario is projected to be $23 billion above that described in the *Business as usual* scenario (Figure 6.36). This increase is equivalent to that in the *Energy of the future (without constraints)* scenario reflecting the identical assumptions used which informed how the hydrogen sector would expand. The expansion of the hydrogen sector in the *Targeted deployment* scenario while relatively smaller at $10 billion in 2050, also drives much of the growth in Australian GDP.

Figure 6.36 Projected deviation in hydrogen sector output from *Business as usual* scenario, selected policy scenarios



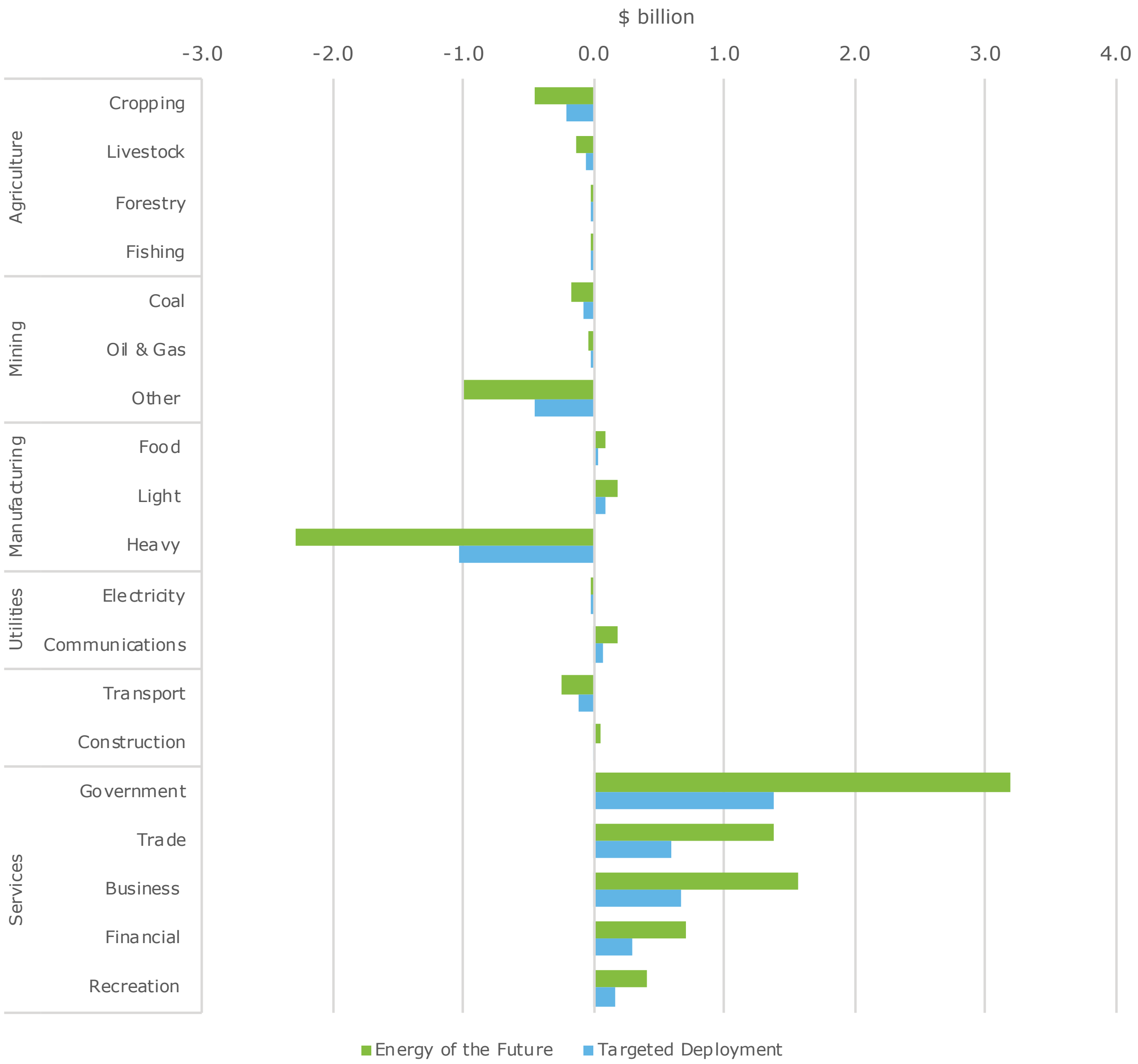
Source: DAE-RGEM

While hydrogen drives Australian GDP higher under the *Energy of the future* and *Targeted deployment* scenarios, the industry has mixed effect on the rest of the Australian economy. While some sectors benefit (mainly services), others face challenges (agriculture, mining and manufacturing). In the *Energy of the future* scenario, the rest of the Australian economy is around $3.4 billion higher by 2050, with *Targeted deployment* around $1.4 billion higher.

Those industries that struggle in the face of a growing hydrogen industry — agriculture, mining and manufacturing —are unable to compete for productive resources against a rapidly expanding hydrogen sector. Hydrogen intensively uses capital and labour limiting the availability of these factors for other industries, thereby crowding them out and restricting their growth.

Export orientated sectors such as agriculture and mining are also negatively impacted by a loss in export competitiveness. Strong demand for Australian hydrogen exports causes an appreciation of the real exchange rate and this results in demand markets substituting away from Australia as a supplier, with production slowing to match weaker demand. Lower production in these sectors also has upstream and downstream flow-on effects, with **transport** notably lower as a key intermediate input to agriculture and mining.

Figure 6.37 Projected deviation in sectoral value added at 2050 from *Business as usual* scenario, *Energy of the future* and *Targeted deployment* scenarios



Source: DAE-RGEM

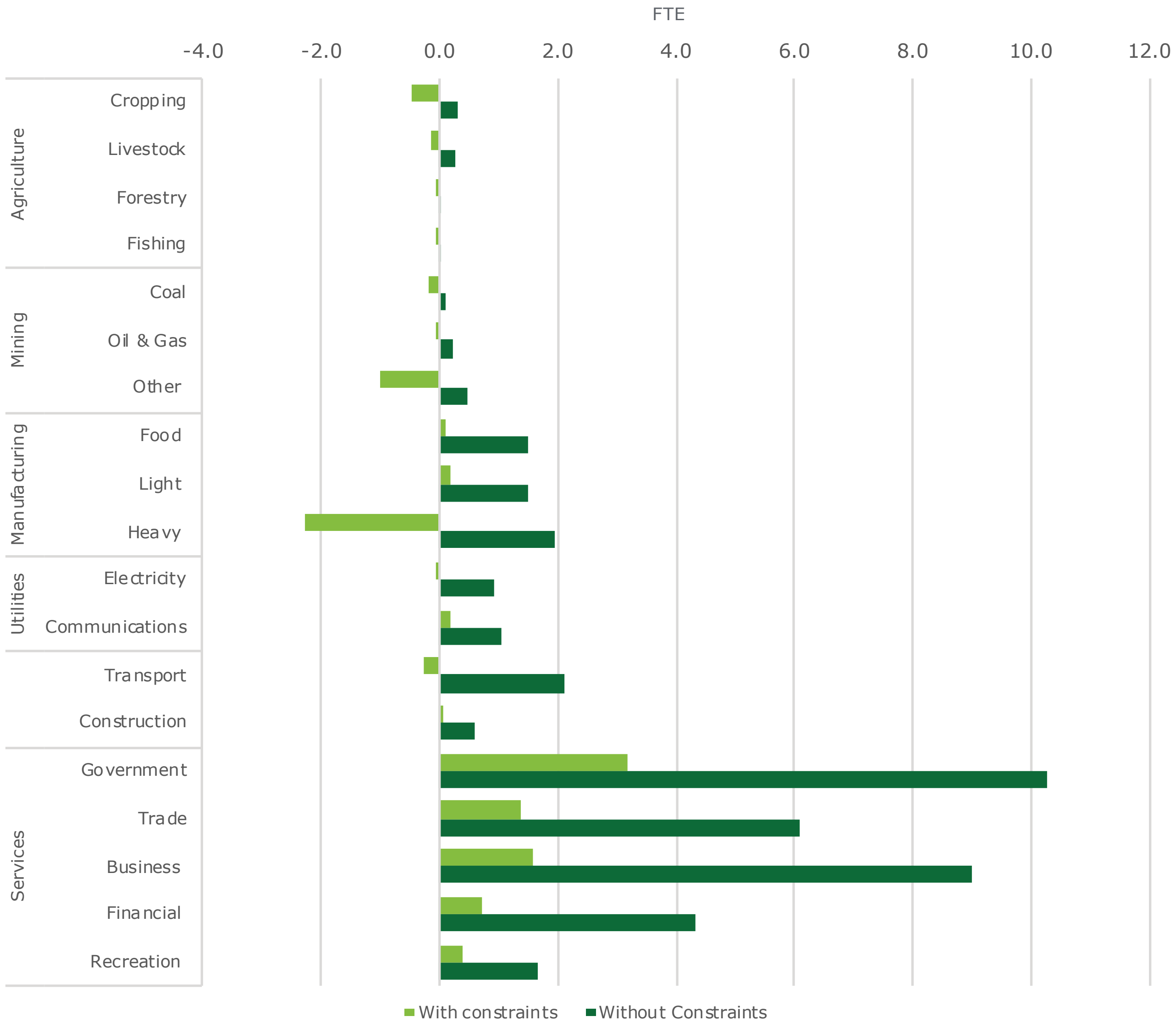
The industries that gain alongside hydrogen production are largely in the **services sector**. These industries benefit from higher real incomes in the *Energy of the future* and *Targeted deployment* scenario that results from a modest increase in Australia's terms of trade — directly increasing the purchasing power of domestic income.

The largest increase in the services sector consists of **Government services**, where the cumulative increase in economic activity results in higher taxes and transfers. More broadly, the larger Services sector also reflects the shift of labour away from the agricultural, mining and manufacturing sectors where growth slows. Labour then flows to the services sector (the primary productive input) allowing an increase in production.

The effect of relaxing constraints around labour and capital mobility, as per the *Energy of the future (without constraints)* scenario, is demonstrated in Figure 6.38 below. Without crowding out, no sector is worse off from the introduction of a rapidly expanding hydrogen sector, indeed agriculture, mining and manufacturing which are worse off under the *Energy of the future* scenario grow, albeit marginally. The services sector expands dramatically under the *Energy of the future (without constraints)* scenario, where labour as the primary input is no longer in scarce supply.

Relaxing capital and labour mobility in the *Energy of the future* (without constraints) scenario is an extreme assumption. It is unlikely to be reflected in the real world in the short or long term. Despite this, the results highlight where capital and labour are likely to be most in demand should the hydrogen sector expand rapidly. Clearly there is significant opportunity for the hydrogen sector to support broader growth in the Australian economy, primarily through the services sector, under the right economic and policy mix.

Figure 6.38 Projected deviation in sectoral employment at 2050 from *Business as usual* scenario, *Energy of the future* with and without constraints



Source: DAE-RGEM

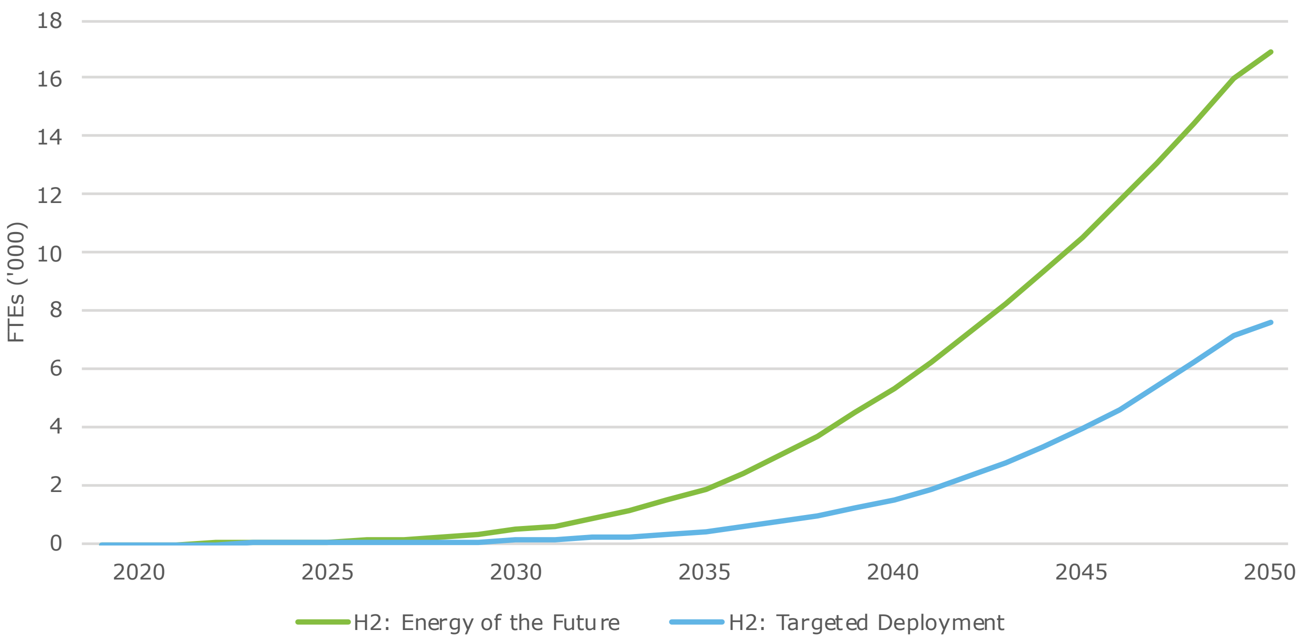
6.3.1.3 Employment impacts

The impact of the Hydrogen sector has a net positive impact on Australian employment, although this impact is relatively modest. Compared to the *Business as usual* scenario, employment in the *Energy of the future* scenario is projected to be around 16,700 Full Time Equivalent (FTE) jobs higher (0.09%) in 2050 (Figure 6.39). Similarly, the *Targeted deployment* scenario is projected to result in employment being 7,600 FTE's (0.04%) higher (Figure 6.39).

Without constraints to labour or capital as in the *Energy of the future* (without constraints) scenario, employment in Australia rises dramatically. By 2050, the economy is projected to add around 273,000 jobs, 16-times that in the *Energy of the future* scenario. Of these positions, 81% would be added in the services sector.

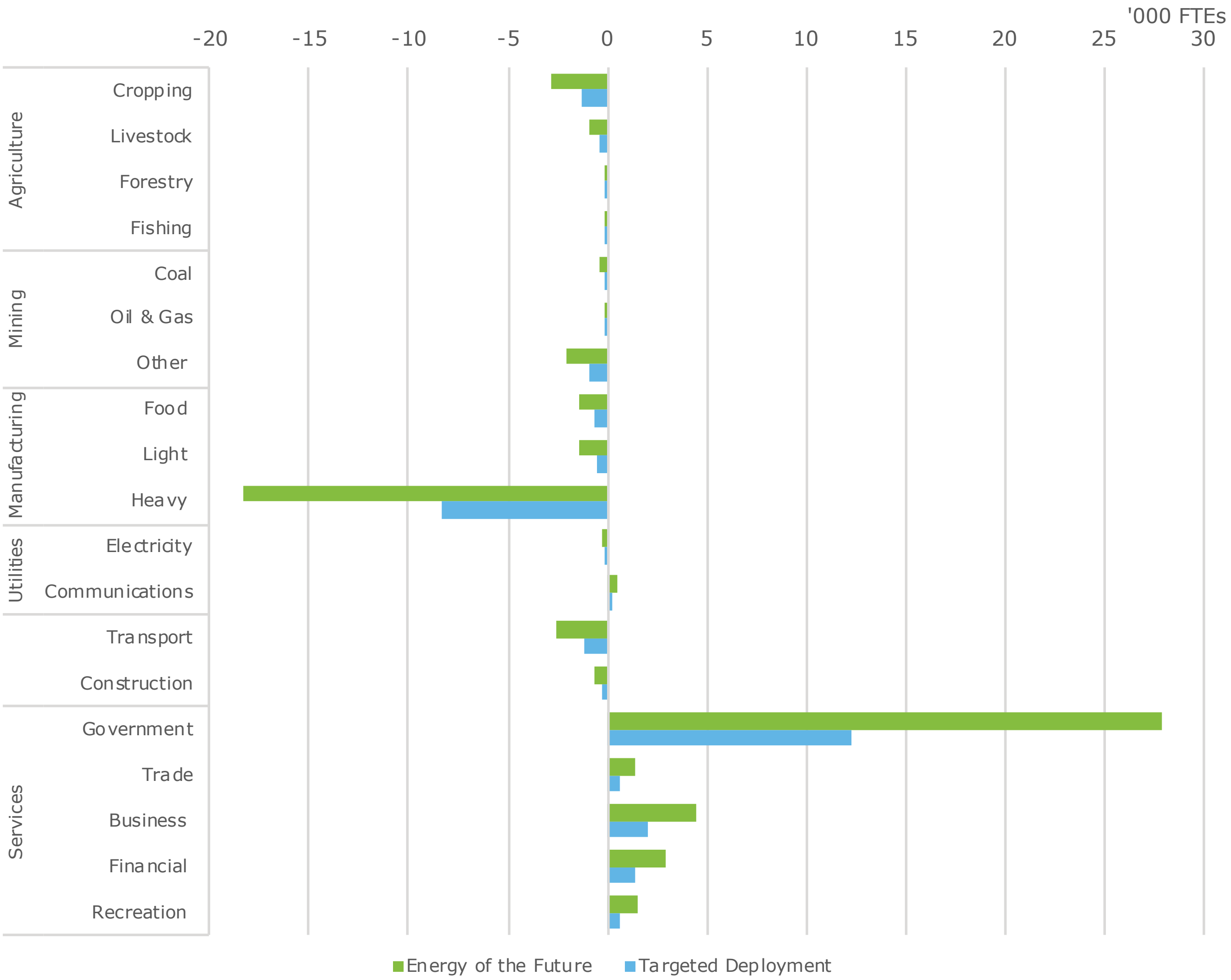
In contrast to GDP, much of the headline impact to employment comes from outside the hydrogen sector. As the expanding hydrogen sector diverts capital and natural resources (which it uses intensively) from other sectors (such as agriculture, mining and manufacturing), these sectors slow. This frees up labour as a resource as these slowing sectors are more intensive users of labour as an input to production. Consequently, labour flows to other industries, principally in the services sector, where it is a significant input into production. The largest increases in employment are therefore occur in industries such as Government services and Retail trade (Figure 6.40).

Figure 6.39 Projected deviation in employment from *Business as usual* scenario, *Energy of the future* and *Targeted deployment* scenarios



Source: DAE-RGEM

Figure 6.40 Projected sectoral deviation in employment at 2050 from *Business as usual* scenario, *Energy of the future* and *Targeted deployment*



Source: DAE-RGEM

Note: Forestry, Fishing and Oil and Gas mining are all negative employment impacts

6.4 Consolidated modelling outputs

6.4.1 Hydrogen Production by Technology Type

Currently, hydrogen production is dominated by fossil-fuel based technologies, such as coal gasification and steam methane reformation. Whereas electrolysers currently only make up 3-4% of total hydrogen production. In a decarbonising world, this proportion is likely to grow as hydrogen produced using green electrolysers has significant potential in reducing the carbon emissions related to hydrogen production.

The type of technology used to produce hydrogen in Australia and globally is expected to differ significantly across all four scenarios due to different technology learning curves, and the degree to which decarbonisation requires hydrogen to be produced in carbon-neutral ways. The scenarios and the modelling does not require or target any specific technology or requirements for the production of green hydrogen.

Electrolyser proportions impact the carbon intensity of Australia's hydrogen production as certain technologies such as coal gasification and steam methane reformation are very carbon intensive and do not benefit from a decarbonising electricity grid.

A hydrogen industry that is heavily dependent on these technologies will have a significantly higher amount of emissions, outweighing emissions avoided from hydrogen use in domestic and export markets. These emissions may however be abated through the use of CCS or carbon offsets.

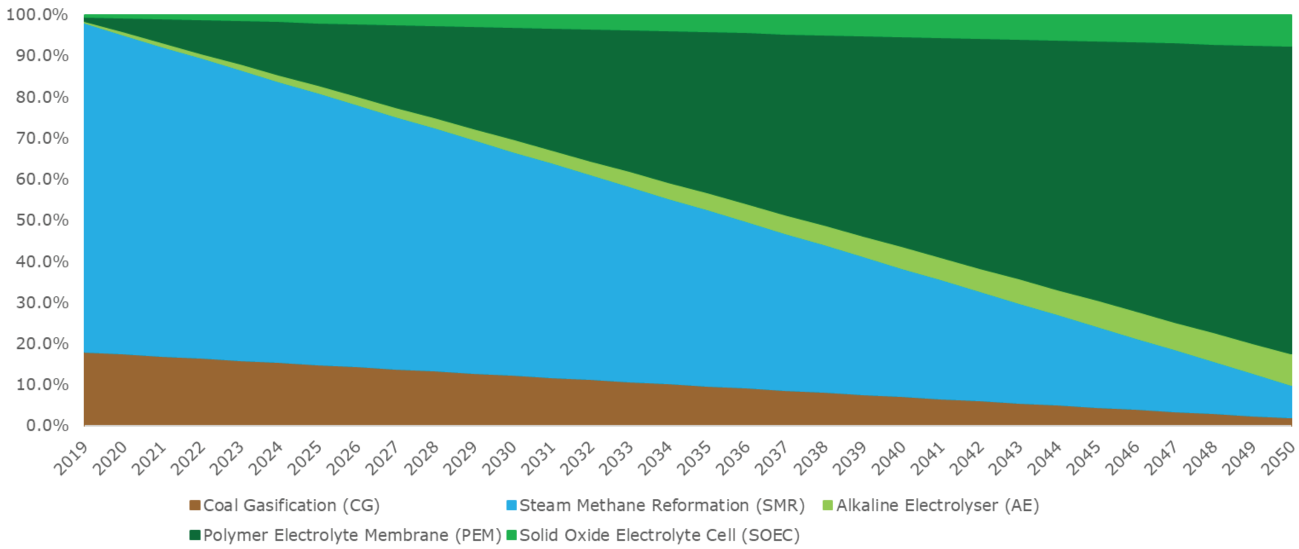
The use of carbon offsets and CCS technology adds additional costs to hydrogen production, which under certain scenarios, may spur additional investment into making electrolyser-based technologies more cost-competitive. Under the *Energy of the future* and the *Electric breakthrough*, electrolyser technology becomes the dominant method of producing hydrogen by 2050.

In contrast, the *Targeted deployment* and *Business as usual* scenarios see relatively slower uptake in electrolyser technology and, in the case of *Targeted deployment*, a heavy reliance on carbon offsets to maintain a relatively carbon-neutral industry. In the *Business as usual* scenario, fossil-fuel based hydrogen producers are not constrained by the need to use carbon offsets, meaning technologies such as coal gasification and SMR retain their cost competitiveness over electrolysers for much longer.

Water consumption is also impacted as some technologies are particularly water intensive, such as coal gasification production. A hydrogen industry that is heavily dependent on coal gasification technology would require significantly more water than an equivalent industry with more water-efficient technologies.

The following sections explain the electrolyser proportion by technology across all scenarios and the impacts they have on emissions produced and water consumption.

Figure 6.41 Electrolyser proportion by technology – Scenario 1



Source: Deloitte Analysis

Under the *Energy of the future* scenario, the proportion of electrolysers in Australia grows rapidly at the expense of the currently dominant hydrogen-producing technologies such as Steam Methane Reforming and Coal Gasification. Polymer Electrolyte Membrane technology sees the fastest growth due to relatively rapid reductions in costs due to its technological maturity amongst other electrolyser technologies. Hydrogen production from fossil fuels as a proportion of the total hydrogen-producing fleet falls from 98% in 2019 to 10% in 2050.

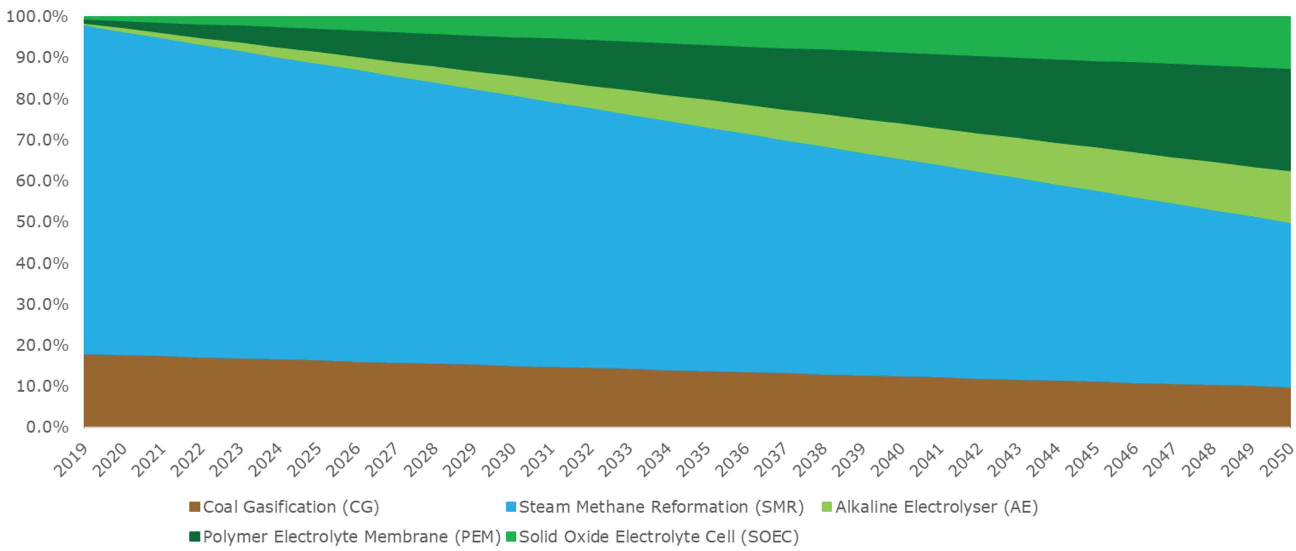
The *Energy of the future* scenario depicts a large hydrogen industry dominated by electrolysers using a low-carbon grid, with a hydrogen industry that produces less carbon emissions and consuming relatively less water. Under this scenario, by 2050 Australian annual hydrogen production consumes 3,095 Mt of coal in coal gasification technology, 5,237 Mt of natural gas through SMR technology and 912 TWh of electricity through all electrolysers.

Under the *Targeted deployment* scenario, the proportion of electrolysers in Australia grows much more modestly than in the *Energy of the future* scenario, with Steam Methane Reforming being the main technology displaced. Hydrogen being produced from fossil fuels retains a significant proportion of hydrogen production, producing 50% of hydrogen in 2050.

The *Targeted deployment* scenario depicts a relatively large hydrogen industry that remains driven significantly by Steam Methane Reforming and Coal Gasification technologies, with a moderately decarbonised grid. Water intensity is also high in this technology mix due to the high proportion of coal gasification use.

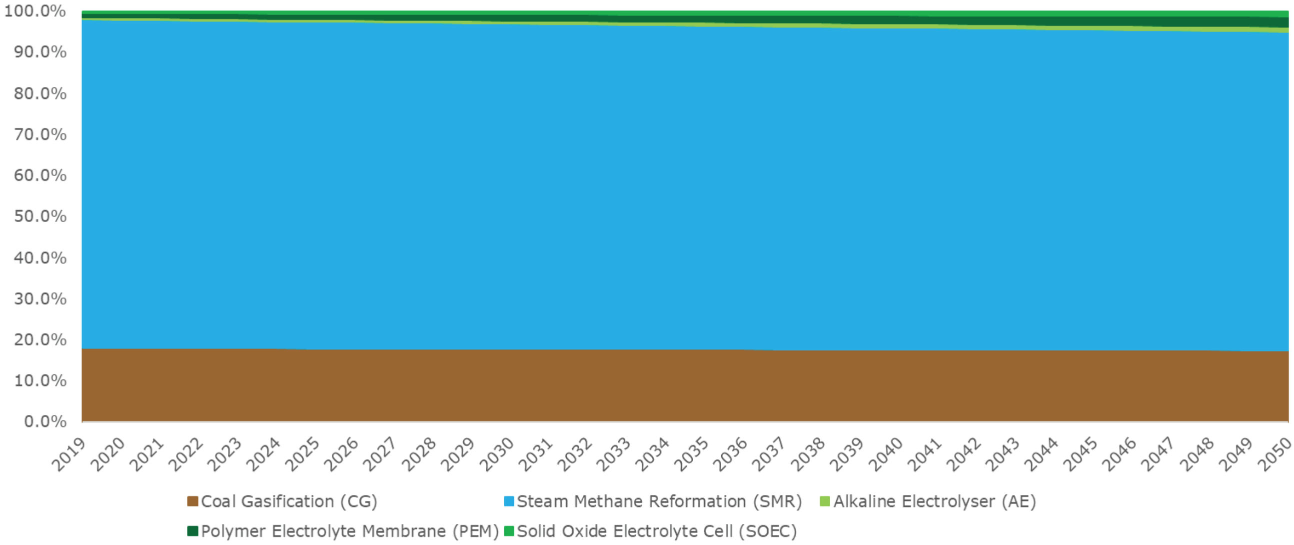
Under this scenario, by 2050 Australian annual hydrogen production consumes 6,012 Mt of coal in coal gasification technology, 10,174 Mt of natural gas through SMR technology and 188 TWh of electricity through all electrolysers.

Figure 6.42 Electrolyser proportion by technology – Scenario 2



Source: Deloitte Analysis

Figure 6.43 Electrolyser proportion by technology – Scenario 3



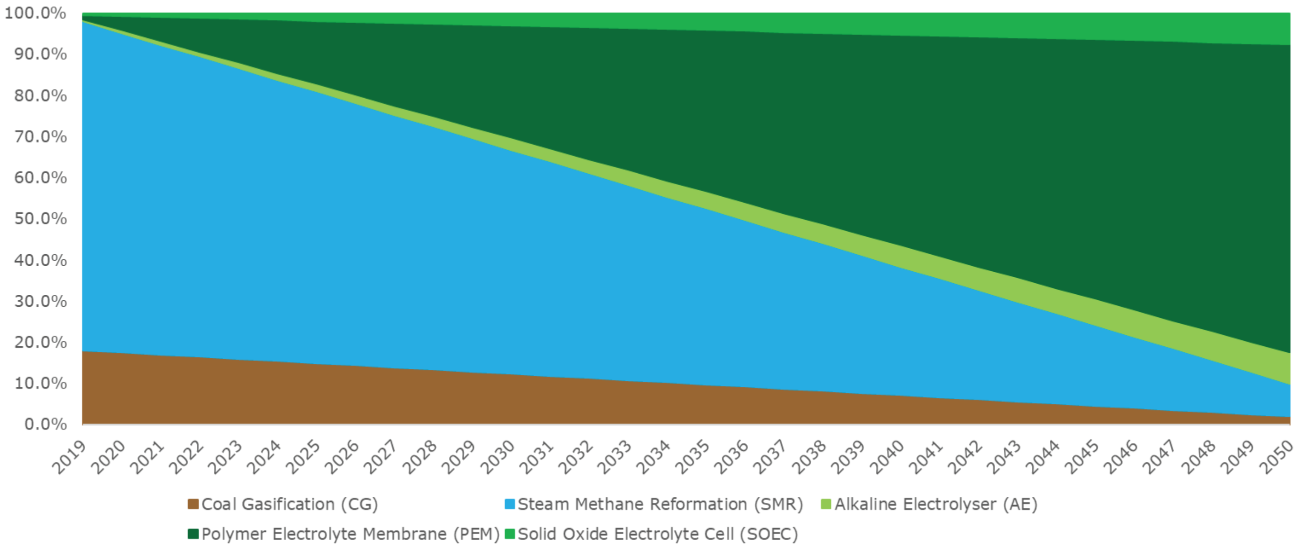
Source: Deloitte Analysis

Under the *Business as usual* scenario, the technology mix of hydrogen production is largely unchanged with Steam Methane Reforming and Coal Gasification making up 95% of the total hydrogen-producing technologies in Australia, only down 2% from 2019. The minimal changes in technology mix are in part due to slower cost reduction rates for green hydrogen production.

This scenario depicts a small hydrogen industry using a grid with a relatively low amount of decarbonisation. Because of this, carbon emissions produced by the hydrogen industry outweighs emissions avoided through using hydrogen, but the low overall production means this overall figure is relatively low. Water intensity is relatively high for each kilogram of hydrogen produced due to the high proportion of coal gasification technology, but the low overall production means that total water consumption is low.

Under this scenario, by 2050 Australian annual hydrogen production consumes 2,380 Mt of coal in coal gasification technology, 4,475 Mt of natural gas through SMR technology and 5 TWh of electricity through all electrolysers.

Figure 6.44 Electrolyser proportion by technology – Scenario 4



Source: Deloitte Analysis

The *Electric breakthrough* scenario is similar to the *Energy of the future* scenario in terms of the growth of electrolyser use in Australian hydrogen production coming at the expense of fossil-fuel dependent hydrogen production.

This scenario differs from the *Energy of the future* scenario because the Australian hydrogen industry is relatively small, with a moderately decarbonised grid. As this technology mix is heavily dependent on electricity as an input for hydrogen production, this means that emissions related to hydrogen production outweighs emissions avoided through use of hydrogen in this scenario. Water intensity is not significantly high and total water consumption is low due to low overall hydrogen production.

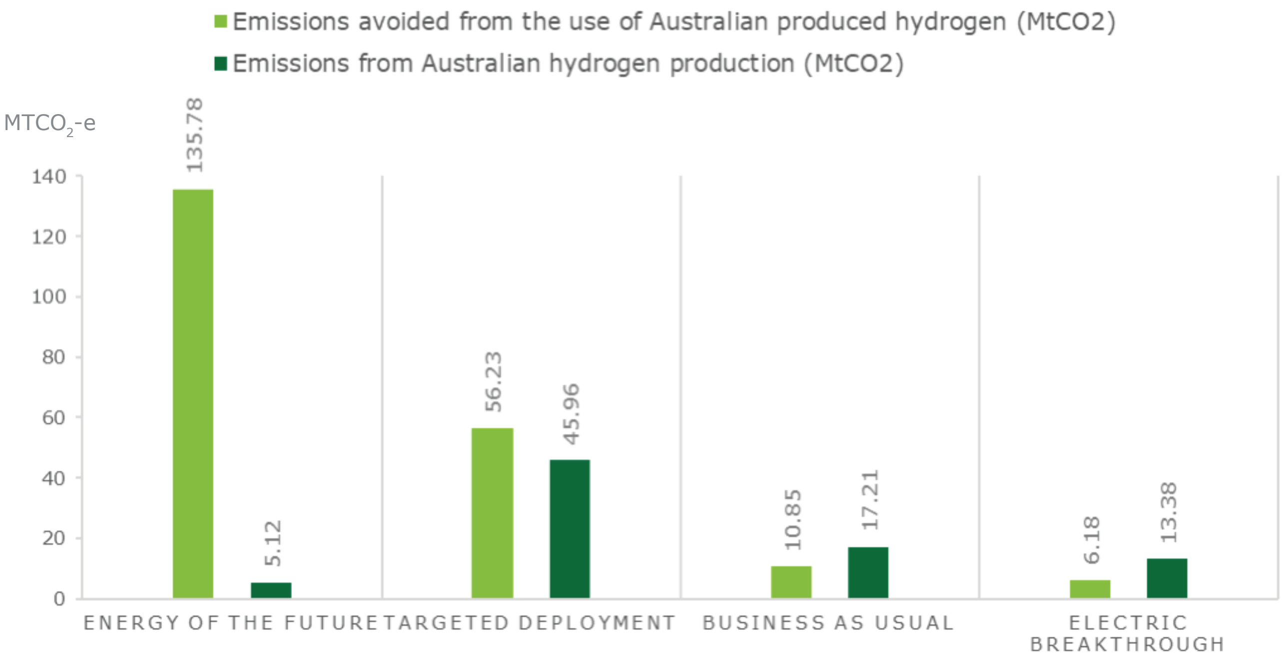
Under this scenario, by 2050 Australian annual hydrogen production consumes 222 Mt of coal in coal gasification technology, 376 Mt of natural gas through SMR technology and 65 TWh of electricity through all electrolysers.

6.4.2 Carbon Impacts

Figure 6.45 shows the difference between emissions avoided and emissions produced through hydrogen production over the forecast period for each of the four scenarios. The amount of carbon abated looks at the carbon emissions from producing hydrogen and the amount of carbon avoided as a result of using hydrogen for global end-uses as a substitute for fossil-fuels. Therefore, where hydrogen is produced using renewable energy and electrolysers ('green hydrogen') the net reduction in emissions is greater than when hydrogen is produced using fossil fuel feedstock without any associated CCS or offsets ('brown hydrogen'). The following graphs show the hydrogen industry's emissions after CCS or offsets have been applied.

Hydrogen producers who are dependent on fossil fuel feedstock, such as those using coal gasification or SMR technology have the option of selecting between using ACCU offsets or CCS technology to abate their emissions, and would choose the cheaper of the two. Under our scenario analysis assumptions, CCS technology becomes cost competitive with ACCU costs in 2039 in the *Energy of the future* scenario and in 2041 in the *Targeted deployment* and *Electric breakthrough* scenarios. In the *Business as usual* scenario, hydrogen producers do not use either offsets or CCS technology.

Figure 6.45 2050 impacts on emissions from Australian hydrogen production

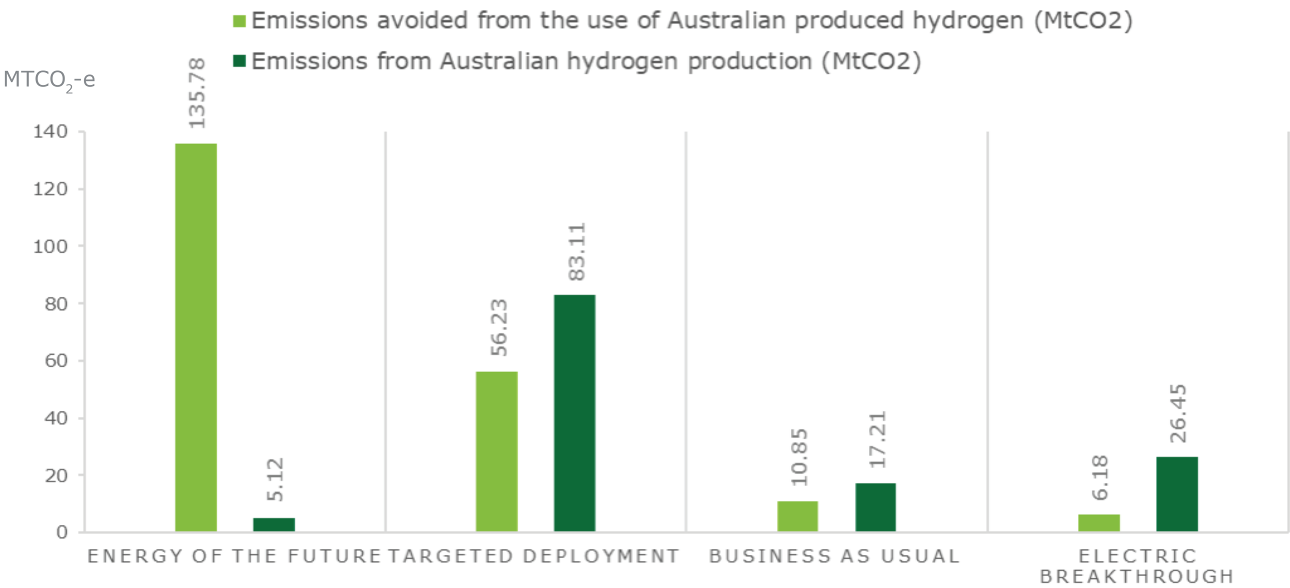


Source: Deloitte Analysis

Under the *Energy of the future*, *Targeted deployment* and *Electric breakthrough* scenarios, fossil-fuel based production such as Coal Gasification and Steam Methane Reforming technologies offset their carbon emissions using either ACCUs or CCS technology to ensure hydrogen production is carbon-neutral. Under our scenario assumptions, CCS technology becomes cost competitive with ACCUs towards the late 2030s and early 2040s in the above scenarios, and fossil fuel based hydrogen producers switch to using CCS technology at this point in time. As CCS technology does not have a 100% capture rate, carbon emissions from Australia's hydrogen production grow slightly once CCS technology is deployed.

In the *Business as usual* scenario there is much less incentive to utilise carbon offsets, and hydrogen production is heavily driven by fossil-fuel based technologies. Total hydrogen production is also a key factor for overall emissions produced as the reduced scale of the lower bound scenarios reduces the overall impacts.

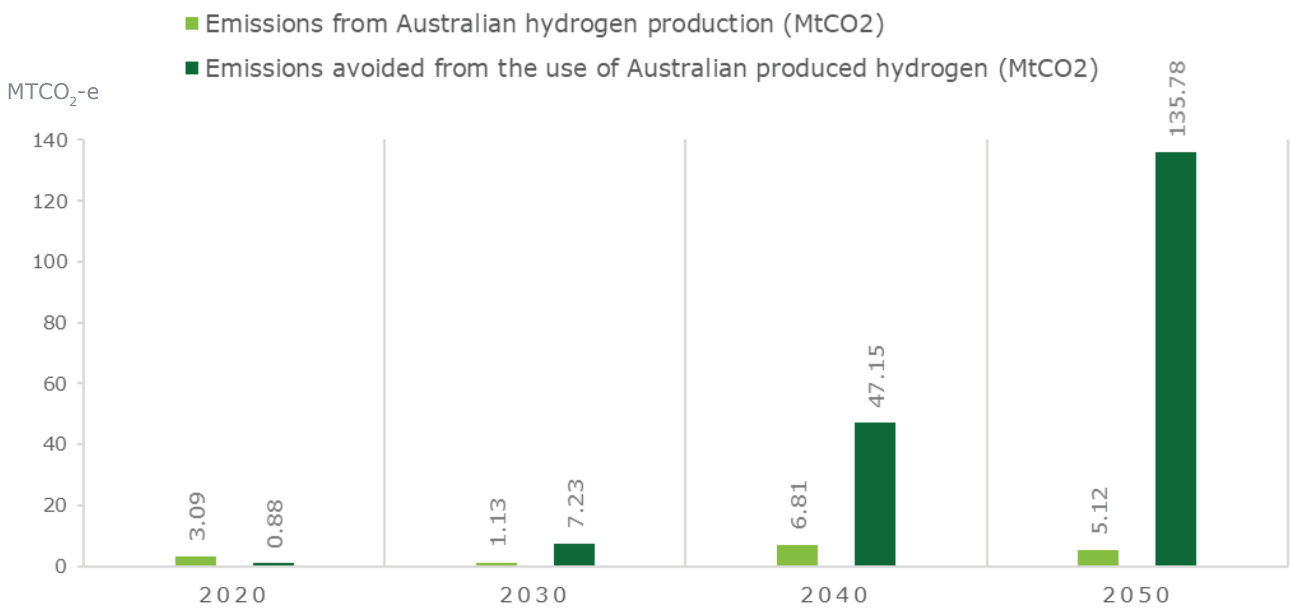
Figure 6.46 2050 impacts on emissions from Australian hydrogen production (if grid decarbonisation for scenarios 2,4 were the same as 3)



Source: Deloitte Analysis

In scenarios *Targeted deployment* and *Electric breakthrough*, Australia's electricity grid's carbon intensity reduces much quicker than the *Business as usual* scenario. If the electricity grid under these two scenarios followed the same carbon intensity trends as the *Business as usual* scenario, carbon emissions from production of Australian hydrogen are significantly higher, with both emissions from production outweighing emissions avoided under both scenarios.

Figure 6.47 Impacts on emissions from Australian hydrogen production – Scenario 1



Source: Deloitte Analysis

The *Energy of the future* scenario is one of two scenarios where the emissions from hydrogen production in Australia is significantly outweighed by emissions avoided through using Australian-produced hydrogen in 2050. As a clean burning fuel, the consumption of hydrogen in pipeline gas, steelmaking operations, industrial uses and transport avoids emissions as it displaces more carbon intensive fuels like natural gas, metallurgical coal and diesel.

In this scenario, fossil fuel-based hydrogen producers using Coal Gasification and Steam Methane Reforming technologies purchase carbon offsets to ensure hydrogen production is carbon-neutral. As the hydrogen-production mix shifts heavily towards electrolysers using a heavily decarbonised grid, the total carbon emissions from hydrogen production drops rapidly relative to the emissions avoided from the use of Australian hydrogen.

Under the *Energy of the future* scenario, CCS technology becomes cost competitive with ACCUs in 2039, due to the rapid growth in ACCU prices. As CCS technology does not fully capture the carbon emissions from the remaining fossil fuel based hydrogen production, carbon emissions from Australian hydrogen production do increase slightly in this scenario, although this is more than offset by the emissions that are avoided.

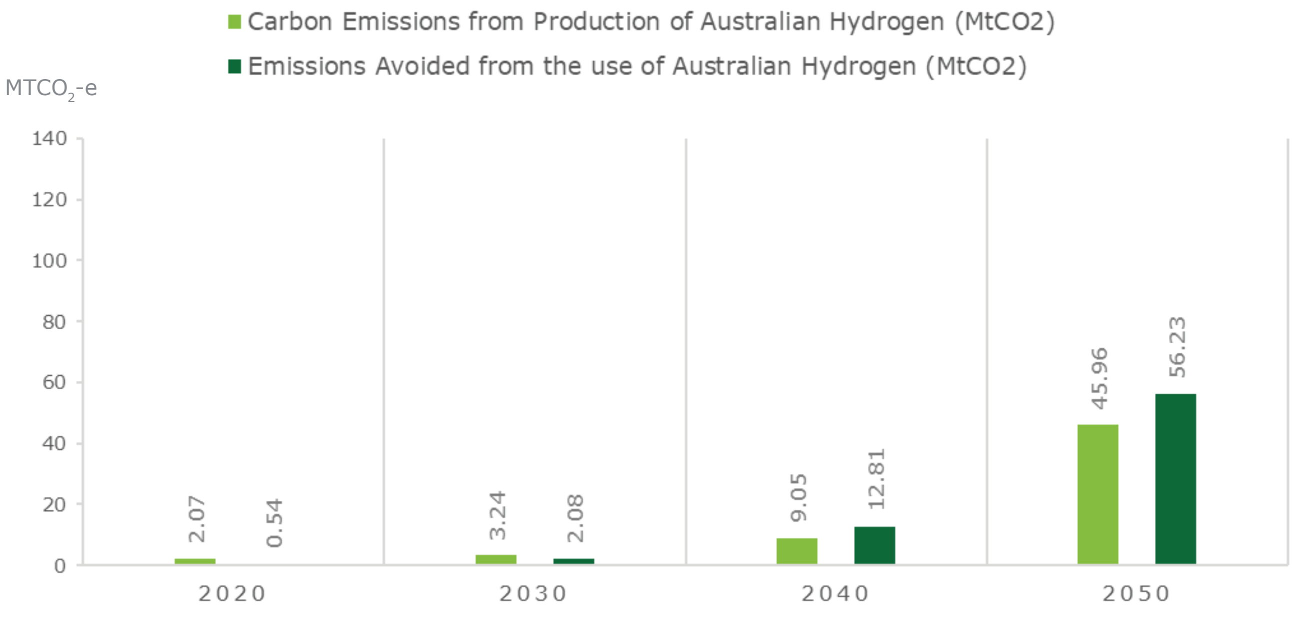
The difference between emissions avoided and emissions produced by Australia's hydrogen industry under the *Energy of the future* scenario in 2050 is 131 MtCO2 with a cumulative total to 2050 of 1,079 MtCO2.

The *Targeted deployment* scenario is characterised by an emissions profile that is moderately outweighed by emissions avoided through using Australian-produced hydrogen in 2050, despite a production-mix that remains dominated by technologies such as Coal Gasification and Steam Methane Reforming. Similarly to the *Energy of the future* and *Electric breakthrough* scenarios, fossil-fuel-based hydrogen producers purchase increasing quantities of carbon offsets to ensure that the production stage of hydrogen moves towards net zero carbon impact. A grid that decarbonises at only a moderate rate means that electrolysers do not provide any significant positive impact upon the carbon intensity of hydrogen production.

Under the *Targeted deployment* scenario, CCS technology becomes cost competitive with ACCUs in 2041, due in part to the growth of ACCU prices. As CCS technology does not fully capture the carbon emissions from the remaining fossil fuel based hydrogen production, carbon emissions from Australian hydrogen production do increase in this scenario, more significantly than in the *Energy of the future* scenario due to the heavy proportion of fossil fuel based hydrogen production.

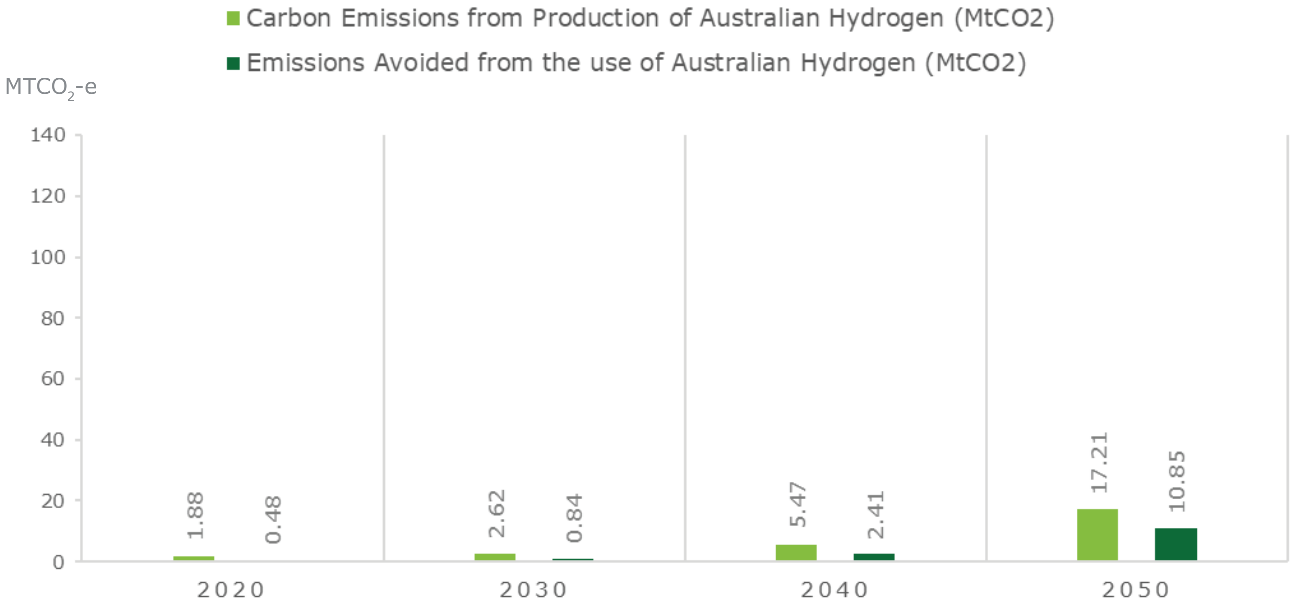
The difference between emissions avoided and emissions produced by Australia's hydrogen industry under the *Targeted deployment* scenario in 2050 is 10 MtCO2 with a cumulative total to 2050 of 46 MtCO2.

Figure 6.48 Impacts on emissions from Australian hydrogen production – Scenario 2



Source: Deloitte Analysis

Figure 6.49 Impacts on emissions from Australian hydrogen production – Scenario 3

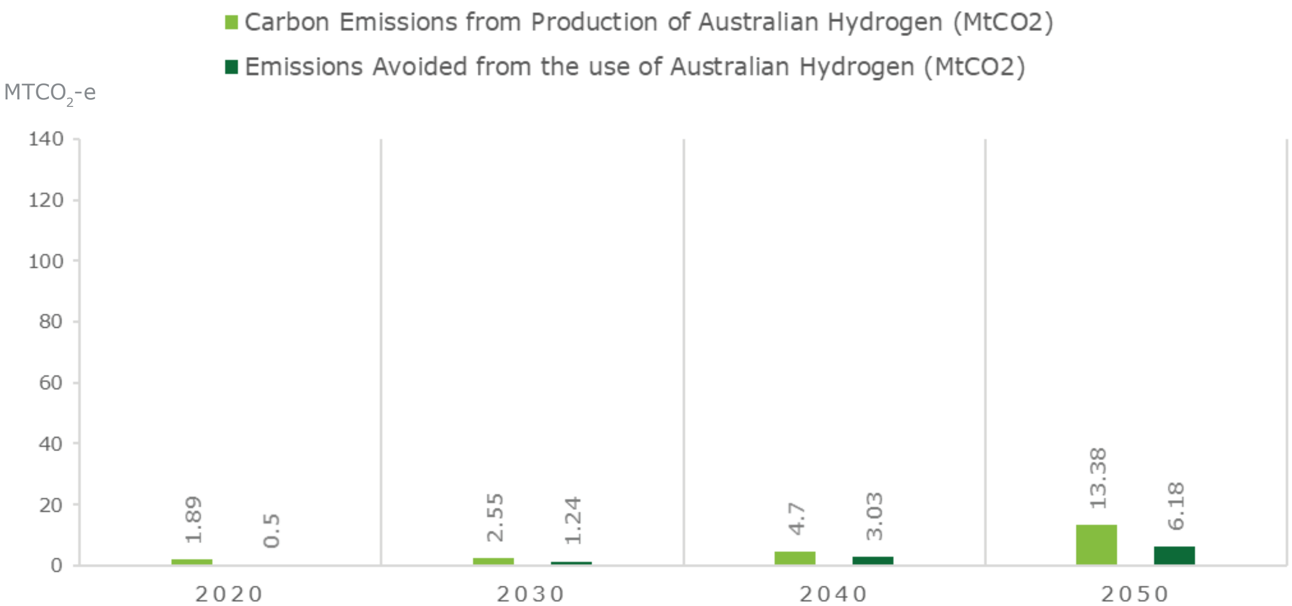


Source: Deloitte Analysis

The *Business as usual* scenario is characterised by a higher amount of emissions produced in the hydrogen production stage than emissions avoided through using that hydrogen in 2050, largely due to a hydrogen-production mix that remains disproportionately dependent on fossil-fuel driven technologies such as Coal Gasification and Steam Methane Reforming. In this scenario, fossil-fuel based hydrogen producers do not purchase any carbon offsets, and CCS technology is not utilised either. Australia's electricity grid only decarbonises at a relatively low rate, meaning that electrolysers do not provide a significant positive impact upon the carbon intensity of hydrogen production. Relatively low demand for Australian hydrogen reduces the overall carbon impact of the hydrogen industry in this scenario.

The difference between emissions avoided and emissions produced by Australia's hydrogen industry under the *Business as usual* scenario in 2050 is -6 MtCO2 with a cumulative total to 2050 of -91 MtCO2.

Figure 6.50 Impacts on emissions from Australian hydrogen production – Scenario 4



Source: Deloitte Analysis

The *Electric breakthrough* scenario is characterised by the emissions from Australian-produced hydrogen slightly outweighing the emissions avoided from hydrogen use in 2050, largely due to an electricity grid that only decarbonises in line with domestic decarbonisation policies adopted under this scenario. This means that hydrogen produced through electrolysis still produces relatively more emissions than electrolysers in scenarios where Australia's electricity grid decarbonises more rapidly. In this scenario, hydrogen produced through fossil-fuel based technologies like Coal Gasification and Steam Methane Reforming increasingly purchase carbon offsets to ensure hydrogen production is eventually carbon neutral. The hydrogen-production mix does diversify away from these technologies across the forecast period, which accelerates the carbon intensity of hydrogen production. Very low demand for Australian hydrogen reduces the overall carbon impact of the hydrogen industry in this scenario.

Under the *Electric breakthrough* scenario, CCS technology becomes cost competitive with ACCUs in 2041, due in part to the growth of ACCU prices. As CCS technology does not fully capture the carbon emissions from the remaining fossil fuel based hydrogen production, carbon emissions from Australian hydrogen production do increase in this scenario, although not as significantly as in the *Targeted deployment* scenario due to the lower proportion of fossil fuel based hydrogen production.

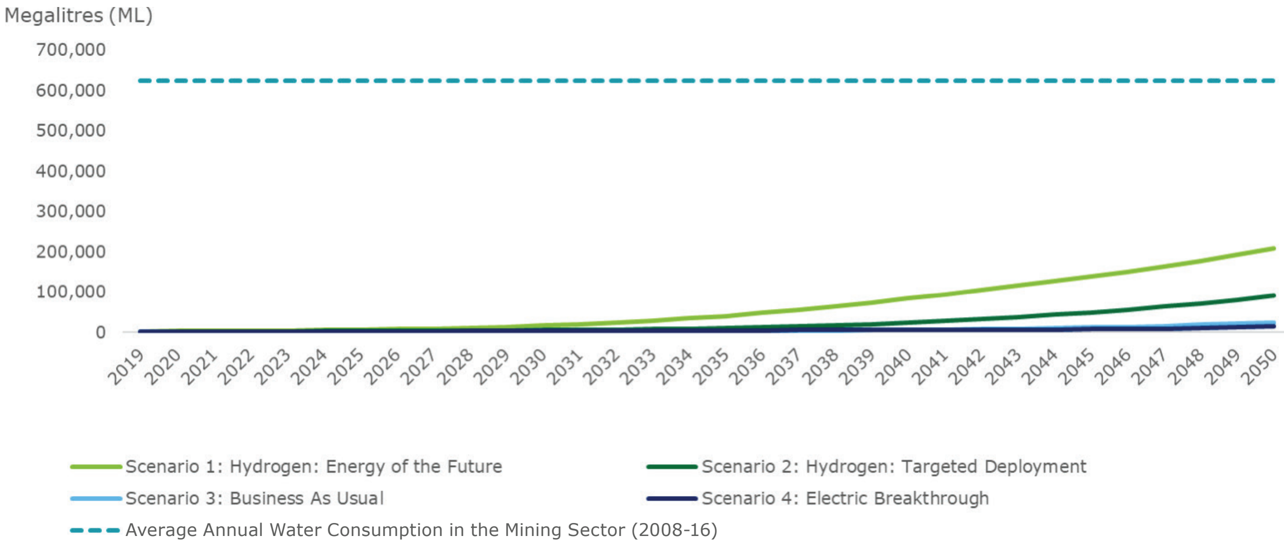
The difference between emissions avoided and emissions produced by Australia's hydrogen industry under the *Electric breakthrough* scenario in 2050 is -7 MtCO2 with a cumulative total to 2050 of -66 MtCO2.

6.4.3 Domestic Water Consumption

Figure 6.51 shows the annual water consumption by Australia's hydrogen industry over the forecast period based on the assumptions for each of the four scenarios. The annual water consumption by Australia's mining sector averaged over the period 2008-2016 of 624 GL has been included to illustrate the relative quantity of water consumed by this industry.

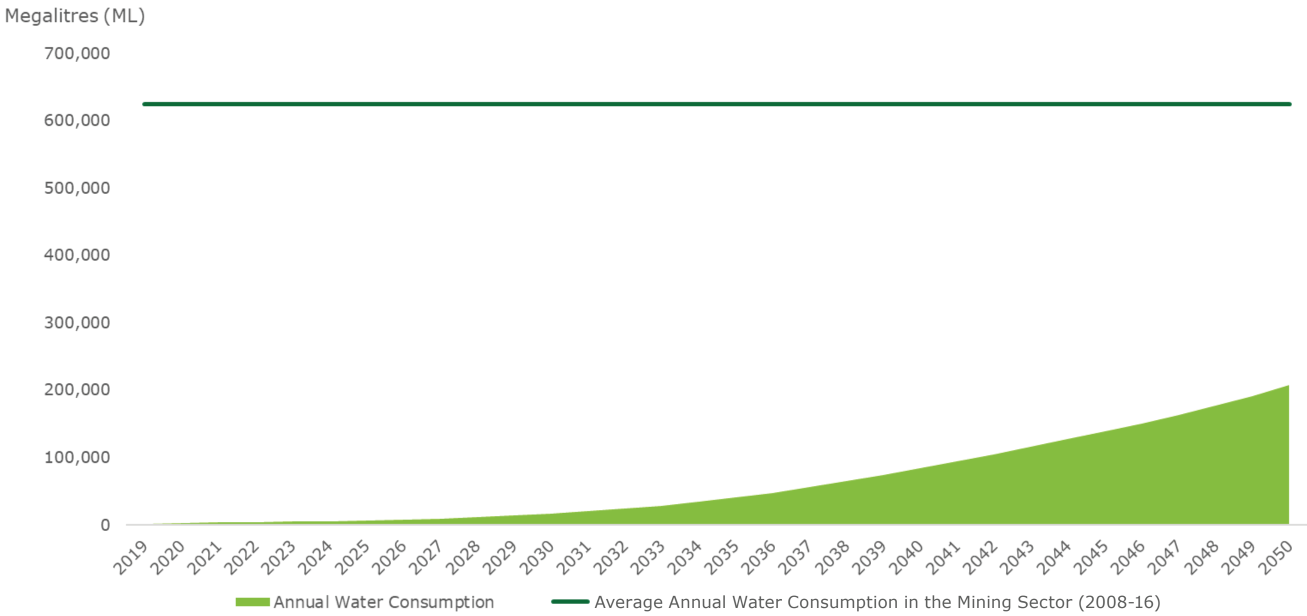
Water consumption is heavily driven by overall demand for Australian hydrogen, meaning that the *Energy of the future* and *Targeted deployment* scenarios have hydrogen-producing industries that consume the most water. Certain technologies such as coal gasification are comparatively water-intensive, and hydrogen-producing mixes that are overly dependent on them have higher water consumption. The below figures depict annual water consumption required for the additional hydrogen production modelled under the four scenarios, compared to the annual water consumption of the mining sector averaged over the period 2008-2016.

Figure 6.51 National annual water consumption of hydrogen produced in Australia



Source: Deloitte Analysis, ABS (4610.0)

Figure 6.52 National annual water consumption of Australian-produced hydrogen – Scenario 1

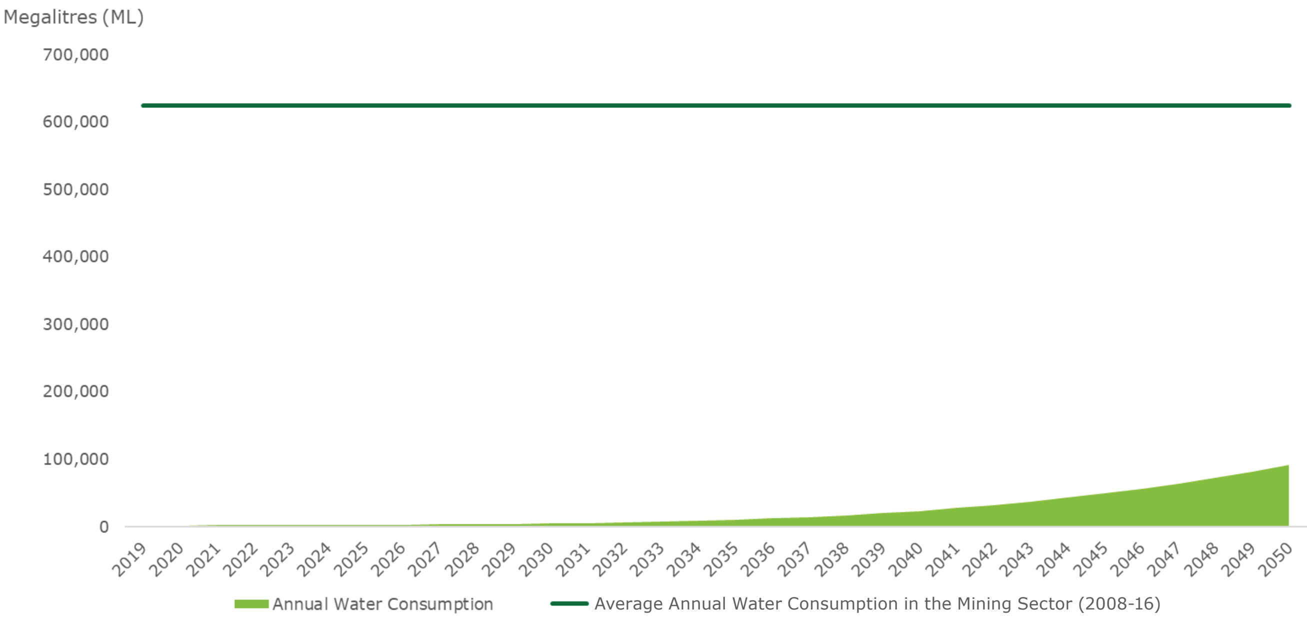


Source: Deloitte Analysis, ABS (4610.0)

The *Energy of the future* scenario has the highest water consumption, due to the size of demand for Australian-produced hydrogen. Hydrogen production from relatively water-intensive technologies such as Coal Gasification is however limited in this scenario.

In 2050, the annual water consumption by Australia's hydrogen industry in this scenario would be 207 GL (207,000 ML) or 33% of the average annual water consumption across Australia's mining sector.

Figure 6.53 National annual water consumption of Australian-produced hydrogen – Scenario 2

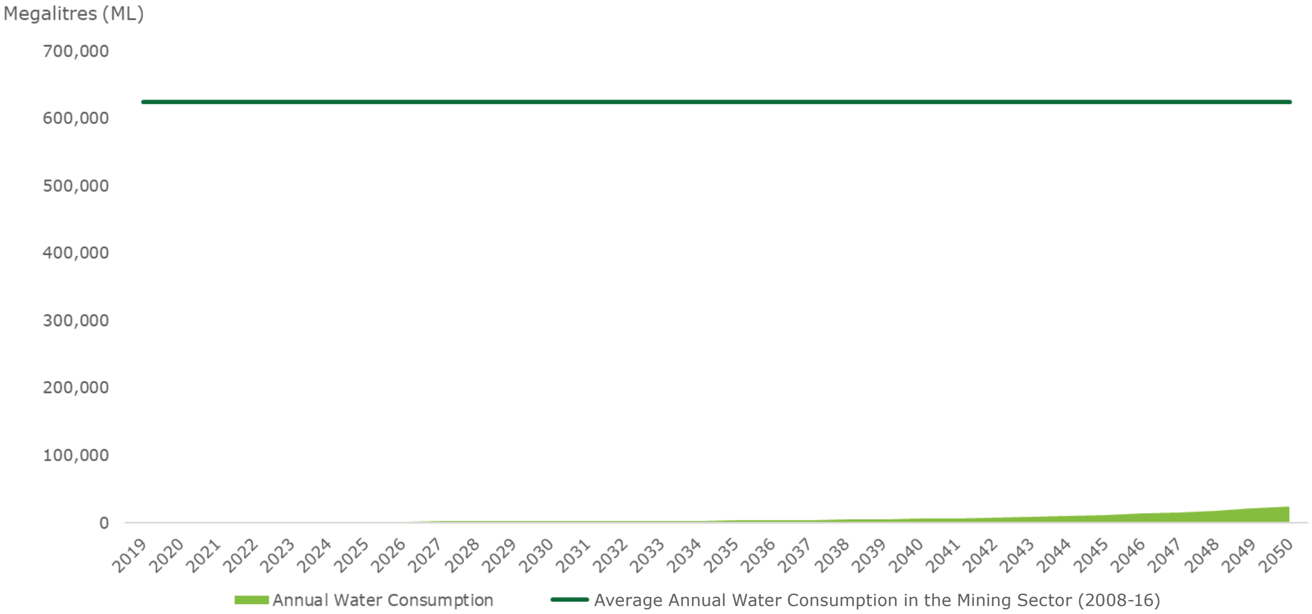


Source: Deloitte Analysis, ABS (4610.0)

Water consumption in the *Targeted deployment* scenario is the second highest of all scenarios, due to the size of demand for Australian-produced hydrogen. Coal Gasification technology remains relatively significant throughout the forecast period in this scenario, increasing the water intensity of hydrogen production in this scenario.

In 2050, the annual water consumption by Australia's hydrogen industry in this scenario would be 91 GL or 15% of the average annual water consumption across Australia's mining sector.

Figure 6.54 National annual water consumption of Australian-produced hydrogen – Scenario 3

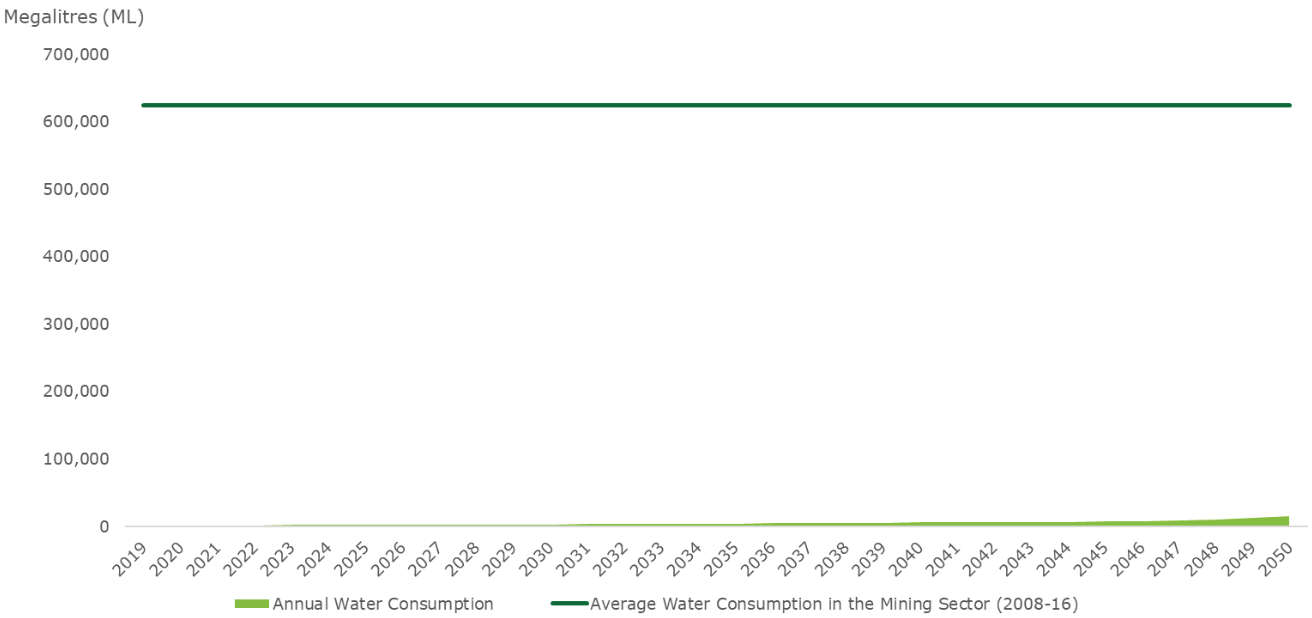


Source: Deloitte Analysis, ABS (4610.0)

Water consumption in the *Business as usual* scenario is the second lowest of all scenarios, due to the limited demand for Australian-produced hydrogen. Coal Gasification technology remains relatively significant throughout the forecast period in this scenario, increasing the water intensity of hydrogen production in this scenario.

In 2050, the annual water consumption by Australia's hydrogen industry in this scenario would be 24 GL or 4% of the average annual water consumption across Australia's mining sector.

Figure 6.55 National water consumption of Australian-produced hydrogen – Scenario 4



Source: Deloitte Analysis, ABS (4610.0)

Water consumption in the *Electric breakthrough* scenario is the lowest of all scenarios, due to the very limited demand for Australian-produced hydrogen. Hydrogen production from relatively water-intensive technologies such as Coal Gasification is limited in this scenario.

In 2050, the annual water consumption by Australia's hydrogen industry in this scenario would be 15 GL or 2% of the average annual water consumption across Australia's mining sector.

6.4.4 Land Use

Figure 6.56 gives an illustration of the total land that would be needed to be set aside for renewable energy generation to power all of the electrolysers to meet the demand profiles for each scenario. Example solar and wind projects were selected to provide an indication of approximate land area required per MWh and these were then scaled up for the total estimated electricity requirements for each scenario. The analysis takes into account the capacity factors of solar and wind farms.

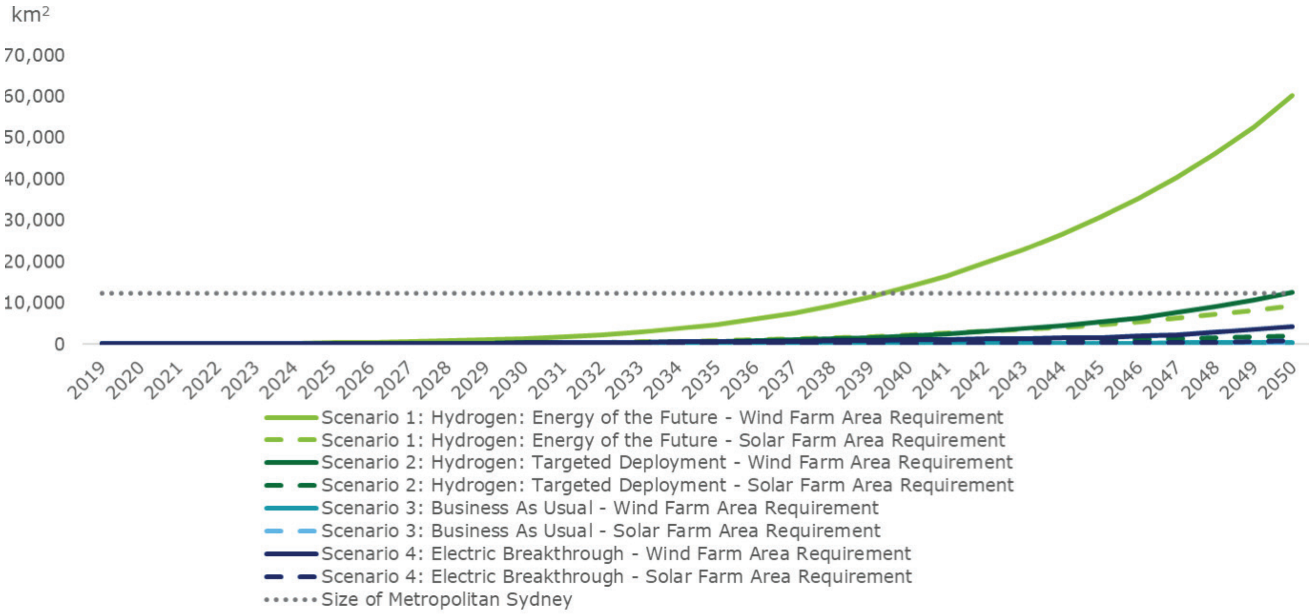
Hydrogen production using fossil-fuel based technology like coal gasification or SMR does not use significant quantities of electricity and were not included in this analysis.

Table 6.1 Land use for renewable generation if all electrolysers use renewables

Scenario	Total 2050 Electrical Load Requirement (TWh)	Equivalent Number of Average 78MW Solar Farms	Required Land Area (km2)	Equivalent Number of Average 106MW Wind Farms	Required Land Area (km2)	Total Wind Farm Area in Proportion to Metropolitan Sydney (1,238,000 km2)
Scenarios 1 Energy of the future	912	4,764	9,290	2,337	60,154	~5x
Scenario 2 *Targeted deployment*	188	983	1,917	482	12,413	~1x
Scenario 3 Business as usual	5.5	28.7	56	14	362	<1
Scenario 4 *Electric breakthrough*	65	342	666	168	4,313	<1

Source: Deloitte Analysis

Figure 6.56 Land requirements if Australia's hydrogen industry was powered purely by renewables



Source: Deloitte Analysis, ABS (4610.0)

Under the *Energy of the future* and *Electric breakthrough* scenarios, hydrogen production is largely driven by electrolysers by 2050, with fossil-fuel based technologies playing a minor role.

Under the *Targeted deployment* and *Business as usual* scenarios, hydrogen production is largely driven by fossil-fuel based technologies by 2050, with electrolysers playing a minor role.

7 Further analysis

In the development of the demand scenarios, competitive advantage assessment and modelling assumptions and output, a wide range of analysis has been undertaken. The results presented above provide a largely linear view of this analysis working through from scenario development to primary drivers and through to modelling outputs. The challenge for developing effective and resilient pathways for the development of the hydrogen industry in Australia is that there are many interconnected elements and sector linkages that cannot be easily modelled or forecast.

This necessitates an approach to the sector development that recognises potential sector linkages and develops signals and signposts that highlight the path that is being followed. From this it is possible to react through adopting a range of policy options facilitating the optimum path for the Australian economy. It is only through combining all of these elements that effective pathways can be developed.

The purpose of this report was not to review the full scope of developing the pathways but rather to provide the information on global and local market potential that could enable this to happen. This section does however provide input and guidance on how the results generated to date can be utilised in the further work to be undertaken by the COAG Energy Council.

7.1 Sector linkages

There are three viewpoints that are likely to drive the need to consider sector linkages as one of the driving factors for hydrogen sector growth: maximising the benefit to Australian communities; building increased value for early adoption; and, ensuring long-term growth of a sector in which Australia has a competitive advantage.

7.1.1 Maximising the benefit to Australian communities

The growth of the hydrogen sector globally is highly unlikely to be driven by a single use case. Similarly, the Australian market is unlikely to grow in the most effective manner and generate the greatest potential benefits for the economy and the community if it is built to service only one local use case, even if that case is to meet a large export demand.

7.1.2 Increasing the value from early adoption

Deloitte analysis shows that hydrogen will not be economic in terms of direct fuel substitution for most use cases on an unsubsidised basis for at least a decade with some use cases taking significantly longer. It is only where multiple value streams can be designed into solutions that it may be possible to justify the earlier use of hydrogen to any great extent.

7.1.3 Creating the long-term market

If hydrogen does become a large-scale global commodity then Australia has a significant opportunity to be a major supplier to this market. However, if it takes too long for hydrogen to become truly competitive, then the window of opportunity will pass and other energy and material solutions will become established.

To help accelerate the use of hydrogen requires the creation of multiple value streams and this will not be achieved through targeting simple fuel substitution. It may only be through creative sector coupling to provide value through, for example, fuel security, asset valuation protection and enhanced grid stability in addition to fuel substitution that the economic case can be optimised. Through this type of cross-sector demonstration, the local and global case for hydrogen could be significantly enhanced.

The issue of sector coupling was addressed to some extent in the Issues Papers with the following examples of particular note:

Issues Paper No.1 – *Hydrogen at Scale: "New technologies and markets are increasingly coupling the gas, electricity and transport sectors. For example, as electric vehicles come into the Australian market, the transport and electricity sectors will be coupled together. Greater use of gas generation couples electricity and gas. This coupling means that there is a need to ensure regulation or incentives in one sector do not have unintended or perverse consequences in another."*

Issues Paper No.8 – *Hydrogen for Transport: "Since hydrogen can also be used in the electricity, gas, and industrial sectors, investments in one sector enable shared benefits. This minimises costs for the whole community. For example, transport refuelling infrastructure could be made available to industrial users, such as forklift warehouse operations, for higher asset utilisation. In another example, electrolysers could produce hydrogen for blending into natural gas networks and for co-located refuelling stations. A remote mine site could produce hydrogen fuel on-site to use in vehicles as well as back-up power supply, with reduced local air pollution by replacing fossil fuel sources."*

Whilst the benefits are noted, the potential to drive earlier adoption and enhance Australia's long-term prospects is not. This may be a critical insight into the further development of the pathway options.

Another advantage of encouraging a cross-sectoral approach to adoption may be that it could be used to enhance trade relationships with potential export customers. Joint demonstration projects could be commissioned in Australia and, say, Japan and/or Korea to test the differing market balances for sectoral linkages. This would facilitate knowledge sharing and joint industry development and provide a natural route to enable export discussions to be progressed in parallel. A conversation around how the countries are each facing the same challenge and jointly working to solve those challenges will prove to be a much easier discussion then one in which it is simply about selling a global commodity at the best price.

In this way, Australia may be able to improve its opportunity to secure major export demands by building the local domestic sector and demand. This would not only demonstrate the Australia's commitment to the fuel source but also build skills, capability and scale ahead of the likely growth in export markets and could put Australia in an unassailable global supply position.

An equivalent example of the need to build a value stack to justify project development is the current pricing and development of lithium-ion batteries. Deloitte has modelled a number of large-scale projects to understand the current commercial opportunities and the drivers of value. The first options considered by many parties are energy arbitrage and the ability to utilise curtailed renewable energy generation. We have found, however, that it is highly unusual to be able to commercially support the capital expenditure needed to construct the battery if only these obvious value drivers are considered. Only when additional value sources are identified and built into the project can a viable business case be developed. For batteries, these additional drivers might include grid stability services or avoided network augmentation costs. There remains an additional challenge in that, even if additional value can be created, it is not always straightforward to be able to find someone willing to pay for this value delivery.

Similar challenges will be encountered in the potential sectoral linkages for hydrogen projects but it may be that this is the only way to secure early growth of the market. Some guidance is provided to possible early use cases through the Issues papers:

Issues Paper No.8 – *Hydrogen for Transport: "Early prospective options – The Working Group has identified urban buses, passenger ferries, long haul freight, light vehicles, remote mine site vehicles and non-road vehicles as prospective early use cases for FCEVs."*

Issues Paper No.9 – *Hydrogen for Industrial Users: "…particularly in harder-to-abate sectors such as cement and steel, has led industries to chart their readiness to transition."*

One area that has the potential to create significant value for companies and for Australia more broadly is the opportunity to avoid value destruction of existing assets and resources in the longer term. As the world decarbonises, there are real long-term risks to companies that own gas pipelines and networks and those that own resources including natural gas, iron ore and metallurgical coal.

- Gas pipelines and networks have the risk of declining use of natural gas due to it being a fossil fuel source. A transition to hydrogen blended initially with natural gas and over time with biogas might enable that infrastructure to continue to be used and avoid the need to substantially augment the electricity network.
- Natural gas resources are currently being highly utilised through the export of LNG with substantial benefit to Australia. Eventually, the demand for natural gas as an energy source seems likely to plateau and decline in developing countries and there is a risk that Australia is left with stranded resources that it is unable to commercialise. Utilising natural gas to also drive the growth of the global hydrogen sector has the dual advantages of benefitting from a current resource and enabling Australia to benefit from hydrogen exports from green sources in time.
- Iron ore and metallurgical coal are major export earners for Australia. As the pressure on emissions sources increases, it appears likely that the emissions from global steel making will come under increasing scrutiny. This has already started with shareholder resolutions placed at the AGMs of major iron ore producers. Hydrogen in steel making presents an option to protect the value of Australia's iron resources even if the use of metallurgical coal is phased out as a result. The alternative is that there could be a significant loss of value to iron ore reserves in the longer-term.

The need to protect value in existing assets will be a strong motivation for action for both industry and governments. At the same time however, they are likely to be significant growth opportunities that emerge. If the global pressure on emissions drives the above circumstances, then it will at the same time drive an increased demand from other industries for products such as 'Green' or 'Carbon-neutral' Steel, Copper and Chemicals. By driving ahead with solutions that help protect the value of existing assets, Australia may also be able to position itself as a leading supplier of products that will emerge strongly over the same period. It will not be that customers will necessarily pay a premium for the carbon-neutral products, it will just be that they will insist on this as part of procurement specifications and so many suppliers will be unable to compete.

This combination of factors could position the countries that are able to produce these products in a strong and privileged supply position.

The Ammonia market also offers a potential option to provide an easy first step into the hydrogen market and also potentially add value to that sector and assist it in transitioning to a more sustainable future state. Ammonia uses hydrogen as its primary feedstock and can therefore act as both a foundation and a balancing load for early stages of the sector. Globally, there will be an increasing demand for 'green' or at least blended 'partially green' ammonia, so enabling Australia to become a leader in this sector may also have long term economic benefits. From discussion with industry stakeholders, Ammonia in Australia is currently produced across seven facilities with an estimated total annual production capacity of over 2 Mtpa of ammonia.

The most economical way to develop a renewables powered ammonia facility is likely to be a colocated facility with onsite renewables and local water access feeding a hydrogen plant that then connects directly into the ammonia production facility. This might fit well with the concept of a single integrated hub which is explored in more detail below.

To develop valid and effective pathways therefore necessitates a strong focus on cross-sectoral linkages, the development of multiple parallel use case and the consideration of seeking value streams that are in addition to direct fuel substitution.

Projects that might assist in positioning Australia at the forefront of global hydrogen value creation might combine a variety of demonstration projects into a single integrated hub. The combination of use cases and demonstrations could present a unique global opportunity for Australia. Examples of this type of integrated project could include:

1. Export Ramp Up Loads – an export orientated demonstration project that builds sufficient volumes for export by providing hydrogen for:
   - Pipeline blending and transport;
   - Production of Australia's first green ammonia; and,
   - Downstream hydrogen separation from the pipeline to provide heavy transport refuelling and steel or chemical demonstration plants.
2. Distributed Production Facilities – domestically focussed utilisation and medium-scale distributed production providing combined solutions for industrial uses, grid stability and heavy transport solutions.
3. Off-Grid Solutions – focussed on mining operations and the combined utilisation for energy storage, heavy transport and materials handling. This project could also be linked to a future export facility.

The different regions of Australia are going to be more suited to some types of hub development and the design of this type of program should ensure that the competitive advantages of different regions are fully considered.

The work undertaken in completing the analysis for this and other projects provides strong evidence that pursuing a single value stream for hydrogen will present significant economic challenges in the near term. By building and demonstrating effective value-stacks through this type of integrated project might present a way for Australia to put itself in the best position to take advantage of future global growth of the sector.

7.2 Policy options

There a wide variety of policy options that could be considered when looking to stimulate sector growth and facilitate the enhancement of competitive advantage. The Issues papers highlighted a range of options as follows:

Issues Paper No.1 – Hydrogen at Scale: *"Facilitating and enabling international trade and engagement.*

- *Improving investor certainty though setting clear and long-term targets and policy settings.*
- *Ensuring stable and supportive governance and regulation.*
- *Providing measured and targeted supply and demand side stimulus.*
- *Developing and sharing relevant resource, industry and market information.*
- *Building community awareness and understanding of hydrogen"*

Issues Paper No.2 – Attracting Hydrogen Investment: *"… to develop hydrogen value chains, government policy efforts should aim to:*

- *Establish targets and/or long-term policy signals*
- *Support demand creation*
- *Mitigate investment risks*
- *Promote R&D, strategic demonstration projects and knowledge sharing*
- *Harmonise standards and removing barriers."*

The table provided in Issues Paper No.2 has been enhanced below to include some additional descriptions and options of available government levers.

Table 7.1 Attracting hydrogen investment

	Direct Intervention: Government directly providing funds, goods or services	**Indirect Measures: Creating regulations, mandates, standards or rules**
Supply side	• Grant funding for technology development and pilot/ demonstration projects • Public Private Partnerships (PPPs) • Equity co-investments • Loans • Tax incentives • Government investment into enabling infrastructure	• Mandated supply side targets • Underwriting risk • Foreign Direct Investment attraction facilitation
Demand side	• Grants, rebates and subsidies for offtakers or through market mechanisms such as the RET • Government backed off-take agreements and guarantees • Government purchases • Contracts for difference • Tax Incentives	• Mandated demand side targets – fuel mix, blending targets etc • Legislated performance standard

This wide range of options could be applied differentially across specific targeted use-cases or production technologies so can be designed to shape the market as it grows.

The detailed design work on an effective policy portfolio will need to emerge as the global market evolves but there appear to be some potential outcomes that would help both the overall market demand to accelerate and to enhance Australia's ability to meet a greater share of this demand. Some initial policy goals for creating this optimum outcome could include:

- **Long Term Commitment –** the growth of the market is going to take at least a decade to build towards scale. This will require a concerted long-term effort to enable Australia to be a significant participant should the higher levels of growth eventuate. Long-term commitment will also enable ongoing early engagement with potential buyers in government and industry to build the confidence in Australia as a long-term supplier. Example policy measures that could drive this include:
  - Setting of 2030 targets for hydrogen utilisation across one or more of the use cases;
  - Enabling industry growth through facilitating long term domestic supplier agreements with government or industry; and,
  - Widespread demonstration projects showing long-term commitment to explore use cases and interdependences.
- **Building Capability –** to be able to meet potential future global demand is going to require a significant effort to build capability, capacity and understanding across industry and the community. Example policy measures that could drive this include:
  - Focussed training and education programs and accreditation;
  - Setting targets for utilisation that drives industry to upskill and gain the necessary capabilities; and,
  - Facilitating a certification scheme for guarantee of origin and emissions footprint of the full value chain. Part of this work might to consider developing a full lifecycle assessment of the hydrogen production and delivery methodologies in the sameway as has been undertaken by the Japanese Ministry of the Environment.[68]
- **Driving Cost Reductions –** For hydrogen to achieve the high end of its growth potential will require step-change improvements in technology and the consequent cost reductions. It is therefore going to be important to both focus on incremental improvements in more mature technologies to provide base level growth and investment in emerging technologies to explore the potential for significantly higher levels of growth to be achieved. It will be important to ensure this work is completed across the value chain from production through transport and storage to utilisation. Example policy measures that could drive this include:
  - Grant funding rounds for demonstration of mature technologies if they drive innovation into existing project configurations;
  - Research support for emerging high potential technologies; and,
  - Hydrogen specific challenge program providing mentoring and support to innovative hydrogen solutions sourced globally and developed in Australia.
- **Creating Demand –** The key to industry stimulation is going to be demand. Some foreign governments are helping to drive this forward for export markets and Australian governments can encourage and assist in this work as well as looking about facilitating domestic demand. The question as to whether it is best to focus on the use cases that appear to offer the best current economics or the most prospective uptake would seem to be a reasonable tactic. However, given the early stage of the market's development and the highly uncertain nature of the pathway that uptake will take in different markets, it is unlikely that sufficient confidence can be built at this stage to warrant such a focussed approach. In the development of the signals and signposts noted below, the determination of the most attractive market segments would be a prime objective. Example policy measures that could drive this include:
  - Funding, research or industry partnerships facilitated jointly by Australian and target country governments such as Japan;
  - Mandating or the setting of targets for domestic use cases;
  - Develop the economic case for utilising hydrogen to create increased value-adding potential from Australian resources; and,
  - Working with asset owners, such as the owners of gas pipelines or iron ore deposits, to launch a joint funding mechanism to drive uptake of demand within their sectors. The program could be linked to innovation initiatives and sector specific uptake targets.

7.3 Signals and signposts

The pathway for evolution of the hydrogen sector is far from certain and hence it is critical to develop a number of pathways that may be followed. To be able to gauge which of these pathways is being followed, and hence know which policy interventions are most suitable to remove barriers, it is necessary to develop signals and signposts.

Scenarios can signpost key indicators that might alert the economy to a potential opportunity or risk in the future. The signposts discussed above can help to indicate which of the pathways is being followed at any one time and can assist in providing decision support as events unfold.

The role of Government will be critical under all hydrogen pathways and extends beyond policy interventions. This includes investment in enabling infrastructure, capacity building and providing clear market signals to enable investment.

Table 7.1 Attracting hydrogen investment

Heavy transport use case	
Signposts	**Signals**
• **Number of hydrogen technology end users in heavy transport** • **Emissions profiling – full lifecycle analysis of available technologies** • **Technology readiness, specifically Battery Electric Vehicles (BEVs) vs. Fuel Cell (FCs)** • **Haul truck fleet size** • **OEM Truck Development initiative globally** • **Unit cost and NPV for primary technologies**	• Hydrogen fleet size greater than minimum viable • Emissions profile better than current technology • Emissions cost starts to be valued • FC vehicles demonstrate superior characteristics when compared to BEVs • Total market size of fleet increasing more quickly • Significant effort and publicity being seen from major global OEMs Economics of truck replacement favourable

In overview terms the Signpost provides guidance on a factor that may be influential in determining the future pathway and the Signal provides the specific trigger point where a direction can be inferred or an action might need to be taken. There is not necessarily a one-to-one relationship between signposts and signals but rather there can be groups of indicators that together provide guidance on a particular element of an industry's development. As an example, the Figure 7.1 shows some possible signals and signposts that could be developed to assess the pathway being followed for the heavy transport use case.

Understanding the major signposts for each use case in Australia and globally will enable a periodic stock take of the status of the sector and the probability of specific pathways being followed. In addition to the above, other signposts that might be worth developing include delivered energy costs for each use-case and then taking into account both input feedstock costs (water, renewable energy, gas, coal, electrolysers, transport, storage) and output costs (energy, carbon). Further information on specific signals and signposts developed for all use-cases can be found in Appendix D.

7.4 Pathway development

The work completed as part of this report has developed and considered four scenarios for varying rates of growth for the hydrogen sector globally and in Australia. These four scenarios were designed to test the plausible limits of what could happen in consideration of sector development and policy options. The scenarios consider overall uptake and, to some extent, the development of technology solutions but are not prescriptive on the exact activities that might happen to allow that outcome to be achieved and are not intended to be forecasts.

This process of having a clear end point but being flexible in the route to achieving it, as envisaged in the scenarios, can be challenging and requires the development of pathways that consider the wide range of potential options.

As part of the pathway development, different use cases may have very different trajectories towards becoming economic on a subsidy-free basis. This then increases the importance of the use case interdependencies where one or more economic use cases then potentially underwrites the further development of other uses as price reductions are achieved.

This paper does not seek to develop the pathways in any detail but, as the result of the research and analysis undertaken, there are a number of criteria that we believe should be considered as part of this development process, with the following provided by way of example:

- **Multi-sector use cases –** as discussed above, there are strong linkages across the various use cases and any pathway development must be cognisant of these linkages and monitor how they are evolving. In particular, the potential for an economic case in one use-case being able to help drive scale up and greater uptake in other use-cases.
- **Decarbonisation ambition –** the Paris Climate Agreement commits its signatories to achieve a Net Zero emissions target in the second half of the century. The level of ambition and timing of action currently varies significantly across nations and is likely to continue to change over time. The most economically efficient way to decarbonise will be different in different regions and for some uses in some regions, hydrogen may well pay a major part of decarbonisation efforts. It is possible that some countries will mandate green or clean hydrogen usage and this could have a material impact on the development pathway of the global sector. Building in consideration of the moving global policy environment will be an important part of the pathway development.

- **Hydrogen transitions –** linked with decarbonisation is the method of production of hydrogen and the emissions impact of any associated fuel switching. Whilst green hydrogen produced from renewable energy and with no emissions appears to be the long-term goal of both producers and buyers, the reality of the economics is likely to drive a pathway through other methods in the first instance.

  As noted in Issues Paper No.4 *'The Japan Basic Hydrogen Strategy notes that imports will need to be 'carbon-free' from 2030 onwards. Korea's [Hydrogen Strategy] indicates that major overseas production of hydrogen should come from water electrolysis and be 'CO2-free' between 2030 and 2040.'*

  Whilst this sets out a clear intent for the major target markets to be CO2-free it does not necessarily indicate that renewable energy need to be the source of all the energy. It would be possible to meet these obligations both by using steam reformation of gas or coal gasification combined with Carbon Capture Utilisation and Storage (CCUS) and by offsetting any emissions generated through the production process.

  This opens up a number of other potential pathways beyond an industry assumption that hydrogen will need to be produced using renewable energy and electrolysis by 2030. With the development and price reductions of CCUS continuing to take time to become economic in many regions, this provides greater optionality to develop and scale-up the industry. This could include:

  – Offsetting of brown hydrogen production to provide a partially or fully carbon neutral product;
  – Blending of brown hydrogen with green hydrogen over time as the economics of electrolysers improve, the costs of offsets increase or the social license of fossil fuel becomes challenged;
  – The introduction of Blue Carbon using geosequestration as the costs become favourable when compared to purchasing or creating carbon offsets, noting that this option may be limited to certain geographic constraints dependent on reservoir availability; and,
  – Development of other carbon utilisation technologies that would allow for mineralisation of carbon into a durable solid form.

The analysis completed for this report indicates that green hydrogen whilst the desired final goal for most sector participants is unlikely to be competitive against other hydrogen production solutions in the near term. To maintain consistency with the long term goals and yet still enable short term growth of the sector will require the development of a range of hydrogen transition pathways for Australia. There is no clear single 'right' path for this and the National Hydrogen Taskforce will need to remain agile and flexible in its approach to provide Australia with its best chance of becoming a major global player in the hydrogen market.

7.5 Further work

This further analysis has highlighted a range of further work that will need to be addressed through the development and/or delivery of the National Hydrogen Strategy. Some specific areas we highlight for additional consideration are:

- **Develop sectoral linkage expertise –** Research and develop opportunities to develop trials and pilots demonstrating sectoral linkages and the potential to demonstrate multiple use cases.
- **Facilitate export projects by stimulating domestic demand –** Work with major providers seeking to develop large scale export orientated projects and help them to progress through stimulating ramp-up demand in the domestic market to demonstrate local commitment to the sector and further explore cross-sectoral linkages.
- **Develop long-term commitments –** Demonstrate local commitment to hydrogen adoption to enable the creation of long-term relationships with potential international buyer governments/markets.
- **Develop credible hydrogen transition pathways –** Develop pathways to build infrastructure using hydrogen with emissions that are partially or fully offset with the aim to transition through blending as demand for 'clean hydrogen' grows by 2030. This will allow early domination of export markets that will enable the exploitation of Australia's competitive advantage in renewable energy when the right price point is achieved and international decarbonisation policies create demand for it.
- **Support step-change technology development –** Provide funding for research into step-change technologies that have the potential to dramatically reduce the costs along the hydrogen value chain and thereby enable fast market growth. Without a rapid drop in the delivered price of hydrogen, there is a risk that the electrification of everything will block large-scale hydrogen adoption.
- **Support geosequestration development –** Develop a suite of support mechanisms to assist in the development of geosequestration sites for carbon dioxide. To date, the economics of geosequestration to support coal fired power stations has not proven to be economic. However it is noted that the majority of the cost for this is in the 'capture' portion of CCS, for which costs are lower for hydrogen as a relatively concentrated stream of carbon dioxide is produced as a by-product of the hydrogen production process. A revised assessment of the economic potential for transport and storage considering this point should be considered in support of the hydrogen sector.

- **Support alternative carbon sequestration technologies –** Research into alternatives to geosequestration that may more readily enable the use of Australia's abundant fossil fuels in the production of competitively priced hydrogen.
- **Short term policy goals –** Decide on the intermediate impacts required from policy actions with respect to demonstration, development of a specific expertise within Australia or securing long-term relationships with off-takers. Whilst the long-term goals are clear for the National Hydrogen Strategy, there also needs to be clarity on what is the focus of the initial work up to 2025.
- **Instigate signpost monitoring –** Develop governance measures and reporting protocols for periodic reporting of major signposts to allow for regular adjustment of pathways and the associated policy settings.

There is of course a large body of work that will need to be undertaken by government and industry before the hydrogen sector achieves the potential that it has and the above suggestions are only a subset of this.

8 Conclusion

Countless applications exist for hydrogen. Across all sectors and all aspects of the value chain, hydrogen's unique properties present advantages. Its high amount of energy per kg means it can carry significant amounts of energy, for its release at the end point of use. Currently, its utilisation is limited to petroleum refining and fertiliser production. In the wake of all-time high energy demand and countries looking to maintain energy security and reliability, hydrogen is becoming the solution. The future proposes many possibilities to hydrogen in relation to transport, utilities, electricity, and power and heat generation.

8.1.1 Australia's competitive position

Australia could be one of the top global exporters of hydrogen. Blessed with an abundance of national resources, hydrogen provides a large unique opportunity to grow our economy. By capitalising on the growing global interest in hydrogen, Australia can position itself to be a strong competitor and a large exporter in the ever-growing hydrogen market.

As a leading producer of natural gas, the country has technical know-how which can be leveraged to deliver hydrogen. Australia has strong existing trade relationships with the growing Asian markets including both Japan and South Korea who have made hydrogen commitments. Australian government has an agenda that aligns with the pursuit of hydrogen, with almost all states and territories as well as the Commonwealth establishing hydrogen roadmaps or focus groups to drive forward hydrogen opportunities. Australia rates highly in terms of global competitive advantage in the hydrogen supply market.

8.1.2 Considerations to capitalise

For Australia to capitalise on the opportunity hydrogen presents, efforts need to focus on developing supportive and appropriate policies. Clear policy targets and specific hydrogen targets are important for a country's development of their domestic hydrogen economy – it gives stakeholders and investors insight into the government's direction. From an international perspective, announcing policy and targets puts the domestic economy on the radar of the key players in the global industry – indicating to potential importers/exporters of their position and appetite. Regulations, standards and acceptance will also be a hurdle for the industry. Around the world, regulations and standards do not yet fully support hydrogen uptake or new uses of hydrogen, as a result limiting the benefits that it can provide. The way forward for Australia must include policies and regulations addressing these issues, removing the barriers and enabling access for hydrogen.

Given the enormous opportunity hydrogen presents, significant investment has either been committed or planned. Whilst there is much excitement around the growth in the hydrogen industry between now and 2050, the timing, scale and growth trajectory is less certain. The exact pathway forward to hydrogen deployment domestically and internationally is not yet known.

The work completed as part of this report has developed and considered four scenarios for varying rates of growth for the hydrogen sector globally and in Australia. These four scenarios test the limits of what could happen and consider all options for sector development and policy setting. The scenarios consider overall uptake and, to some extent, the development of technology solutions but are not prescriptive on the exact activities that might happen to allow that outcome to be achieved.

The value proposition hydrogen presents is enormous. What size that will actually materialise depends on many factors. Economic factors domestically and globally, government policy, technology costs and learning rates present a plethora of uncertainties which will all shape the growth and design on the hydrogen industry.

8.1.3 Further research

This work answered the question as to what the global market for hydrogen (and hydrogen-based energy carriers, such as ammonia) could look like into the future and what share of this market Australia could capture. As expected, this work highlighted more questions that will need to be addressed through the development and/or delivery of the National Hydrogen Strategy. Some areas include researching and developing opportunities to develop trials and pilots demonstrating sectoral linkages and the potential to demonstrate multiple use cases. As well as a definitive set of signals and signposts that will be able to guide the understanding of pathway progress. This represents a large body of work that will need to be undertaken by government and industry before the hydrogen sector achieves the potential.

8.1.4 Final thoughts

Support from industry, government and stakeholders for developing a domestic hydrogen industry is burgeoning. All Australian state, territory and Commonwealth governments agree that hydrogen presents opportunities for Australia to become a major hydrogen producer for use domestically and to export.

Australia is not alone on this expedition. Several other countries internationally are currently exploring hydrogen strategies. Some countries are solely developing policies to reduce barriers to the import of hydrogen. Where others, like Australia, are considering how they can best place themselves to also capitalise on the growing hydrogen export market.

Australia needs to start making decisions now, so that prosperous hydrogen industry will reap benefits for the Australian economy in the future. The COAG Energy Council is committed to a vision of making Australia a major player in a global hydrogen industry by 2030. With the advice provided by the Hydrogen Working Group, informed by this work by Deloitte, Australia can select the best possible pathway for the National Hydrogen Strategy and the development of the hydrogen industry in Australia.

Appendices

Appendix A: Detailed multi-criteria analysis

Criteria	USA	China	Germany	Norway	France
Trade relations	The USA has several existing trade relationships with key importers. However, under the current administration the US is re-negotiating key trade relationships and facing difficult trade negotiations which may have impacts on key relationships in the long-term.	China has a significant export driven economy but some difficult trade relationships have arisen as of late. In addition, the top exports are generally not energy related.	Large export economy with strong trade relationships but not historically a large energy exporter in relation to other competitors.	Exports of energy resources form a significant portion of Norway exports. Norway has existing trade relationships with numerous countries expected to be importers and the ability to build on those relationships to build its hydrogen export market.	France has some pre-existing trade relations and in particular in relation to other European countries and some Asian countries. The export of Energy resource falls outside of the top 5 exports from France but there is a potential for them to leverage off of non-energy relationships if it pursues hydrogen exports.
Access to finance[69]	The World Bank rating is 3.	The World Bank rating is 73.	The World Bank rating is 44.	The World Bank rating is 85.	The World Bank rating is 99.
Ease of doing business[70]	The World Bank rating is 8.	The World Bank rating is 46.	The World Bank rating is 24.	The World Bank rating is 7.	The World Bank rating is 32.
Extent of existing hydrogen applications in-country	Domestic use is primarily limited to historic industrial uses. There are some hydrogen transport initiatives, primarily in California, which includes a target of 200 hydrogen refuelling stations.[71] There is a question about whether these types of policies will be rolled out to other states.	China has made several announcements related to investments to the industry through 2023.	Germany is looking at hydrogen use in transmission and distribution pipelines as well as in the transport sector. Germany currently has a number of hydrogen demonstration and commercial projects underway, including hydrogen injections in the gas network.	Historically, hydrogen has not been a major domestic use focus but this is likely to change in the short-term.[72]	France has adopted a Hydrogen Plan which although there is some focus on other sectors is primarily aimed at transport.
Ports and other infrastructure[73, 74] Note: it is not proposed that hydrogen will use the same pipeline infrastructure as oil and gas, but rather the experience gained through development of that infrastructure can be leveraged for hydrogen development.	Strong oil and gas pipeline infrastructure throughout the continental US and experience in exporting fuels globally.	Strong oil and gas import terminal infrastructure. This experience can be leveraged for hydrogen exports.	Port infrastructure is developed; however, given that oil and gas is not one of the top exports, fuel and pipeline infrastructure is not as developed.	Large natural gas exporter with developed pipeline infrastructure.	Export infrastructure such as ports are heavily developed but not as much experience or infrastructure with export of fuels.

Brazil	Qatar	Australia	Singapore	Saudi Arabia
Brazil has some existing trade relationships, however, the stability of the political climate in Brazil impacts on the ability to expand those relationships.	Qatar has existing relationships in relation to natural resources and energy and trade has increased recently with China. However, the political and social conditions in Qatar has an impact on expansion of its trade relationships.	Australia has strong trade relationships with numerous Asian countries who are likely to be major importers – China, Japan and South Korea. Further, Australia is heavily involved in the export of natural resources and energy resources which can be leveraged for the hydrogen export market.	Singapore is a highly developed open market economy. Over recent decades the country has maintained strong trade relations and liberal inflows and outflows of Foreign Direct Investment (FDI), in particular as major destination for European investment in Asia and vice versa.	The top export destinations of Saudi Arabia are China, Japan, India, South Korea and the United states. The top exports of Saudi Arabia are Crude Petroleum and Refined Petroleum.
The World Bank rating is 99.	The World Bank rating is 124.	The World Bank rating is 8.	The World Bank rating is 32.	The World Bank rating is 112.
The World Bank rating is 109.	The World Bank rating is 83.	The World Bank rating is 18.	The World Bank rating is 2.	The World Bank rating is 92.
No major domestic developments in the hydrogen sector at this time but nothing that leads to a barrier to hydrogen.	No major domestic developments in the hydrogen sector at this time but nothing that leads to a barrier to hydrogen.	Australia both at the federal and state level is examining the role of hydrogen and is trialling several applications or projects.	Singapore is looking to hydrogen as a new fuel source, with the government posting consultancy tenders for feasibility studies.	Currently, the majority of hydrogen is used in petroleum refining. Saudi Aramco and Air Products inaugurated Saudi Arabia's first hydrogen refuelling station in June 2019.
Strong maritime and/or gas pipeline infrastructure and experience in exporting fuels.	Strong maritime and/or gas pipeline infrastructure and experience in exporting fuels.	Strong maritime and/or gas pipeline infrastructure and experience in exporting fuels.	The island nation has highly developed port infrastructure, particularly for receiving oil and petroleum imports. It's also located in the Malacca Strait – a major global trade route and portal to Asia.	Saudi Arabia has ports and infrastructure available given its position as a leading crude oil exporter.

Criteria	USA	China	Germany	Norway	France
Feedstock for generation[75, 76]	The US has large tracts of land for renewable development and ample sun and wind resources. Also has significant natural gas resources.	Large amounts of renewable generation but remains a large importer of LNG.	Germany does not have access to the same degree of land, sun or wind resources.	Large amounts of natural gas and access to intermittent generation.	France has good access to water and some intermittent generation but imports gas.
Delivery times and distances	Further from key Asian markets than competitors.	Close to Asian and European markets.	Close to European markets.	Close to European markets.	Close to European markets.
Access to electricity for hydrogen production[77]	The World Bank rating is 54.	The World Bank rating is 14.	The World Bank rating is 5.	The World Bank rating is 19.	The World Bank rating is 14.
Government stability and support	Political partisanship has been on the rise and creating uncertainty in the overall policy direction.	The same political party has retained power for a significant period of time with a stable long-term strategy for policy and innovation.	Party politics that can lead to changes in policy positions, including environmental and economic policies.	Party politics that can lead to changes in policy positions, including environmental and economic policies	Party politics that result in changes in policy positions, including environmental and economic policies
Regulatory settings	Some policies aimed at decarbonisation but not necessarily directly aimed at hydrogen development.	Although there are some regulatory frameworks in place there is less understanding regarding the laws and customs related to business more broadly.	Specific hydrogen policies aimed at specific sectors of the economy. Other policy settings including licensing and approvals processes are easily understood.	Norway has not specifically looked at hydrogen deployment but rather environmental policies more generally.	Has implemented a hydrogen plan but is primarily focused on transport sector. Other licensing and approvals processes are not as straightforward as in some other places.
Government transparency[78]	Minimal corruption, clearly set out public processes related to many resource developments.	Potential corruption with unclear processes.	Minimal corruption with clearly set out public processes.	Limited to no incidence of corruption with clear public processes.	Minimal corruption, clearly set out public processes.
Experience in delivering similar technologies or resources/ parallel industries	Large natural gas exporter and consumer of hydrogen and vehicles.	Innovator in relation to production technologies that can be leveraged for hydrogen.	Exports some natural gas and is known for innovative processes and developments.	Large gas exporter and associated infrastructure and processes.	Some experience in exporting fuels and technology adaptation but not as great as other countries.

Brazil	Qatar	Australia	Singapore	Saudi Arabia
Good renewable energy and gas resources, the network constraints impact on overall feedstock availability.	Minimal renewable generation and potential water supply issues. Significant natural gas resources.	Large tracts of land, together with ample natural gas, sun and wind. Generally, water access is available.	Limited land and natural resources makes the country heavily reliant on external sources for raw energy sources. Further, Singapore has limited availability of resources to develop CCS sites.	Large amounts of crude oil generation. Great exposure to solar resources
Close to North American market but further from key Asian markets.	Close to Asian and European markets.	Close to Asian markets and can service European markets.	Close to Asian markets and strong ties with European markets	Close to Asian and European markets.
The World Bank rating is 40.	The World Bank rating is 69.	The World Bank rating is 52.	The World Bank rating is 16.	The World Bank rating is 64.
Unstable government that does not allow for long-term policy or strategy to gain any momentum.	The monarchy provides government stability but policy certainty is not as stable as social and international pressures impact on long-term policies and strategy.	Party politics that can lead to changes in policy positions, including environmental and economic policies. Most state governments have or will be shortly publishing state strategies for hydrogen. The Commonwealth is also pursuing a National Hydrogen Strategy.	A quasi-authoritarian political setting has the advantage of supporting a clear policy and agenda while maintaining the stability needed for long term planning.	Saudi Arabia has a more stable government compared to Qatar.
No significant investment in hydrogen strategy and less straightforward processes related to doing business generally.	Although some policies have been announced, the ability to navigate business practices given the regime in place is not always understood.	No specific policies aimed at hydrogen deployment to date. Energy policies aimed more directly to renewable generation rather than hydrogen.	A quasi-authoritarian political setting has the advantage of supporting a clear policy and regulation agenda with significant potential for long term planning.	Shortage of domestic policies to help support investment in hydrogen. Significant investment in Solar as part Vision 2030 plan to reduce dependence on oil. Investment of industry in hydrogen (Saudi Aramco) could have positive impact on regulatory settings.
Corruption is more common place which limits the effectiveness of all processes.	Some corruption may be present and less transparent processes.	Limited to no corruption with transparent processes.	Singapore is consistently ranked among the least corrupt nations in the world.	Some corruption may be present and less transparent processes.
Experience in exporting fuel resources but less ability to leverage this for use in other industries.	Large LNG exporter and technological improvements to resource export technology.	Recent large LNG exporter to Asia so learnings can be easily leveraged.	Singapore has a demonstrated petroleum refining capacity with the capital to extend capabilities to other technologies	Large crude oil exporter and technological improvements to resource export technology.

Criteria	USA	China	Germany	Norway	France
Availability of human and technological resources[79]	Has high-levels of highly skilled labour as well as a pool of unskilled labour (at varying economics). Technology is available for use in most sectors of the economy.	Does not have the same proportionate levels of highly skilled labour but has economic lower skilled labour with the ability to deploy technology.	Is a leader in technology and innovation. Has high-levels of highly skilled labour with unskilled labour not available at economic rates.	Is generally a highly-skilled workforce. Is not generally as innovative as some other countries.	France labour force is not as highly-skilled as some other countries but also does not have as economic low-skilled workers.
Adaptability in a changing environment[80]	Is a leader in technology innovation including battery technology, data and energy efficiency. However, environmental and energy policies have not fully adapted to the needs and wants of the consumer.	Is a leader in technology development and innovation but is not always quick to change or adapt domestic policies.	Is a leader in technology and innovation and has deployed new technology in the energy market. However, interconnectedness of the market makes quick adjustments more difficult.	Is not generally as innovative as other countries and although makes some changes in how it deploys new technology, it may not be as quick as other countries.	Has deployed numerous renewable generators to adapt to the changing energy market but similar to Germany, given the interconnectedness is limited in the swiftness by which it can adapt.

Brazil	Qatar	Australia	Singapore	Saudi Arabia
Brazil does not possess high-levels of highly-skilled workers nor access to numerous technological resources.	Qatar does not have the same proportion of highly-skilled labour as some other countries but has access to and is willing to deploy technological resources.	Australia has shown an ability to innovate and develop new technologies. The workforce is generally highly-skilled.	The proximity to Asia and open market characteristics of Singapore place it as an ideal destination for Foreign Direct Investment (FDI) and skilled labour.	Saudi Arabia does not have the same proportion of highly-skilled labour as some other countries but has shown high interest in new (hydrogen) technologies.
Brazil is not overly innovative historically nor does the political climate allow for easy adaptation.	Qatar has shown the ability to innovate in some circumstances but generally not as much as other countries. The structure of the government and institutions can limit the ability to adapt quickly.	Some evidence of ability to adapt to changes in the energy market or embrace of new technologies but not both	Singapore has shown some adaptability in the past and has the ability to embrace new technologies.	The structure of government in Saudi Arabia can limit the ability to adapt quickly.

Appendix B: SSP scenarios

Narrative	Summary
SSP1	*Sustainability – Taking the Green Road (Low challenges to mitigation and adaptation)* The world shifts gradually, but pervasively, toward a more sustainable path, emphasising more inclusive development that respects perceived environmental boundaries. Management of the global commons slowly improves, educational and health investments accelerate the demographic transition, and the emphasis on economic growth shifts toward a broader emphasis on human well-being. Driven by an increasing commitment to achieving development goals, inequality is reduced both across and within countries. Consumption is oriented toward low material growth and lower resource and energy intensity.
SSP2	*Middle of the Road (Medium challenges to mitigation and adaptation)* The world follows a path in which social, economic, and technological trends do not shift markedly from historical patterns. Development and income growth proceeds unevenly, with some countries making relatively good progress while others fall short of expectations. Global and national institutions work toward but make slow progress in achieving sustainable development goals. Environmental systems experience degradation, although there are some improvements and overall the intensity of resource and energy use declines. Global population growth is moderate and levels off in the second half of the century. Income inequality persists or improves only slowly and challenges to reducing vulnerability to societal and environmental changes remain.
SSP3	*Regional Rivalry – A Rocky Road (High challenges to mitigation and adaptation)* A resurgent nationalism, concerns about competitiveness and security, and regional conflicts push countries to increasingly focus on domestic or, at most, regional issues. Policies shift over time to become increasingly oriented toward national and regional security issues. Countries focus on achieving energy and food security goals within their own regions at the expense of broader-based development. Investments in education and technological development decline. Economic development is slow, consumption is material-intensive, and inequalities persist or worsen over time. Population growth is low in industrialised and high in developing countries. A low international priority for addressing environmental concerns leads to strong environmental degradation in some regions.
SSP4	*Inequality – A Road Divided (Low challenges to mitigation, high challenges to adaptation)* Highly unequal investments in human capital, combined with increasing disparities in economic opportunity and political power, lead to increasing inequalities and stratification both across and within countries. Over time, a gap widens between an internationally-connected society that contributes to knowledge – and capital-intensive sectors of the global economy, and a fragmented collection of lower-income, poorly educated societies that work in a labour intensive, low-tech economy. Social cohesion degrades and conflict and unrest become increasingly common. Technology development is high in the high-tech economy and sectors. The globally connected energy sector diversifies, with investments in both carbon-intensive fuels like coal and unconventional oil, but also low-carbon energy sources. Environmental policies focus on local issues around middle and high income areas.
SSP5	*Fossil-fuelled Development – Taking the Highway (High challenges to mitigation, low challenges to adaptation)* This world places increasing faith in competitive markets, innovation and participatory societies to produce rapid technological progress and development of human capital as the path to sustainable development. Global markets are increasingly integrated. There are also strong investments in health, education, and institutions to enhance human and social capital. At the same time, the push for economic and social development is coupled with the exploitation of abundant fossil fuel resources and the adoption of resource and energy intensive lifestyles around the world. All these factors lead to rapid growth of the global economy, while global population peaks and declines in the 21st century. Local environmental problems like air pollution are successfully managed. There is faith in the ability to effectively manage social and ecological system, including by geo-engineering if necessary.

Source: The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An Overview

Appendix C: CGE modelling

Introduction

A change in any part of the economy has impacts that reverberate throughout the economy. For example, the doubling of government expenditure on disability support services will involve increased economic activity in the disability services industry but it will also have a range of impacts in other parts of the economy:

- As the sector expands, it will draw in an increased volume of primary factors as well as intermediate inputs from related service, manufacturing and mechanical repair sectors.
- The additional taxation associated with funding the scheme may have an impact on peoples' labour supply (given it is partly funded by the Medicare levy) as well as other firm and household decisions (given it is also funded from consolidated revenue and thus company tax and a collection of indirect taxes).
- Apart from the direct effects of expanding services and taxation, the rollout will result in changed consumer spending by households whose income and employment have changed with the change in economic activity. This could mean a change in investment flows and consequently a changed capital stock.
- Importantly, increased activity will be recorded in the regions where this transformation is concentrated but there will also be altered activity levels in other areas which export to those more directly affected.

A Regional Computable General Equilibrium (CGE) model is the best-practice method available for capturing the different impacts highlighted above. The reason for this is that it is able to explicitly account for behavioural response of consumers, firms, governments and foreigners while evaluating the impacts of a given policy change. At the same time, it observes resource constraints meaning that the estimated economic impact which comes from a CGE model will account for 'crowding out' whereby increased activity will draw resources from other sectors.

This is especially important in the context of modelling small regional economies where key sectors account for a major share of output and thus changes in these sectors' activity levels will have large ramifications within the region.

DAE-RGEM

The Deloitte Access Economics regional general equilibrium model (DAE-RGEM) belongs to the class of models known as Computable General Equilibrium (CGE), or Applied General Equilibrium (AGE) models. Other examples of models in this class are the Global Trade and Analysis Project (GTAP) model, the Victoria University Model (the Vic-Uni Model) and The Enormous Regional Model (TERM).

Like GTAP, DAE-RGEM is a global model, able to simulate the impact of changes in any of the 140 countries in the GTAP database (including Australia) onto each of the 140 countries. The ability to incorporate the flow-on impacts of changes that may occur in rest of the world is a key feature of global models that is not available in single-country models, such as the Vic-Uni Model or TERM.

However, like those models, DAE-RGEM is a bottom-up model of regional Australia. Therefore, DAE-RGEM is able to project the impacts on different States and sub-State regions of Australia of changes occurring in any region of Australia or in rest of the world within a single, robust, integrated economic framework.

This model projects changes in macroeconomic aggregates such as GDP, employment, export volumes, investment and private consumption. At the sectoral level, detailed results such as output, exports, imports by commodity and employment by industry are also produced.

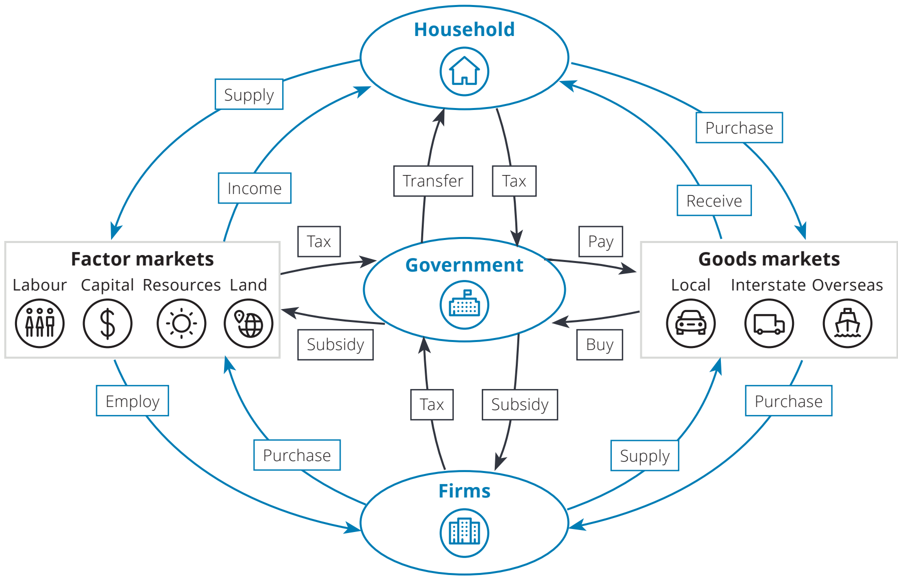
The following diagram gives a stylised representation of DAE-RGEM, specifically a system of interconnected markets with appropriate specifications of demand, supply and the market clearing conditions determine the equilibrium prices and quantity produced, consumed and traded.

The model rests on the following key assumptions:

- All markets are competitive and all agents are price takers
- All markets clear, regardless of the size of the shock, within the year.
- It takes one year to build the capital stock from investment and investors take future prices to be the same as present ones as they cannot see the future perfectly
- Supply of land and skills are exogenous. In the *Business as usual* case, supply of natural resource adjusts to keep its price unchanged; productivity of land adjusts to keep the land rental constant at the base year level.
- All factors sluggishly move across sectors. Land moves within agricultural sectors; natural resource is specific to the resource using sector. Labour and capital move imperfectly across sectors in response to the differences in factor returns. Inter-sectoral factor movement is controlled by overall return maximizing behaviour subject to a CET function. By raising the size of the elasticity of transformation to a large number, we can mimic the perfect mobility of a factor across sectors and by setting the number close to zero we can make the factor sector specific. This formulation allows the model to acknowledge the sector specificity of part of the capital stock used by each sector and also the sector specific skills acquired by labour while remaining in the industry for a long time. Any movement of such labour to another sector will mean a reduction in the efficiency of labour as a part of the skills embodied will not be used in the new industry of employment.

DAE-RGEM is based on a substantial body of accepted microeconomic theory. Key features of the model are:

Figure 8.1: A stylised representation of DAE-RGEM



- The model contains a 'regional household' that receives all income from factor ownerships (labour, capital, land and natural resources), tax revenues and net income from foreign asset holdings. In other words, the regional household receives the gross national income (GNI) as its income.
- The regional household allocates its income across private consumption, government consumption and savings so as to maximise a Cobb-Douglas utility function. This optimisation process determines national savings, private and government consumption expenditure levels.
- Given the budget levels, household demand for a source-generic composite goods are determined by minimising a CDE (Constant Differences of Elasticities) expenditure function. For most regions, households can source consumption goods only from domestic and foreign sources. In the Australian regions, however, households can also source goods from interstate. In all cases, the choice of sources of each commodity is determined by minimising the cost using a CRESH (Constant Ratios of Elasticities Substitution, Homothetic) utility function defined over the sources of the commodity (using the Armington assumption).
- Government demand for source-generic composite goods, and goods from different sources (domestic, imported and interstate), is determined by maximising utility via Cobb-Douglas utility functions in two stages.
- All savings generated in each region are used to purchase bonds from the global market whose price movements reflect movements in the price of creating capital across all regions.
- Financial investments across the world follow higher rates of return with some allowance for country specific risk differences, captured by the differences in rates of return in the base year data. A conceptual global financial market (or a global bank) facilitates the sale of the bond and finance investments in all countries/regions. The global saving-investment market is cleared by a flexible interest rate.
- Once aggregate investment level is determined in each region, the demand for the capital good is met by a dedicated regional capital goods sector that constructs capital goods by combining intermediate inputs in fixed proportions, and minimises costs by choosing between domestic, imported and interstate sources for these intermediate inputs subject to a CRESH aggregation function.
- Producers supply goods by combining aggregate intermediate inputs and primary factors in fixed proportions (the Leontief assumption). Source-generic composite intermediate inputs are also combined in fixed proportions (or with a very small elasticity of substitution under a CES function), whereas individual primary factors are chosen to minimise the total primary factor input costs subject to a CES (production) aggregating function.

A CGE model is the best-practice method available for capturing the different impacts highlighted above. The reason for this is that it is able to explicitly account for behavioural response of consumers, firms, governments and foreigners while evaluating the impacts of a given policy change. At the same time, it observes resource constraints meaning that the estimated economic impact which comes from a CGE model will account for 'crowding out' whereby increased activity will draw resources from other sectors. This is especially important in the context of modelling small regional economies where key sectors account for a major share of output and thus changes in these sectors' activity levels will have large ramifications within the region.

Unlike some many models, the Deloitte Access Economics regional general equilibrium model (DAE-RGEM) is able to simulate the impact of changes in any of the 140 countries. The ability to incorporate the flow-on impacts of changes that may occur in rest of the world is a key feature of global models that is not available in single-country models.

The model projects changes in macroeconomic aggregates such as GDP, employment, export volumes, investment and private consumption. At the sectoral level, detailed results such as output, exports, imports by commodity and employment by industry are also produced.

Appendix D: Signals and signposts

General signposts that are common across all end-use applications

Global government/corporate investment in hydrogen growth

This signpost refers to government and corporate investment in hydrogen technologies – ranging from upstream production technologies, to end-use applications that utilise hydrogen. High government and/or corporate investment into the sector stimulates R&D activity, and drives down costs as the uptake of hydrogen technology grows. This signpost is a key determinant of global market size and – by extension, how significant Australia's hydrogen industry could be. Many of the signals identified contain both leading and lagging indicators. Leading indicators are those things that point to a future state and show how things are likely to progress. A lagging indicator is one that is known after the fact and clarifies and confirms a certain path forward for the hydrogen industry in Australia.

Global government/corporate investment in hydrogen	
Qualitative analysis (Leading indicators)	Scenario 1: *Hydrogen: Energy of the future*
	Scenario 2: *Hydrogen: Targeted deployment*
	Scenario 3: *Business as usual*
	Scenario 4: *Electric breakthrough*

Signals	
2025	2030
• Governments provide policy support for R&D, such as tax breaks for all hydrogen-related technologies, including upstream production and applications. • Governments begin investing in hydrogen technologies through government agencies like ARENA and the CEFC. • Concern amongst corporates that government investment is beginning to "crowd out" hydrogen investment leads to governments taking a less proactive role in investing in "mainstream" hydrogen technologies.	• Investments in hydrogen-related technologies are commonplace across the corporate sector, with a strong understanding of the risks and benefits associated with the technology.
• Governments provide policy support for R&D but only for specific hydrogen technologies, for specific applications. • Corporate investments made in hydrogen technology follows governments' general policy support focusing on specific hydrogen technology.	• Investments made in certain hydrogen-related technologies are commonplace across the corporate sector, with a strong understanding of the risks and benefits associated with the technology. • Limited corporate investment in other hydrogen-related technologies.
• Investments made in hydrogen technology limited to government agencies like ARENA and the CEFC, but this investment is seen as peripheral to electrification technology.	• Corporate investment in hydrogen technology is limited to specific applications where electrification is less practical than hydrogen.
• Corporate investment is dominated by electrification technology, with little/none being invested in hydrogen technology. • Investments in electrification technologies are commonplace across the corporate sector, with a strong understanding of the risks and benefits associated with electrification technology.	• Government and corporate investment is almost entirely focused on electrification technology, as even hard to abate sectors – such as resources and steel manufacturing, are being addressed through electrification technology rather than hydrogen.

Cost competitiveness

This signpost refers to the general cost of hydrogen technologies – ranging from upstream production costs, to storage/transport costs and end-use applications of hydrogen like FCEVs or hydrogen-driven steelmaking operations. In scenarios such as *Energy of the future* and *Targeted deployment*, hydrogen becomes cost competitive compared to alternative fuel sources for certain, if not most hydrogen applications. Cost competitiveness is driven by sustained investments made by governments and corporations, as well as consistent government policy.

Cost competitiveness	
Qualitative analysis (Leading indicators)	*Scenario 1: Hydrogen: Energy of the future*
	Scenario 2: Hydrogen: Targeted deployment
	Scenario 3: Business as usual
	Scenario 4: Electric breakthrough
PEM – upstream CAPEX plus midstream CAPEX* (Lagging indicators) Note: Cost competitiveness is driven by a multitude of factors so an examples has been provided in the form of technology costs for PEM.	Scenario 1: Hydrogen: *Energy of the future*
	Scenario 2: Hydrogen: *Targeted deployment*
	Scenario 3: *Business as usual*
	Scenario 4: *Electric breakthrough*

*Note: for the purposes of the modelling undertaken upstream CAPEX costs include stack costs (anode, cathode, plates and membranes), balance of plant costs (compressors, heat exchanges, pump, control systems and valves) and associated infrastructure and installation costs. Midstream CAPEX costs include compressors, pipeline infrastructure (where relevant) and associated infrastructure and installation costs. There may be other CAPEX costs incurred in particular projects, either upstream or midstream, however, only the above costs have been included in the modelling.

Signals	
2025	2030
• Analysis of early technology development is showing that hydrogen production and utilisation technologies are experiencing high learning rates relative to alternatives. • Announcement of technology breakthroughs are commonplace in the market, across both production and utilisation. For example breakthroughs in the cost of catalysts and membrane technology are commonplace. • Multiple multinational corporations are pursuing aggressive growth in the sector, driving a high level of innovation and competition.	• High rates of adoption are driving hydrogen technologies rapidly down their cost curves. • Balance of plant cost reductions are a key focus due to their increasing materiality in overall capital costs.
• Analysis of early technology development is showing that hydrogen production and utilisation technologies are experiencing low learning rates relative to alternatives. • Some trials of hydrogen are underway but there is not significant adoption to drive the technology down its cost curve. • No/few hydrogen technology breakthroughs are being reported.	• Decarbonisation policies and investment agendas of governments are not speaking directly to hydrogen deployment or development.
• Investments made in hydrogen technology limited to government agencies like ARENA and the CEFC, but this investment is seen as peripheral to electrification technology.	• Corporate investment in hydrogen technology is limited to specific applications where electrification is less practical than hydrogen.
• R&D investment by both OEMs and governments is focusing on electrification technologies with hydrogen receiving a relatively low level of effort • The infrastructure to support battery electric vehicles is widespread, creating an unassailable position for hydrogen vehicles and associated refuelling infrastructure.	• Hard to abate sectors, such as resources and steel manufacturing, are being addressed through electrification technology rather than hydrogen technology.
$1.34/kgH2	$1.06/kgH2
$1.41/kgH2	$1.17/kgH2
$1.48/kgH2	$1.29/kgH2
$1.42/kgH2	$1.20/kgH2

Australia's market share

This signpost refers to the proportion of total economy-wide energy consumption of key export markets that Australian hydrogen exports are able to capture. Factors that may affect how much of this market share Australia is able to capture include the existence and the effective operation of enabling infrastructure – including the labour force and capital required to operate this infrastructure. Australia's geographical proximity to key export markets such as China, Japan or Korea should be an advantage. Factors that negatively impact Australia's market share include relatively high costs of producing Australian hydrogen due to immaturity of technology and industry.

Australia's market share	
Qualitative analysis (Leading indicators)	*Scenario 1: Hydrogen: Energy of the future*
	Scenario 2: Hydrogen: Targeted deployment
	Scenario 3: Business as usual
	Scenario 4: Electric breakthrough
Proportion of Australia's market share (Lagging indicators)	Scenario 1: Hydrogen: *Energy of the future*
	Scenario 2: Hydrogen: *Targeted deployment*
	Scenario 3: *Business as usual*
	Scenario 4: *Electric breakthrough*

Signals	
2025	2030
• Domestic policy removes barriers and streamlines processes, allowing for timely infrastructure investment. • Capital is directed to construction activities to support the increasing number of hydrogen production facilities. • Skills and capabilities are leveraged from our extractive industries and export sectors. • Energy policies encourage coordination between the location of hydrogen facilities with generation and network resources. • The Commonwealth Government actively pursues trade relationships with countries that have set hydrogen targets or are expected to set hydrogen targets.	• Australia leads technological innovation and adoption providing a cost advantage relative to other countries. • Australia leads exports of hydrogen from green, blue and alternative sources. • Domestic consumption is the highest per capita compared to other comparable economies.
• Australian governments adopt policies to remove barriers and stimulate access for hydrogen deployment in specific sectors. • Government agencies collaborate with Australian industry participants to grow their export markets, focusing on targeted sectors. • Increased activity in sectoral and commodity coupling to identify synergistic opportunities	• Domestic and overseas consumers accept the use of hydrogen in targeted sectors of the value chain and the use of electrification technologies in non-targeted sectors. • Policies are adopted that provide certainty for investors for specific hydrogen applications, reducing the risk of investment in Australia and increasing attractiveness to international investors.
• Some trials of hydrogen deployment are taking place in Australia, but these are mostly led by overseas companies. • There is limited to no cost advantage to the use of hydrogen domestically compared to alternatives. • There is a low level of domestic policy focusing on hard to abate sectors including resources, chemical and steel manufacturing, resulting in less proliferation of hydrogen throughout the value chain.	• The costs of hydrogen technologies in Australia are staying roughly constant rather than experiencing a sharp decline. • There is a low level of domestic policy to encourage domestic update.
• Australia uses electricity to decarbonise hard to abate sectors including resources, chemical and steel manufacturing. • Domestic policies focus on removing barriers for electrification technologies. • A high domestic uptake of electric vehicles with associated charging infrastructure creates strong competition for the deployment of hydrogen vehicles and refuelling infrastructure. • Domestic electricity costs are decreasing.	• The laggard group of technology adopters (stage 5) in Australia is adopting the most mature electrification technologies. • The lowest cost solutions in Australia for industrial processes and heat is electric.
3%(Chn)/6%(Jpn)/ 3%(Kor)/1%(RoW)	5%(Chn)/10%(Jpn)/ 5%(Kor)/1%(RoW)
1%(Chn)/2%(Jpn)/ 1%(Kor)/0%(RoW)	1%(Chn)/3%(Jpn)/ 1%(Kor)/0%(RoW)
3%(Chn)/6%(Jpn)/ 3%(Kor)/1%(RoW)	5%(Chn)/10%(Jpn)/ 5%(Kor)/1%(RoW)

Signposts that are end-use application specific

Light transport	
Qualitative analysis (Leading indicators)	*Scenario 1: Hydrogen: Energy of the future*
	Scenario 2: Hydrogen: Targeted deployment
	Scenario 3: Business as usual
	Scenario 4: Electric breakthrough
Proportion of light transport market captured by hydrogen (Lagging indicators)	Scenario 1: Hydrogen: *Energy of the future*
	Scenario 2: Hydrogen: *Targeted deployment*
	Scenario 3: *Business as usual*
	Scenario 4: *Electric breakthrough*

Heavy transport	
Qualitative analysis (Leading indicators)	*Scenario 1: Hydrogen: Energy of the future*
	Scenario 2: Hydrogen: Targeted deployment
	Scenario 3: Business as usual
	Scenario 4: Electric breakthrough
Proportion heavy transport market captured by hydrogen	Scenario 1: Hydrogen: *Energy of the future*
	Scenario 2: Hydrogen: *Targeted deployment*
	Scenario 3: *Business as usual*
	Scenario 4: *Electric breakthrough*

Signals	
2025	2030
• Governments provide policy support such as car sales rebates and incentives for building refuelling infrastructure. • Deployment of hydrogen refuelling infrastructure in major cities. • At least three major global OEMs are marketing light vehicle products. • Costs of hydrogen accepting vehicles are competitive with traditional options.	• Widespread deployment of hydrogen refuelling infrastructure including major cities and highways • Major OEMs are marketing products across a wide range of light transport applications and are continuing to invest in ongoing product development
• Deployment of hydrogen refuelling infrastructure in major cities to service niche applications (like taxis)	• High percentage uptake in niche applications (like taxis)
• Hydrogen starts to become cost competitive with fossil fuels	• Low uptake in niche applications (like taxis)
• OEMs' expenditure on R&D and product development of light transport BEV is greater than 10x the investment in light transport FCEV	• Continued innovation and efficiency gains in light transport BEV significantly outpaces light transport FCEV
4%	9%
1%	2%
1%	1%(dom)/2%(int)
1%	1%

Signals	
2025	2030
• At least three major global OEMs are marketing heavy transport products.	• At least five major global OEMs are marketing products across a wide range of heavy transport applications and are continuing to invest in ongoing product development.
• Supported with R&D funding, OEMs are developing products for niche applications.	• High percentage uptake in niche applications.
• Hydrogen starts to become cost competitive with fossil fuels.	• Bespoke applications (such as rail, off-grid systems and remote heavy mobile equipment).
• OEMs' expenditure on R&D and product development of heavy transport BEV is greater than 10x the investment in heavy transport FCEV.	• Continued innovation and efficiency gains in heavy transport BEV significantly outpaces heavy transport FCEV.
4%	9%
1%	2%
1%	1%(dom)/2%(int)
1%	1%

Pipeline gas	
Qualitative analysis (Leading indicators)	*Scenario 1: Hydrogen: Energy of the future*
	Scenario 2: Hydrogen: Targeted deployment
	Scenario 3: Business as usual
	Scenario 4: Electric breakthrough
Proportion of pipeline gas market captured by hydrogen (Lagging indicators)	Scenario 1: Hydrogen: *Energy of the future*
	Scenario 2: Hydrogen: *Targeted deployment*
	Scenario 3: *Business as usual*
	Scenario 4: *Electric breakthrough*

Industrial heat	
Qualitative analysis (Leading indicators)	*Scenario 1: Hydrogen: Energy of the future*
	Scenario 2: Hydrogen: Targeted deployment
	Scenario 3: Business as usual
	Scenario 4: Electric breakthrough
Proportion of industrial heat market captured by hydrogen (Lagging indicators)	Scenario 1: Hydrogen: *Energy of the future*
	Scenario 2: Hydrogen: *Targeted deployment*
	Scenario 3: *Business as usual*
	Scenario 4: *Electric breakthrough*

Signals	
2025	2030
• Governments announce plans for pipeline infrastructure to be able to transport 100% hydrogen without degradation. • At least one beta+ global city conducts hydrogen trials as part of a national strategy. Multiple cities conduct 100% hydrogen trials utilising new distribution infrastructure. • End-use appliances are designed to accept hydrogen.	• At least one nationwide rollout planned of hydrogen injection into pipeline infrastructure.
• Several city-level partial hydrogen injection trials are conducted without needing to retrofit existing pipeline infrastructure. • New pipeline infrastructure is built without the capability to transport 100% hydrogen without degradation.	• At least one beta+ global city plans to conduct partial hydrogen trials that do not require retrofitting pipelines.
• Small partial hydrogen injection trials are conducted in a piecemeal fashion without a national strategy.	• Plans are announced at a precinct level to trial and deploy hydrogen injection into pipelines.
• Announcements of policy support for electrical applications which displace the market share of natural gas.	• Announcements are made to greatly expand electricity generation to effectively wholly displace natural gas energy consumption.
3%(dom)/2%(int)	7%(dom)/4%(int)
1%(dom)/1%(int)	2%(dom)/2%(int)
1%(dom)/1%(int)	1%(dom)/1%(int)
1%(dom)/1%(int)	1%(dom)/1%(int)

Signals	
2025	2030
• Environmental constraints downstream lead to increased focus on technologies to decarbonise industrial heating processes • Major manufacturers announce plans to trial using hydrogen for specific industrial heating purposes • At least three major global industrial OEMs begin marketing industrial equipment that can accept 100% hydrogen	• Major OEMs are marketing products across a wide range of industrial applications that can accept 100% hydrogen • Major manufacturers announce plans to completely deploy equipment that can accept 100% hydrogen
• Several successful trials in niche applications within industrial heat improves perception and industrial community acceptance of hydrogen deployment	• Several manufacturers announce plans to deploy hydrogen for niche applications within industrial heat
• Some trials are conducted for niche applications within industrial heat	• Electrification technologies tend to outpace hydrogen technologies for industrial heating purposes
• Significant number of trials for electrification technology for industrial heating processes are made At least three major global industrial OEMs begin marketing industrial equipment that uses electricity for industrial heating processes	• Continued innovation and efficiency gains in electrification technology significantly outpaces hydrogen technology. • Major OEMs are marketing products across a wide range of industrial applications that use electricity for industrial heating processes.
4%(dom)/2%(int)	9%(dom)/5%(int)
1%(dom)/1%(int)	2%(dom)/2%(int)
1%(dom)/1%(int)	1%(dom)/1%(int)
1%(dom)/1%(int)	1%(dom)/1%(int)

Steelmaking	
Qualitative analysis (Leading indicators)	*Scenario 1: Hydrogen: Energy of the future*
	Scenario 2: Hydrogen: Targeted deployment
	Scenario 3: Business as usual
	Scenario 4: Electric breakthrough
Proportion of steelmaking market captured by hydrogen (Lagging indicators)	Scenario 1: Hydrogen: *Energy of the future*
	Scenario 2: Hydrogen: *Targeted deployment*
	Scenario 3: *Business as usual*
	Scenario 4: *Electric breakthrough*

Feedstock use	
Qualitative analysis (Leading indicators)	*Scenario 1: Hydrogen: Energy of the future*
	Scenario 2: Hydrogen: Targeted deployment
	Scenario 3: Business as usual
	Scenario 4: Electric breakthrough
Proportion of feedstock market captured by green hydrogen (Lagging indicators)	Scenario 1: Hydrogen: *Energy of the future*
	Scenario 2: Hydrogen: *Targeted deployment*
	Scenario 3: *Business as usual*
	Scenario 4: *Electric breakthrough*

Signals	
2025	2030
• Hydrogen utilisation in blast furnaces becomes increasingly technically/economically viable compared to steel reclamation and composites • Emissions profile better than current technology based on an intensity basis • Environmental constraints downstream (e.g. Decrease in furnace utilisation due to local airshed issues)	• 100% of all new steel manufacturing facilities utilising iron ore as the primary feedstock is designed for hydrogen • Majority of existing steel blast furnaces announce plans to utilise hydrogen
• Policy instruments are focused on utilising hydrogen for steelmaking (tax R&D etc) • Agreements between iron ore exporters/hydrogen producers/downstream operators • Environmental constraints downstream (e.g. Decrease in furnace utilisation due to local airshed issues)	• Hydrogen is a targeted application resulting in 100% of all new steel manufacturing facilities utilising iron ore as the primary feedstock is designed for hydrogen • Majority of existing steel blast furnaces announce plans to utilise hydrogen
• Market limited to customers demanding green products • OEMs and steel manufacturers invest in early stage hydrogen adoption through R&D	• Market limited to customers demanding green products • Hydrogen utilisation in blast furnaces becomes increasingly technically/economically competitive with metallurgical coal feedstock
• Market is skewed towards reclaiming steel and reprocessing through electrification (EAF)	• Hydrogen used in bespoke applications (new steel manufacturing plants) in the international market only.
8%(dom)/8%(int)	19%(dom)/19%(int)
8%(dom)/8%(int)	19%(dom)/19%(int)
1%(dom)/1%(int)	2%(dom)/2%(int)
1%(dom)/1%(int)	1%(dom)/1%(int)

Signals	
2025	2030
• Consumers of hydrogen as a chemical feedstock are starting to place additional value on green hydrogen and are placing significant orders with producers. • Major feedstock producers start to trial production of green hydrogen, seeing it as an area of future demand growth.	• The cost premium of green hydrogen is reducing as a result of advances in technology. • Major feedstock producers are seen to be upgrading their existing facilities to produce green hydrogen
• Existing producers of hydrogen as a chemical feedstock continue to use traditional methods, such as reforming of natural gas or petroleum fractions, rather than trialling production of green hydrogen	• A small minority of consumers are demanding green hydrogen with the majority of consumers placing no additional value on green hydrogen.
3%(dom)/3%(int)	3%(dom)/3%(int)
3%(dom)/3%(int)	3%(dom)/3%(int)
1%(dom)/1%(int)	2%(dom)/2%(int)
1%(dom)/1%(int)	1%(dom)/1%(int)

Appendix E:
Modelling input sources

The following are the modelling inputs sourced from publically available information that were used in completing the analysis contained in the report. Other inputs also formed the basis of the modelling undertaken but were developed through a combination of publically available information and Deloitte analysis based on multiple sources, industry knowledge and current projects. These inputs are proprietary information of Deloitte and are not included here.

Energy value conversion

Description	Value	Unit	Source
Energy content of H_2	120	GJ/ton	NGER – http://www.cleanenergyregulator.gov.au/NGER/Legislation/Measurement-Determination

Fuel carbon intensity: natural gas distributed in pipeline

Description	Value	Unit	Source
Density	0.8	kg/m3	https://www.engineeringtoolbox.com/gas-density-d_158.html
Energy content	0.039	GJ/m3	National Greenhouse and Energy Reporting (Measurement) Determination 2008
Emission factor	51	kgCO2/GJ	National Greenhouse and Energy Reporting (Measurement) Determination 2008

Fuel carbon intensity: metallurgical coal (coking coal)

Description	Value	Unit	Source
Density	850	kg/m3	https://www.engineeringtoolbox.com/fuels-densities-specific-volumes-d_166.html
Energy content	30	GJ/ton	National Greenhouse and Energy Reporting (Measurement) Determination 2008
Emission factor	92	kgCO2/GJ	National Greenhouse and Energy Reporting (Measurement) Determination 2008

Fuel carbon intensity: thermal coal (bituminous coal)

Description	Value	Unit	Source
Density	800	kg/m3	https://www.engineeringtoolbox.com/fuels-densities-specific-volumes-d_166.html
Energy content	27	GJ/ton	National Greenhouse and Energy Reporting (Measurement) Determination 2008
Emission factor	90	kgCO2/GJ	National Greenhouse and Energy Reporting (Measurement) Determination 2008

Fuel carbon intensity: diesel

Description	Value	Unit	Source
Density	0.8	kg/L	https://www.engineeringtoolbox.com/fuels-densities-specific-volumes-d_166.html
Density	845	kg/m3	https://www.engineeringtoolbox.com/fuels-densities-specific-volumes-d_166.html
Energy content	38.6	GJ/kL	National Greenhouse and Energy Reporting (Measurement) Determination 2008
Emission factor	70	kgCO2/GJ	National Greenhouse and Energy Reporting (Measurement) Determination 2008

Fuel carbon intensity: gasoline

Description	Value	Unit	Source
Density	0.71	kg/L	https://www.engineeringtoolbox.com/fuels-densities-specific-volumes-d_166.html
Density	780	kg/m3	https://www.engineeringtoolbox.com/fuels-densities-specific-volumes-d_166.html
Energy content	34.2	GJ/kL	National Greenhouse and Energy Reporting (Measurement) Determination 2008
Emission factor	67	kgCO2/GJ	National Greenhouse and Energy Reporting (Measurement) Determination 2008

Fuel carbon intensity: hydrogen

Description	Value	Unit	Source
Density	0.09	kg/m3	https://www.engineeringtoolbox.com/gas-densities-d_158.html

Carbon intensity factors for the grid

Description	Value	Unit	Source
New South Wales and Australian Capital Territory	0.82	kgCO2/kWh	https://www.environment.gov.au/system/files/resources/80f603e7-175b-4f97-8a9b-2d207f46594a/files/national-greenhouse-accounts-factors-july-2018.pdf
Victoria	1.07	kgCO2/kWh	
Queensland	0.80	kgCO2/kWh	
South Australia	0.51	kgCO2/kWh	
South West Intercon-nected System in Western Australia	0.70	kgCO2/kWh	
North West Intercon-nected System in Western Australia	0.60	kgCO2/kWh	
Darwin Katherine In-terconnected System in the Northern Terri-tory	0.56	kgCO2/kWh	
Tasmania	0.19	kgCO2/kWh	
Northern Territory	0.64	kgCO2/kWh	

Energy consumption by region

Description	Value	Source
South West Interconnected System proportion of Western Australia	98%	http://www.treasury.wa.gov.au/uploadedFiles/Site-content/Public_Utilities_Office/Industry_reform/Final-Coverage-Decision-2-February-2018.pdf
North West Interconnected System proportion of Western Australia	2%	
Darwin Katherine Interconnected System proportion of Northern Territory	88%	http://www.utilicom.nt.gov.au/PMS/Publications/UC-PSR-2016-17.pdf
New South Wales and Australian Capital Territory	69085 GWh	https://assets.cleanenergycouncil.org.au/documents/resources/reports/clean-energy-australia/clean-energy-australia-report-2019.pdf
Victoria	48014 GWh	
Queensland	13506 GWh	
South Australia	13506 GWh	
Western Australia	18950 GWh	
Tasmania	12083 GWh	
Northern Territory	2983 GWh	https://www.energy.gov.au/sites/default/files/aes-table-o-2016-17_2017.pdf

Carbon intensity of the grid – annual changes

Description	Annual change	Targeted carbon Intensity	Year	Source
Net Zero by 2050	-21%	0.00	2050	http://climatechangeauthority.gov.au/files/files/Target-Progress-Review/Analysis-of-electricity-consumption-electricity-generation-emissions-intensity-and-economy-wide-emissions/Australia%20electricity%20and%20emissions%20final%20report%20 2013%2010%2018.pdf
Consistent with a linear extrapolation to 0.4 kg CO2/kwh produced in 2050	-2%	0.61	2030	
Consistent with a linear extrapolation to 0.2 kg CO2/kwh produced in 2050	-4%	0.47	2030	

Implied international cost of decarbonisation

Description	Annual change	Targeted carbon Intensity	Year	Source
High cost of decarbonisation	7%	146	2050	https://19january2017snapshot.epa.gov/sites/production/files/2016-12/documents/sc_co2_tsd_august_2016.pdf
Low cost of decarbonisation	3%	40	2050	

Cost elasticity function: formula when hydrogen is cost competitive with alternative fuel

Description	Value	Source
Every percentage fall in price leads to a percentage increase in demand	0.58	Average gasoline elasticity (cross-price) – https://web.stanford.edu/group/emf-research/docs/special_reports/EMF_SR12.pdf

Note: the following average growth rates represent the percentage in fraction form.

Domestic forecasted demand: domestic pipeline gas forecasted demand

Description	Value	Source
Previous 5 years average growth rate	0.008	https://www.iea.org/statistics/?country=AUSTRALI&year=2016&category=Natural%20gas&indicator=NatGasCons&mode=chart&dataTable=GAS
Forecasted aver-age growth rate	0.046	https://www.eia.gov/outlooks/ieo/pdf/nat_gas.pdf

Domestic forecasted demand: domestic steelmaking forecasted demand

Description	Value	Source
Previous 5 years average growth rate	0.041	https://www.worldsteel.org/en/dam/jcr:96d7a585-e6b2-4d63-b943-4cd9ab621a91/World%2520Steel%2520in%2520Figures%25202019.pdf

International forecasted demand: pipeline gas

Description	China	Japan	Korea	Source
Previous 5 years average growth rate	0.086	-0.017	0.002	https://www.eia.gov/outlooks/ieo/pdf/nat_gas.pdf

International forecasted demand: industrial heat

Description	China	Japan	Korea	Source
Previous 5 years average growth rate	0.013	-0.005	0.013	https://www.iea.org/statistics/? country=AUSTRALI &year =2016&category=Natural%20gas&indicator = NatGasCons&mode=chart&dataTable=GAS

International forecasted demand: steelmaking

Description	China	Japan	Korea	Source
Previous 5 years average growth rate	0.013	-0.005	0.013	https://www.iea.org/statistics/? country=AUSTRALI &year =2016&category=Natural%20gas&indicator = NatGasCons&mode=chart&dataTable=GAS

International forecasted demand: Alternative-Drive Transport

Description	FCEVs	Year	Source
China – FCEV target	1,000,000	2030	https://www.iea.org/tcep/energyintegration/hydrogen/
Japan – FCEV target	800,000	2030	https://www.reuters.com/article/us-japan-hydrogen/japan-venture-aims-to-build-80-hydrogen-fuelling-stations-by-2022-idUSKBN1GH072
Korea – FCEV target	500,000	2030	https://www.iea.org/tcep/energyintegration/hydrogen/
Rest of the world – FCEV target	2,500,000	2030	https://www.iea.org/tcep/energyintegration/hydrogen/

Industrial heating proportion of gas consumption

Description	Gas used in industry	Industrial heating (proportion of industrial gas)	Industrial heating (proportion of all gas)	Source
Australia	55%	50%	28%	https://www.iea.org/statistics/?country=WORLD&year=2016&category=Natural%20gas&indicator=ShareNatGasCons&mode=chart&dataTable=GAS
China	38%	50%	19%	
Korea	35%	50%	17%	
Japan	34%	50%	17%	
Rest of the World	37%	50%	19%	

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