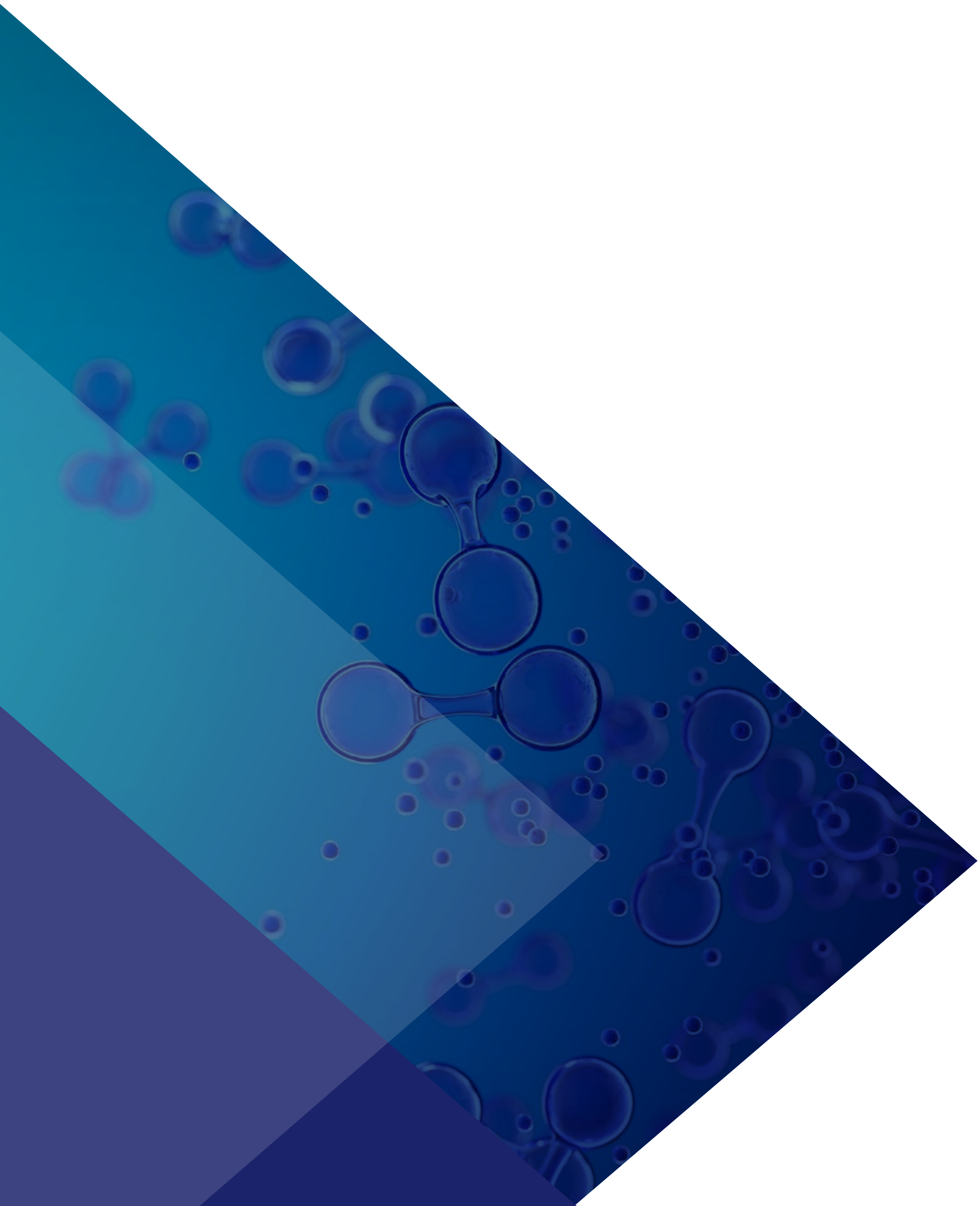
HYDROGEN TECHNOLOGY CLUSTER AUSTRALIA

Powering Up: Seizing Australia's Hydrogen Opportunity by 2040

Report 2023



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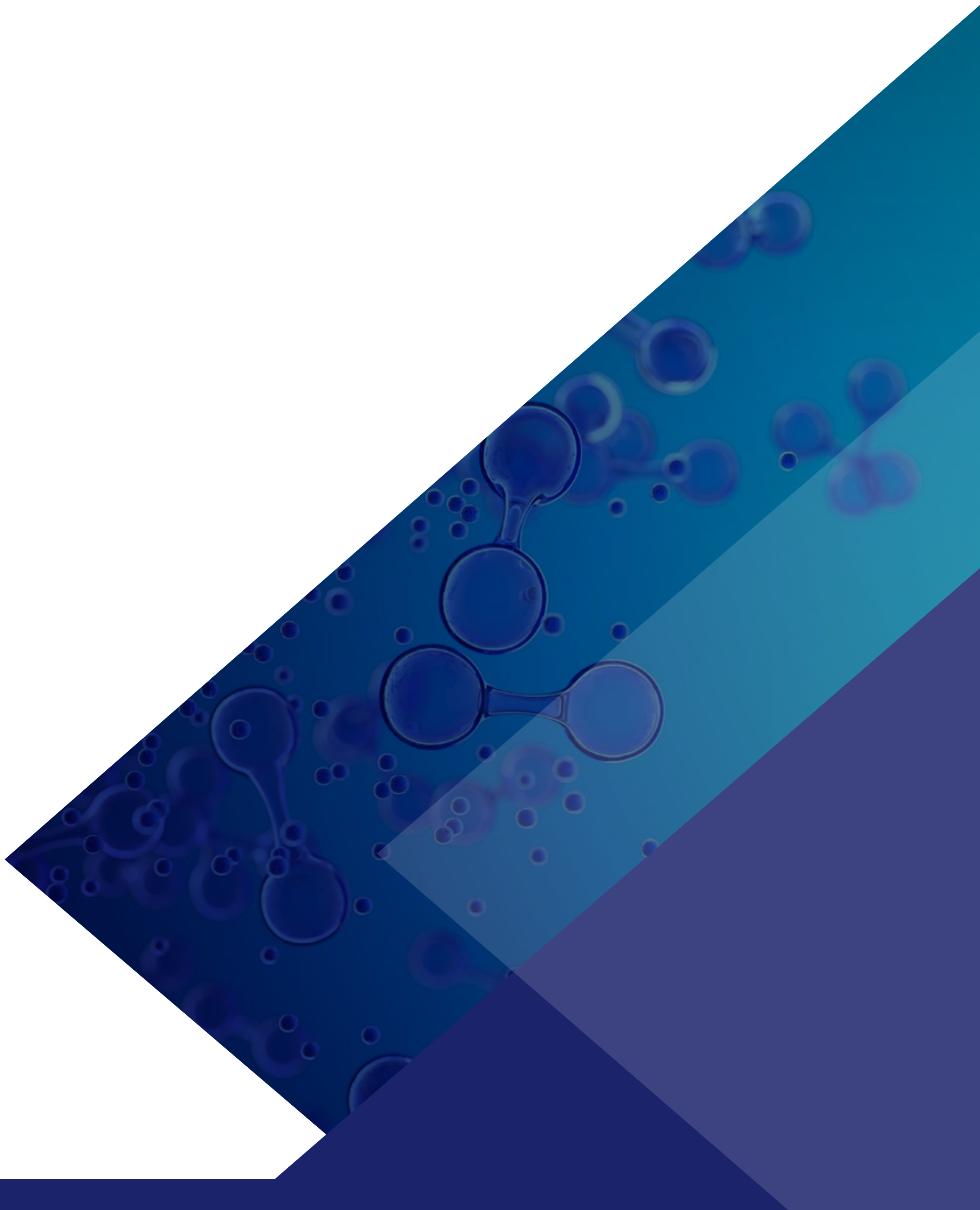
Acknowledgment

We acknowledge Aboriginal and Torres Strait Islander people as the traditional custodians of country throughout Australia and recognise their continuing connection to land, waters and community. We pay our respects to their Elders past and present.

Note

For this report, the analysis of the Australian supply chain has been based on a desktop assessment using in-house references and online materials. Whilst this approach provides a good base, Arup are aware that there will be other companies operating in these areas that they did not identify, and welcome further information from wider stakeholders on these companies.



Glossary and terminology

Acronym/ phrase	Term
AEMO ISP	Australian Energy Market Operator Integrated System Plan
ABS	Australian Bureau of Statistics
APS	Announced Pledges Scenario
ARENA	Australian Renewable Energy Agency
bn	Billion
BNEF	Bloomberg New Energy Finance
CCS	Carbon Capture and Storage
CO_2	Carbon Dioxide
DCCEEW	Department of Climate Change, Energy, the Environment and Water
DFMA	Design for Manufacture and Assembly
DRI	Direct Reduced Iron
EAF	Electric Arc Furnace
EERE	The Office of Energy Efficiency and Renewable Energy
FCETs	Fuel cell electric trucks
FTE	Full Time Equivalent
H_2	Hydrogen
H&S	Health and Safety
HESC	Hydrogen Energy Supply Chain
HETS	Hydrogen Equipment Technology and Services
GVA	Gross Value Added
GL	Gigalitre
GW	Gigawatts
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
kt	Kilotonne

Acronym/ phrase	Term
L	Litre
LCOH	Levelised cost of hydrogen
MCH	Methylcyclohexane
MEA	Monoethanolamine
MMT	Million metric ton
NERA	National Energy Resources Australia
NHIA	National Hydrogen Infrastructure Assessment
O&M	Operations and Maintenance
OEM	Original Equipment Manufacturer
PEM	Polymer Electrolyte Membrane
PGM	Platinum Group Metal
RAG	Red, Amber, Green
REZ	Renewable Energy Zone
SCADA	Supervisory control and data acquisition
SME	Small-to-Medium Enterprise
SMR	Steam Methane Reformation
SWOT	Strength, Weaknesses, Opportunities and Threats
t	Tonnes
TEG	Triethylene glycol
TRL	Technology Readiness Level
WTG	Wind turbine generator

Executive summary

Overview

Hydrogen has the potential to enhance Australia's energy security, create new domestic and export markets, and reduce national and global carbon emissions. However, the Hydrogen Equipment, Technology and Service (HETS) industry is in its infancy. It must be developed to support the supply chain and activate business opportunities and jobs in cross-sector industrial settings. NERA (National Energy Resources Australia) commissioned Arup to assess the HETS industry in Australia. The objectives of this study are to:

1. Define the industry, mapping the hydrogen supply chain's current status within Australia and quantifying the scale and opportunity the market presents.
2. Understand the growth and change within the supply chain, current and future roles that domestic firms may play, including jobs and economic outlooks, and investigating barriers to and drivers of participation.
3. Describe the gaps and key opportunities for Australian firms within the HETS market to identify areas of competitive advantage and high-value and niche opportunities.

The National Hydrogen Infrastructure Assessment (NHIA) 2040 Low Emissions Central Demand Scenario (herein referred to as the 'NHIA Central Demand Scenario') has been used as a baseline for this study. The model that underpinned the NHIA assessment developed the lowest infrastructure cost method of meeting hydrogen demands identified throughout Australia by an independently commissioned demand assessment.

Outcomes

Supply chain assessment

This supply chain assessment builds on the NHIA to consider one possible configuration of the hydrogen supply chain in 2040 alongside supporting functions that must develop to enable implementation. The assessment is also based on Arup's experience in hydrogen projects and a review of literature and modelling.

The HETS supply chain is wide-reaching, ranging from the generation of feedstock through to production, transport, storage, processing and consumption at the point of demand. The configuration of organisations and functions to enable this network to meet future demands is still emerging, presenting a level of uncertainty.

By 2040 most hydrogen production in Australia is anticipated to be via electrolysis, with 51GW of electrolyser capacity to be developed. Meeting the forecast demand will involve rapid acceleration of solar and wind energy generation infrastructure installation and operation, over and above the requirements for the decarbonisation of the grid, transport and other industries. It is anticipated that most hydrogen electrolysers will use renewable energy installed 'behind the meter', meaning electrolyser installations will be concentrated in dedicated renewable energy zones requiring domestic transport of hydrogen to points of consumption or export.

The construction of electrolyser production infrastructure involves complex supply chains to make and deliver electrolyser parts and the supporting equipment. The manufacture of electrolyser modules involves raw materials that may have constrained supply (including platinum group metals) and complex assembly of subcomponents and the modules themselves. The development and supply of fuel cells for mobility and other applications may be a related opportunity due to a similar configuration to electrolysers. The management of risk and realisation of opportunities related to this supply chain element will influence the way the hydrogen system develops.

The supply of hydrogen compressors, liquefaction and carrier conversion equipment will be critical to enabling the transit of hydrogen from production to the point of consumption. Hydrogen will likely be moved domestically as compressed hydrogen gas. Pipeline transport (through new or repurposed pipelines) is preferred for consistent, high-volume hydrogen movement, and road and rail transport to carry out smaller distribution tasks with specialised equipment. Longer-term, strategic storage of hydrogen will likely be done in naturally occurring or constructed salt caverns, with smaller-scale tactical storage throughout the network done in tanks and vessels. The feasibility of using salt caverns as storage will depend on their location in relation to where the hydrogen is being produced and consumed, as well as the availability of necessary infrastructure to bridge any gaps in the transportation network.

Where transport of gaseous hydrogen is not appropriate, other hydrogen carriers such as methylcyclohexane (MCH), ammonia and liquefied hydrogen may be needed. Ammonia and liquefied hydrogen will likely be preferred for export purposes, while MCH may be used for transport and storage locally.

Infrastructure for the conversion of hydrogen to carriers, transport of carrier liquids or solids, and reconversion of carriers to hydrogen (where the demand is for hydrogen gas rather than the carrier itself) must be developed (domestically or abroad in the case of export) to facilitate this supply chain element.

Economic analysis

The amount of investment and annual operational, maintenance and capital expense necessary to achieve the quantity of real economic activity in 2040 at each node has been quantified through the economic analysis included in this report. A node refers to a specific point of value add, including production, processing, handling or transformation, as well as applications such as electrolysis and salt cavern storage. Costs at each node have been mapped to jobs and domestic Gross Value Added (GVA) across the supply chain using ratios and multipliers calculated from Australian input-output tables.

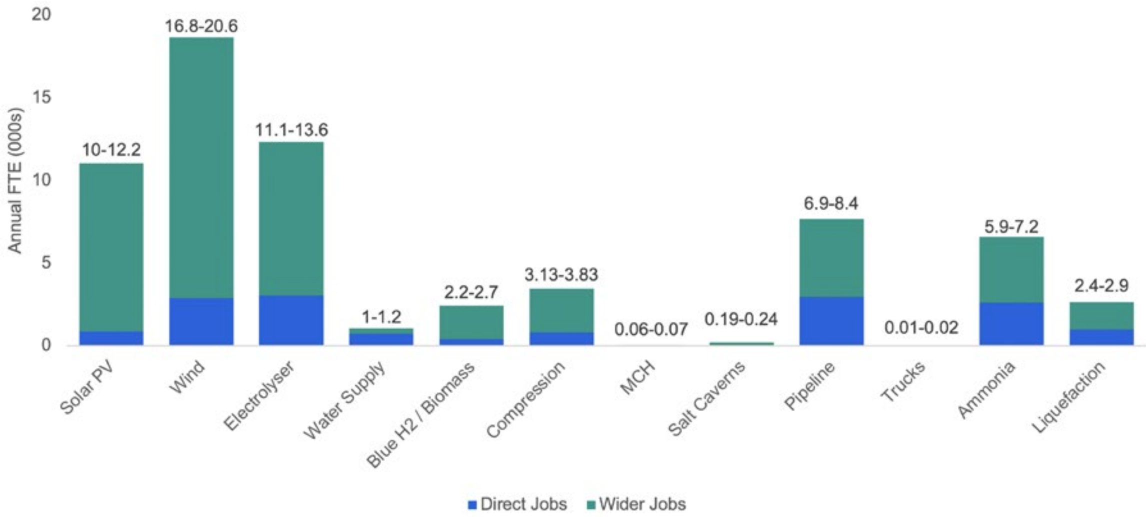
The Australian hydrogen economy could support $30-$40 bn in domestic GVA (1.0%-1.25% of total Australian GVA) and 58,000-72,000 jobs annually across the wider supply chain by 2040 (see table below). One job directly related to the hydrogen industry will approximately create a further three jobs in the broader economy. Recognising the existing Australian economy, a significant share of investment (44%-61%) will be on imported goods, particularly specialised goods such as solar panels, electrolyser components, wind turbines and compression components.

An investment increase from 2025 is required, with investment averaging around $25-$30 bn a year from the late 2020s through to 2040. As with the supply chain, projections within the economic analysis have a level of uncertainty and are intended to provide an indicative estimate of the potential size of the hydrogen economy and what is needed to achieve it.

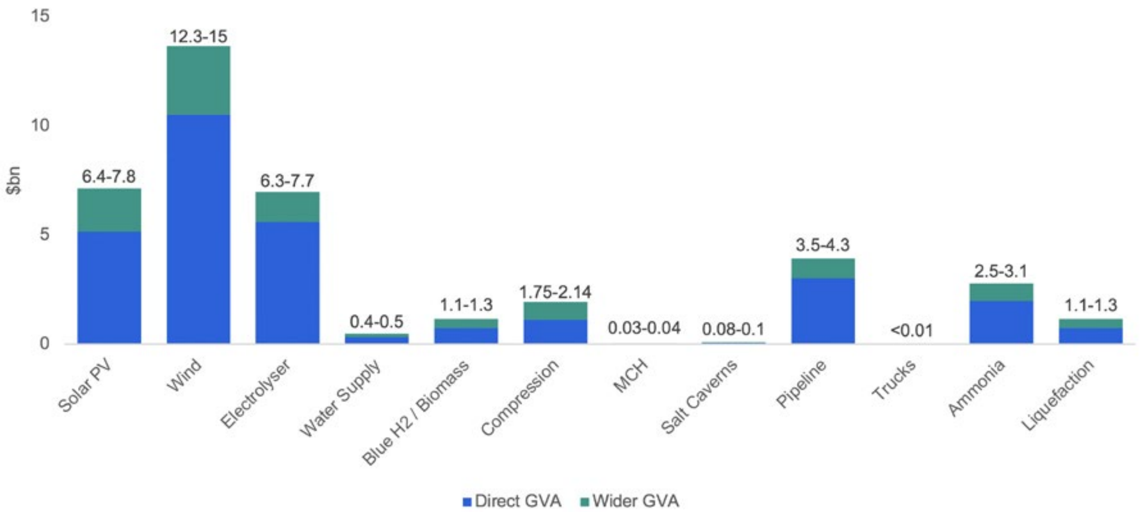
Item	Description	Value
Annual turnover	Annual revenues of H_2 economy.	$30-$40 bn (1.0%-1.25% of Australia's GVA)
Direct GVA (2040)[1]	Annual GVA in the domestic economy in 2040 directly associated with the production, storage, and transport of hydrogen. This also includes the GVA from direct expenditure on materials to support the production, storage, and transport of hydrogen, including the capital investment required to establish the domestic production capacity.	$26-$32 bn (0.80%-0.95% of Australia's GVA)
Wider GVA (2040)	Annual GVA in the wider supply chain in 2040.	$9-$11 bn (0.25%-0.35% of Australia's GVA)
Direct annual employment	Jobs directly related to annual production, transport and storage of hydrogen and the regular maintenance of assets in 2040.	13,000-17,000 jobs
Wider annual employment	Jobs in the wider supply chain in 2040, including indirect jobs from suppliers that support the production, storage, and transport of hydrogen. This also includes jobs for non-routine maintenance and replacement of capital goods (such as electrolysers or wind turbines) and associated roles in construction services.	45,000-55,000 jobs
Total investment	Total investment required to achieve 2040 production levels between now and 2040.	$340-$420 bn

Wind power has the largest annual job requirements, with jobs supported through building, maintaining, and replacing wind turbines. In terms of direct jobs, operational jobs such as monitoring and control of electrolysis, pipeline and ammonia production take up the largest share of jobs created at around a few thousand per node.

1 Direct GVA is reflective of the capital investment required to deliver the hydrogen production capacity to 2040, and the Direct GVA delivered by hydrogen in 2040. For this reason, the Direct GVA and Wider GVA will not sum to equal the annual turnover displayed in the table.



In GVA terms, the split between direct production and operations and the wider supply chain is reversed. This is because the hydrogen industry requires significant capital investment to fund production and operations. The majority of income (around 90%[2]) generated by annual activities flows to capital (investors) rather than to labour (salaries).



Australian capability and capacity and complementary sectors

Australian suppliers with strong capabilities to provide equipment, technology, and services are concentrated in a few supply chain nodes. To further develop the HETS supply chain and maximise the benefits for Australia, a mixture of local and international supply chain competition will be required.

Australian firms are involved in developing electrolysis technologies, and there is a strong Australian capability for anaerobic digestion and gasification. Hydrogen storage in pressurised vessels is a mature technology, but MCH, liquid hydrogen and geological storage options such as for salt caverns require development. Similarly, fuel cell technology is largely mature, but emerging technologies such as solid oxide fuel cells will also need further development.

Few manufacturers are based solely in one country and most source components from different nations. Analysis shows that the Australian economy accrues significant benefits when Australian-based companies manufacture within Australia, whilst there are several other methods available to work with international suppliers to provide other national benefits.

The most required and relevant complementary sectors are professional, scientific and technical services, construction, manufacturing and electricity, gas, water and waste services.

2 This is in line with existing ratios in the oil and gas, mining and electricity generation sectors.

Gap analysis

The gap analysis compared the current scenario with the potential 2040 demand to highlight key opportunities. It highlighted that across all nodes, the forecast demand is significant compared to the current size and investment is required to meet the future demand and foster Australian capability. To support this in the short term, there should be a focus on creating partnerships with international manufacturers, understanding alternative business models, and investigating material supply chain opportunities.

The gap analysis also demonstrated that significant knowledge, planning and foresight will be required to ensure that the skilled workforce is retrained and a new workforce is active ahead of the NHIA Central Demand Scenario. This is essential to ensure there is no lag between technology developments and skills. The greatest technology gaps are around enabling emerging technologies to become commercially viable. For example, long-duration and large-scale storage technologies are relatively novel and will require investment.

Considering gaps along with local advantage and industry competition, the following supply chain nodes are the most advantageous and present the greatest opportunity for Australia: electrolysis, hydrogen storage and distribution. These nodes have a significant amount of demand forecast in relation to their current size and require investment to foster Australian capability.

Recommendations and conclusions

Enabling a strong supply chain is key to underpinning future expansion. The demand for hydrogen is expected to be great enough that direct and indirect labour will be required to complete several GW-scale projects currently in the pipeline in Australia. It is recommended that investment is made in hydrogen technology cluster locations to enable the development of skilled technology supply chains in regions across Australia. These clusters have been established to develop skills, capability, and commercialisation opportunities in the hydrogen supply chain[3]. The provision of HETS will be instrumental in growing the hydrogen industry in these regions.

A series of primary recommendations are highlighted below, and further recommendations to accelerate the development of the HETS supply chain can be found at the end of this report.

Equipment

Focussed investment is needed in onshore manufacturing combined with advanced manufacturing techniques and research and development (R&D) to build upon existing supply chain capacity. Anecdotal market evidence envisages longer lead times for equipment as manufacturers attempt to keep up with growing global demand. Australian companies can capitalise on the lengthy lead time for equipment from international suppliers by building local capacity and investing for future supply chain delivery. This can ensure that Australian companies and products are competitive in the future. Between 2025 and 2040, at least $340-$420 bn ($25-$30 bn a year) of investment will be required to build up the infrastructure necessary to produce hydrogen at the scale envisioned in the NHIA scenario. Further consideration could be given to encouraging international manufacturers to onshore their manufacturing capabilities in Australia. Partnerships, competitive and innovative commercial models and eliminating or reducing structural barriers such as quotas will all contribute to and attract international organisations.

In the near term, it will be important to identify opportunities early and begin to invest in manufacturing capability for Australian suppliers across several supply chain nodes. Australia could draw upon its advances in novel electrolyser technologies. In addition, Australia has untapped reserves of platinum and iridium[4], which could be used to secure these essential materials for electrolysers, as well as High Purity Quartz (HPQ) reserves that could meet the growing demand for silica to manufacture solar cells. To reduce the cost of building electrolysis plants, efforts should be made to design and develop affordable electrolyser modules for local production. Recommendations to develop Australia's electrolyser production capacity include:

- Forming partnerships between research organisations, engineering businesses, and fabricators with suitable skillsets (e.g., oil and gas equipment, pressure vessels, HV electrical, supervisory control and data acquisition (SCADA)).
- Using advanced manufacturing principles such as Design for Manufacture and Assembly (DFMA), lean manufacturing, Industry 4.0, etc., for whole-of-life cost reduction.
- Securing supplies of key raw materials (e.g., platinum group metals) and other key components.

3 https://www.nera.org.au/regional-hydrogen-technology-clusters

4 Bruce S, Delaval B, Moisi A, Ford J, West J, Loh J, Hayward J (2021). Critical Energy Minerals Roadmap. CSIRO, Australia.

Technology

Hydrogen storage is one of the primary technology challenges for large-scale hydrogen production. For Australia to offer a competitive advantage globally, investment in low-cost and large-scale hydrogen storage options is needed. Hydrogen storage R&D and technical investigations are necessary to accelerate and realise these projects. Australia needs 89.5kt storage by 2040; resultantly, up to $0.7-$0.9 bn of investment is required in salt cavern and MCH. In the near term:

- Ramp up investment in R&D of novel and emerging electrolyser and fuel cell technologies to improve asset lifetimes, efficiency and cost. Early investments offer large long-term payoff potential.
- Undertake a detailed evaluation of Australian technologies within other attractive supply chain nodes. For example, in hydrogen storage (e.g., safe and low-cost hydrogen storage technologies), salt cavern technology, alternative carriers, MCH conversion technology, and in transport, carbon capture and storage (CCS), MCH and liquid hydrogen tankers.
- Accelerate investment into nearer-term technologies close to commercial viability to bridge the gap. This includes technologies with high Technology Readiness Level (TRL) ratings, such as liquid hydrogen storage tanks and tankers for distribution.

Services

Limited workforce skillsets across the existing HETS supply chain restrict the pace at which the supply chain can be developed – this is a major challenge to realise national goals. Building a highly skilled and capable workforce across all facets of the supply chain is fundamental. An estimated 170,000-200,000 full time equivalent (FTE) construction jobs will be required, and a further 58,000-72,000 jobs annually could be supported across the operational (direct) and wider HETS supply chain. To make this transition possible, it will be necessary to establish clear paths for current workers to transition to new roles and for future workers to receive the necessary training through TAFE. In addition, indirect services such as risk assessment, policy creation and environmental management related to expanding hydrogen production must be developed to ensure a smooth transition of capabilities and a thorough understanding of potential consequences.

Schools and tertiary education institutions need to collaborate with industry to create relevant courses to train the future generation of industry professionals. Existing workers need to be supported to transition existing skillsets. This can be through formal and on-the-job training or micro-credentials. Consistency is needed across the training spectrum, particularly to foster quality health, safety and environmental credentials across the Australian workforce. To do this, a coordinating body that can define the type of skills required is essential. This body would need to work closely with education institutions to define the curriculum. In the near term, the body would:

- Begin to invest in roles that will support the hydrogen supply chain, such as professional, scientific, and technical services, as well as construction and manufacturing. These will be pivotal in supporting technology development and providing general support to the HETS supply chain.
- Undertake a wider supply chain component assessment to identify specific support roles and ensure funding is targeted.
- Gain support from governments (state and federal) within the health and safety (H&S) and environmental regulations to initiate a regulated and governed hydrogen economy.
- Where it does not exist already, undertake a detailed investigation into individual supply chain nodes to identify Australian raw inputs, skills, and capabilities. Grow investment in workforce upskilling to develop manufacturing, construction, professional, scientific, and technical capability. This can be done by implementing early workforce upskilling and transition pathway plans nationally. Ensure there is a collaboration with education institutions, and relevant courses and micro-credentials are developed (and continue to be developed) to facilitate the transition.
- Communicate workforce transition pathway options with clear transition goals.

1. Introduction

1.1 Background

Hydrogen has the potential to enhance Australia's energy security, create new domestic and export markets, and reduce domestic and global carbon emissions. Australia can seize the opportunity to be a world leader in the global hydrogen market. Initial efforts have been focussed on procuring, developing and enabling the export of hydrogen to neighbouring countries through the creation of hydrogen hubs, and this remains a continued focus. The next step is opening up opportunities for a local transition to cleaner energy, new industries and a future with fewer carbon emissions.

The Australian Hydrogen Equipment, Technology and Services (HETS) industry is in its infancy and must be developed to activate business opportunities and jobs in cross-sector industrial settings.

Arup has been commissioned by NERA to undertake an assessment of the HETS industry in Australia. The objectives of this study are to:

1. Define the industry, mapping the hydrogen supply chain's current status within Australia and quantifying the scale and opportunity the market presents.
2. Understand the growth and change within the supply chain, current and future roles that domestic firms may play, including jobs and economic outlooks, and investigate barriers to and drivers of participation.
3. Describe the gaps and key opportunities for Australian firms within the HETS market to identify areas of competitive advantage and high-value and niche opportunities.

The HETS supply chain encompasses aspects of hydrogen production through to end-use. The table below identifies the core elements of HETS.

Hydrogen Equipment, Technology and Services (HETS)	
Equipment	Includes manufactured items (plant, machinery, equipment) that contribute to the production, storage, transportation or utilisation of hydrogen; parts for machinery and equipment; industry-specific supplies such as chemicals; and construction and civil engineering.
Technology	Includes engineering design; information and communications technology (such as data analytics, real-time monitoring and sensors); and scientific research into production, storage, transportation and utilisation.
Services	Includes equipment maintenance and repairs, specialised consulting, e.g. risk, policy implementation, applied sciences such as laboratory work, environmental sciences, data processing, supporting hydrogen utilisation, training and education.

1.2 Aim and scope

The aim of this study is to gain a deeper understanding of the scale, capacity, and capability of the HETS industry within an Australian context and to understand where the focus should be in order to grow the hydrogen economy. This scope of work is split into three key stages.

1.2.1 Stage 1 - Understanding the hydrogen market and its potential

Objectives:

- Articulate a clear plan and methodology that will guide the engagement, confirming the scope, methodology, deliverables, and timelines.
- Build a deeper understanding of the future hydrogen sector by mapping the hydrogen supply chain with respect to equipment supply, technology, and services.
- Quantify the economic activity arising from the entire hydrogen supply chain.
- Consider future demand scenarios, their drivers and the risks around these scenarios.

Key activities:

- Hold a workshop to discuss and agree on a baseline hydrogen market.
- Undertake a supply chain assessment.
- Undertake an economic assessment and identify economic benefits.

1.2.2 Stage 2 - The Australian context – current capability and capacity

Objectives:

- Understand the number of domestic suppliers currently servicing the hydrogen industry.
- Explore the capabilities of Australian businesses.
- Investigate the potential for firms within other sectors to support the growing HETS industry.
- Understand the barriers and challenges of entry into the HETS industry, now and as the market grows in the future.

Key activities:

- Investigate current domestic capability.
- Investigate the capability of complementary sectors.
- Understand barriers to market entry.

1.2.3 Stage 3: Gap analysis and opportunity identification

Objective:

- Develop an understanding of the missing links between current capability and future market demand to identify high-value, high-growth opportunities for Australian businesses.

Key activities:

- Undertake a gap analysis within the Australian market.

2. Baseline hydrogen market

2.1 Extent of the supply chain

Figure 1 illustrates the hydrogen supply chain scope agreed upon with NERA for this study. Further detail is also provided in Appendix A.

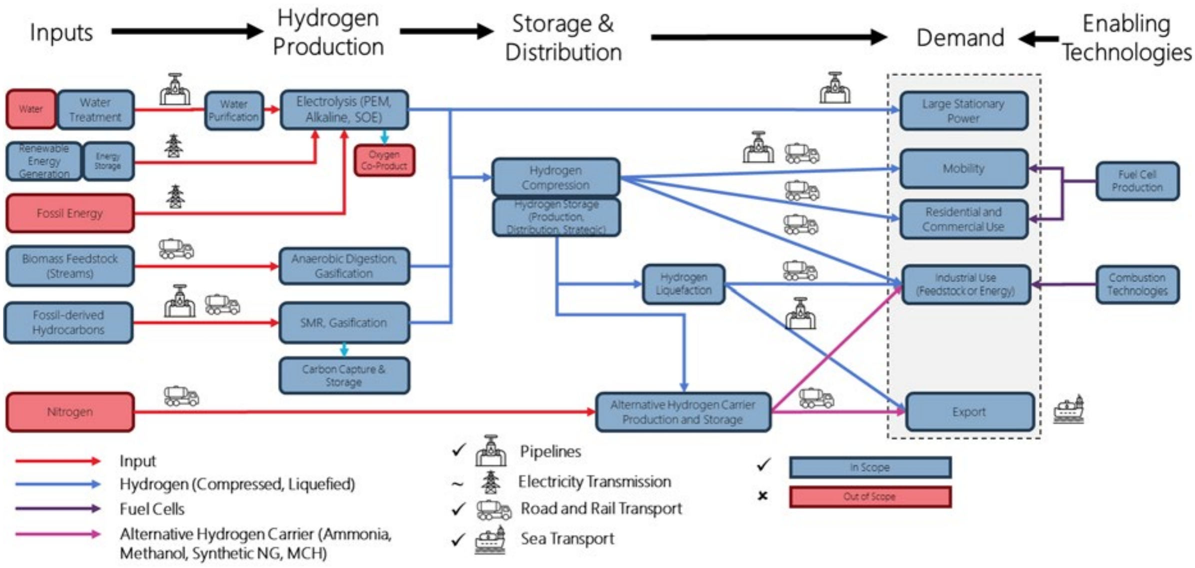


Figure 1 Scope extents

2.2 National Hydrogen Infrastructure Assessment

The National Hydrogen Infrastructure Assessment (NHIA) provides a review of existing infrastructure and a robust and transparent prioritisation of supply chain opportunities under a number of agreed scenarios considering economic, environmental and social outcomes. This assessment was coordinated by the Department of Climate Change, Energy, the Environment and Water (DCCEEW) on behalf of Commonwealth, State and Territory Governments.

2.2.1 NHIA model outcomes

With agreement from DCCEEW, the NHIA 2040 Central Demand Scenario has been used as a baseline for this study. The model that underpinned the assessment developed the lowest infrastructure cost method of meeting demands for hydrogen identified throughout Australia by an independently commissioned demand assessment. It considered the costs to produce, transport and store hydrogen throughout the system to meet the demands based on a robust underlying economic framework and set of assumptions. The 2040 NHIA Central Demand Scenario was chosen because it could represent the most likely scenario for Australia's future hydrogen economy and is a moderate estimate.

The outputs of the assessment are summarised below:

- The NHIA assessment forecasts a total demand of 9.5MMT H_2, 54% for domestic uses and 46% for export in the selected scenario once system losses are incorporated.
- Hydrogen is produced in Australia to meet this demand – there is no imported hydrogen considered.
- All hydrogen is produced by electrolysis in Renewable Energy Zones (REZ) until saturation, where small overflows are assumed to be produced at the point of demand through renewable energy available through the grid.

- Renewable energy to power the electrolysers is constructed on-site (behind the meter) as either solar or onshore wind power.
- Hydrogen is transported throughout the domestic network as compressed H_2 gas via (predominately) pipelines constructed between locations of production and demand centres. There is a 1,415 tonne H_2 per hour transport capacity.
- Where storage is needed, storage in salt caverns (89.5kt H_2 capacity) and as methylcyclohexane (MCH) (44kt capacity) is preferred.
- The levelised cost of hydrogen is $2.5-$3.4 per kg, based on system infrastructure costs.
- Assumes 100% utilisation of all hydrogen produced.

The future demand for hydrogen is uncertain, and there have been a large number of reports released containing a wide variety of demand scenarios for the sector. The information in this report is solely based on the NHIA assessment scenario outlined above.

2.2.2 NHIA limitations

The limitations of the NHIA that should be considered as part of this assessment are as follows:

- Offshore wind was not included as a potential renewable energy generation for hydrogen production due to the NHIA being completed before the release of the *Offshore Electricity Infrastructure Act 2021*.
- Existing or announced projects for hydrogen production (electrolysis, steam methane reforming (SMR) with CCS or biomass gasification) were not incorporated into the production assessment.
- Power transmission cost is modelled as a flat percentage of electricity cost.
- The data within the NHIA is two years old, and so excludes more recent developments in policy and target setting.

3. Supply chain mapping

3.1 Overview

The configuration of organisations and functions that will form the supply chain to produce and ultimately deliver hydrogen to meet demand throughout Australia is emerging and uncertain, with current assumptions regarding the price and viability of various methods of production, transmission, storage, and consumption to be tested as the industry grows. This assessment builds on the NHIA to consider one possible configuration of the hydrogen supply chain in 2040 alongside the supporting and enabling functions that must develop to enable its implementation.

The assessment considers the following:

- The potential structure of the supply chain.
- Material flows through the supply chain based on the NHIA and assessment of currently announced projects.
- A summary of development at supply chain nodes within supply chain segments to enable the material flows identified (refer to terminology below).
- For selected critical nodes, assessment of critical competencies, organisational enablers, and supply elements.

For the purposes of this report:

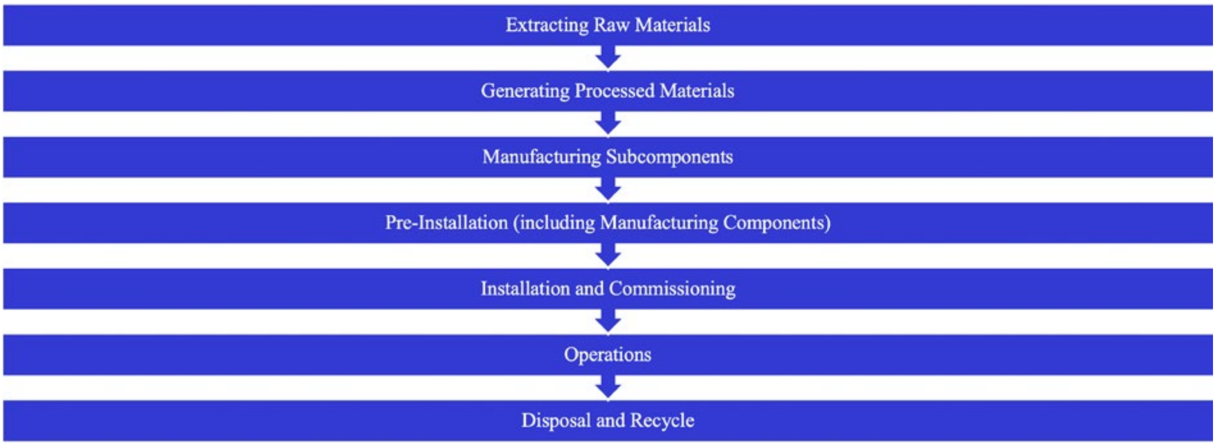
- A **segment** refers to feedstock, production, distribution, storage and demand required to enable the material flows identified.
- A **node** refers to a specific point of value add, including production, processing, handling or transformation, including applications such as electrolysis and salt cavern storage.

3.2 Methodology

The material generated within the supply chain assessment is based on Arup's experience in hydrogen projects, a review of available literature and detailed modelling, incorporating the outcome of the NHIA. The assessment involved:

1. Evaluation of supply chain structure and supporting functions.
2. Evaluation of production, consumption, storage, and transportation parameters generated by the NHIA by region and state within Australia.
3. Incorporating currently announced projects across production types to determine growth requirements to meet 2040 demands.
4. Review of material flow through the supply chain to determine the level of development necessary to support operation.
5. For identified critical nodes, assess the detailed supply chain parameters across the development life cycle.

Supply chain development life cycle



3.3 Supply chain assumptions

In order to address the limitations of the NHIA study, a number of assumptions have been made to broaden the scope of the supply chain assessment. This is done by noting the uncertainty of the development path for hydrogen in the future.

- The NHIA models that all hydrogen in the Central Demand Scenario in 2040 is produced through electrolysis. To capture the development of other hydrogen production methodologies, it is assumed in this assessment that 1% of hydrogen supplied (95kt H_2 per year) is produced by biomass gasification or reformation and that 4% of hydrogen supplied (380kt H_2 per year) is produced through natural gas reforming or coal gasification with CCS. The remaining 95% of supplied hydrogen is produced by electrolysis.
- It is assumed that new biomass processing generation capacity will be developed in similar areas throughout Australia as currently announced biomass processing facilities due to access to feedstock.
- It is assumed that fossil fuel processing capacity will be allocated throughout Australia based on the production of feedstock (natural gas and coal seam gas).
- It is assumed that hydrogen is exported in the form of liquefied H_2 (20%) and ammonia (80%), based on current trends.

3.4 Hydrogen production and global context

Australia's forecast production (9.5MMT H_2 per year in 2040) sits within the global production capacity for hydrogen, which is forecast to increase dramatically as part of the renewable energy transition. The global production capacity for hydrogen in 2022 was assessed to be 65-100MMT H_2[5], though none of this production is green hydrogen. In order to be a viable component of the future supply system, the global production of hydrogen must be redeveloped to focus on production methods that meet sustainability goals. Current installations of electrolysers globally are at the pilot stage, but announced projects at various stages of development are forecast to increase global capacity significantly in the next ten years.

5 https://www.energy.gov/eere/fuelcells/water-electrolyzers-and-fuel-cells-supply-chain-deep-dive-assessment

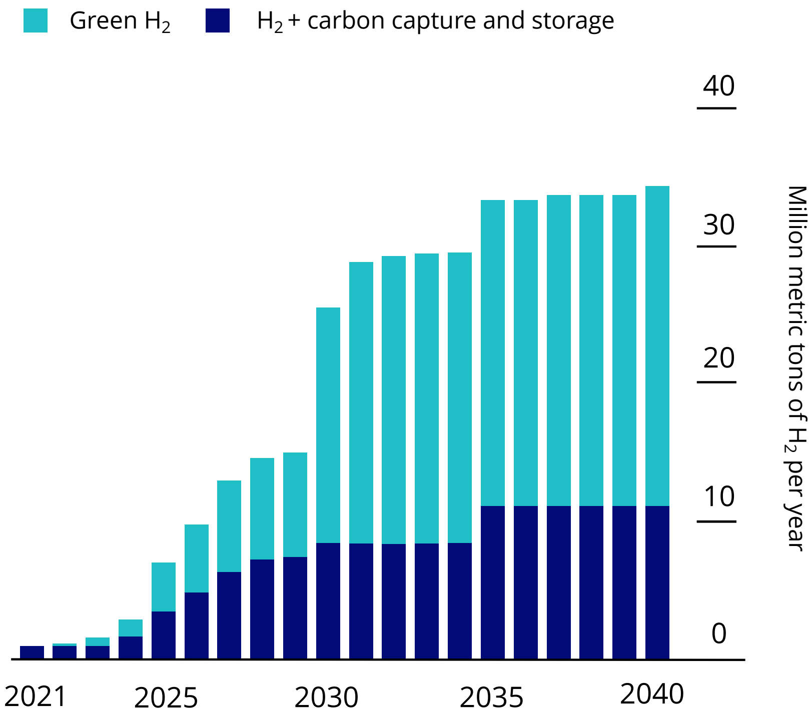


Figure 2 Global cumulative clean hydrogen supply pipeline[6]

Figure 2 shows the current global outlook for clean hydrogen production capacity based on currently announced projects, with an additional 9.7MMT H_2 per year associated with projects that have been announced without a forecast commissioning date. Although current clean hydrogen production is limited in scale, the prevailing method is through steam methane reforming (SMR) with carbon capture and storage (CCS). However, the landscape is rapidly evolving, and it is projected that by 2030, around half of global clean hydrogen production will be via electrolysis. This share is set to increase significantly in the following years, with electrolysis predicted to become the leading method of hydrogen production.

Within this forecast, projects producing approximately 4.7MMT H_2 per year have been announced within Australia, representing 49% of the production capacity needed as per the NHIA. The additional capacity to meet the requirement must be developed through new or expanded projects.

The IEA, as part of its Announced Pledges Scenario (APS)[7], forecasts that global demand for clean hydrogen will reach 130MMT per year by 2030. Bloomberg New Energy Finance (BNEF) notes that to reach net zero by 2050 as part of its 'Green Scenario', global hydrogen production must reach 800MMT per year by 2040, which may indicate that additional demand over the 9.5MMT H_2 per year for Australia may be required. There is an opportunity for Australia to assist in meeting this significant global demand both directly, through increased production, consumption and export of hydrogen, and indirectly, through contribution to the equipment, technology and services that are essential to facilitate the development and supply of this capacity.

6 BNEF 'Race to Net Zero: The Hope and Hype of Hydrogen in Five Charts', *(https://link.bnef.com/view/631029590548a6ab730328eahd9da.abu/21333b1e)*

7 IEA 'Global Hydrogen Review 2022', *(https://iea.blob.core.windows.net/assets/c5bc75b1-9e4d-460d-9056-6e8e626a11c4/GlobalHydrogenReview2022.pdf)*

3.5 Key supply chain risks

As the hydrogen industry rapidly expands, all elements of the supply chain must be developed simultaneously to meet demands and facilitate the use of the resource. However, the precise nature of the development of the hydrogen industry is uncertain. This includes points of production, location of demands and the storage and distribution between these points. Given this uncertainty, high-level risks and constraints may be identified throughout the supply chain to guide government or market intervention. Failure to address risks may result in bottlenecks or imbalances throughout the supply chain, wastage of generated value and the failure to meet emissions reduction goals.

Examples of risks that may impact the development of the supply chain are:

- **Technological risk** – technology and infrastructure are required that are yet to be developed or remain immature or uncommercialised.
- **Material or component risk** – equipment is reliant on large amounts of uncommon materials or components, or materials or components that are needed at large scale in other applications.
- **Skills risk** – skills necessary to plan, develop, and operate infrastructure are not well-developed or widespread.
- **Concentration risk** – suppliers of equipment, components or skills are concentrated and not diverse.
- **Spatial risk** – applications need significant space to be enacted at scale. Land constraints and/or availability may limit the ability of these to be situated at strategic locations within supply chains or areas of high demand.

3.6 Supply chain framework

The framework for the supply chain is summarised in Figure 3. The supply chain (including feedstock, production, storage, distribution, carrier conversion, enabling technology and demand) is supported by specific development and operation functions (project and infrastructure development, installation and commissioning, operations, and maintenance) as well as broader enabling functions within Australia's economy. While this report will discuss the elements of the supply chain individually, the functioning of the hydrogen system by which demands are met by production is reliant on the operation of the system as a whole. Therefore, all elements of supply and development are critical to enabling the realisation of the opportunities presented by the hydrogen economy.

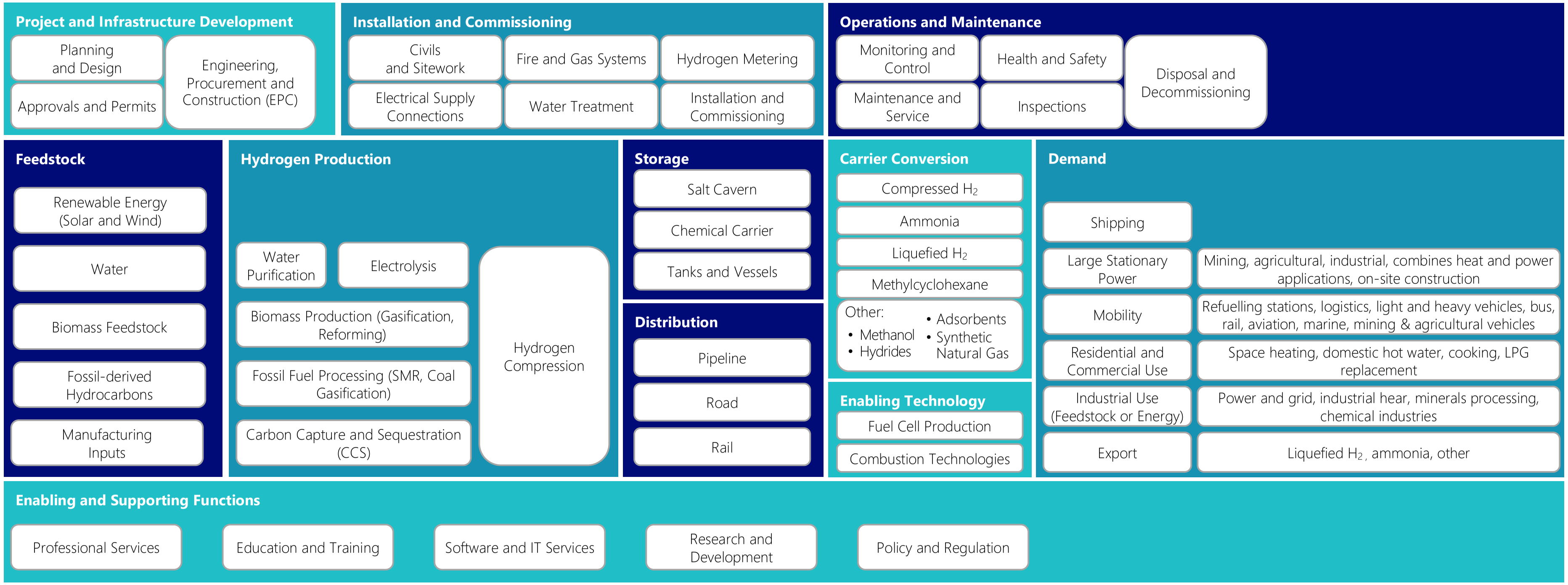


Figure 3 Supply chain framework

3.6.1 Material flow assessment

Based on the NHIA Central Demand Scenario, the flows shown in Figure 4 are anticipated for the H_2 supply chain in 2040.

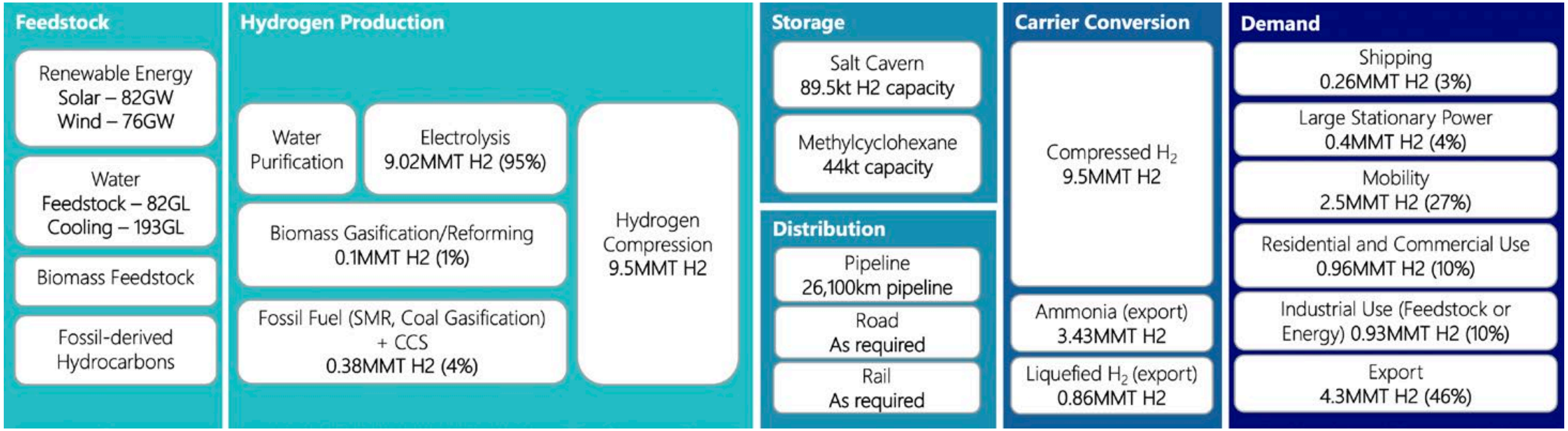


Figure 4 Material flows

3.7 Feedstock

3.7.1 Renewable energy

Solar

A significant number of hydrogen electrolyser projects will be powered by solar energy generation (52% of electrolyser demand as per the NHIA), with infrastructure installed on-site and 'behind the meter' to minimise the transmission infrastructure needed. The static capacity requirement will vary for each project, depending on the generation efficiency of assets and whether battery or other storage is included in the design. Based on the NHIA modelling, 82.31GW of solar power generation is needed for the production of hydrogen to meet demand in 2040, over and above other solar generation developed to meet other electricity needs throughout Australia. For context, Australia's generation in 2020-21 is 18GW (11GW household solar and 7GW in large-scale solar farms[8]). The development of solar assets to meet hydrogen demand as well as grid demand will necessitate an aggressive acceleration of installation and operation.

Significant equipment and logistics activity are essential to enable the development of the needed solar generation capacity. Modelling based on moderate-scale solar generation projects indicates infrastructure requirements will be approximate as listed below:

- Over 246M solar panels installed in over 2,700km^2 of land (an area greater than the size of the Australian Capital Territory).
- Over 12,800 control units (including PCU, control cabins and inverters).
- Over 270,000km of cabling.

The development is equivalent to 329 very large (250MW) solar farms. Figure 5 outlines the distributed modelled solar energy generation in each state and region.

Onshore wind

Electrolysers not powered by solar energy will utilise wind power, which will most commonly be constructed on-site and supply 'behind the meter'. The NHIA model suggests that approximately 76GW of wind generation capacity will be constructed to power hydrogen production – compared to 16GW of generation capacity online at the end of 2018[9]. Similar to solar, this level of development requires an acceleration of installations alongside those needed to meet the nation's increasing renewable electricity needs.

Based on a reference 3.3MW wind turbine generator (WTG), to meet the demand requires the installation of 22,927 WTGs. This development will generate a significant level of logistics activity, with just over 343,000 road and rail inputs necessary to facilitate the installations across Australia.

The capacity and distribution of solar and wind installations needed for hydrogen production by 2040 are shown in Figure 5.

8 ARENA. https://arena.gov.au/

9 ARENA. https://arena.gov.au/

Figure 5 Solar and wind installations needed by 2040 for hydrogen production

3.7.2 Water

Water is the chemical feedstock for hydrogen electrolysis. The NHIA model assumes a production methodology that requires 9L of water per kilogram of hydrogen as feedstock (82GL per year to meet the forecast production).

In addition to the water for feedstock, water is required to supply the cooling equipment that forms part of the electrolysis applications. Approximately 21L of water per kilogram of hydrogen is needed for this purpose (193GL per year). This water needs to be treated but not purified to the same standard as feedstock water.

3.7.3 Other feedstock (biomass and fossil-derived hydrocarbons)

While it is anticipated that, based on cost and environmental considerations, the development of hydrogen production to meet demand will be done in the form of electrolysis, other hydrogen production techniques are expected to be developed (blue and green hydrogen) to take advantage of available feedstock throughout Australia. These techniques include:

- Natural gas reforming.
- Coal gasification.
- Biomass gasification.
- Biomass anaerobic digestion.

The production may incorporate CCS to meet environmental requirements.

It is assumed that the use of these techniques will be to take advantage of available feedstock generated as an output of another process or operation, and therefore there is not anticipated to be any development of feedstock generation associated with these hydrogen production techniques. In particular, natural gas reforming and coal gasification are anticipated to be developed close to feedstock production throughout Australia, largely in Western Australia and Queensland, respectively.

3.8 Hydrogen production

3.8.1 Water purification

Water must be purified to a high level prior to electrolysis, meaning proximity to good quality raw water creates a more economically viable electrolysis plant. Proton exchange membrane (PEM) electrolysers require very pure deionised water, such as the standard of American Society for Testing and Materials (ASTM) Type II[10], and it is anticipated that feedstock water for electrolysis will typically be purified on-site at the electrolysis plant. Currently, purification units can typically generate 1,000m^3 per day of water to the required specification. The scope and scale of equipment needed will depend on the distribution of electrolysers and their capacity.

3.8.2 Electrolysis

The majority of hydrogen production in the system is anticipated to be done through electrolysis (the separation of hydrogen from water through the application of direct current), most commonly alkaline and PEM type, accounting for 9.02MMT H_2 (95% of total production) in 2040. Approximately 51GW of electrolyser capacity must be developed in Australia to meet this demand, including the manufacturing of the electrolysis units and their installation and operation. The IEA estimated that the global installed capacity of electrolysers would reach 1GW by the end of 2022[11], with accelerated global deployment to meet global demand anticipated over the next ten years.

The NHIA assessed the distribution of electrolyser capacity throughout Australia by considering the proximity to:

- Available renewable energy generation, typically within renewable energy zones throughout Australia.
- Locations of demand.

Based on this assessment, the projected spread of electrolyser generation throughout Australia in 2040 is shown in Figure 6. The scale of electrolyser installations is expected to increase dramatically by 2040 – the capacity per large plant (currently modelled at 100MW) is envisioned to increase to GW scale in the next decade. Regardless of the scale of plants installed, the generation of this volume of hydrogen involves a significant level of project activity to reach the required capacity – using the currently envisioned 'large plant' (100MW) as an average installation size (to take into account both current plant size under construction and future expansion past this capacity), just over 500 operating electrolysis plants must be constructed and operated across the 36 areas considered in the model.

10 Daniel Symes, Bushra Al-Duri, Aman Dhir, Waldemar Bujalski, Ben Green, Alex Shields, Matt Lees (2012). Design for On-Site Hydrogen Production for Hydrogen Fuel Cell Vehicle Refueling Station at University of Birmingham, U.K. https://doi.org/10.1016/j.egypro.2012.09.070

11 https://www.iea.org/reports/electrolysers

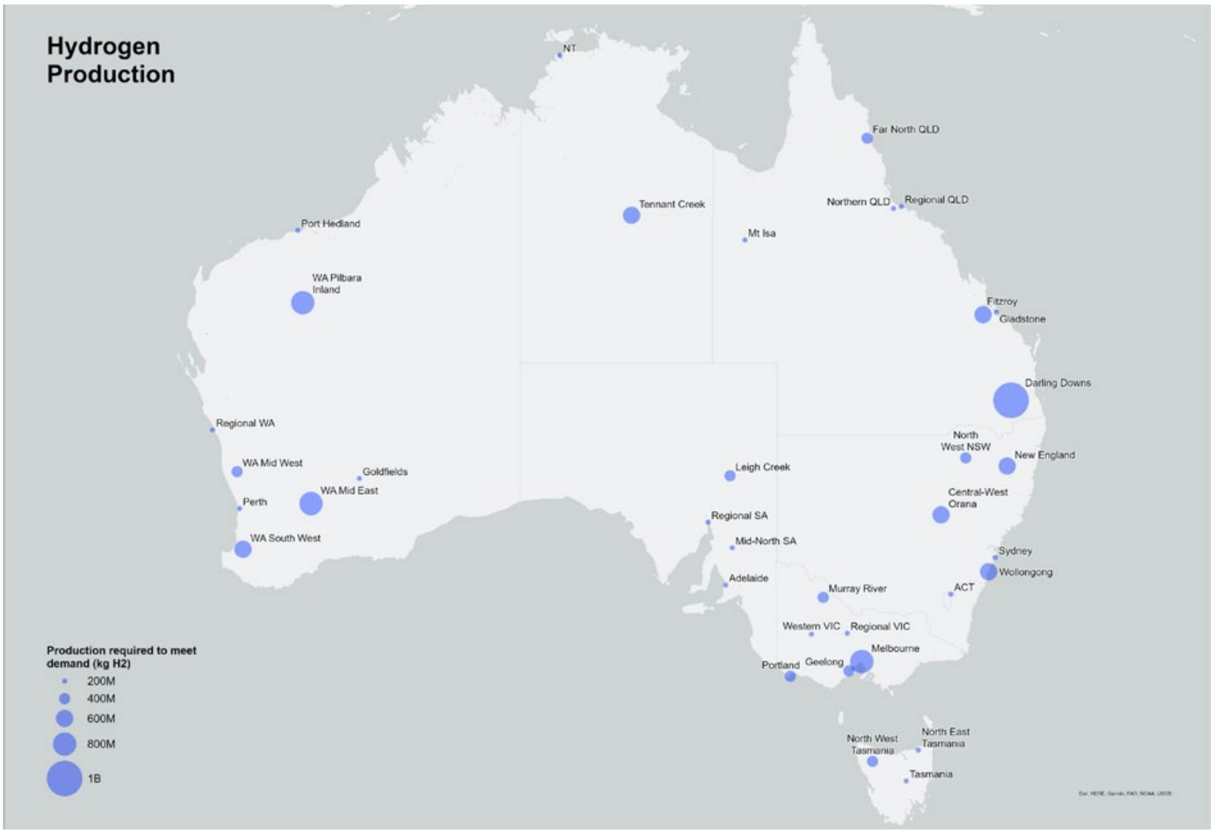


Figure 6 Map of regional production required to meet demand

To support the development of the generation capacity required, all elements of the development life cycle for electrolysers must function across the material and human domains of the supply chain. A breakdown of key elements (pre-installation, installation, and operation) in the development life cycle for electrolysers is shown in Figure 7, incorporating the key supply chain elements and capabilities needed for delivery of the projects[12]. Given the geographic dependence of the installation element, the supply chain elements adjacent to this step (being pre-installation, operation and disposal) must also be done in Australia. The more distant stages (including the extracting and processing of raw materials or the manufacture of sub-components and components) may provide opportunities for Australia or rely on imports.

Figure 7 Electrolyser supply chain elements

12 https://www.publications.qld.gov.au/dataset/hydrogen-industry-workforce-development-roadmap-2022-2032/resource/5fffcbcc-7605-46ed-86b4-2c2a91e7acad

The components that comprise the electrolyser plant, incorporating fluid systems and electrical equipment that facilitate the operation of the electrolyser module, are shown in Figure 8.

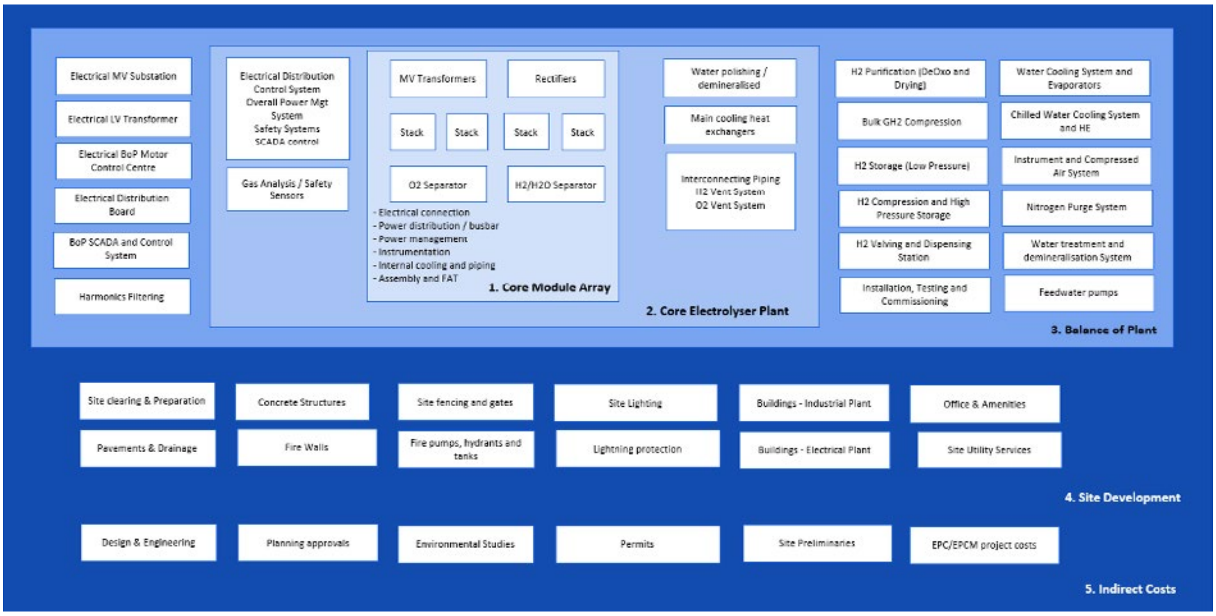


Figure 8 Electrolyser plant components[13]

The critical element of the development is electrolyser modules – these are manufactured off-site and installed at the project location in a modular fashion to achieve the required site capacity. The manufacture of the units is subject to its own supply chain constraints – per the IEA, global electrolyser manufacturing capacity reached 8GW per year in 2021 and could increase to 65GW by 2030[14]. There may be an opportunity for Australia to manufacture electrolysers for local and global use, but it will compete on the global market to supply the electrolysers needed.

The US Department of Energy outlined the breakdown of PEM electrolyser components to their raw elements, as shown in Figure 9[15]. Opportunities to extract, process and manufacture the required materials as part of the supply chain may be investigated by the Australian market. The reliable and cost-effective supply of raw materials and subcomponents is critical to enabling the significant electrolyser development needed to meet demand.

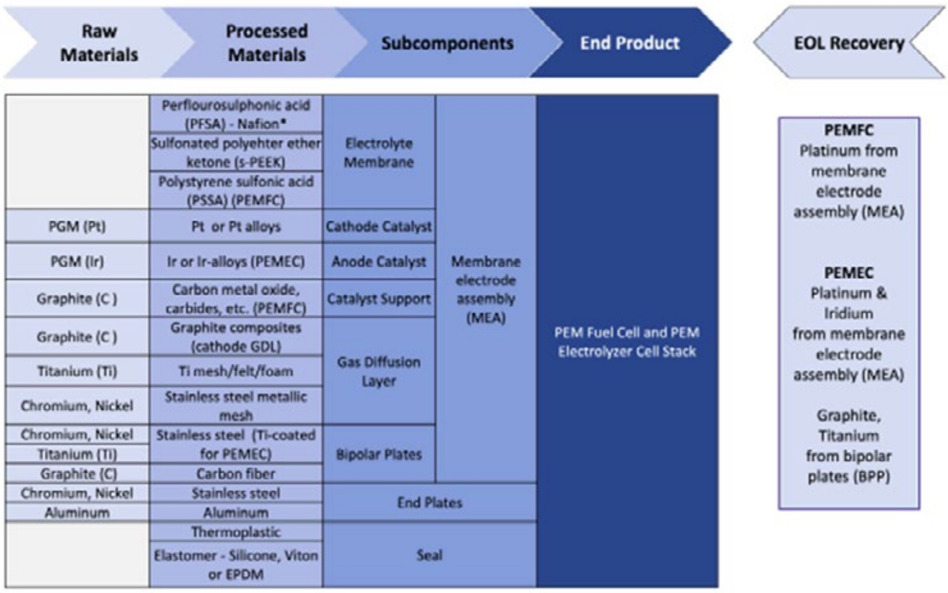


Figure 9 PEM electrolyser components

13 Developed from previous Arup project

14 https://iea.blob.core.windows.net/assets/c5bc75b1-9e4d-460d-9056-6e8e626a11c4/GlobalHydrogenReview2022.pdf

15 https://www.energy.gov/eere/fuelcells/water-electrolyzers-and-fuel-cells-supply-chain-deep-dive-assessment

Due to the significant expansion of electrolyser capacity required, alongside the related expansion of other renewable energy technologies to meet emissions reduction obligations, there is a risk of shortage or undersupply of critical materials to facilitate electrolyser manufacture globally. In particular, the supply of Platinum Group Metal (PGM) catalysts presents a risk to the rapid deployment of electrolysers due to their relative scarcity and competition for use – the US Department of Energy has noted that iridium (a component of PEM electrolysers) is at significant risk of shortage[16]. Australia is home to natural deposits of iridium and other PGM[17], which may present an opportunity to increase resource recovery as demand grows.

Shortage and undersupply of components can slow and discourage the deployment of electrolysis and increase system costs. Processes and systems to enable the recycling of rare and critical components at the end of product life are critical for ongoing manufacturing to meet demand. Additionally, resources and supply chains to supply materials for all plant components, including stainless steel, electrical componentry and fluid systems, must be secured.

While the technology that underpins electrolysis is well-developed and understood, the widespread and commercialised use of the technology is still emerging. The US Department of Energy notes the following research focus areas[18], which may impact the ongoing cost and viability of electrolysis units during the period considered by this report:

- Developing an improved understanding of performance, cost and durability trade-offs of electrolyser systems under predicted future dynamic operating modes using renewable energy.
- Reducing the capital cost of the electrolyser unit and the balance of the system.
- Improving energy efficiency for converting electricity to hydrogen over a wide range of operating conditions.
- Increasing understanding of electrolyser cell and stack degradation processes and developing mitigation strategies to increase operational life.

There will be opportunities for Australian researchers and manufacturers to contribute to the exploration and development of these research areas as the capacity and network expands. The potential for other emerging electrolyser technologies to be implemented may lead to alternative requirements for raw materials or components to enable the production of green hydrogen.

3.8.3 Biomass production

Bioenergy currently provides 47% of Australia's renewable energy production and approximately 3% of Australia's total energy consumption, with the potential to provide up to 20%[19]. Biofuels from non-food resources will play a key role in decarbonising hard-to-abate sectors. Direct combustion of biomass for industrial heating is well-established. Global demand for biomass pellets, currently at 20MMT per annum (320PJ per year), is experiencing sustained growth. Biomethane for gas grid injection is helping drive regulatory reform that complements future hydrogen blending. Biofuels for jets is one of the few options to reduce emissions in aviation in the short to medium term. Road transport biofuels are set to complement hydrogen-electric and battery-electric vehicles, in particular in long-haul transport. The production of hydrogen from biomass is another mechanism by which biomass can contribute to the future energy makeup.

Biomass-derived hydrogen is estimated to be 1% of production (~95kt H_2 per year) and will not form a significant component of the production mix to meet the demand volumes in 2040.

Hydrogen is most commonly produced from biomass via gasification or anaerobic digestion, creating a net-zero emission fuel or feedstock. Gasification involves the heating of biomass waste feedstock in an oxygen-depleted chamber to produce syngas, from which hydrogen can be extracted. Anaerobic digestion involves the breakdown of biomass by microorganisms in the absence of air. The process primarily produces methane (biogas), which is then reformed to produce hydrogen. Carbon capture via the co-production of hydrogen plus biochar during gasification, or hydrogen plus graphite in the Hazer process[20], can offer additional environmental and economic benefits.

16 US DoE 'Platinum Group Metal Catalysts – Supply Chain Deep Dive Assessment' (https://www.energy.gov/sites/default/files/2022-02/PGM%20catalyst%20supply%20chain%20report%20-%20final%20draft%202.25.22.pdf)

17 https://www.mindat.org/min-2045.html

18 https://www.energy.gov/eere/fuelcells/hydrogen-production-electrolysis

19 https://arena.gov.au/knowledge-bank/australias-bioenergy-roadmap-report/

20 https://arena.gov.au/projects/the-hazer-process-commercial-demonstration-plant/

In Australia, there are currently five major projects planned or announced utilising biomass to produce hydrogen totalling 6,765t of H_2 per year[21]. Further capacity will be based on opportunistic development to take advantage of feedstock generated by other industries (commonly residues or by-products from agriculture, forestry, or pulp and paper) and is not expected to significantly grow market share in hydrogen production as electrolyser production ramps up. While biomass may be an abundant domestic resource, this pathway will compete for feedstock with other biomass-consuming processes (including biofuels) and relies on continued technological advances to establish feasibility in the medium to long term, as per the US Office of Energy Efficiency & Renewable Energy (EERE)[22].

3.8.4 Fossil fuel processing with Carbon Capture and Storage

The reformation of natural gas or gasification is commonly used globally as a method to produce hydrogen from fossil fuel feedstock. Whilst the processes, including a number of sub-typologies, produce carbon emissions (grey hydrogen), they may be made zero-emission through the use of CCS.

Based on global trends, steam methane reforming may be taken as the most common example of this type of hydrogen production. At a high level, the process involves the following[23]:

- Reforming (conversion of natural gas to syngas).
- Water-gas shift reaction, to produce carbon dioxide and hydrogen.
- Removal of carbon dioxide using solvent absorption and storage.
- Purification and compression of hydrogen.

Several projects are currently at feasibility or in the planning stages in Australia[24], with a total potential capacity of 43,300t of H_2 per year. While NHIA modelling indicates that new and emerging demand will prefer electrolyser-produced hydrogen due to costs and sustainability drivers, it is possible that the availability of feedstock may lead to some additional development – on this basis, for the purpose of this assessment, it has been estimated that up to 4% (~380kt H_2 per year) of production may be through this mechanism.

Any process for hydrogen production that involves the generation of emissions must be paired with CCS to be viable in the energy system of the future. CCS can also be used in conjunction with industries that are difficult to decarbonise, older power plants, or processes that produce a lot of carbon and heat to reduce emissions. The technology for capturing carbon on a large scale is already established and uses readily available materials.

Currently, the US Department of Energy anticipates that the most common CCS application will be based on the following process[25]:

- Solvent-based capture with monoethanolamine (MEA) as the solvent.
- Carbon dioxide drying using triethylene glycol (TEG).
- Transportation via steel pipeline.
- Geological storage of carbon.

A wide variety of other chemical processes, utilising other solvents, membranes, sorbents, or cryogenic systems, are in various stages of development[26], which may deliver resilience to the system. Emissions from blue hydrogen production may not be a significant contributor to the demand for CCS in Australia, meaning that the ongoing development and viability will be driven by other factors.

Based on the estimated production of blue hydrogen in 2040, and assuming a 90% CO_2 capture rate (meaning that 8.9kg of CO_2 must be stored to produce 1kg of H_2, with 1kg of CO_2 lost to the atmosphere)[27], blue hydrogen generation will result in the storage of 3.4 MMT of CO_2.

21 https://www.bnef.com/

22 https://www.energy.gov/eere/fuelcells/hydrogen-production-microbial-biomass-conversion

23 https://www.energy.gov/eere/fuelcells/hydrogen-production-natural-gas-reforming

24 BNEF. https://www.bnef.com/

25 https://www.energy.gov/fecm/carbon-capture-transport-and-storage-supply-chain-review-deep-dive-assessment

26 https://www.ipcc.ch/report/carbon-dioxide-capture-and-storage/

27 IEA, February 2017, 'IEAGHG Technical Report 2017-02, Techno-Economic Evaluation of SMR Based Standalone (Merchant) Hydrogen Plant with CCS' *(https://ieaghg.org/exco_docs/2017-02.pdf)*

3.8.5 Compression

The compression of hydrogen streams will occur at many points throughout the supply chain, and throughout its journey to consumption, including:

- Following production.
- Prior to storage or transport to meet vessel requirements.
- Prior to any conversion or consumption process to meet process requirements.

The specification of compressors throughout the supply chain will be widely varied and bespoke to each individual application, relating to:

- Compressor throughput.
- Compression ratio, based on input and output pressure requirements.
- Compressor type (reciprocating, rotary, centrifugal or ionic) based on the above.

Due to the extreme variation in compressor size, throughput, and distribution throughout the supply chain, it is difficult to accurately estimate the number of compressors needed, with designers and operators at each location of requirement responsible for specifying and procuring units to suit their individual purpose.

Compressor units are based on well-established technology in compressing process gas, albeit manufactured with very fine tolerances to prevent gas leakage (a particular issue for rotary compressors). They are manufactured based on common and well-established materials, components and systems, meaning that there is relatively low risk to their supply. Large-scale compressors can process 76,000t H_2 per annum (30-350 bar) alongside medium-scale compressors (30-100 bar).

A minimum of 143 large-scale compressors operating at the point of generation are needed within the system to facilitate the required production based on throughput, depending on the configuration of the generation infrastructure. Assuming a standard level of compression for each large-scale compressor, this processing step will draw 15,101 GWh of power (1.59kWh per kg H_2) or approximately an additional 3% of the power necessary to generate the equivalent quantity of hydrogen by electrolysis. Additional equipment and power needed to facilitate the medium-scale compression throughout the system will be dependent on application and compression ratio requirements.

The operation of compressors is augmented by the supply of enabling components (control systems and valves, safety systems, vessels, etc.) and by the supply of power to undertake the compression itself. This power must be considered in excess of the power required for electrolysis feedstock and may necessitate additional installed capacity on-site (at electrolysis and other production steps) or in the grid (for distributed compressors at the point of storage or consumption).

3.9 Storage

3.9.1 Salt cavern storage

The requirement for storage is ubiquitous throughout the supply chain, with most points of production, processing or transport requiring some level of storage for buffer or input and output stabilisation purposes. On-site storage will be done in tanks and vessels specified for their specific requirement (in terms of capacity, throughput, temperature and pressure), with the supply of this equipment forming part of the development of infrastructure at these locations.

Larger, long-term storage is also needed to balance production and demand of hydrogen across the network. NHIA modelling shows that salt cavern storage is the preferred option, with an estimated capacity of 89.5kt needed. It is anticipated that approximately 750,000t of H_2 per year will be stored throughout the network. Other options for underground hydrogen storage (depleted hydrocarbon reservoirs, aquifers or other engineered caverns) may also form a component of the storage network in cases where opportunities present.

Storage in salt caverns may be done in natural formations or in constructed salt cavern infrastructure. The current mapped capacity of Australia's potential for hydrogen salt storage in natural deposits is approximately 310 million tonnes[28]. The viability of these natural geological deposits for use will depend on their location and proximity to production and demand hubs, with developed infrastructure expected to fill gaps in the network. Naturally occurring underground caverns for salt storage are located at the Canning Basin in Western Australia, the Adavale Basin in Queensland and the Amadeus Basin in the Northern Territory, amongst other locations[29]. Refer to Figure 10 for a map of salt deposits across Australia, which suggests that most requirements for storage on Australia's East Coast must be met by constructed storage.

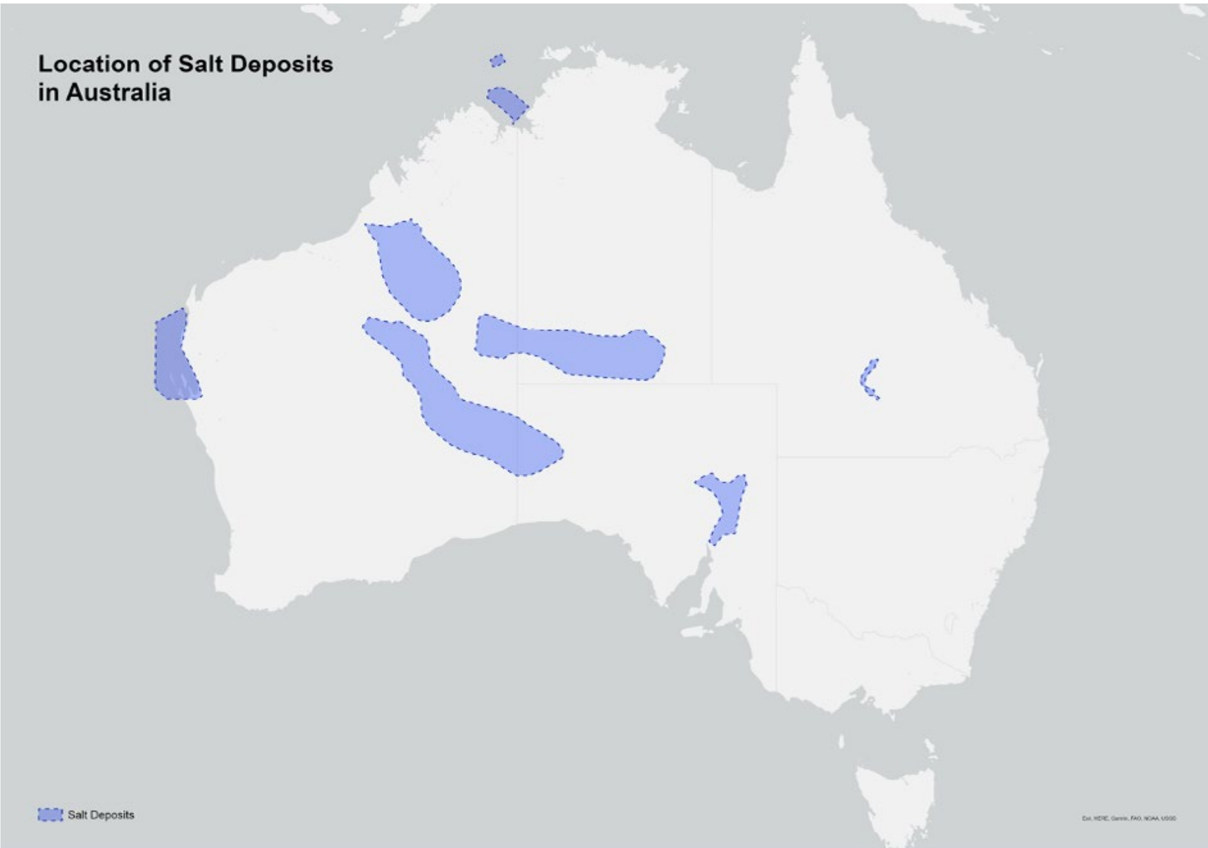


Figure 10 Location of salt deposits in Australia

28 https://www.futurefuelscrc.com/project/underground-storage-of-hydrogen-mapping-out-the-options-for-australia-rp1-1-04/

29 https://www.ga.gov.au/news-events/news/latest-news/salt-caverns-and-minerals-across-australia-unlock-our-nations-hydrogen-industry

The development of constructed salt cavern infrastructure is dependent on specialised design and engineering consultancy services. In particular, design services to develop infrastructure to handle the operating pressure cycle and develop a detailed understanding of geological formation are critical disciplines. The ongoing development of these skills in Australia will be necessary to facilitate the level of storage required at the right place throughout the supply chain.

The supply and maintenance of components needed to enable the operation of salt caverns will be of critical importance to their viability. These include:

- Heaters and coolers.
- Compressors.
- Electrical components.
- Industrial chemicals.
- Pipes and process fluid vessels.
- Control systems and monitoring.
- Facilitating infrastructure (buildings, roads, civil works, other).

Figure 11 outlines the life cycle elements and capabilities required for the development of storage within salt caverns.

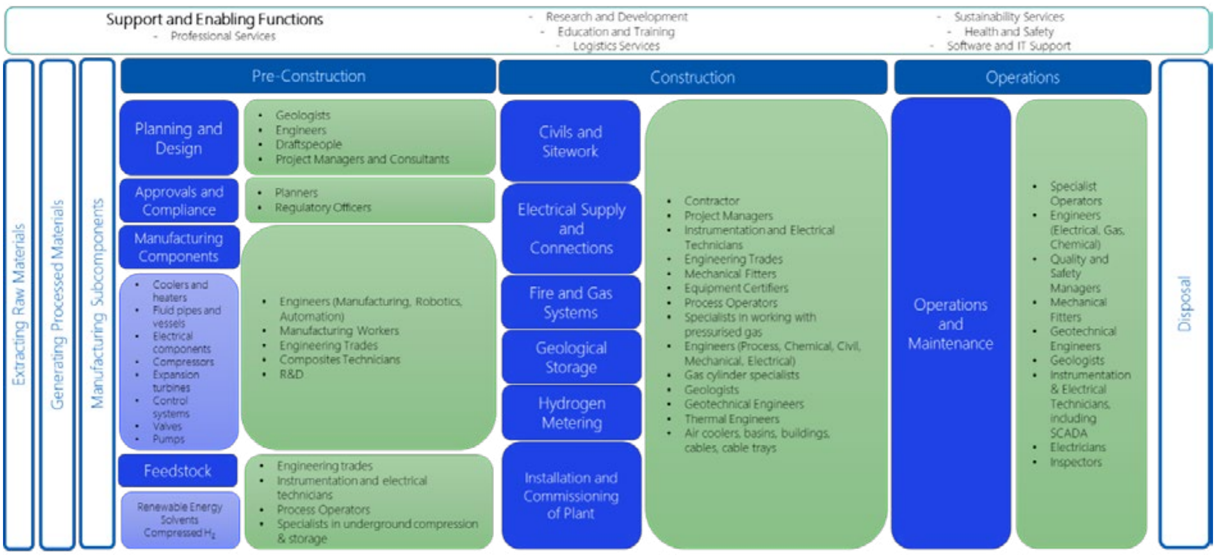


Figure 11 Salt cavern supply chain elements

3.9.2 Carrier conversion

The potential for hydrogen to be converted to an alternative carrier for the purpose of storage is discussed in section 3.11. This methodology is typically preferred where the inventory of hydrogen is not of a scale to dictate a constructed long-term store and provides some flexibility in that the carrier may be moved prior to reconversion to hydrogen gas.

3.10 Distribution

3.10.1 Pipelines

The NHIA model indicates that in the absence of significant constraints or specific demand, the majority of hydrogen will be moved domestically as compressed hydrogen rather than as liquefied or as an alternative hydrogen carrier.

Pipelines represent the quickest method of moving large quantities of hydrogen long distances but incur high construction costs. High volumes of stable hydrogen are necessary to make long-distance pipelines commercially viable. As indicated by the outcome of the NHIA modelling, pipelines are well suited to hydrogen transport, for transporting from points of high-volume production (the zones modelled) to points of large, stable demand (for example, export or stationary fuel cell) or to the centroid of intermittent demand for off-take to road or rail transport (for mobility or commercial applications).

The NHIA modelled the development of 26,146km (straight line) to facilitate hydrogen delivery to locations of demand. Pipeline installation is an established industry, and there may be an opportunity to consider the use of repurposing established pipelines in the future if challenges associated with access and operation (including hydrogen embrittlement corrosion) can be met. The existing gas pipeline network in Australia, shown in Figure 12, is extensive, with opportunities to either blend hydrogen with natural gas or repurpose pipeline infrastructure to take clean hydrogen streams, potentially presenting themselves throughout the evolution of the industry. The use of existing infrastructure may significantly reduce the raw material and development requirements for pipeline transport, although noting that a level of modification to the pipeline is essential to transport blended or pure hydrogen[30].

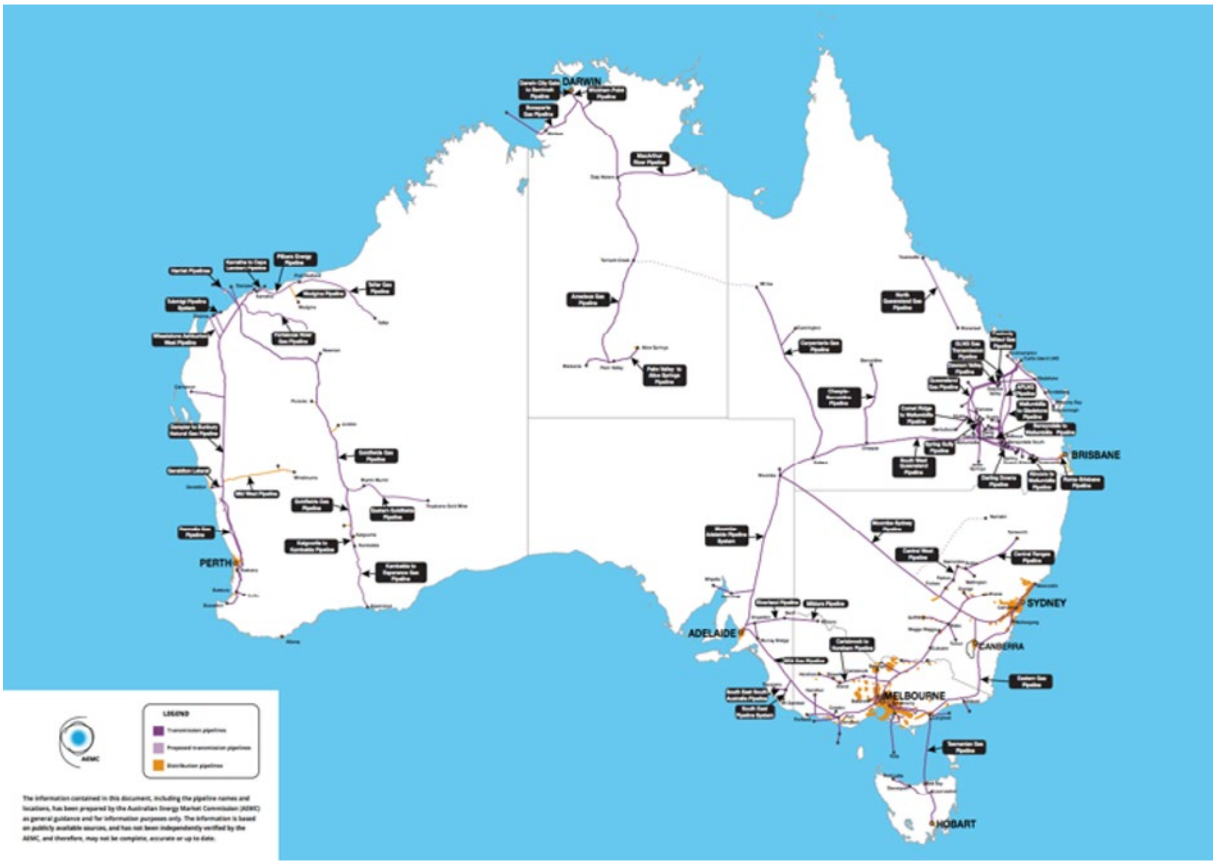


Figure 12 Location of gas pipelines in Australia[31]

30 Melaina, M W, Antonia, O, & Penev, M. Blending Hydrogen into Natural Gas Pipeline Networks: A Review of Key Issues. United States. https://doi.org/10.2172/1068610

31 https://www.aemc.gov.au/energy-system/gas/gas-pipeline-register

Pipeline construction permitting and approvals (particularly environmental) are of critical importance to assessing the viability of individual projects.

Despite the established industry, innovation in pipeline construction may influence the development required to support the hydrogen supply chain. For example, Perth-based organisation 'Long Pipes' is developing continuous, high-pressure composite pipes that are installed in large modules using an innovative installation mechanism for rapid deployment[32]. Efficient deployment of transport infrastructure will reduce the cost to serve demand, which may hasten the uptake of hydrogen through its impact on price.

In addition to the pipes themselves, the other materials necessary to construct and operate pipelines (including associated compression, cabling, control systems and valves, filters, fittings and supports) must be supplied by local manufacturers or imported. Services to construct, operate and maintain the pipelines may be transferred across from existing industry capability associated with the current pipeline network. An overview of the development life cycle for pipelines is shown in Figure 13.

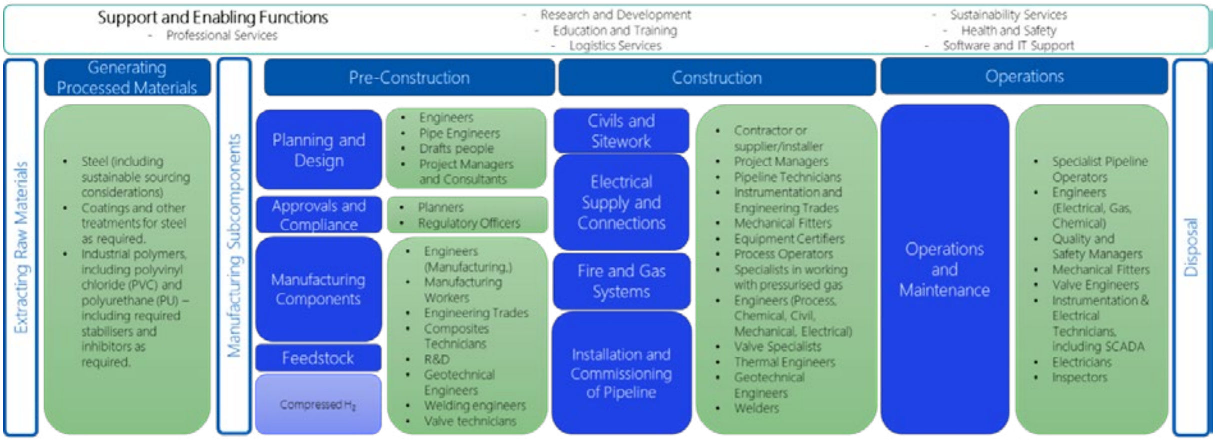


Figure 13 Pipeline supply chain elements

3.10.2 Road and rail transport

Road and rail transport of hydrogen will be used where smaller or intermittent hydrogen is required. For road transport, this may be from the point of production or point of offtake from the pipeline to a distributed demand point (i.e., refuelling stations). For rail transport, a scale of demand that is too small or sporadic to justify pipelines or as an interim solution during pipeline construction will be key drivers. For rail, the location of supply and delivery points near railways are more of a driver than transport distance.

Tube trailers are used to transport compressed hydrogen with a capacity of 300kg of H_2 compressed to 180 bar (200 bar dispensing pressure) at ambient temperature. Alternative vehicles exist to transport hydrogen stored as liquid hydrogen or ammonia, but neither medium is preferred by the NHIA model for domestic transport. 32,000km of rail network movement may be used for hydrogen, with a capacity limitation of 15 MT per annum.

The need for road and rail vehicles for transit will be tied to the uptake of demand in applications that lend themselves to the transit type (mobility, small-scale industrial and agricultural). The supply of vehicles and enabling equipment (compressors, process instruments, valves, tanks, vessels and hydrogen loading infrastructure) will depend on the level of requirement.

Based on the potential use case for road vehicles outlined above (demands for mobility, residential, commercial and industrial uses being moved by road a short distance from offtake to distribution by 300kg tube trailer making two deliveries per day), the fleet of truck/trailers needed would be approximately 20,000 – 25,000 vehicles. Some vehicles currently used to move petroleum or other liquid or gaseous fuels may be repurposed to deliver hydrogen. For context, in 2021, the size of the Australian truck fleet that may be repurposed to suit hydrogen was approximately 365,000 heavy rigid vehicles and 110,000 articulated vehicles[33], meaning that partial repurposing and refurbishment may be sufficient to meet demands.

32 https://www.austrade.gov.au/news/success-stories/australian-pipe-innovator-set-to-transform-hydrogen-supply-networks

33 Australian Bureau of Statistics (31 January 2021), Motor Vehicle Census, Australia, ABS Website, accessed 14 November 2022.

3.11 Carrier conversion

Throughout the supply chain, hydrogen may be converted to alternative substances (carriers) for consumption, storage, or to facilitate transport domestically or internationally. Potential carriers for hydrogen include:

- Ammonia
- Methylcyclohexane (MCH)
- Methanol
- Hydrides
- Adsorbents
- Synthetic Natural Gas
- Liquefied H_2

Based on current and anticipated practices for international trade, it is expected that all exported hydrogen will be converted into ammonia (80%) or liquefied hydrogen (20%). These processes are discussed in Section 3.13.1.

Several carrier options may be referred to as Liquid Organic Hydrogen Carriers (LOHCs), which function in the supply chain similarly to currently more common liquid fuels. The operation of LOHCs involves loading a carrier molecule with hydrogen, transporting it as a liquid and extracting pure hydrogen at the point of consumption. The potential advantage of LOHCs (transporting as a liquid without the need for compression or cooling) must be balanced with the cost of infrastructure for both converting to and from the carrier and the energy requirements of the conversion[34].

The NHIA modelling indicates that the majority of hydrogen (for use as hydrogen) will be domestically transported as compressed H_2, but where LOHCs may be needed, MCH will be the preferred carrier. The model indicates that an inventory of 44kt of MCH is required at peak to facilitate the supply chain, with ~8,000t H_2 per year being converted to and from ~130,000t of MCH over the year. Challenges, including management of the toxic carrier molecule (toluene), must be managed as part of the supply chain development.

The supply of infrastructure to undertake the conversion and reconversion steps of the MCH conversion will be a critical enabler of this element of the supply chain – both steps involve catalytic reactors operating in a continuous process at high heat. Between conversion and reconversion, existing vessels and infrastructure for transporting liquid fuels may be repurposed to undertake transport, including ships, trains, barges and tank trucks.

3.12 Enabling technologies

3.12.1 Fuel cell manufacture

Fuel cells facilitate the efficient consumption of hydrogen to generate electricity. There are many applications and opportunities to manufacture fuel cells in industries including within mobility, residential, commercial and industrial. The use of fuel cells generates energy more efficiently than the direct combustion of the hydrogen gas itself.

Fuel cells operate like 'electrolysers-in-reverse', reacting hydrogen and oxygen to generate electricity with water as a by-product, meaning that there may be opportunities to manufacture fuel cells and electrolyser units as part of similar production processes. A key difference is that while electrolysers are more likely to be produced at a standard size and modularised to meet requirements, fuel cells will be produced at different sizes and configurations to meet specific demand needs, necessitating a slightly different manufacturing approach. Similar to electrolysers, a number of different configurations are possible, with PEM fuel cells currently being the most common.

Fuel cells vary in size from very small (for personal electronic equipment), medium (fuel cell vehicle, bus or heavy vehicle) to very large (stationary power direct to the grid). A fuel cell that is sized to serve a passenger car would output ~120kW[35], with large stationary fuel cells capable of reaching a multi-MW scale.

Due to the similar materials and components of construction, fuel cells are subject to similar risks related to the supply of materials and components, particularly the PGM catalysts inherent in their design[36].

34 https://iea.blob.core.windows.net/assets/9e3a3493-b9a6-4b7d-b499-7ca48e357561/The_Future_of_Hydrogen.pdf

35 https://www.bosch.com/stories/fuel-cell-stack/

36 https://www.energy.gov/eere/fuelcells/water-electrolyzers-and-fuel-cells-supply-chain-deep-dive-assessment

Additionally, fuel cell manufacturing will be subject to the same global competition as electrolysers, with local manufacturing competing with imported equipment for market share.

The level of requirement for manufacturing different fuel cell types will depend on the growth in demand in their specific category, in competition with other applicable methods of decarbonisation. Applications for small and medium-sized fuel cells will be subject to competition from direct electrification or battery-powered alternatives, which will influence the size of the market. Due to the narrow demand profile, the total manufacturing capacity for fuel cells will be significantly smaller than for electrolysers.

3.12.2 Combustion technologies

The direct combustion of hydrogen to generate energy is less efficient than processing through a fuel cell. Combustion may be preferable in some scenarios where the performance and reliability of fuel cells are not yet established (for example, where vehicles are required to operate in extreme heat or in significant vibration). The development of combustion technologies is well established globally, with the opportunity to utilise existing expertise and infrastructure potentially creating an opportunity for this technology to be utilised in the future[37].

3.13 Demand

As modelled through the NHIA, demand for hydrogen is unevenly distributed throughout Australia. The locations and size of demand are concentrated around population centres, key industrial zones, and points of export. Clusters have been established across Australia to develop skills, capability, and commercialisation opportunities in the hydrogen supply chain[38]. The distribution of demand is shown in Figure 14, along with the 17 current hydrogen technology cluster locations established in 2020. The provision of HETS will be instrumental in enabling the hydrogen industry, and it is recommended to provide focussed investment in these hydrogen technology clusters to help develop skilled technology supply chains in regions across Australia.

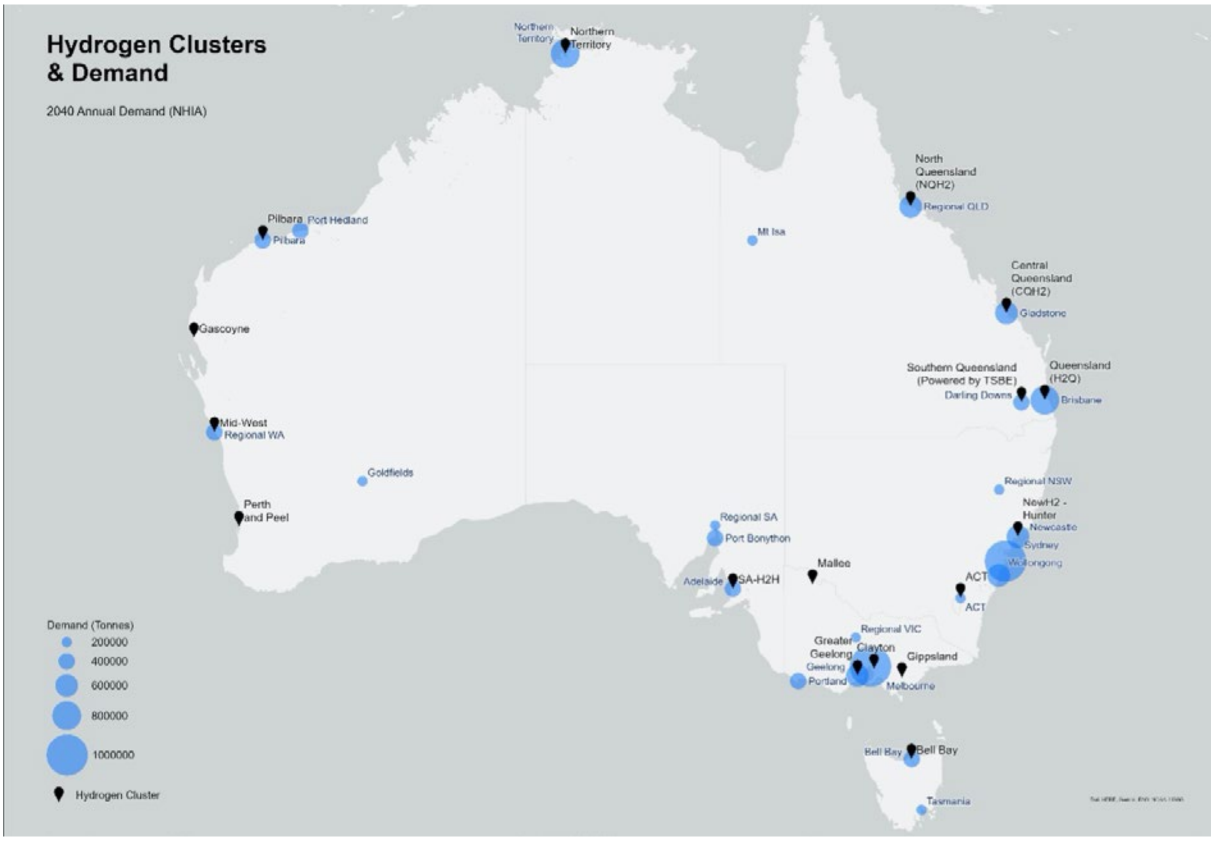


Figure 14 Hydrogen clusters and demand

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37 https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/how-hydrogen-combustion-engines-can-contribute-to-zero-emissions

38 https://www.nera.org.au/regional-hydrogen-technology-clusters

The different demands considered by the assessment have been grouped into the categories shown in Figure 15.

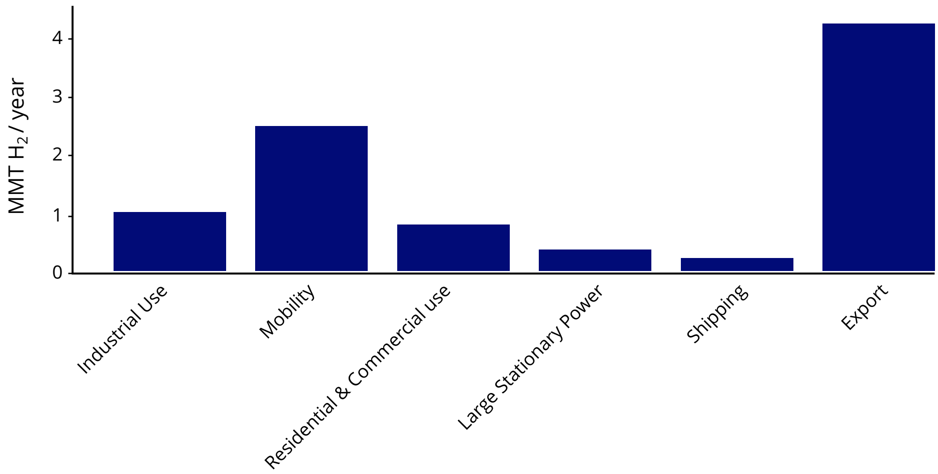

Figure 15 Domestic hydrogen demand

3.13.1 Export

Based on Arup's assessment of the development of the global hydrogen economy, Australia is anticipated to be a net exporter of hydrogen to areas with less available renewable energy feedstock or other supply chain inhibitors to development. Hydrogen will be shipped as a commodity, with liquid forms like liquefied H_2, ammonia or LOHC expected to be more popular for export than shipping it as compressed gas because of the higher energy density. Shipping of liquid fuels and ammonia are well-established industries, increasing the opportunity to retrofit or repurpose existing vessels and equipment rather than the construction of new bespoke vessels.

Based on the demand assessment, 46% of produced hydrogen will be exported, equating to 4.3MMT H_2 per annum. The selection of carriers for export will develop and mature as hydrogen production comes online, and regional and global demand drives the requirement for export. For the purposes of this assessment, it is assumed that 80% (3.4MMT H_2) will be exported as ammonia, and the remaining 20% (0.9MMT H_2) will be exported as liquefied hydrogen.

Export - ammonia

Ammonia is one of the most used forms of hydrogen, having primary uses in agriculture and industry globally. It is also often the preferred medium for use in hydrogen exports due to its energy density which is three times greater than compressed hydrogen and 1.5 times greater than liquefied hydrogen.

Due to its dual purpose in the supply chain (end product for agricultural and industrial use, hydrogen carrier for export), the location of ammonia production infrastructure and its placement within the supply chain may be flexible and varied. Hydrogen can either be produced near the location of demand or near a port where it will be converted to ammonia and shipped. This will depend on how demand for hydrogen develops as the industry grows.

The key advantage of ammonia as an export medium is the widespread existence of export and import infrastructure, allowing the rapid uptake of shipments to new markets without the wait for appropriate infrastructure construction. Figure 16 from The Royal Society[39], the independent scientific academy of the United Kingdom, shows the extensive global and well-established ammonia shipping infrastructure developed as of 2017.

39 https://royalsociety.org/-/media/policy/projects/green-ammonia/green-ammonia-policy-briefing.pdf

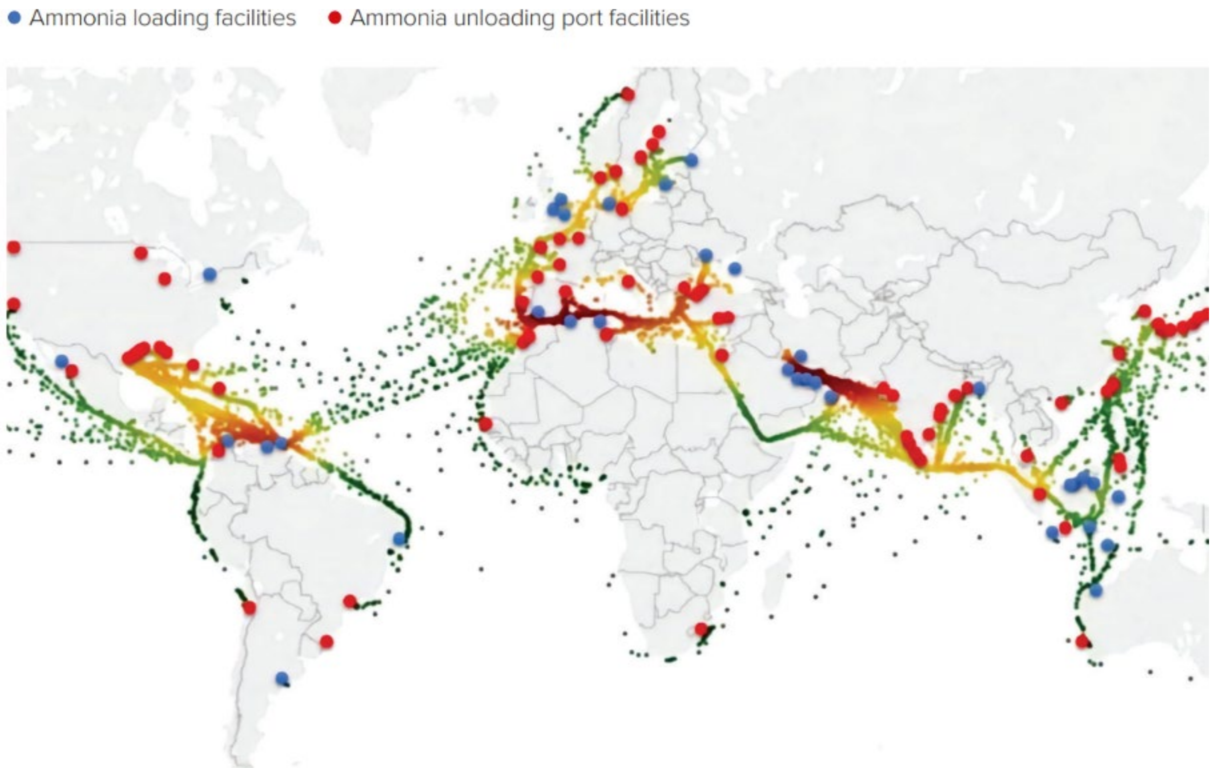

Figure 16 Ammonia shipping infrastructure, including a heat map of carriers

Around 176MMT of ammonia is produced per year globally, mostly using the Haber-Bosch process[40]. It is used to meet the demand for fertilisers, refrigeration, explosives, textiles and pharmaceuticals. The process is currently fed by hydrogen from SMR (producing emissions) and industrial energy from the grid to separate nitrogen feedstock from air and to facilitate the process (producing emissions). To meet emission reduction goals, any large-scale production of ammonia must be based on sustainable electricity for conversion. The development of additional renewable energy generation to power ammonia conversion must be considered as part of the development at the scale of green ammonia production facilities.

Research into potential alternative methods for ammonia production is underway, aiming to reduce the energy intensity and emissions associated with the conversion. As an example, CSIRO (with funding from ARENA and partnering with industry associations Orica Australia Pty and Grains Research and Development Corporation) have developed a pilot plant for a reactor to convert ammonia at lower pressure, reducing energy inputs, cost and plant required[41]. The ongoing establishment of this technology may impact the relative viability of transport carriers and result in a larger share of domestic and international transport utilising ammonia.

Any domestic use of ammonia as a hydrogen carrier (rather than as an end-use product) must accommodate the development of reconversion infrastructure (ammonia cracking) at the point of consumption. Due to the expense and energy requirement of conversion and reconversion, domestic transit of hydrogen as compressed H_2 has been preferred by the NHIA.

40 https://royalsociety.org/-/media/policy/projects/green-ammonia/green-ammonia-policy-briefing.pdf

41 https://arena.gov.au/assets/2022/04/hydrogen-to-ammonia-research-and-development-final-report.pdf

Export - liquefied hydrogen

Hydrogen may also be liquified for transport to increase its energy density for export shipping. This process currently necessitates the gas to be cooled to -253°C, which indicatively would consume ~25-35% of the hydrogen to generate the required energy and represent a large process loss[42]. For this reason, and the additional requirement for energy use on reconversion, NHIA modelling indicates that this process will likely not be selected for domestic transport of hydrogen. It is assumed that liquefication will take place at the point of export (ports) using dedicated infrastructure.

Liquefication involves both compression and cooling applications, the infrastructure being manufactured prior to installation on-site. Large-scale applications of liquefaction will be powered by the Claude cycle process, with the key inputs being power and liquid nitrogen for cooling[43]. Given that the liquefaction plants are likely to be located adjacent to ports where access to behind-the-meter renewable energy may be restricted, access to grid energy from renewable sources will be vital to ensure the environmental benefits of green hydrogen use are preserved.

The development of suitable ships for the transit of liquefied hydrogen must be completed before widespread export can commence. A number of projects are underway to develop vessels which may be powered by hydrogen that boils off during the journey[44]. Additionally, the required infrastructure for liquefication and regasification of the hydrogen must be built at both the loading and receiving terminals prior to the establishment of an export route.

Australia and Japan have run a world-first pilot project termed The Hydrogen Energy Supply Chain (HESC). The project involved the generation of hydrogen through coal gasification from the Latrobe Valley in Victoria prior to liquefaction at the Port of Hastings and loading on the specialised Suiso Frontier vessel, which can carry 1,250m^3 of hydrogen at -253 degrees celsius. The vessel transports the hydrogen to Kobe in Japan, where it is unloaded and stored. The pilot phase was completed in early 2022. The outcomes of this pilot will provide valuable information about the viability of liquefied hydrogen shipping to the market[45]. Progression to the commercialisation phase will be considered after a review of the pilot phase.

3.13.2 Shipping

Shipping is a major contributor to global carbon emissions, which may be partially mitigated through a move to hydrogen as fuel. The demand assessment anticipates that 0.26 MMT H_2 will be required in 2040, which accounts for 5% of all domestic demand in Australia. This is based on an assessment of potential switching from traditional fuels over this time period based on the anticipated price of hydrogen.

Australia currently does not produce a significant quantity of fuel oil for shipping proportionate to its global share of seaborne international cargo. There is an opportunity to develop fuel bunkering at ports which are located throughout the globe based on the supply and cost of fuel. In a future where ships are hydrogen-powered (or potentially by methanol or ammonia), Australia could become a place for bunkering due to its low-cost, abundant supply of hydrogen. This would lead to a strong and constant demand for hydrogen located at ports within Australia.

3.13.3 Large stationary power

0.4 MMT H_2, or 8% of the domestic demand for hydrogen, is anticipated to be burned to generate electricity for the grid or injected into natural gas feedstock for the purposes of electricity generation. This is estimated by assuming the switch from current gas-powered generation through natural gas to using hydrogen. The demand forecast modelled the current gas consumption per region and assumed a similar forecast for hydrogen.

GE Gas has developed gas turbines that will be able to work from a blend of natural gas and hydrogen[46]. In addition, the Tallawarra B project in Illawarra is set to become one of Australia's first green hydrogen and gas power plant[47]. The plant aims to offset its carbon emissions over its operational lifetime. The use of hydrogen-powered plants is important in ensuring renewable energy can still be provided during times when solar or wind is not available. Green hydrogen acts effectively as a storage method until such a time it can be utilised to fill any power shortages in a power station.

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42 https://iea.blob.core.windows.net/assets/9e3a3493-b9a6-4b7d-b499-7ca48e357561/The_Future_of_Hydrogen.pdf

43 AIP Conference Proceedings 1573, 1311 (2014); https://doi.org/10.1063/1.4860858 Published Online: 17 February 2015

44 https://iea.blob.core.windows.net/assets/9e3a3493-b9a6-4b7d-b499-7ca48e357561/The_Future_of_Hydrogen.pdf

45 https://www.hydrogenenergysupplychain.com/supply-chain/the-suiso-frontier/

46 https://www.ge.com/gas-power/future-of-energy/hydrogen-fueled-gas-turbines?utm_campaign=h2&utm_medium=cpc&utm_source=google&utm_content=rsa&utm_term=Hydrogen%20turbine&gclid=Cj0KCQjwkt6aBhDKARIsAAyeLJ2668Z-VNgRHcgCRzYZLMHK9ke5xaZcfyaLAj8Uci9LJ2se9XimegAaAogfEALw_wcB

47 https://www.energyaustralia.com.au/about-us/what-we-do/new-energy-projects/tallawarra-b-project

3.13.4 Mobility

The demand assessment estimated that almost 50% of domestic hydrogen demand would be to enable the decarbonisation of mobility. This includes supplying hydrogen applications in automotive gasoline, aviation fuel, diesel, transport, postal and warehousing. The total demand attributed to this category is 2.5MMT H_2 per year, notably concentrated around population centres to reflect underlying activity (Sydney had the highest demand at 19% of the total, with Melbourne and Brisbane at 15% each).

Applications where hydrogen replaces automotive gasoline and diesel for transport equate to 20% and 14%, respectively, of all domestic hydrogen demand in Australia. Automotive fuel numbers are based on a predicted transition to fuel cells based on five-year trends to reach under 20% uptake of the national fleet. The assessment assumed that the uptake of fuel cell vehicles is likely to be higher in taxis and fleet vehicles, whereas electric vehicles are likely to be the predominant low-emission vehicles for commercial and residential passenger vehicles. It is also anticipated that haulage trucks and freight vehicles will transition to hydrogen mainly through hydrogen-powered fuel cells.

Aviation accounts for almost 8% of domestic demand, through the replacement of current fuel, with synthetic hydrogen fuels. The International Energy Agency suggests this could account for roughly 15% of aviation fuel by 2050. Airbus outline two methods they are investigating for the use of hydrogen in aviation[48]:

- Through hydrogen propulsion, where hydrogen is combusted in modified gas-turbine engines or by using electricity in the turbines generated from fuel cells.
- Through synthetic hydrogen e-fuels.

Freight haulage is an industry with the ability to transition to hydrogen fuel cell electric trucks (FCETs). At Ark Energy's first hydrogen hub, called 'SunHQ,' they are developing the infrastructure to produce green energy, which will power five FCETs in the first phase[49]. This includes a 1MW PEM electrolyser on site, powered by the Sun Metals solar farm. The replacement of five diesel trucks will save 1,300t of CO_2 emissions every year.

Green hydrogen buses and coach technology are also the focus of projects to reduce greenhouse emissions and increase hydrogen uptake. Emerald coaches have committed to a full fleet of hydrogen fuel cell vehicles by 2040[50], and Volgren and Wrightbus have started to bring hydrogen buses into Brisbane[51].

New Energies Service Station in Geelong, Victoria, is developing the offering of hydrogen refuelling and electric vehicle recharging capacity for heavy fuel cell electric vehicles[52]. The project incorporates the co-location of a 2MW electrolyser and 850kg of hydrogen production per day, utilising the electrical infrastructure of the Viva Energy industrial zone and the recycled water from the Barwon Water Northern Water plant.

Retrofitting existing diesel engines with hydrogen fuel injection systems along with innovative fuel cells can replace up to 90% of diesel consumed in traditional internal combustion engines. This is an effective way to utilise the large existing asset base of haulage trucks, mining equipment, generators, and heavy industrial plant. This can be achieved through a couple of different methods of fuel injection and represents a movement towards lowering emissions in carbon-heavy industries.

In South Africa, Anglo American have developed the first hydrogen-powered haulage truck[53]. Around 3.5% of the world's greenhouse gas emissions are from mining haulage trucks. The truck requires a 2MW hydrogen-battery hybrid power plant to carry a payload of 290t and is an important step forward for a heavily polluting industry.

The breakdown of transportation hydrogen demand by 2040 is outlined in table 1.

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48 https://www.airbus.com/en/innovation/zero-emission/hydrogen#:~:text=At%20Airbus%2C%20we%20believe%20hydrogen,aircraft%20to%20market%20by%202035.

49 https://arkenergy.com.au/sunhq-hydrogen-hub/

50 https://www.emeraldcoaches.com.au/e-mission-zero-strategy/

51 http://volgren.com.au/volgren-and-wrightbus-to-deliver-hydrogen-buses-into-brisbane/

52 https://www.vivaenergy.com.au/energy-hub/new-energies-service-station-project

53 https://www.angloamerican.com/media/press-releases/2022/06-05-2022

Table 1 Transportation demand

Demand category (per demand assessment)	2040 hydrogen demand (tonne per year)	Percentage of total domestic hydrogen demand
Automotive fuel	1,008,259	19.9%
Aviation fuel	398,816	7.9%
Diesel - Transport	726,617	14.4%
Rest of Diesel	324,960	6.4%
Transport, postal and warehousing	50,230	1.0%
Total	**2,508,882**	**49.60%**

3.13.5 Residential and commercial use

The demand model outlines that about 17% of domestic hydrogen demand will be used for residential and commercial uses. The 0.87MMT H_2 per year will cover uses in fuel-cell technology or replacing natural gas in heating buildings, homes and water and potentially in cooking. It is assumed that existing gas customers will switch to hydrogen gas or a blend of hydrogen and natural gas on the network. However, 20% will switch to electricity. The cost of hydrogen supply in the network is still to be determined, so its economic viability is still not known and could strongly affect a consumer's choice in whether to switch to electric instead.

The breakdown of residential and commercial hydrogen demand by 2040 is outlined in table 2.

Table 2 Residential and commercial demand

Demand category (per demand assessment)	2040 hydrogen demand (tonne per year)	Percentage of total domestic hydrogen demand
Commercial	226,781	4.5%
Residential	640,206	12.7%
Total	**866,987**	**17.2%**

3.13.6 Industrial use

The demand assessment models 1.02MMT H_2 per year of demand for hydrogen in industrial uses. This equates to around 20% of the total domestic demand. The model includes industrial uses for hydrogen covering use in agriculture, chemicals, construction, mining, food, textiles, manufacturing, non-metallic mineral processing, and petroleum refining.

More than 10% of all domestic hydrogen demand in Australia is expected for the mining industry. As a heavily polluting industry, research and innovation are currently being undertaken to decarbonise mining processes through utilising hydrogen as a fuel replacement or by powering processing plants on site using green hydrogen methods.

Hydrogen use in petroleum refining can be used to refine fuels and reduce the sulphur content of diesel as well as to replace natural gas for heating purposes. Hydrogen cost for heating in refining compared to natural gas is already competitive, and so the NHIA Central Demand Scenario estimates that hydrogen will fully replace natural gas by 2050.

In chemicals and non-metallic processing, natural gas is used as a fuel or for high-temperature purposes. It is suggested that hydrogen for this purpose could become cost competitive by 2030 and fully replace natural gas by 2050, according to the International Energy Agency Technology Perspectives[54].

The breakdown of industrial hydrogen demand by 2040 is outlined in table 3.

54 International Energy Agency. https://www.iea.org/

Table 3 Industrial demand

Demand category (per demand assessment)	2040 hydrogen demand (tonne per year)	Percentage of total domestic hydrogen demand
Agriculture	684	0.01%
Chemicals	69,606	1.38%
Construction	7,522	0.15%
Diesel for mining and agriculture	341,962	6.76%
Food, textiles, wood, and printing	87,943	1.74%
Mining	286,715	5.67%
Non-metallic mineral processing	174,991	3.46%
Petroleum	51,448	1.02%
Total	**1,020,871**	**20.19%**

3.13.7 Other potential demands

A number of other potential demands for hydrogen feedstock may emerge. These include:

- Manufacturing.
- Metal products.
- Machinery and equipment.
- Green steel.

These potential uses may provide additional opportunities for industry development and increase the demand for hydrogen by 2040.

Due to its ubiquity in global processes and emissions-intensive production method, the decarbonisation of steel production is a critical step in meeting the emissions reductions required in the future. Alongside an increase in the use of recycled steel, 'green steel' production using green hydrogen may meet a component of this demand. As a significant exporter of iron ore, the key feedstock of steel production, the development of significant hydrogen generation capacity may make Australia a competitive location for green steel production.

Hydrogen may replace fossil fuels in steel production in a number of different ways, including:

- Replacement of fossil fuels in blast furnace applications, alongside potential replacement of coal with biomass in the main body of the furnace.
- Implementation of Direct Reduced Iron (DRI) process for primary processing before steel processing in Electric Arc Furnace (EAF), with hydrogen as a key feed and fuel.
- Applications in steel finishing (hot rolling) by either hydrogen or electric heaters.

Both technologies will require CCS alongside processing to deal with some CO_2 emissions inherent in production. A significant push into steel manufacturing could materially alter the level of demand for hydrogen in Australia. The global steel market produced just under two billion tonnes of steel in 2021, to which Australia contributed only 5.5 million tonnes (0.28% of production)[55], whilst exporting just under 900 million tonnes of iron ore per year[56]. If key challenges for the development of green steel (ongoing development, scaling and cost reduction of production methods, cost and supply of renewable energy and hydrogen, development of supply chain and export capability, development of skills and private investment in infrastructure) can be met, this may be a significant opportunity to drive local development.

55 https://worldsteel.org/media-centre/press-releases/2022/december-2021-crude-steel-production-and-2021-global-totals/

56 https://theconversation.com/green-steel-is-hailed-as-the-next-big-thing-in-australian-industry-heres-what-the-hype-is-all-about-160282

4. Economic analysis

4.1 Overview

The economic analysis quantifies the economic activity arising from the hydrogen supply chain, detailed in section 3. Based on a series of assumptions, the Australian hydrogen economy could be supporting $30-$40 bn (1.0%-1.25% Australian GVA) in domestic GVA and 58,000-72,000 jobs annually across the wider supply chain by 2040.

4.2 Methodology

At a high level, the amount of investment and the amount of annual operational, maintenance and capital expense necessary to achieve the quantity of real economic activity in 2040 at each node is quantified. Costs at each node are then mapped to jobs and domestic GVA across the supply chain using ratios and multipliers calculated from the Australian input-output tables[57].

Analysis of each node involves the following process:

1. Calculate the capital investment required to achieve the necessary production capacity (for example, 51.2GW of electrolyser capacity or 82.3GW of solar production).
2. Map the investment to specific activities and industries in the supply chain using techno-economic case studies.
3. Calculate the annual capital expenditures to pay back this investment using a weighted average cost of capital of 5.9% and the investment's expected lifetime (for example, 20 years). This capital expense flows into the LCOH and the gross operating surplus in the domestic GVA.
4. Calculate supply chain node-specific fixed operating expenses and node-specific variable expenses not costed elsewhere in the supply chain (for example, by assuming fixed operating expense as a per cent of capital expense).
5. Map industry-level expenditure of investment and operating expenses to direct and indirect[58] parts of the supply chain using ratios and multipliers from the input-output tables. This also maps import expenditure where we assume, as a baseline across all industries, that by 2040 the domestic share of expenditure in the hydrogen supply chain builds up to domestic shares observed in similar industries in Australia today.
6. Map from GVA to jobs (direct and wider) using industry-specific shares of compensations in GVA and average compensation by industry.

This analysis has been informed by benchmarks from techno-economic literature, including from the Australian Energy Market Operator Integrated System Plan (AEMO ISP) 2020[59] scenarios, IRENA hydrogen cost reduction report[60], the UK Government's hydrogen supply chain report[61] and the assumptions in the International Energy Agency's (IEA) future of hydrogen report[62]. Key capital cost assumptions used in the NHIA modelling have been used for consistency. Further costing assumptions are detailed in Appendix B. All monetary values are expressed in Australian dollars (AU$) at 2022 price levels[63]. The conversion is from US$ to AU$ using the 10-year average exchange rate of US$0.78 to AU$1.

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57 2018-19 input output tables. See (accessed 19/10/2022): https://www.abs.gov.au/statistics/economy/national-accounts/australian-national-accounts-input-output-tables/2018-19

58 The indirect supply chain covers expenditure following on from direct expenditure on goods and services to produce hydrogen. This includes activities such as financial services and administrative services.

59 See (accessed 19/10/2022): https://aemo.com.au/en/energy-systems/major-publications/integrated-system-plan-isp/2020-integrated-system-plan-isp/2020-isp-inputs-and-assumptions

60 See (accessed 19/10/2022): https://www.irena.org/publications/2020/Dec/Green-hydrogen-cost-reduction

61 See (accessed 19/10/2022): https://www.gov.uk/government/publications/supply-chains-to-support-a-uk-hydrogen-economy

62 See (accessed 19/10/2022): https://www.iea.org/reports/the-future-of-hydrogen/data-and-assumptions

63 This means the costs are as they would be in 2022. Costs reflect the real expected amount to be paid in 2040 but presented without the effect of trend inflation between 2022 and 2040.

As an example, Figure 17 illustrates the flows of investment and revenues associated with producing 9.5MMT of hydrogen throughout Australia.

To build up to that production capacity, $305-$370 bn of investment is required between now and 2040, of which:

- $130-$160 bn is spent on imported goods and services and
- $175-$210 bn flows directly into the domestic economy.

Of that $175-$210 bn, a further:

- $41-$51 bn indirectly is spent on imports and
- $70-$85 bn is spent on the wider supply chain.

Annual investment and revenue in 2040

Once production capacity is achieved, around $24-$29 bn in revenue is needed to pay back investors annually and compensate them for ongoing capital maintenance.

A further $2.2-$2.7 bn is needed for annual fixed operating expenses, and $3.1-$3.7 bn is spent on annual imports to maintain production.

A final $3.7-$4.5 bn makes its way into the wider economy every year.

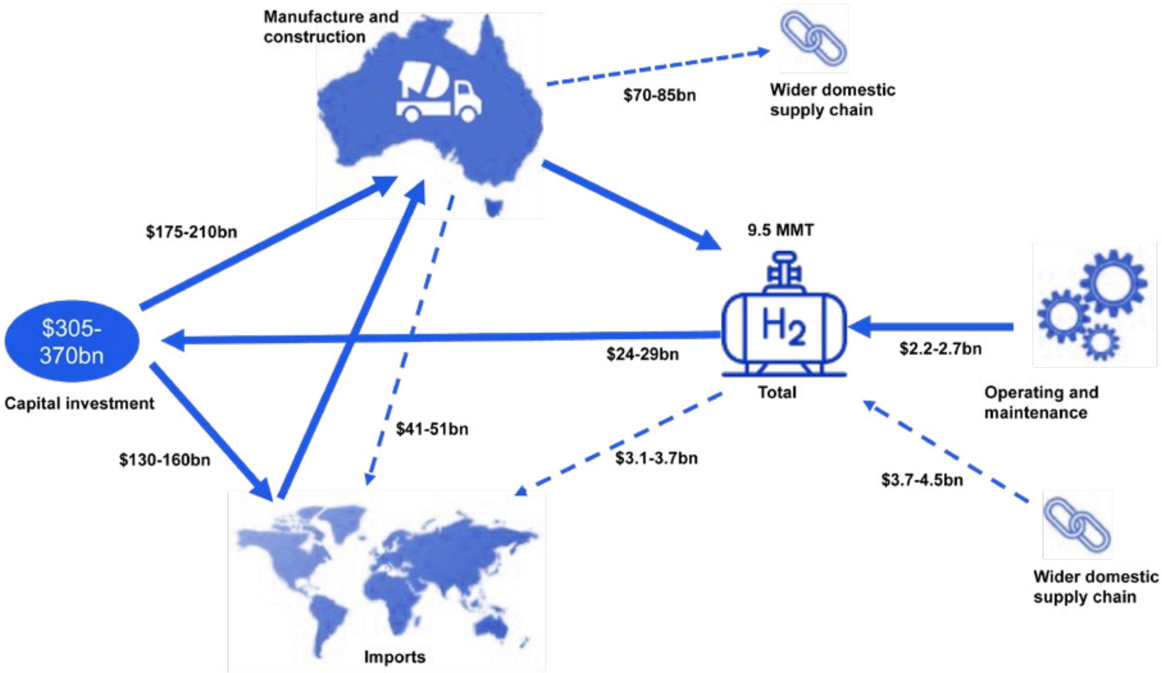


Figure 17 Investment and revenue flows to develop 9.5MMT of hydrogen capacity in Australia

4.2.1 Context and limitations

The estimates rely on emerging international techno-economic benchmarks and extrapolations from similar industries and supply chain structures in the current Australian economy. Furthermore, the hydrogen industry is in its infancy and improved benchmarking and returns to scale estimates are likely to improve exercises such as this in the future. As such, these projections are uncertain and only designed to provide an indicative estimate of the potential size of the hydrogen economy and what is required to achieve it.

Omitted from this analysis are costs, GVA and jobs related to final industrial/retail use (for example, filling stations or portside storage and transfer). The LCOH reported is, therefore, best understood as a wholesale cost LCOH. We are also assuming that sufficient demand exists at this LCOH to match supply.

While this economic analysis focuses on the jobs needed for the development of the hydrogen economy, there will be additional supporting jobs created in industries like the education and training sectors to build this capacity. These jobs would be considered additional to this analysis.

There is uncertainty around the extent to which the wider hydrogen supply chain can be onshored. Initially, specialised equipment and materials will need to be almost wholly imported. As the industry develops, some of this production is likely to move into Australia.

Australia currently imports most of its specialised equipment and machinery (67%)[64]. As a baseline, it is assumed that Australia can achieve penetration in the hydrogen economy as it has achieved in similar industries to date. This leaves significant space for expanded domestic production should Australia develop a technical advantage in hydrogen technologies. These key factors and related opportunities are explored further in section 5.

This analysis is focussed on production and operations in 2040 with only an indicative phasing of gross annual investment between now and 2040 provided, based on an extrapolation of announced projects to date in Australia sourced through BNEF.

This analysis is also constrained by the Central Demand Scenario produced by the NHIA. These constraints have been discussed previously in this report.

64 2018-19 input output tables. See (accessed 19/10/2022): https://www.abs.gov.au/statistics/economy/national-accounts/australian-national-accounts-input-output-tables/2018-19

4.3 Analysis

4.3.1 Hydrogen economy in 2040

Table 4 presents high-level numbers describing the economic footprint of a potential Australian hydrogen economy. Annual revenues from hydrogen could amount to around 1% of GVA in Australia[65] in 2040 and could support 58,000-72,000 jobs annually across the operational (direct) and wider supply chain. Most jobs associated with the hydrogen supply chain fall into the latter category. The wider supply chain includes supporting activities such as financial services and jobs in construction or manufacturing. Such jobs may be related to both investing in and maintaining capital goods and infrastructure to support hydrogen production.

Table 4 Key numbers for a potential hydrogen economy in 2040

Item	Description	Value
Annual turnover	Annual revenues of H_2 economy	$30-$40 bn (1.0%-1.25% of Australia's GVA)
LCOH	Average production cost per kg H_2.	$3.70-$3.90
Direct GVA (2040)[66]	Annual GVA in the domestic economy in 2040 directly associated with the production, storage, and transport of hydrogen. This also includes the GVA from direct expenditure on materials to support the production, storage, and transport of hydrogen, including the capital investment required to establish the domestic production capacity.	$26-$32 bn (0.80%-0.95% of Australia's GVA)
Wider GVA (2040)	Annual GVA in the wider supply chain in 2040. This includes GVA from: • Indirect expenditure on materials (through suppliers) to support the production, storage, and transport of hydrogen. • Supporting operations like financial services • GVA in non-routine maintenance and replacement of capital goods (for example, electrolysers or compressors). It also includes activities related to capital construction and installation annualised by the assumed lifetime of the capital	$9-$11 bn (0.25%-0.35% of Australia's GVA)
Total GVA (2040)	Direct and wider combined.	$35-$43 bn (1.05%-1.30% of Australia's GVA)
Direct annual employment	Jobs directly related to annual production, transport and storage of hydrogen and the regular maintenance of assets in 2040. This includes (non-exhaustive list): • Technicians. • Construction services. • Safety managers. • Electricians. • Water and utilities. • Maintenance of pipelines. • Transport and freight.	13,000-17,000 jobs

65 We assume Australian real GVA grows at 1.75% per year from 2022, in line with RBA estimates of Australia long run potential growth rate.

66 Direct GVA is reflective of the capital investment required to deliver the hydrogen production capacity to 2040, and the Direct GVA delivered by hydrogen in 2040. For this reason, the Direct GVA and Wider GVA will not sum to equal the annual turnover displayed in the table.

Item	Description	Value
Wider annual employment	Jobs in the wider supply chain in 2040, including indirect jobs from suppliers that support the production, storage, and transport of hydrogen. This includes jobs supporting operations like (non-exhaustive list): • Financial services. • Insurance services. • Engineering and other technical services. • Water and utilities. • Administrative services and human resources. This also includes jobs for non-routine maintenance and replacement of capital goods (such as electrolysers or wind turbines) and activities related to capital construction and installation annualised by the assumed lifetime of the capital.	45,000-55,000 jobs
Jobs per MMT	Total direct and wider jobs per megaton	6,200-7,700 jobs
Total investment (2040)	Total investment required to achieve 2040 production levels between now and 2040. This includes the capital expenditure required to build production capacity, the annual expenditure required to compensate investors, and annual operational and capital expenses.	$340-$420 bn

The costs across the supply chain build up to an overall LCOH of around $3.70-$3.90 (or US$2.97-$3.04). The contributions to this from each supply chain node are illustrated in Figure 18, with the largest contributions associated with power production (solar and wind), actual hydrogen production via electrolysis and transportation principally via pipeline. Due to the extensive pipeline infrastructure installed, relatively few truck movements are assumed in this scenario which led to a negligible contribution, but this could be higher in alternate scenarios.

Comparing the LCOH with other studies

When considering the calculated LCOH, it is important to note that this analysis has been defined based on the NHIA modelling outputs. The NHIA model was built off a demand forecast for hydrogen, and the scenarios were optimised based on the lowest cost to meet this demand. It was not a price-driven model that compared the cost competitiveness between fuels in optimisation. For this reason, it is difficult to compare this LCOH with other models, and the reader should be aware of this when referring to this analysis.

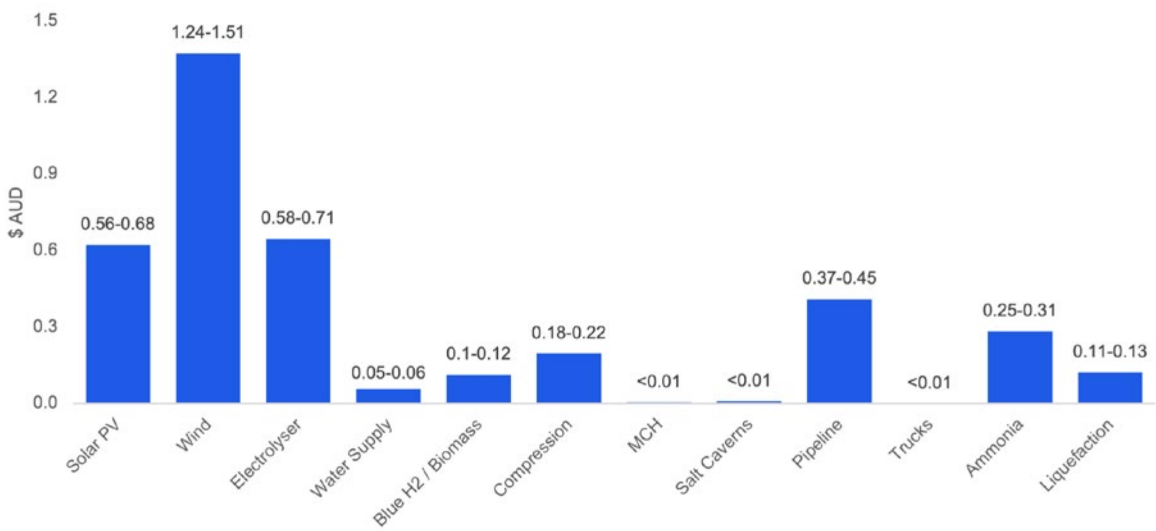


Figure 18 LCOH contribution of each node

4.4 Annual impacts in 2040

Annual jobs and GVA by node in 2040 are shown in Figure 19 and Figure 20 and are in line with the contribution to the LCOH.

Wind power has the largest annual job requirements, with jobs supported through building, maintaining, and replacing the turbines. In terms of direct jobs, operational jobs such as monitoring and control of electrolysis, pipeline and ammonia production take up the largest share at around a few thousand per node.

In GVA terms, the split between direct production and operations and the wider supply chain is reversed. This is due to the capital-intensive nature of the industry, with most of the income (around 90%[67]) generated by annual activities flowing to capital (investors) rather than labour.

When interpreting Figures 19 and 20 charts:

- Direct refers to activities relating to annual fixed and variable operations and maintenance (O&M).
- Wider includes indirect supply chain activities related to O&M activities. It also includes activities related to capital construction and installation annualised by the assumed lifetime of the capital.

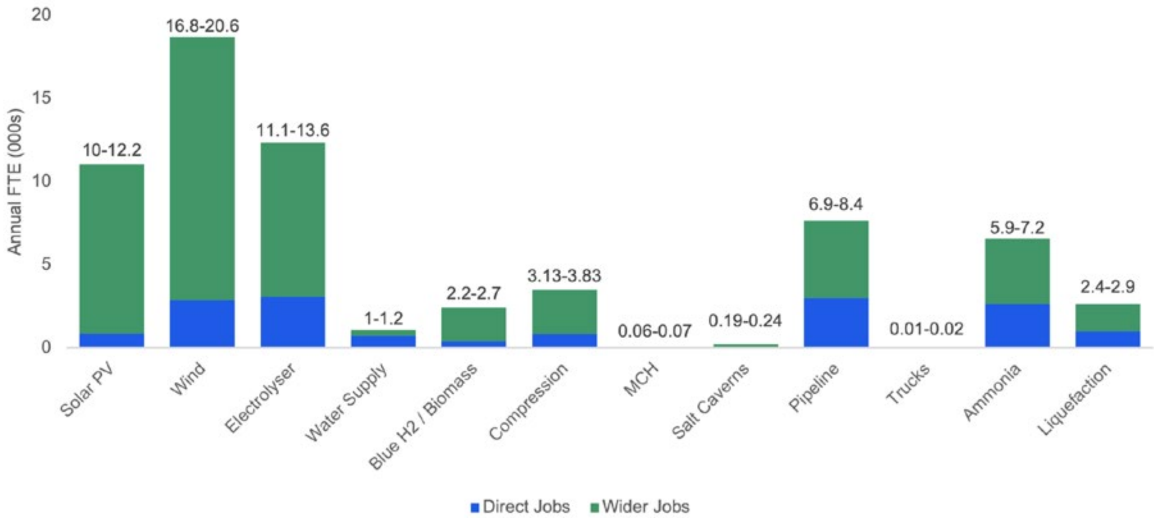


Figure 19 Annual jobs by node in 2040 (000s)

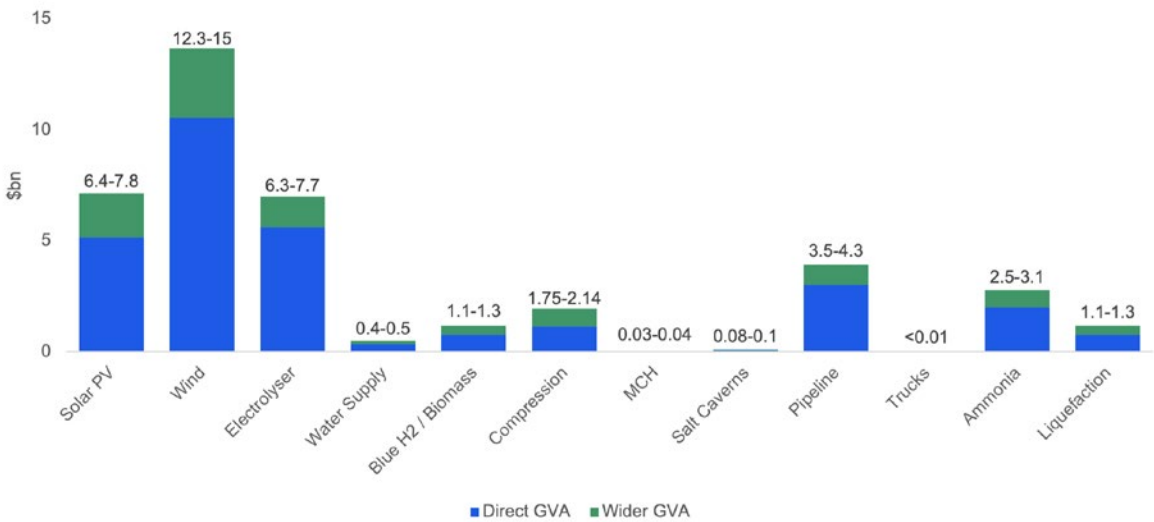


Figure 20 Annual GVA by node in 2040 ($bn)

67 This is in line with existing ratios in the oil and gas, mining and electricity generation sectors.

4.4.1 Considering the regional impacts

The Australian input-output tables were used at a national level to aggregate the economic impact of the hydrogen supply chain in 2040. Jobs that support the hydrogen economy in 2040 will not necessarily be uniformly distributed across the country or by industry.

Recognising these constraints, a high-level estimate of where jobs will be generated across the country is broken down by the hydrogen demand at each reference location in the NHIA modelling. These numbers provide an indication of where economic activity is being driven from in 2040 (through the production, storage, and transport of hydrogen) rather than where this activity is occurring.

Based on the NHIA, the economic activity in the hydrogen economy is expected to be in regional areas (where approximately 91% of the hydrogen production is expected to be). This is a general estimate only. Additional analysis is required to understand the exact composition and location of this economic activity.

Table 5 Generation of jobs and GVA in 2040 split by metropolitan and regional Australia

Location	Annual GVA ($bn)	Annual jobs (FTEs)
Metropolitan	3.2-3.9	5,000-6,000
Regional	31.9-39.0	53,000-66,000
Total	**35.0-42.8**	**58,000-72,000**

4.5 Industry analysis

Figure 21 provides a perspective across broad industry groups. The largest industry classes supporting the supply chain are in electricity generation, hydrogen carriers[68] (hydrogen, ammonia and MCH) and pipeline services. The size of the demand in these industries is significant relative to their current size. The pre-pandemic size of the electricity generation industry in Australia is only around $5 bn, less than a third of the size needed to support this level of hydrogen production. There is also only around $4 bn in activities currently related to basic chemical manufacturing. Industries related to the wider supply chain, like construction, are much larger at around $80 bn today and can more easily absorb the growth of the hydrogen economy.

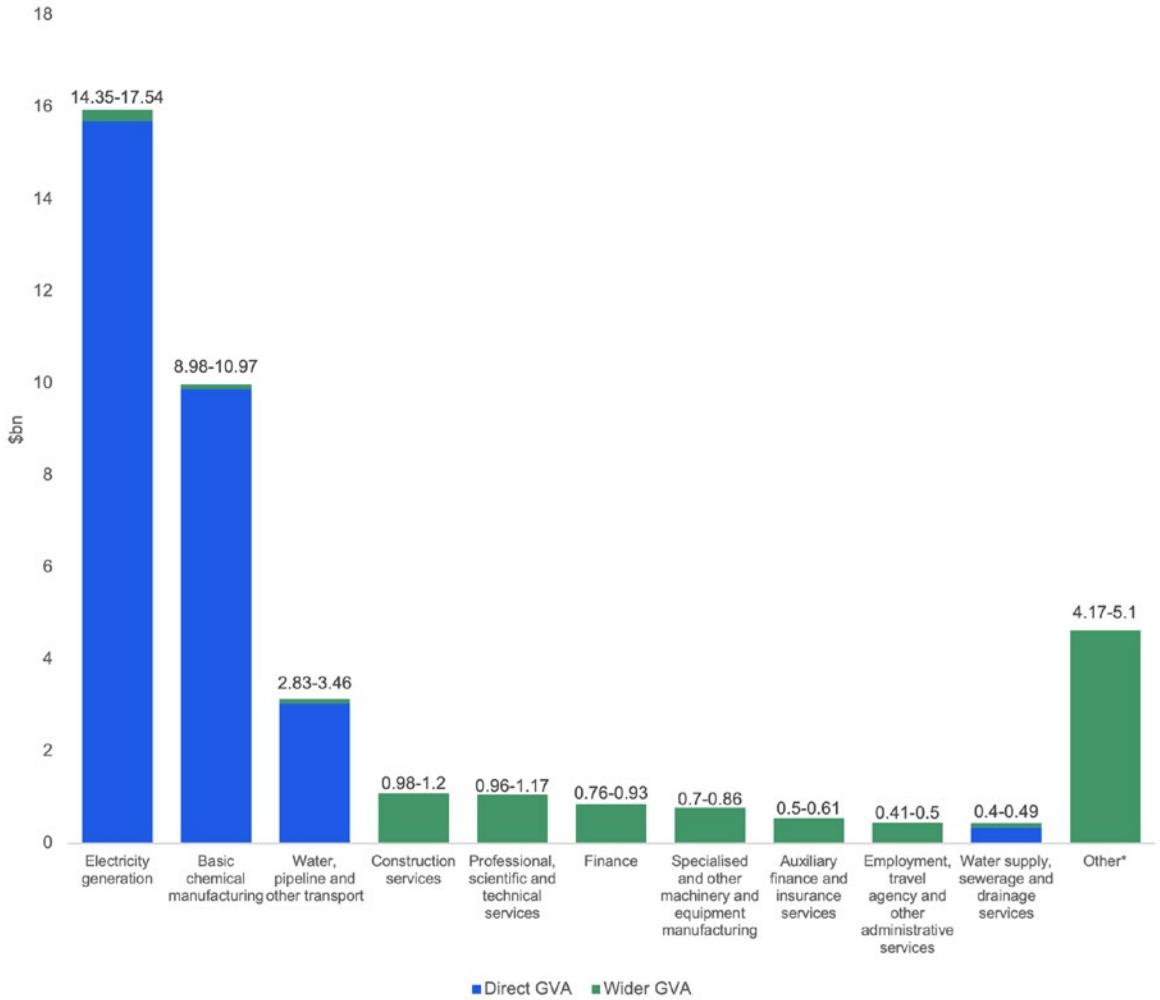


Figure 21 Total direct and wider GVA across top 10 industries in 2040 ($bn)

** Other includes the remaining industries contained in the supply chain. This includes industries such as heavy and civil engineering construction, electrical equipment manufacturing, electricity transmission, distribution, on selling and electricity market operation.*

68 Falling within the broader basic chemical manufacturing industry.

4.6 Capital goods and services supply

The major categories of spending across the supply chain are concentrated in the specialist equipment that is needed to generate the energy to produce hydrogen. Capital expenditure in these industries is dominated by imported capital goods.

Specialised equipment, like wind turbine components and electrolysis packages, represent a large portion of the total investment across the supply chain. Suppliers of these components are mostly based overseas, meaning that investment in these components will result in the majority of spending flowing to non-domestically based companies.

The major service components of the supply include project management, construction, and engineering roles. By virtue of their industry type, this spending is almost exclusively domestically supplied.

A breakdown of domestic and international proportions for the ten largest capital goods and service categories is provided in Figure 22. Domestic refers to the revenue that is spent on domestic goods and services. A full breakdown of capital goods and services supply for each node is provided in the appendix.

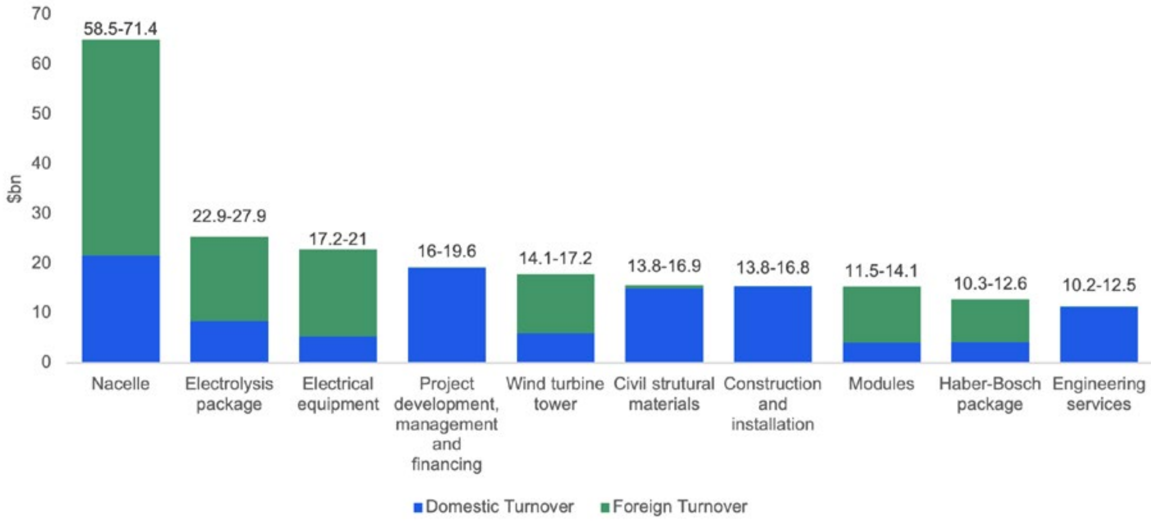


Figure 22 Total capital goods and services supply (2040) across the supply chain – top 10 categories

4.7 Building the hydrogen economy

Between 2022 and 2040, at least $340-$420 bn ($19-$23 bn a year) of investment and 170,000-200,000 constructions jobs (FTE) will be required to build up the infrastructure necessary to produce Hydrogen in the magnitudes envisioned in the NHIA Central Demand Scenario. The amount of investment by nodes is shown in Figure 23 and Figure 24, with the largest share devoted to building up sufficient power generation, particularly in onshore wind. Based on the existing Australian economy, a significant share of investment (44%-61%) will be on imported goods, particularly specialised goods such as solar panels, electrolyser components, wind turbines and compression components.

Figure 23 and Figure 24 also show the relative share of investment between the domestic economy and imports across each node of the supply chain. This is based on the existing import intensity of non-specialised Australian industries. The categories are as follows:

- Domestic (Current State), showing the share of investment the domestic economy would receive if Australia did not onshore the specialised equipment to manufacture hydrogen.
- Domestic (Potential), showing the share of domestic investment if Australia is able to achieve similar domestic intensity in specialised and electrical equipment manufacturing in the hydrogen economy as it has today in other existing industries.
- Domestic (Optimistic), showing a more optimistic scenario where Australia becomes a market leader in specific elements of hydrogen production and supply chain manufacturing.
- Imported, showing the share of investment that will flow overseas.

The Domestic (Potential) and Domestic (Optimistic) scenarios will not be achieved without investment in Australia's sovereign manufacturing capacity. This would result in a greater share of imports than is currently observed in other existing industries.

Australia's domestic potential

Investment and coordination in new capabilities and manufacturing are needed if Australia wants to achieve the potential domestic investment over the next two decades. The pace of investment in Australia's capability and capacity will dictate how much of this opportunity is captured.

Building Australia's capacity as a market leader

A more optimistic scenario where Australia becomes a market leader in hydrogen production and supply chain manufacture could see Australia capturing a greater share of investment (eating into the imported share).

Based on the supply chain and industry analysis, an alternate scenario where Australia onshores major manufacturing capabilities were considered. Under this scenario, it is assumed that by 2025 Australia will be producing approximately 75% of the specialist machinery and technology associated with each supply chain node.

This can be seen as a potential opportunity at each node. It is not expected that Australia will be able to develop this capacity across all nodes. To be successful, this investment would need to be complemented by suitable skills and training, government support and coordinated policy to ensure that the opportunity can be maximised. Australia would also need to produce these goods in a cost-competitive way to ensure that there is sufficient demand from the market for these products.

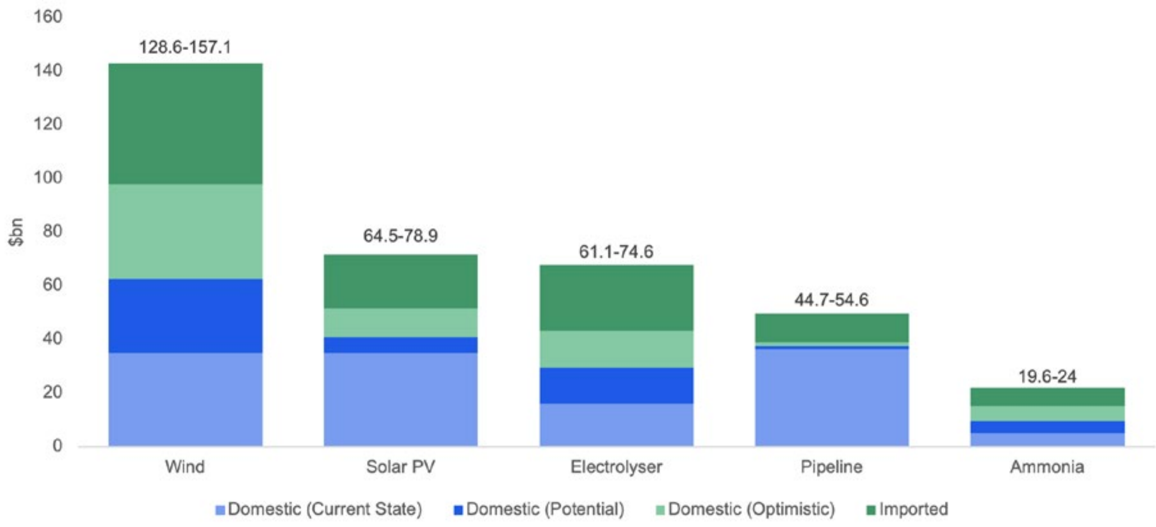


Figure 23 Potential investment by selected larger nodes ($bn)

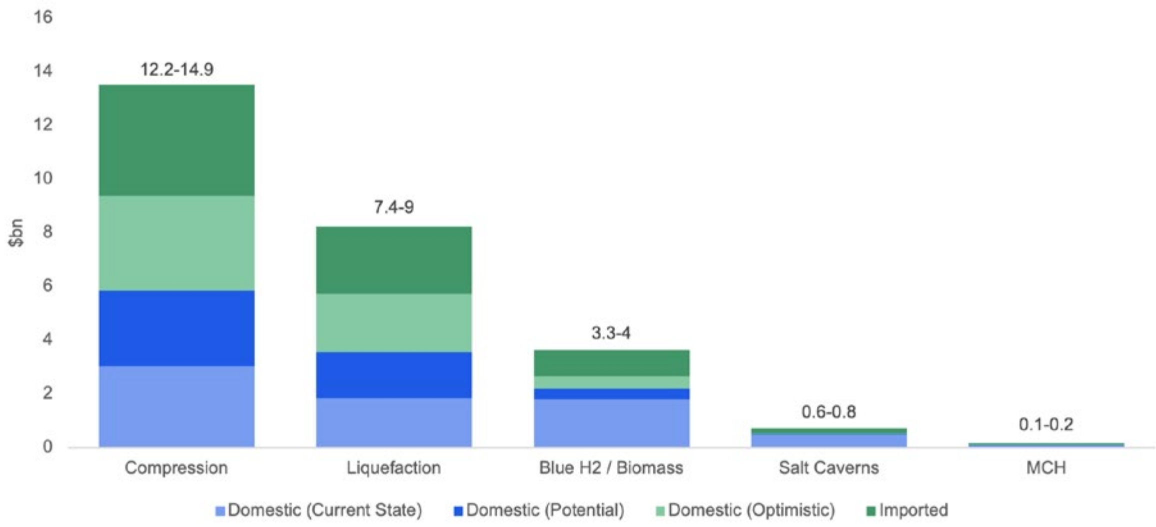


Figure 24 Potential investment by selected smaller nodes ($bn)

4.7.1 Optimistic impact on annual jobs in 2040

Table 6 outlines job opportunities at each node delivering approximately 9,500-11,500 additional annual jobs to the Australian economy. The increase in direct jobs would be aligned with specialised equipment manufacturing.

Table 6 Additional economic activity in 2040 under domestic (optimistic) scenario by node

Node	Additional annual jobs (FTE)	Additional annual GVA ($m)
Ammonia	800-1,000	100-120
Blue H_2 / Biomass	<100	8-10
Compression	500-600	60-80
Electrolyser	1,900-2,300	240-300
Liquefaction	300-400	40-50
MCH*	N/A	N/A
Pipeline	70-80	8-10
Salt Caverns*	N/A	N/A
Solar PV	1,900-2,300	225-275
Wind	3,900-4800	500-600
Total	**9,500-11,500**	**1,200-1,450**

* Volume too small to report

4.8 Investment phasing

Figure 25 presents an indicative time profile of the required investment over time considering the announced[69] projects to date, an indicative build time of three years and technological progress that should see the cost of certain components fall by 15%-40% by 2040. A large ramp-up of investment from 2025 is necessary, with investment averaging around $25-$30 bn a year from the latter part of the 2020s through to 2040.

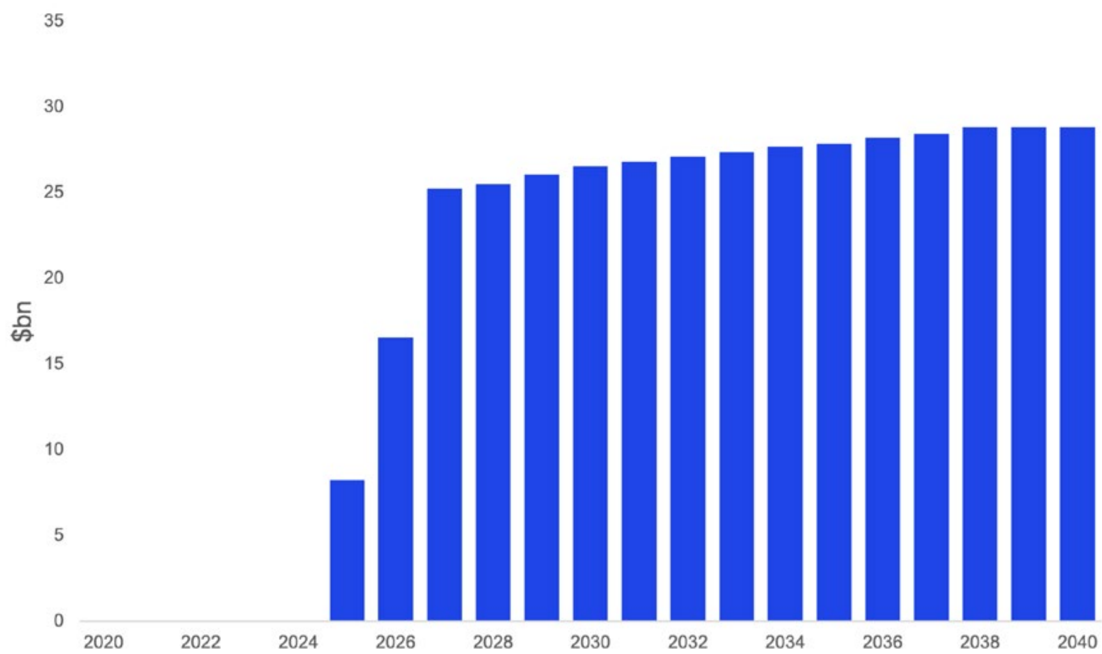


Figure 25 Investment to 2040

69 As recorded by BloombergNEF.

5. Industry capability and capacity

5.1 Overview

This section outlines the current landscape of hydrogen equipment, technology, and services with respect to the Australian industrial context. The hydrogen economy in its nascent state in Australia will require significant advancement across the equipment, skills, and services to support the 2040 production target. Building upon the mapped supply chain components in section 3 and incorporating the NHIA 2040 projections, a review of the current and required capabilities to deliver the hydrogen ambitions has been carried out.

The analysis has focussed on the current technical capability from similar industries, the number of competitors and the overall maturity of the sector to focus on the priority areas to establish a hydrogen economy.

With content from the supply chain mapping in section 3, Table 7 outlines the scale of infrastructure needed in Australia to produce 9.5MMT per annum of hydrogen by 2040.

Table 7 Infrastructure requirements

Supply chain node	Demand to reach the 2040 hydrogen production target
Renewable energy generation	• Over 246M solar panels installed in over 2,700km^2 of land • Over 12,800 control units (including PCU, control cabins and inverters) • Up to 22,927WTG at 3.3MW each • Over 270,000km of cabling
Water treatment	• 82GL for electrolyser feedstock and 192GL for cooling requirements
Electrolysis	• Over 9,500 5MW electrolysers with up to 51GW of energy
Anaerobic digestion or gasification (biomass production)	• 32 regasification plants
Natural gas reforming and carbon, capture and storage (fossil fuel processing with CCS)	• Up to 126MMT of hydrogen produced from natural gas reforming with carbon capture and storage
Hydrogen compression	• 117 large-scale compressors (30 bar to 350 bar) • 1,030 medium-scale compressors (30 bar to 100 bar)
Hydrogen storage	• 5,200 hydrogen storage tanks at 10t HYD capacity
Distribution	• Over 26,000km of new straight-line pipes • Over 103,000km of new multi-directional pipes
Alternative carrier production	• Assumed that 80% of exported hydrogen is in the form of ammonia
Hydrogen liquefaction	• Assumed that 20% of exported hydrogen is liquefied
Hydrogen fuel cell	• Considered at the demand point
Hydrogen combustion systems	• Considered at the demand point
Dispensing / refuelling	• Over 5.2MMT of hydrogen per annum for domestic • Over 4.3MMT of hydrogen per annum for export

5.2 Methodology

The hydrogen supply chain is a complex ecosystem and leverages several existing technologies, as well as being contingent on a number of emerging technologies. The following analysis methods were applied to evaluate current industry capability and capacity:

1. **Matched pairs analysis** – Comparing each supply chain node against each other utilising pre-determined definitions of 'Complexity' and 'Local advantage' to evaluate equipment groups at a high level and gauge the most promising opportunities for Australia.
2. **Supply chain capability assessment** – To gauge the capability of suppliers in Australia and globally, a desktop review was undertaken on potential organisations that may be part of a future hydrogen economy. A detailed list is provided in Appendix C. Over 150 companies were captured across the mapped supply chain. A Red-Amber-Green (RAG) analysis was applied to identify key gaps in the Australian market.
3. **Technological readiness assessment (TRL)** – A review of the TRL was applied to each detailed equipment piece in the supply chain node. This assessment helps identify which areas are already being developed and may therefore present the greatest opportunity in Australia.

5.3 Analysis

5.3.1 Matched pairs analysis

Arup conducted a high-level scan of the hydrogen economy supply chain nodes to determine the high-priority areas for focus in Australia. This assessment was conducted based on a qualitative matched-pairs analysis with the following definitions:

- **Complexity:** Degree to which new specialist skills and /or value-add inputs are needed.
- **Local advantage:** The extent to which this node is advantageous in Australia due to growing technical capability, R&D, and experience in similar industries.

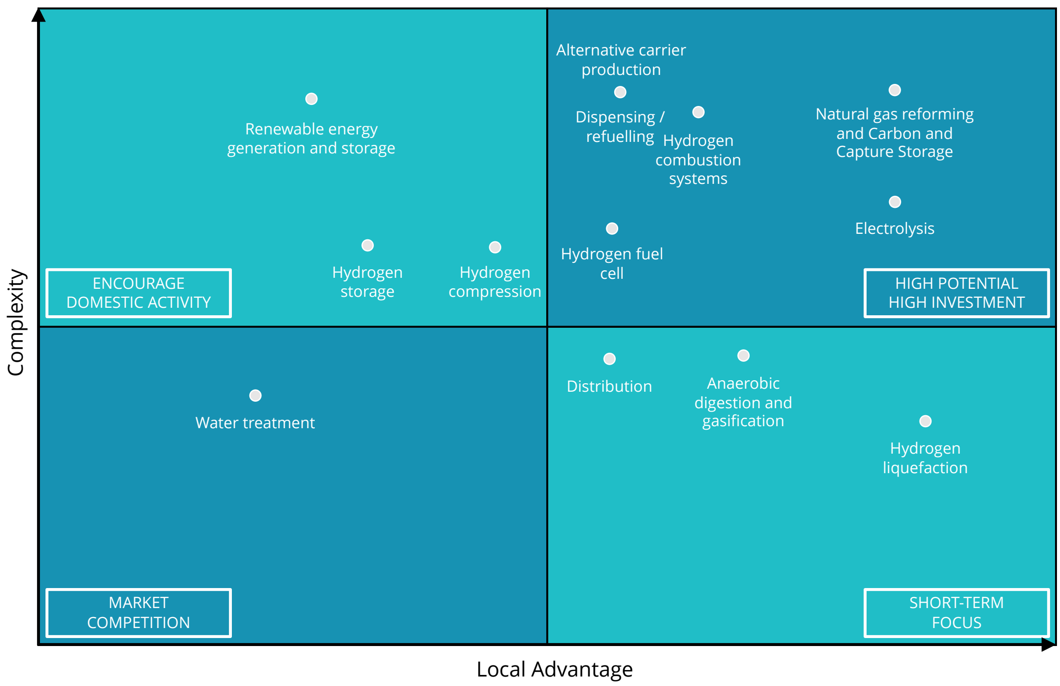


Figure 26 Matched pairs analysis on complexity and local advantage

The right-hand side of Figure 26 identifies priority hydrogen segments that can be targeted by leveraging Australia's technical capability and growing experience. Items on this side of the quadrant are split between high potential value add components and lower complexity short-term focus segments. In the high potential, high investment category, these components require further investment in technological development.

However, given the current progress in R&D and relevancy to similar industries, it provides Australia with a competitive edge. These hydrogen segments may also represent an opportunity to export globally, given the high degree of complexity and value add potential.

The left-hand side of Figure 26 outlines hydrogen segments where Australia has a lower competitive advantage given the maturity of the industry and lesser focus on R&D. Items such as renewable energy storage and water treatment are well-established and should be less of a priority for focus and investment.

This assessment conveys where the opportunities are based on the definitions of complexity and local advantage. This assessment alone identifies where each supply chain node sits relative to each other. Further analysis into the extent of local and international competition and technological maturity to further distil opportunities for Australia is outlined below.

5.3.2 RAG analysis

An analysis of supply chain capability has been carried out using a RAG (Red-Amber-Green) assessment to highlight areas of strength and weakness related to the number of suppliers, range of capabilities, and existing integration of each supply chain node within the existing HETS supply chain. The purpose of this analysis is to provide an indication of each HETS supply chain node's industry capability and competitiveness at a high level, comparing Australian suppliers against international suppliers. We acknowledge that specific elements within the supply chain nodes may be advantageous within an Australian market and have highlighted these within the text.

The assessment approach is limited due to the controlled list of supplier companies and supply chain node equipment included and publicly available information regarding the capability and integration of each supplier. However, it provides an indicative illustration to assess the capacity of Australian firms within each supply chain node to significantly expand or the level of investment support they might need.

It is recommended that a follow-up study should be considered, in which individual supply chain nodes could be investigated in greater detail to assess their raw inputs, skills and capabilities in Australia.

Table 8 outlines the RAG criteria, rationale and rating definitions used for the assessment. Table 9 illustrates the RAG assessment ratings.

Table 8 RAG analysis criteria, rationale, and rating definitions

		Rating		
		1	2	3
Number of suppliers	How many suppliers are related to the supply chain node	More than 10	Between 5 and 10	Fewer than 5
Capability	What is the range of capability of the suppliers within the supply chain node	Sufficient capability, minor investment required	Some capability, requires investment	Little to no capability, significant investment required
Integration	How well established is the supply chain node within the HETS supply chain	Integrated and established within the HETS supply chain	Defined supply chain node but not established within HETS supply chain	Not well defined

Table 9 HETS supply chain node RAG analysis summary

RAG analysis table	Rating					
	Australian suppliers			International suppliers		
Water treatment	2	1	1	3	2	3
Renewable energy generation	3	3	3	1	1	1
Electrolysis	2	2	2	1	1	1
Anaerobic digestion or gasification	1	1	2	2	1	2
Natural gas reforming and carbon capture and storage	3	3	3	1	1	2
Hydrogen compression	3	2	2	1	1	1
Hydrogen storage	2	2	2	1	1	2
Hydrogen fuel cell	3	3	3	2	1	2
Hydrogen liquefaction	3	3	3	2	1	2
Alternative carrier production	3	3	3	2	1	2
Hydrogen combustion systems	3	3	3	2	2	2
Dispensing / refuelling	3	3	3	1	1	3
Distribution	1	1	3	1	2	3

Based on the RAG Analysis, the following observations are outlined for each supply chain node of interest. The observations reflect the local versus international supplier capability, competition, and integration, in addition to some insights relevant to the HETS supply chain nodes.

Renewable energy generation

The renewable energy generation supply chain node displays a lack of Australian suppliers, supplier capability and integration within the overarching HETS supply chain. International suppliers dominate this supply chain node, providing a range of capabilities and, as such, are likely to leverage this to integrate with future HETS supply chain developments.

For local suppliers to compete within this supply chain node, significant investment will be required, and existing capabilities will need to be leveraged in key equipment areas such as battery energy storage.

Considerable amounts of renewable energy generation will be required to produce low-carbon hydrogen. The cost reductions of the renewable energy generating equipment offered by international suppliers will be advantageous (if not critical) to accelerate the deployment of hydrogen production infrastructure in Australia. This includes technologies such as wind and solar, where there are limited Australian companies contributing to the HETS supply chain.

Local suppliers may be best placed to provide support to existing internationally based companies that operate in Australia rather than trying to compete with them directly. In addition, Australia has High Purity Quartz (HPQ) reserves that could meet the growing demand for silica to manufacture solar cells.

Electrolysis

The electrolysis supply chain node faces strong capability and competition from international suppliers. Australian suppliers could compete, but an appetite for investment needs to be considered alongside the technology and equipment offerings of Australian suppliers.

Electrolysis is vital for producing hydrogen, and future supply chains will need reduced production costs. If Australian suppliers can offer technology that is cost-competitive to international offerings, this will benefit the deployment of hydrogen infrastructure. This presents Australia with an opportunity for export to the global market. This is a supply chain node that could leverage existing mining industry experience and natural resources to reduce technology capital costs through local raw materials and/or processing materials for electrolytic catalysts, which are typically the major cost component of electrolysers.

Anaerobic digestion or gasification

The anaerobic digestion or gasification supply chain node illustrates a competitive offering for both Australian companies and international suppliers who could potentially participate in the Australian market. Both provide a range of capabilities and limited integration with the HETS supply chain. This node provides an alternative method of producing hydrogen and is dependent on materials from other supply chain waste streams, which could prove beneficial to leverage the circular economy benefits.

Natural gas reforming and carbon capture and storage

The natural gas reforming and carbon capture and storage supply chain node illustrates limited Australian suppliers, supplier capability and integration within the HETS supply chain. However, Australia does have advantages in terms of significant CO_2 storage potential and an abundant supply of gas that could be used to grow the supply chain.

International suppliers dominate this supply chain node, providing a range of capabilities that could be leveraged to integrate with future HETS supply chain developments. For local suppliers to compete within this supply chain node, significant investment will be required, and existing capabilities will need to be leveraged in key equipment areas such as direct air capture.

Depending on future blue hydrogen developments, natural gas reformation and carbon capture and storage equipment, technology and services may provide immediate decarbonisation potential. International suppliers have limited integration within this supply chain node, therefore providing a potential opportunity to invest in Australian suppliers to compete locally and globally.

Hydrogen compression

There is predicted to be a significant amount of demand for compressors in Australia; however, there is a lack of Australian hydrogen compressor suppliers, and the hydrogen compression supply chain is currently dominated by international suppliers. Compression technology is mature and international suppliers will likely provide a range of compression options across varying compressor scales, leveraging their manufacturing scale and experience. Unless Australian suppliers provide a cost-competitive option, there may be limited opportunities to establish a firm position in this supply chain node. However, if Australian suppliers provide a cost-competitive solution, perhaps within a specific section of this market, this could create an opportunity to compete in the international market.

Hydrogen storage

The hydrogen storage supply chain node shows a moderate number of Australian suppliers with capability across the node, except in salt cavern hydrogen storage equipment and/or technology. International suppliers are present and capable in this supply chain node, however, with limited integration across the HETS supply chain.

Hydrogen storage is critical. Future supply chains will require decreased storage costs, and if Australian suppliers can offer technology that is cost-competitive to international offerings, this will benefit the deployment of hydrogen infrastructure. There is an opportunity for Australia to be an exporter of hydrogen storage equipment.

Hydrogen fuel cell

The hydrogen fuel cell supply chain node illustrates relatively high international supplier competition compared to Australia's limited number of companies operating in this node. There are relatively few Australian hydrogen fuel cell suppliers. Fuel cell technology is mature, and international suppliers will likely provide a range of options, leveraging their economies of manufacture. Unless Australian suppliers provide a cost-competitive option, there may be limited opportunity to leverage a position in this supply chain node.

Novel fuel cell technology is being developed in Australia. If innovative technologies prove to illustrate cost competitiveness, an investment could be made to foster Australian capability within the supply chain node and enable Australia to take advantage of a strong export opportunity for hydrogen fuel cell technology.

Dispensing / refuelling

The overall dispensing/refuelling supply chain node shows a lack of Australian suppliers, supplier capability and integration within the HETS supply chain. International suppliers dominate this supply chain node. However, there is some Australian capability related to hydrogen refuelling and dispensing. For other areas, such as hydrogen metering systems and safety systems, international suppliers already have a significant presence in this space, and local suppliers may be best to support such global companies already operating in Australia rather than trying to compete with them directly.

Hydrogen combustion systems

Combustion systems relate to large gas-fired appliances, in particular for high heat users, which include hydrogen burners (air mixing, nozzles), specialised valves, metering, safety valves, and flue gas handling. These hydrogen-fuelled appliances will need to be integrated with specialised industrial kilns, furnaces, ovens, incinerators, thermal oxidisers, calciners, etc. There are a limited number of Australian manufacturers in this node to support a transition from traditional gas-fired appliances to hydrogen combustion systems. However, the technical knowledge is available to support this future supply chain and is well placed to provide the necessary integration role between global component original equipment manufacturers (OEM), domestic industry, and local regulations. There is existing international capability in this space that could be leveraged to promote the growth of the Australian supply chain.

Distribution

The distribution supply chain node has numerous Australian and international suppliers who offer capability across the supply chain, although they may not be currently integrated within the HETS supply chain. This presents an opportunity for Australian suppliers to compete and leverage their capability to fully integrate across the HETS supply chain.

Australia is a nation with large distances between its major cities and ports, providing an opportunity for suppliers to grow to meet demand in this node in areas such as long-haul freight.

RAG analysis summary

The number and capacity of hydrogen production facilities in Australia are relatively small compared to what is required for a successful and sufficient low-carbon hydrogen economy. Due to the relative novelty of the Australian HETS supply chain, some nodes have limited integration with the wider HETS supply chain. This will change as the demand for hydrogen increases and the market grows.

Table 10 summarises the supply chain nodes in which Australian suppliers are best placed to support the HETS industry compared to international firms. This has been broken into three categories, (1) Opportunity to compete, (2) Limited barriers to compete and (3) Significant barriers to compete.

Table 10 RAG analysis supply chain node competition summary

Opportunity for Australian suppliers to compete	Limited barriers to compete	Significant barriers to compete
• Hydrogen storage • Electrolysis • Water treatment • Distribution • Hydrogen combustion systems	• Anaerobic digestion and gasification • Hydrogen fuel cell	• Hydrogen liquefaction • Hydrogen compression • Renewable energy generation • Natural gas and carbon capture • Dispensing / refuelling • Alternative carrier production

5.3.3 Technological Readiness Level (TRL) analysis

An analysis of key HETS supply chain technologies has been performed to provide insight into the current state of industry technology and to identify areas where technology is still advancing and therefore presents an opportunity for Australian suppliers to compete and lead.

The TRL scale is an internationally recognised scale for describing where new technology is in relation to the R&D process. For this assessment, we have based our TRL rankings on the IEA classification detailed in Appendix C.

Table 11 outlines each supply chain node, the evaluated equipment and respective equipment TRL ranking and the average TRL for the supply chain node.

Table 11 TRL scores by node and equipment[70]

Supply chain node	Equipment	TRL equipment rating	TRL node average rating
Water treatment	Sewage treatment	11	11.0
	Reverse osmosis treatment	11	
	UV treatment	11	
	Ultrafiltration	11	
Renewable energy generation	Solar panels	11	11.0
	Wind turbines	11	
	BESS	11	
	Inverters	11	
	Rectifiers	11	
	Transformers	11	
Electrolysis	PEM electrolyser	10	7.4
	Alkaline electrolyser	10	
	Solid oxide electrolyser	7	
	Anion exchange membrane electrolyser	6	
	Capillary fed electrolyser	4	
Anaerobic digestion or gasification	Anaerobic digestor	10	8.0
	Biomass gasification/pyrolysis	6	
Natural gas reforming and carbon capture and storage	Steam Methane Reforming	11	9.5
	Carbon capture, transport, and storage	8	
Hydrogen compression	Hydrogen compressor	11	11
Hydrogen storage	MCH tank	10	9.75
	Pressure vessels	11	
	Liquid hydrogen tanks	9	
	Salt cavern	9	
Hydrogen fuel cell	Fuel cell	10	10.0
Hydrogen liquefaction	Hydrogen liquefaction plant	9	10.0
	Heat exchangers	11	
Alternative carrier production	Ammonia synthesis technology	11	10.0
	MCH conversion technology	6	
	Haber-Bosch catalysts	11	
	Air separation unit	11	
	Haber-Bosch reactors	11	
Hydrogen combustion systems	Hydrogen-integrated process equipment	8	9.5
	Hydrogen-compatible components (burners, valves, flame arresters, instruments)	11	
Dispensing / refuelling	Metering systems	11	10.0
	Hydrogen safety systems	9	
	Hydrogen refuelling and dispensing	10	
Distribution	Piping	11	10.0
	Liquid hydrogen tanker	7	
	Compressed hydrogen tube trailer	10	
	Ammonia tanker	11	
	MCH/solvent tanker	11	

70 TRL ratings sourced from IEA ETP Clean Energy Technology Guide, https://www.iea.org/data-and-statistics/data-tools/etp-clean-energy-technology-guide and IEA Energy Technology Perspectives, Clean Energy Technology Guide (2020), https://iea.blob.core.windows.net/assets/355d9b26-b38c-476c-b9fa-0afa34742800/iea_technology-guide-poster.pdf

Based on the TRL analysis, the following observations are outlined for each supply chain node that presents an opportunity within the Australian supply chain.

Electrolysis

Based on the equipment evaluated in the electrolysis supply chain node, the TRL ranges from 4 to 10, with an average TRL rating of 7.4. This illustrates an opportunity for suppliers to innovate and produce competitive equipment if adequate investment is provided. There is an opportunity for the technologies which are available commercially but need greater deployment at scale and/or further cost reductions, as well as the technologies which require significant technical development prior to becoming commercially available.

Australian firms are involved in the development of electrolyser technologies such as solid oxide and capillary-fed electrolysers. Solid oxide electrolyser technology has better electrical efficiencies (~90%) compared to PEM and alkaline fuel cells (60-75%), and they have the potential to operate in reverse and act as a fuel cell. This reversible capability could be beneficial for supporting electric grid resilience via hydrogen. This offers a strong opportunity for Australian suppliers to compete in this supply chain node as well as the electrolysis supply chain node both locally and globally. Providing a node upon which Australia could leverage further supply chain opportunities due to the criticality of the electrolysis in the production of green hydrogen.

Hydrogen fuel cell

The TRL of 10 reflects existing commercially available technologies such as phosphoric acid, PEM and alkaline fuel cells. However, other novel technologies, such as solid oxide fuel cells, are being developed in Australia by companies like Ceramic Fuel Cells Limited, a CSIRO organisation. As mentioned, solid oxide electrolytic cells can be operated as fuel cells and as electrolysis cells. Existing stack sizes of 300kW are commercially available. However, the reversible operation has not been demonstrated. Solid oxide cells do not require rare earth element catalysts like platinum, which is common in PEM and phosphoric acid fuel cells; therefore, solid oxide fuel cells offer a significant advantage over existing alternative technologies when considering supply chain material constraints.

Hydrogen storage

The TRL ranges from 9 to 11, with an average TRL rating of 9.75. This highlights a node in which emerging equipment developments are required. Hydrogen storage across a range of scales and durations is necessary for a successful hydrogen economy. There is a lack of Australian suppliers providing hydrogen storage equipment. However, there are pressure vessel manufacturers in Australia that could transition to provide these solutions. In addition, long-duration and large-scale storage technologies are relatively novel, presenting an opportunity for Australian firms to innovate and compete.

Hydrogen carrier storage technologies are also considered emerging technology and with further investment, could be an opportunity to export this internationally. The size of storage required has been addressed in Table 7, and the materials used have been specified in section 3.6.1. The type of storage equipment and technology is assessed in section 5.3.3.

Distribution

The TRL ranges from 7 to 11, with an average TRL rating of 10. This highlights a node in which emerging equipment developments are required. There are several Australian firms with the capability to manufacture specialised tank containers, road tankers and aerospace tanks. This presents an opportunity to develop and compete within the supply chain node and across the wider HETS supply chain, both locally and globally.

MCH is a Liquid Organic Hydrogen Carrier that can be used for the distribution and storage of hydrogen. LOHCs are typically liquid oil derivatives that are loaded or charged with hydrogen (hydrogenation) at the point of export or storage and then unloaded or discharged (dehydrogenation) at the point of import or use. MCH use is not currently carried out on a large scale and is limited by the size of hydrogenation and dehydrogenation plants available. LOHC systems are well suited to long-term storage since they offer loss-free storage of hydrogen with a reasonable volumetric and gravimetric density, minimised safety concerns, as well as an opportunity to repurpose existing infrastructure from the oil and gas industry. If Australia developed a strong capability to provide MCH equipment and technology, this would offer a strong export opportunity and as well as bolster the capability to export hydrogen safely in large quantities.

Anaerobic digestion or gasification

The TRL ranges from 6 to 10 with an average TRL rating of 8. This highlights a node in which emerging equipment developments and commercial demonstrations are required. There are many Australian firms with existing capability in this supply chain node, including design and equipment supply services relating to anaerobic digestors and biomass gasification. This illustrates existing capability in this node and the opportunity for suppliers to continue to innovate and produce competitive equipment if adequate investment is provided.

Hydrogen combustion systems

The TRL ranges from 8 to 11 with an average TRL rating of 9.5. Combustion systems relate to large gas-fired appliances, in particular for high heat users, which include hydrogen burners (air mixing, nozzles), valves, metering, safety valves, and flue gas handling. These hydrogen-fuelled appliances will need to be integrated with specialised industrial kilns, furnaces, ovens, incinerators, thermal oxidisers, calciners, etc., which are commonly direct-fired and purpose-built. The components that make up these systems, such as burners and valves, have a high TRL, given their widespread use in oil and gas. Industrial hydrogen-fired kilns and equipment, such as glass furnaces, DRI furnaces, thermal oxidisers, calciners, etc., are at the demonstration stage.

Dispensing / refuelling

The TRL ranges from 9 to 11, with an average TRL rating of 10. There are emerging domestic equipment and technology providers for refuelling and dispensing. Given the relatively high TRL for this equipment type, this presents an opportunity for Australian manufacturers already operating in this space to expand operations, as well as for new companies to enter the market and support this supply chain node.

5.4 Analysis summary

Across the HETS supply chain, there is a wide range of international suppliers with the capability to provide equipment, technology and services compared to Australian suppliers who have strong capabilities concentrated in a few supply chain nodes. To further develop the HETS supply chain and maximise the benefits for Australia, a mixture of local and international supply chain competition will be required.

Recognising the international nature of modern supply chains, few manufacturers are based solely in one country and most source their components from a range of different nations. There are several supply chain business configurations that may be feasible within the HETS supply chain that provide varying benefits for Australia. For example:

- International suppliers with an Australian registered subsidiary or local stockist can supply Australian projects and manage the process of importing their products from a variety of countries where they manufacture.
- Australian businesses to licence international technology for manufacture in Australia.
- Some suppliers may be incentivised to consider manufacturing sites in Australia which would provide considerable benefits depending on the forecast market size.
- International and national supply partnerships that focus on operation and maintenance or export to third markets close to Australia.

However, the greatest benefits for the Australian economy accrue when an Australian-based company manufactures within Australia.

Considering the above perspectives, the following supply chain nodes are the most advantageous in relation to local advantage and industry competition and in which investment should be prioritised:

- Electrolysis.
- Hydrogen storage.
- Distribution.

Novel, cost competitive, safe, and reliable technologies will be needed across the supply chain creating a competitive market as the number of technologies offered by suppliers are developed and commercialised. A secondary set of supply chain nodes should also be considered; however, these nodes involve emerging technologies and, therefore, inherently have a degree of developmental uncertainty:

- Hydrogen fuel cell.
- Anaerobic digestion and gasification.

The hydrogen supply chain will play a key role in transitioning hard-to-abate industries, especially those involving high-heat processes. Domestic firms are well placed to facilitate and support the transition of these existing operations by integrating established hydrogen components and equipment into existing or new manufacturing/processing plants within the local regulatory context.

6. Complimentary sectors and support services

6.1 Complimentary sectors

Australia is well-positioned to lead the global hydrogen economy leveraging on the existing services and industry knowledge of complementary sectors. Data from the Australian Bureau of Statistics (ABS) showcases the volume of employees in each industry segment as well as the industry earnings movement between 2020 and 2021.

The volume of employees and earnings movement in each industry are important metrics to map against the hydrogen supply chain nodes to demonstrate personnel experience and industry growth. Industries in bold represent sectors relevant to the emerging hydrogen economy and provide a foundation for the HETS supply chain to grow.

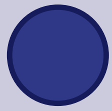
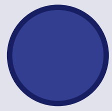
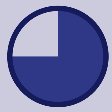
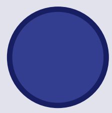
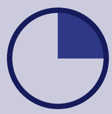
Table 12 Snapshot of employees and growth in industries (source: ABS)

Industry	Number of total employees ('000, as of September 2021)	The proportion of total employees (as of September 2021)	Industry earnings movement between 2020-2021 ($m)
Health care and social assistance	1,937	15%	2,781*
Retail trade	1,329	10%	6,144
Professional, scientific and technical services	**1,196**	**9%**	**6,409**
Construction	**1,134**	**9%**	**5,262**
Accommodation and food services	988	7%	3,293
Education and training	**915**	**7%**	**2,078***
Manufacturing	**876**	**7%**	**2,630**
Public administration and safety	724	5%	233*
Administrative and support services	**685**	**5%**	**1,053**
Transport, postal and warehousing	604	5%	-229
Wholesale trade	568	4%	-522
Other services	508	4%	1,891
Financial and insurance services	466	4%	N/A
Agriculture, forestry and fishing	**428**	**3%**	**5,711**
Rental, hiring and real estate services	266	2%	1,681
Arts and recreation services	178	1%	854
Mining	**178**	**1%**	**6,436**
Information media and telecommunications	157	1%	-947
Electricity, gas, water and waste services	**124**	**1%**	**-806**

* Private industry

Table 13 summarises the industries with relevance to the HETS supply chain and provides a Harvey ball (refer to Table 14) ranking of relevance and justification.

Table 13 Summary of existing complementary industry relevance

Existing industry	Hydrogen supply chain node or segment	Justification	Harvey ball – sector relevance
Professional, scientific and technical services	All nodes	• Transferable skills in technology development, consultancy, legal, regulatory, and planning • Specialised knowledge is required to fully adopt the hydrogen economy • Developing and implementing industry-wide practices for hydrogen transition • Research and development to progress emerging technologies • Thought leadership from a global perspective to drive Australian transition	
Construction	All nodes	• Transferable skills and resources for hydrogen infrastructure construction • Technical expertise with hardware and software for conducting construction operations in Australia • Applying safe systems of work within HETS	
Education and training	All nodes	• Upskilling and transitioning the workforce to work in hydrogen • Provide specialist training for niche hydrogen applications	
Manufacturing	Electrolysis Fuel cell Storage Distribution Anaerobic digestion and gasification	• Leveraging best practices within HETS • Use of IoT and data analytics for production optimisation • Applying safe systems of work within HETS	
Administrative and support services	All nodes	• Knowledge of the Australian environment	

Existing industry	Hydrogen supply chain node or segment	Justification	Harvey ball – sector relevance
Agriculture, forestry and fishing	Dispensing / refuelling Distribution Anaerobic digestion and gasification	• Agriculture will be an end user of hydrogen and associated technology and equipment • Potential for sector coupling utilising hydrogen in the energy system	◔
Mining	Distribution	• Transition workforce to work in HETS	◔
Electricity, gas, water and waste services	All nodes	• Critical infrastructure for hydrogen production and integration requirements will need to be well understood • Highly skilled and experienced workforce • Technical knowledge of integration systems in Australia	●

Table 14 Harvey ball relevance scale definition

Not relevant	Minor relevance	Some relevance	Relevant	Relevant and required
○	◔	◑	◕	●

6.2 Hydrogen support services

The hydrogen economy, along with direct employment opportunities, will also drive growth in ancillary and indirect jobs. From the economic analysis, it was determined that an additional ~48,000 jobs in wider employment could be provided in parallel services. Hydrogen support services to bolster the hydrogen economy are included in the table 15 (non-exhaustive list).

Table 15 Hydrogen support services

Hydrogen supporting services	Capabilities	Recommendations
Health and Safety (H&S)	• Gas pipeline management • Emergency response and management • Carbon accounting • Delivery and supply risk management	H&S is an important area to focus on in the short term to accelerate the hydrogen economy. Currently, the health and safety standards are not as defined and will require clear definitions, processes, and regulatory oversight to alleviate H&S concerns surrounding hydrogen.
Environment	• Environmental impact assessment • Environmental approvals and legislation • Environmental audits and management	Australia is well versed in conducting environmental assessments for large new infrastructure. Whilst many learnings can be transferred from existing projects, the hydrogen economy is diverse, and projects often span across various environmental settings with an impact on air, water, land, and carbon. Current regulatory approvals can be difficult to navigate. A systemic approach to environmental regulations may be required to help ease the burden for new hydrogen projects.
Finance and legal	• Risk analysis • Legal services • Economics and business case • Strategic advisory work • Cost consulting • Private equity and investment analysis	Surrounding finance and legal support will be key to driving hydrogen investments. This is particularly relevant for projects at the feasibility and concept stage, whereby financial and economic feasibility is a key driving risk for investment.
Education and training	• Undergraduate and graduate training • Industry courses for skilled professionals • Hydrogen use education programmes for consumers • Recruitment agencies • Introduction to hydrogen products and solutions • Upskilling for new and existing technicians	A substantial amount of training will be needed for new and existing personnel in the hydrogen industry. As a result, there should be a clear alignment between national goals and tertiary education programmes to support the hydrogen economy.

Hydrogen supporting services	Capabilities	Recommendations
Marketing and stakeholder engagement	• Public awareness • Stakeholder engagement mapping • Energy transition advice • Hydrogen safety and advocacy	As a nascent industry, hydrogen is less widely known in the public eye. Marketing and stakeholder engagement services will be required to educate and inform public awareness of hydrogen and how it is critical for the energy transition.
Policy and regulatory	• Developing hydrogen standards • Industry-wide practices for the energy transition • Public funding support • Lobby and policy development • Hydrogen development regulation • Hydrogen construction standards	From a policy perspective, the regulations are unclear and are still being defined. Clear standards and processes for hydrogen adoption can be prioritised in the short run to aid both the private and public sectors in accelerating the hydrogen economy.

Private organisations often react to the changing conditions of market forces and will respond accordingly as the hydrogen economy in Australia advances. To enable this, regulatory barriers to entry, defined policies and processes, and support of the industry is essential in the short term. A global and national hydrogen supply chain presents challenges in scaling, testing, and understanding the market. Thus, in the short-term, developing hydrogen should be a priority focus. Through local demonstrations, defining the regulatory pathways and health and safety standards at a regional scale can be leveraged across the domestic market. The growth of new hydrogen industries in localised areas can provide an evidence base for longer-term benefits and strategic investments into the hydrogen supply chain. At a regional level, practical steps to drive activity include:

- Developing a regional vision and strategy for hydrogen from both public and private sector perspectives to unify ambitions and strategic objectives.
- Upskill and train regional support services for the hydrogen economy and rollout programmes and courses to support learning opportunities.
- Encouraging partnering and collaboration between local and large corporate entities to ensure hydrogen projects benefit the wider community.
- Stimulate the development of hydrogen-based start-ups and entrepreneurial activity in the region.
- Provide public support mechanisms to support supply chain companies through a regional agency to develop engagement programmes, training, and support.
- Promote and engage with tertiary bodies to develop undergraduate and graduate university offerings and drive hydrogen-related R&D.
- Appoint regional champions that can share knowledge and lessons learnt between public and private sectors across the region with a ‘continuous improvement’ philosophy and open collaboration.

7. Barriers to market entry

The purpose of this section is to identify and assess constraints and barriers to market entry for Australian firms, taken from a holistic perspective of the supply chain. The HETS supply chain nodes are at varying levels of capability and integration within the wider supply chain. A Porter Diamond analysis and a Strengths, Weaknesses, Opportunities, Threats (SWOT) analysis were applied to evaluate the constraints and barriers.

7.1 Porter Diamond analysis

The Porter Diamond theory is a model designed to help understand the competitive advantage that nations or groups possess due to certain demand and factor conditions, firm strategy, and support of related industries available and to explain how they can act as catalysts to improve a country's position in a globally competitive economic environment. The following categories are assessed to derive constraints:

- Demand conditions - Domestic and export demand and the complexity of demand.
- Factor conditions - The natural, capital, and human resources available.
- Firm strategy - Strategy, structure, and rivalry of companies in the sector.
- Related industries - Industries that supply, distribute, or are otherwise related to the industry being examined.

The supply chain constraints, their impact and potential mitigation options are detailed in Table 16.

Table 16 Supply chain constraints identification and analysis

Factor	Constraint	Impact on supply chain	Potential mitigation
Demand condition	Lack of established market infrastructure, activity, and demand	Limited supply chain drivers	Focus on separate elements of the supply chain. Map capability, areas of demand and activity
	Lack of clarity on priorities for domestic market demand	Inhibited growth of the supply chain	Prepare a holistic supply chain development plan
	Lack of clarity on priorities for international market demand	Inhibited growth of the supply chain	Prepare a holistic supply chain development plan
	Market attitudes to non-renewable hydrogen production	Limited market reach	Positive commercial and public engagement. Clear messaging from government and public organisations on hydrogen's role and benefits
	Global competition to hydrogen supply chain investment	Hesitant investment in Australian supply chain development	Incentivise competition by building upon strong capability within supply chain nodes with a local advantage
	Lack of regulations and standards surrounding hydrogen	Limited clarity of market requirements	Prepare a holistic supply chain development plan
	Lack of ports and shipping infrastructure	Inhibited supply chain and market development	Prepare a holistic supply chain development plan
	Some hydrogen technology and equipment still need development and are not commercially available	Related market development weakened	Provide investment and support options to key technology providers

Factor	Constraint	Impact on supply chain	Potential mitigation
Factor condition	Uncertainty around required infrastructure developments	Limited rationale for supply chain/ market development	Prepare a holistic supply chain development plan Clear messaging from government and public organisations on hydrogen's role and benefits
	Limited access to hydrogen based on clusters, hubs, and precincts	Geographic approach to developing supply chain	Prepare a holistic supply chain development plan
	Negative perception of hydrogen and associated energy carriers' safety	Limits market development	Positive commercial and public engagement. Clear messaging from government and public organisations on hydrogen's role and benefits
	Lack of skilled workforce	Inhibited supply chain development	Prepare a holistic supply chain development plan. Map capability, areas of demand and activity. Leverage skills in complementary sectors
	Regulations, codes, and standards not appropriate or available	Inhibited supply chain development	Prepare a holistic supply chain development plan. Invest in regulatory framework development. Lessons learnt from other countries to accelerate the development
Firm strategy	Competition with global supply chain suppliers	Uncertainty around where to focus growth inhibits local-global supply chain integration developments	Support collaboration and partnerships
	Lack of investment in Australian equipment, technology, and services	Inhibited supply chain development	Catalyse through trials and demonstrations
	Limited commercialisation of the Australian R&D portfolio	Inhibited supply chain development	Catalyse through trials and demonstrations
Related industries	Limited engagement across the industry to support hydrogen	Inhibited supply chain development	Support collaboration and partnerships
	Lack of collaboration and cooperation to develop a supply chain	Inhibited supply chain development	Support collaboration and partnerships
	Lack of transparency to transition skills from oil and gas to hydrogen	Lack of skilled resources to support supply chain development	Prepare a holistic supply chain development plan. Map capability, areas of demand and activity

7.2 SWOT analysis

A SWOT analysis of the Australian HETS supply chain has been completed based on a review of the evidence gathered in this study. This is presented below in Table 17.

Table 17 SWOT analysis

Strengths	Weaknesses
• Australian Hydrogen capability, export, and decarbonisation strategies – a commitment to net zero • Australian-based technology providers for electrolysis, hydrogen storage, anaerobic digestion and gasification, hydrogen fuel cell, and distribution supply chain nodes • Industrial commitment to progress solutions • Capacity to leverage skills and workforce from complementary sectors such as construction, mining, and manufacture • Commitment to geographically implement hydrogen hubs at or nearby ports • Internationally trusted trading partner with established trading relationships • Salt cavern capacity for hydrogen storage • State ambitions for up to 80% renewable electricity mix within the Australian electric grid • Government and industry focus on resilient global supply chains • Strong R&D, education and training capability • Geographical size, access to sun and wind resources • Experience in mobilising and executing major capital development projects	• Lack of clarity on supply chain development priorities • Shortage of cost-competitive hydrogen production technologies • Shortage of suppliers to provide Hydrogen Liquefaction, Alternative Carrier Production and Dispensing / Refuelling supply chain node technology and equipment • For blue hydrogen, carbon capture and storage suppliers are limited • The volatility of electricity costs impacted by global market fluctuations
Opportunities	**Threats**
• Widespread conversion of equipment and infrastructure to accommodate hydrogen • Develop commercial offerings in electrolysis, hydrogen storage, anaerobic digestion and gasification, fuel cells and distribution supply chain nodes • Develop capabilities in the design and engineering of salt cavern technology • Large-scale hydrogen export • Become the market leader in the export of clean hydrogen • Foster skills in complementary skills to support the HETS supply chain	• Competition from other hydrogen export nations • Competition from other decarbonisation solutions • Lack of high-quality water available • International supply chains can provide cost-effective solutions • Investor uncertainty • Lack of renewable electricity generation • Competition for renewable energy generation capacity • Australia is currently a long distance from key equipment manufacturing locations • Social licensing

Typical of SWOT analyses, the current perceived strengths can be undermined by future threats, whilst areas of weakness can be turned around into opportunities for expansion. The links between some of the strengths and threats and future opportunities are discussed below.

Linking strengths and threats

- Australian hydrogen strategy – building public and investor confidence takes years to develop and can be fragile and easily undermined; therefore, consistent policy and government support are critical.
- The potential for low-carbon hydrogen production is significant but may be undermined if there is not a supportive framework for hydrogen demand.
- Australian supply chain strengths in electrolysis, innovative fuel cell technology, hydrogen storage and distribution should be supported to ensure they can compete locally and/or internationally.
- Australian geographical advantages, such as large areas of land and port location and infrastructure, can be leveraged.
- For the production of green hydrogen, Australia has an advantage in terms of consistent solar resources, large areas of land and increasing offshore wind developments, which can be developed over the coming decades. However, green hydrogen will compete with these other applications for low-carbon electricity due to the demands to supply households and an increasing number of electric vehicles.

Linking weaknesses and opportunities

- Whilst Australia has a broad range of companies that have developed to support the oil and gas, mining, and oil refining industries, further engagement would be vital to understand whether many of these companies are aware of, or are actively preparing to support, the expansion of hydrogen as an energy vector.
- A follow-up study in which individual supply chain nodes could be investigated in greater detail to assess their raw inputs, skills and capabilities in Australia would be valuable.
- Early deployment within industrial clusters provides an opportunity to encourage international companies to establish Australian bases for either manufacture of equipment themselves or for packaging the compressors, ready for delivery.
- Future storage of hydrogen for daily or seasonal fluctuations will become increasingly important as hydrogen provides a greater proportion of Australia's energy supply. In the long term, this may be through offshore aquifers and exhausted gas reservoirs. In the short term, salt cavern storage may provide buffer capacity. There is a small number of salt caverns already in use in Australia. The expertise for designing salt caverns is, therefore, limited within Australia. Broader use of salt caverns for the storage of hydrogen may provide an opportunity for Australian-based consultancies to expand their knowledge base and target this market.

Summary

The Porter Diamond and SWOT Analyses show that Australia has several strengths that could support its position in the global hydrogen economy, including a strong commitment to net-zero emissions, established hydrogen capability and export strategies, and a large area of land and port locations. On the other hand, there are several key barriers to entry, including a lack of clarity on supply chain development priorities, a shortage of cost-competitive hydrogen production technologies, competition from other hydrogen export nations, and competition from other decarbonisation solutions.

Australia must take a proactive approach to support businesses to overcome these barriers. Key actions include comprehensively mapping capability and demand, preparing a holistic supply chain development plan, building positive commercial and public engagement, supporting collaboration and partnerships, leveraging skills in complementary sectors, catalysing through trials and demonstrations, and investing in R&D and workforce development.

By addressing the barriers and taking advantage of the opportunities, Australian businesses can establish a competitive position in the global hydrogen economy and contribute to a sustainable future.

8. Gap analysis

The purpose of this section is to provide an understanding of the missing links between existing Australian capability and future market demands to identify high-value, high-growth opportunities for Australian businesses.

8.1 Methodology

To further identify the high value, high growth opportunities for Australia in the hydrogen economy, the below evaluations have been undertaken to provide an indication of the steps necessary to transition from the existing capability to future capabilities required to realise the future market supply chain demands.

- Gap analysis - This compares results from stages 1 and 2 (market potential and Australian context) to summarise the supply chain nodes that present an attractive opportunity for investment.
- Opportunity mapping - Map opportunities throughout the value chain accounting for optimistic and pessimistic scenarios in line with the Australian Hydrogen Strategy.

8.2 Gap analysis and opportunity mapping

To identify gaps within the HETS market that will be needed to realise the future supply chain, Table 18 outlines the existing and 2040 supply chain node demands, highlighting the gap and whether the supply chain node presents an attractive market opportunity based on this comparison.

Table 18 Gap analysis

Existing capability	Forecast demand	Gap/opportunity	Investment opportunity attractiveness
Supply chain mode: Water Treatment			
• Established and mature technology. • Good coverage by Australian suppliers to provide key equipment. • Future electrolyser technology may be capable of handling impure water, and therefore, the supplier integration opportunity within this node may be reduced; however, it is likely that some form of water treatment will be required.	• Proximity to good quality raw water creates a more economically viable hydrogen production plant. • An additional 82GL for electrolyser feedstock and 192GL for cooling is required by 2040.	• Size and scale of local suppliers within the water treatment industry to increase. • Australian suppliers are expected to keep up with forecast demand.	Less attractive
Supply chain mode: Renewable energy generation			
• Established technology. • International suppliers dominate this supply chain node, providing a range of capability and, as such, are likely to leverage this to integrate with future HETS supply chain developments	• Aggressive acceleration of installation and operation is needed to meet hydrogen demand as well as grid demand. • Power production is one of the largest contributors to the levelised cost of hydrogen. • One of the largest industry classes necessary to support the 2040 supply chain. • Wind power has the largest annual job requirements through building, maintaining, and replacing the turbines.	• The forecast demand for this node is significant compared to its current size. • Solar panels and wind turbine blades are expected to need a significant share of investment in comparison to other specialised goods. • Requires comparatively large levels of investment for specialised equipment such as wind turbine blades. • International capability should be leveraged to accelerate the deployment of renewables in Australia with alternative business model frameworks and material supply chain opportunities investigated to maximise benefits to the Australian economy.	Less attractive

Existing capability	Forecast demand	Gap/opportunity	Investment opportunity attractiveness
Supply chain mode: Electrolysis			
• Different types of electrolysis technology are at varying stages of development. Some commercially available technologies require commercial scale-up, such as PEM and Alkaline electrolysers. Some technologies need further technological advancement before becoming commercially available. Emerging technologies have the potential to offer greater efficiencies to existing commercially available technologies. • Australian firms are involved in the development of electrolysis technologies. • Offers a strong opportunity for Australian suppliers to compete in this supply chain node locally and globally via export. • Providing a node to leverage further supply chain opportunities due to the criticality of electrolysis in the production of green hydrogen. • Suitable skills and workforce required to maximise opportunity. Existing skills in manufacturing can be utilised to leverage best practices within HETS. • Processes and systems to enable the recycling of rare and critical components at the end of product life are critical for ongoing manufacturing to meet demand.	• The scale of electrolyser installations is expected to increase dramatically by 2040 –with GW-scale increases in the next decade. • A risk of shortage or undersupply of critical materials to facilitate electrolyser manufacture globally, which can slow and discourage the deployment of electrolysis and increase system costs. • Electrolysis packages require comparatively large levels of investment for specialised equipment in relation to other supply chain nodes. • Electrolysis components are expected to need a significant share of investment in comparison to other specialised goods. • Electrolysis is one of the largest contributors to the levelised cost of hydrogen. • Operational jobs in Electrolysis are a large share of required direct jobs for the 2040 forecast. • Electricity generation is one of the largest industry classes required to support the 2040 supply chain. The forecast demand for this node is significant compared to its current size.	• Forecast demand for this node is significant in relation to its current size. • Significant levels of investment required to foster Australian capability. • Currently, commercially available technologies are manufactured abroad. • In the near term, there is an opportunity to form partnerships with international manufacturers, integrate alternative business model frameworks and investigate material supply chain opportunities, e.g. rare mineral supply for electrolyser catalysts. • In the long term, significant investment should be made to support emerging Australian technology developments and commercialisation. This also presents an export opportunity.	More attractive

Existing capability	Forecast demand	Gap/opportunity	Investment opportunity attractiveness
Supply chain mode: Anaerobic digestion or gasification			
• Anaerobic digestion technology is mature but requires commercial scale-up. • Strong Australian capability. • Provides an alternative method of producing hydrogen. It is dependent on materials from other supply chain waste streams and could prove beneficial to leverage the circular economy benefits within the HETS supply chain.	• The use of these alternative hydrogen production techniques requires available feedstock generated as an output of another process or operation, and therefore there is not anticipated to be any development of feedstock generation associated with these hydrogen production techniques. • Biomass-derived hydrogen is not anticipated to form a significant component of the production mix to meet the high volumes demanded in 2040. • Further capacity will be based on opportunistic development to take advantage of feedstock generated by other industries (commonly residues or by-products from agriculture, forestry, or pulp and paper), and therefore, it is not expected to significantly grow its market share in hydrogen production as electrolyser production ramps up.	• Limited growth is expected in this node due to reliance on opportunistic feedstock. • Any future opportunity will be on a case-by-case basis, and Australian suppliers are expected to have the capability to compete with international suppliers and deliver.	Less attractive
Supply chain mode: Natural gas reforming and carbon, capture and storage			
• Natural gas reformation is a mature technology and could be scaled up more commercially; however, carbon capture technology still requires technology developments to achieve cost reductions. • For Australian suppliers to compete within this supply chain node, significant investment will be necessary. • International suppliers have limited integration within this supply chain node.	• Several projects are currently at the feasibility or planning stage in Australia, with a total potential capacity of 43,300 t of hydrogen per year. • NHIA modelling indicates new and emerging demand will prefer electrolyser-produced hydrogen due to costs and sustainability drivers. However, it is possible that the availability of feedstock may lead to some additional development.	• Depending on future blue hydrogen developments, natural gas reformation and carbon capture and storage equipment, technology and services will be required. • Forecast demand for this node is relatively great in relation to its current size. However, it has a level of uncertainty. • Carbon capture and storage technologies need significant investment to enable the cost-effective implementation of equipment.	Less attractive

Existing capability	Forecast demand	Gap/opportunity	Investment opportunity attractiveness
Supply chain mode: Hydrogen compression			
• Compression technology is mature and international suppliers will likely provide a range of compression options for varying compressor scales, leveraging off their economies of manufacture. • Unless Australian suppliers provide a cost-competitive option, there will be limited opportunity to leverage a position in this supply chain node.	• Supply of compressors will be critical to enable the transit of hydrogen from production to consumption to enable the supply chain. • Compression components are expected to need a significant share of investment in comparison to other specialised goods.	• Increased demand for hydrogen compressors is forecast, with international suppliers expected to fulfil the majority of demand. • Opportunity for Australian suppliers to compete in scale-specific compressor offerings, but international capability should be leveraged to grow the HETS market as technology is mature. • Alternative business model frameworks can be integrated to maximise the benefit to the Australian economy.	Less attractive

Existing capability	Forecast demand	Gap/opportunity	Investment opportunity attractiveness
Supply chain mode: Hydrogen storage			
• Hydrogen storage is critical. The future supply chain will require decreased storage costs. If Australian suppliers can offer technology that is cost-competitive to international offerings, this will benefit the deployment of hydrogen infrastructure. • Hydrogen storage in pressurised vessels is mature, but storage technologies for MCH, liquid hydrogen and geological storage technology, such as for salt caverns, still need development. • Existing skills in manufacturing can be utilised to leverage best practices within HETS. • The development of constructed salt cavern infrastructure is dependent on specialized design and engineering consultancy services. Design services to develop infrastructure to handle the operating pressure cycle and develop a detailed understanding of geological formation are critical disciplines. The ongoing development of these skills in the Australian market will be needed to facilitate the level of storage required at the right place throughout the supply chain. • If capability in hydrogen storage is developed, this will present an opportunity for technology and service export. Workforce skillsets within the manufacturing industry can be leveraged.	• Storage is vital throughout the supply chain. • NHIA modelling indicates that salt cavern storage will be preferred where this quantity of storage is required. • Australia's potential for hydrogen salt storage in natural deposits is approximately 310 million tonnes (per Future Fuels CRC). • The viability of these natural geological deposits for use will depend on their location and proximity to production and demand hubs, with the developed infrastructure required to fill gaps in the network. • Naturally occurring underground caverns for salt storage are located at the Canning Basin in Western Australia, the Adavale Basin in Queensland and the offshore Polda Basin in South Australia, amongst other locations.	• The forecast demand for this node is significant compared to its current size. • Significant and equipment-specific opportunity for Australian suppliers to develop the capability for emerging technology related to underground storage and hydrogen carriers. • Significant levels of investment are required to foster Australian capability in this supply chain node. • Opportunity to export equipment, technology, and services.	More attractive

Existing capability	Forecast demand	Gap/opportunity	Investment opportunity attractiveness
Supply chain mode: Hydrogen fuel cell			
• Fuel cell technology is largely mature, but emerging technologies such as solid oxide fuel cells require further development. Novel fuel cell technology that offers significant benefits is being developed in Australia, such as solid oxide fuel cells. If innovative technologies prove to illustrate cost competitiveness, an investment could be made to foster Australian capability within the supply chain node. • Australian solid oxide capability presents an opportunity for cross-over with the electrolysis supply chain node due to reversible operating capability. • If technological capabilities are developed, this presents a technology export opportunity. • Workforce skillsets within the manufacturing industry can be leveraged.	• Fuel cell manufacturing will be subject to the same global competition as electrolysers, with local manufacturing competing with imported equipment for market share. • Due to the narrow demand profile, the total manufacturing capacity for fuel cells will be significantly smaller than for electrolysers.	• The forecast demand for this node is comparatively small compared to the Electrolysis supply chain node and its current size. • Technology in this node is complementary to the Electrolysis node and presents a notable opportunity for Australian suppliers to develop the capability.	Less attractive

Existing capability	Forecast demand	Gap/opportunity	Investment opportunity attractiveness
Supply chain mode: Hydrogen liquefaction			
• Hydrogen liquefaction technology requires commercial scale-up. • Limited to no Australian supplier competition. • For local suppliers to compete within this supply chain node, significant investment will be vital.	• Assumed that 20% of exported hydrogen is liquefied. • NHIA modelling indicates that this process will likely not be selected for the domestic distribution of hydrogen. It is assumed that liquefication will take place at the point of export (ports) using dedicated infrastructure. • The development of suitable ships for the transit of liquefied hydrogen must be completed before widespread export can commence. • Additionally, the required infrastructure for liquefication and regasification of the hydrogen must be built at both the loading and receiving terminals prior to the establishment of an export route.	• The forecast demand for this node is greater compared to its current size. • Significant investment is required for local suppliers to compete. International capability can be leveraged to support the HETS supply chain. • Expect an opportunity for Australian companies to benefit from alternative business model frameworks due to the criticality of liquefaction technology at ports in future.	Less attractive
Supply chain mode: Alternative carrier production			
• Largely established technology. MCH conversion technology requires development. • Limited to no Australian supplier competition. • For local suppliers to compete within this supply chain node, significant investment will be necessary.	• It is expected that all exported hydrogen will be converted into ammonia (80%) or liquefied hydrogen (20%). • NHIA modelling indicates that most of the hydrogen (for use as hydrogen) will be domestically distributed as compressed H_2, but where LOHCs may be required, MCH will be the preferred carrier. • Operational jobs in ammonia take up a large share of required direct jobs for the 2040 forecast. • Hydrogen carriers are one of the largest industry classes necessary to support a 2040 supply chain. Forecast demand for this node is significant compared to the current size.	• The forecast demand for this node is greater compared to its current size. • Expect an opportunity for Australian companies to benefit from alternative business model frameworks due to the criticality of hydrogen carrier equipment at ports in future.	Less attractive

Existing capability	Forecast demand	Gap/opportunity	Investment opportunity attractiveness
Supply chain mode: Dispensing / refuelling			
• Largely mature technology. Hydrogen refuelling technology requires commercial scale-up. • Limited to no Australian supplier competition. • For local suppliers to compete within this supply chain node, significant investment will be needed.	• Australia is anticipated to be a net exporter of hydrogen to areas with less available renewable energy feedstock or other supply chain inhibitors to development. • The shipping of liquid fuels and ammonia is well established.	• The forecast demand of this node is greater compared to its current size. • Significant investment is required for Australian suppliers to compete. However, the opportunity for local businesses to collaborate within this node.	Less attractive
Supply chain mode: Hydrogen combustion systems			
• Workforce skillsets within the oil and gas industry can be leveraged. • Hydrogen-fired industrial furnaces and kilns are a developing technology globally that is not widespread within Australia, although the individual components that comprise these systems are understood and have established supply chains.	• Australia's potential for hydrogen combustion systems lies mostly within hard-to-abate high-heat industrial processes, which commonly use large-scale direct-fired equipment. • The specialised and bespoke nature of high-heat industrial process equipment requires a large degree of integration of OEM equipment to suit the specific process needs and local regulations.	• Significant opportunity for Australian suppliers to support the transition of traditional industrial processes from fuel-switching to hydrogen alternatives. • Significant levels of investment are essential to foster Australian capability in this supply chain node.	Less attractive

Existing capability	Forecast demand	Gap/opportunity	Investment opportunity attractiveness
Supply chain mode: Distribution			
• Largely established technology. However, liquid hydrogen tanker needs technical development. • Australian suppliers are limited in number but offer capability across the supply chain. However, they may not currently be integrated into the HETS supply chain. • Australian technology capability could be exported globally. • Workforce skillsets within the mining and manufacturing industry can be leveraged.	• The NHIA model indicates that in the absence of significant constraints or specific demand, most of the hydrogen will be moved domestically as compressed hydrogen rather than as liquefied or as an alternative hydrogen carrier. Pipelines represent the quickest method of moving large quantities of hydrogen long distances but incur high construction costs. • Partial repurposing and refurbishment of existing liquid and gaseous fuels may be sufficient to meet demands. • The uptake of fuel cell vehicles is likely to be higher in taxis and fleet vehicles, whereas electric vehicles are likely to be the predominant low-emission vehicles for commercial and residential passenger vehicles. It is also anticipated that haulage trucks and freight vehicles will transition to hydrogen, mainly through hydrogen-powered fuel cells. • Distribution is one of the largest contributors to the levelised cost of hydrogen. • Operational jobs in pipelines take up a large share of required direct jobs for the 2040 forecast. • Pipeline services is one of the largest industry classes needed to support the 2040 supply chain. The forecast demand for this node is significant compared to its current size.	• The forecast demand for this node is significant compared to its current size. • Investment is required to foster capability in this supply node. • Opportunity for MCH and hydrogen carrier distribution technology development. • Due to the criticality of distribution to the HETS market, numerous business models can be integrated to benefit the Australian economy.	More attractive

Summary

In conclusion, the gap analysis and opportunity mapping have identified three key areas with high-value, high-growth opportunities for Australian businesses in the hydrogen economy: electrolysis, storage, and distribution. These findings provide a high-level overview of the areas with significant potential in the hydrogen economy and serve as a valuable resource for businesses looking to invest. It is important to note that these areas are not the only opportunities for Australian businesses, but rather highlight areas of significant potential. By directing investment and efforts towards these areas, businesses can position themselves at the forefront of the hydrogen economy and capitalise on the opportunities for growth and success. These findings will help guide investment decisions in the future, but businesses should also consider other opportunities in the hydrogen economy that align with their strategic goals and capabilities.

8.3 Success factors

8.3.1 Australia's National Hydrogen Strategy comparison

Australia's National Hydrogen Strategy[71] sets a path to build Australia's hydrogen industry to meet its 2050 net-zero targets. Recognising Australia's resources and experience to take advantage of increasing global momentum for clean hydrogen.

The Strategy outlines actions that aim to remove market barriers, efficiently build supply and demand, and accelerate Australia's global cost competitiveness. The strategy identifies 57 joint actions themed around national coordination, developing production capacity supported by local demand; responsive regulation; international engagement; innovation and R&D; skills and workforce; and community confidence. These actions consider hydrogen in relation to exports, distribution, industrial use, gas networks, electricity systems, and cross-cutting issues such as safety, skills, and environmental impacts.

The Strategy also includes an action for NERA to support small-to-medium enterprises (SMEs) to take advantage of opportunities in the hydrogen industry by forming an industry-led cluster.

The opportunities identified in the gap analysis have been evaluated against Australia's National Hydrogen Strategy measures of success. The recommended supply chain node opportunities that have been highlighted as attractive market opportunities have been correlated with the national strategy actions outlined to realise the future HETS market.

Table 19 outlines Australia's National Hydrogen Strategy industry vision, and Table 20 is a summary of the attractive supply chain nodes and how they are aligned with Australia's National Hydrogen Strategy measures of success and actions.

Table 19 Australia's National Hydrogen Strategy: Industry Vision

Australia's National Hydrogen Strategy: Industry Vision	
Clean	Carbon intensity of Australian hydrogen production meets community, customer and consumer expectations and is decreasing over time.
Innovative	Australia is regarded as having a highly innovative hydrogen industry and supportive research and development environment. The sustainability of water use for Australian hydrogen production continues to improve.
Safe	Australia has an excellent hydrogen-related safety track record.
Competitive	Australian hydrogen is cost-competitive domestically and internationally. Australia has a 'hydrogen-ready' workforce that is responsive to the industry's needs.

Table 20 Summary of attractive supply chain node alignment with Australia's National Hydrogen Strategy

Attractive supply chain node	Alignment with Australia's National Hydrogen Strategy measures of success	Alignment with Australia's National Hydrogen Strategy actions
Electrolysis	**Clean** – Electrolysis is a fundamental supply chain node for enabling green hydrogen. If 100% renewable electricity is supplied, electrolysis produces a net zero-emission fuel. **Innovative** – This is a relatively novel technology that requires commercial scale-up in Australia. In addition, Australian suppliers are developing emerging technology within this node. **Competitive** – As electrolysis is a major contributor to the levelised cost of hydrogen, local capability for deployment of locally manufactured technology would enable a more cost-competitive solution for Australia.	Assessing our hydrogen infrastructure needs Supporting research, pilots, trials, and demonstrations along the supply chain
Hydrogen storage	**Innovative** – Large-scale hydrogen storage is an emerging technology with the potential for skills and services export if developed within Australia. **Safe** – Providing safe, reliable and secure storage of hydrogen is crucial for improving public perception of hydrogen use within the market. **Competitive** – As hydrogen storage is a major contributor to the levelised cost of hydrogen, local capability for deployment of locally manufactured technology would enable a more cost-competitive solution for Australia. In addition, reserves of hydrogen storage would enable energy supply resilience, providing price stability for consumers.	Hydrogen certification Building community knowledge and engagement
Distribution	**Clean** – The distribution of an emission-free fuel to enable emissions-free multi-sector decarbonisation. **Innovative** – Australia has capability across the distribution of several LOHCs, which could be leveraged to develop distribution options for MCH. If technology is successfully developed and commercially deployed, this capability could be leveraged for global export. **Safe** – Providing a hazard-free form of hydrogen and hydrogen carrier distribution within Australia will be critical for the development of a hydrogen economy, hydrogen regulatory frameworks and positive public perception. **Competitive** – As the distribution of hydrogen is one of the major contributors to the levelised cost of hydrogen, local capability for deployment of locally manufactured technology would enable a more cost-competitive solution for Australia.	Initial steps towards using hydrogen for transport Hydrogen certification

Of the attractive market opportunities identified, several additional actions outlined in Australia's National Hydrogen Strategy are applicable across the three supply chain nodes. These actions include:

- Large-scale market activation.
- Integrating hydrogen into energy markets.
- Skills and training for the hydrogen economy.
- National coordination.
- Responsible industry development.
- A coordinated approach to planning and regulatory approvals for hydrogen.
- Hydrogen's role in securing affordable energy supply.

9. Conclusions and recommendations

9.1 Conclusions

Based on the supply chain assessment, economic analysis, and industry capability assessment, electrolysis, hydrogen storage, and distribution supply chain nodes are the most advantageous nodes to invest in between now and 2040 due to their criticality, contribution to the levelised cost of hydrogen and jobs, and relation to local advantage, and capability.

9.1.1 Supply chain conclusions

The HETS supply chain is wide-reaching through production, distribution, storage, processing and ultimately, consumption at the point of demand. The configuration of organisations and functions to enable this network to meet future demands is still emerging, presenting a level of uncertainty.

By 2040 most hydrogen production in Australia is anticipated to be via electrolysis, with 51GW of electrolyser capacity to be developed. This will necessitate rapid acceleration of solar and wind energy generation infrastructure installation and operation to meet the forecast demand. It is anticipated that most hydrogen electrolysers will use renewable energy installed 'behind the meter', meaning electrolyser installations will be concentrated in dedicated renewable energy zones and that distribution of hydrogen domestically to points of consumption or export will be required.

The development of electrolyser production infrastructure involves complex supply chains to support the manufacture and supply of electrolyser modules and the equipment that forms the balance of plant. The development of modules involves raw materials that may have constrained supply (including platinum group metals) and complex manufacturing. The development and supply of fuel cells for mobility and other applications may be a related opportunity due to a similar configuration to electrolysers. The supply of hydrogen compressors, liquefaction and carrier conversion equipment will be critical to enable the transit of hydrogen from production to the point of consumption.

Hydrogen will likely be moved domestically as compressed hydrogen gas, with pipeline transport (through new or repurposed existing pipelines) preferred for consistent, high-volume movement, and road and rail transport to carry out smaller distribution tasks with specialised equipment. Longer-term, strategic storage of hydrogen will likely be done in naturally occurring or constructed salt caverns, with smaller-scale tactical storage throughout the network done in tanks and vessels. Salt cavern viability will depend on cavern location and proximity to production and demand hubs.

Hydrogen carriers such as MCH, ammonia and liquefied hydrogen may be appropriate for non-gaseous transportation. Ammonia and liquefied hydrogen will likely be preferred for export, while MCH may be used for transport and storage domestically. Infrastructure for the conversion of hydrogen to carriers, transport of carrier liquids or solids and reconversion of carriers to hydrogen (where the demand is for hydrogen gas rather than the carrier itself) must be developed to facilitate this element.

9.1.2 Economic conclusions

Based on the economic analysis, the Australian hydrogen economy could support $30-$40 bn (1.0%-1.25% GVA) in domestic Gross Value Added and 60,000-70,000 jobs annually across the wider supply chain by 2040. Recognising the existing Australian economy, a significant share of investment (44%-61%) will be on imported goods, particularly specialised goods such as solar panels, electrolyser components, wind turbines and compression components.

A large ramp-up of investment from 2025 is needed, with investment averaging around $25-$30 bn a year from the latter part of the 2020s through to 2040. However, the projections within the economic analysis have a considerable level of uncertainty and are only intended to provide an indicative estimate of the potential size of the hydrogen economy and what is required to achieve it.

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71 COAG Energy Council. Australia's National Hydrogen Strategy. Access here.

9.1.3 Industry conclusions

The greatest benefit for the Australian economy accrues when Australian-based companies manufacture in Australia, whilst there are various methods available to work with international suppliers to provide other national benefits. Australian suppliers are concentrated in a few supply chain nodes with strong capabilities.

The successful development of the HETS supply chain within Australia will require a mixture of national and international suppliers to cover all elements across the supply chain appropriately. In addition, the balance of national and international suppliers will help accelerate the transition to the hydrogen economy by driving down costs. Therefore, Australia will need a coordinated and focussed approach to drive local supply chain node development to focus investment and reap an optimised return on investment.

Based on the industry capability assessment, electrolysis, hydrogen storage, and distribution are the supply chain nodes that are most advantageous in relation to local advantage, capability, and industry competition. This highlights where investment should be prioritised. Whilst the hydrogen fuel cell and anaerobic digestion and gasification supply chain nodes should also be considered as an opportunity for Australia, these nodes involve emerging technologies and, therefore, inherently have a higher degree of developmental uncertainty when compared to other opportunities. In addition, the most required and relevant complementary sectors are professional, scientific services, construction, manufacturing, electricity, gas, water and waste services.

9.2 Recommendations

Enabling a strong supply chain is key to underpinning future expansion. The demand for hydrogen is intended to be great enough that direct and indirect labour will be necessary to complete the GW-scale projects currently in the pipeline in Australia. It is recommended that investment is made in hydrogen technology clusters to enable the development of skilled technology supply chains in regions across Australia. The provision of HETS will be instrumental in growing the hydrogen industry in these regions.

A set of primary recommendations have been highlighted below. Table 21 synthesises a list of key outcomes of this report into a set of recommendations to progress and accelerate the development of the HETS supply chain.

Equipment – Focussed investment in onshore manufacturing combined with advanced manufacturing techniques and R&D to build upon existing supply chain capacity. Anecdotal market evidence envisages longer lead times for equipment as manufacturers attempt to keep up with growing global demand. Australian companies can capitalise on the lengthy lead time of international supplier equipment by building national capacity - investing for future supply chain delivery to ensure Australian companies and products are competitive in the future. The total supply chain is worth $30-$40 bn annually; therefore, between 2022 and 2040, at least $340-$420 bn ($25-$30 bn a year) of investment will be needed to build up the infrastructure necessary to produce hydrogen at the scale envisioned in the NHIA Central Demand Scenario. Consideration could also be given to encouraging overseas manufacturers to onshore their manufacturing capabilities in Australia. Partnerships, competitive and innovative commercial models and eliminating or reducing structural barriers such as tariffs or quotas will contribute to and attract overseas organisations to manufacture in Australia.

Technology – Hydrogen storage is one of the primary technology challenges for large-scale hydrogen production. For Australia to offer a competitive advantage globally, investment in low-cost and large-scale hydrogen storage is needed. Hydrogen storage R&D and technical investigations are required to accelerate and realise these projects. Australia needs 89.5kt of storage by 2040. Therefore, up to $0.7-$0.9 bn of investment is needed in salt cavern and MCH.

Services – Limited workforce skillsets across the existing HETS supply chain restrict the pace that the supply chain can be developed. This is a major challenge to realise national goals. Building a highly skilled and capable workforce across all facets of the supply chain is needed. An estimated 170,000-200,000 jobs annually (FTE) will be required, and a further 58,000-72,000 jobs annually could support across the operational (direct) and wider supply chain. This will necessitate the creation of existing workforce transition pathways and workforce teaching and training pathways to support the HETS supply chain.

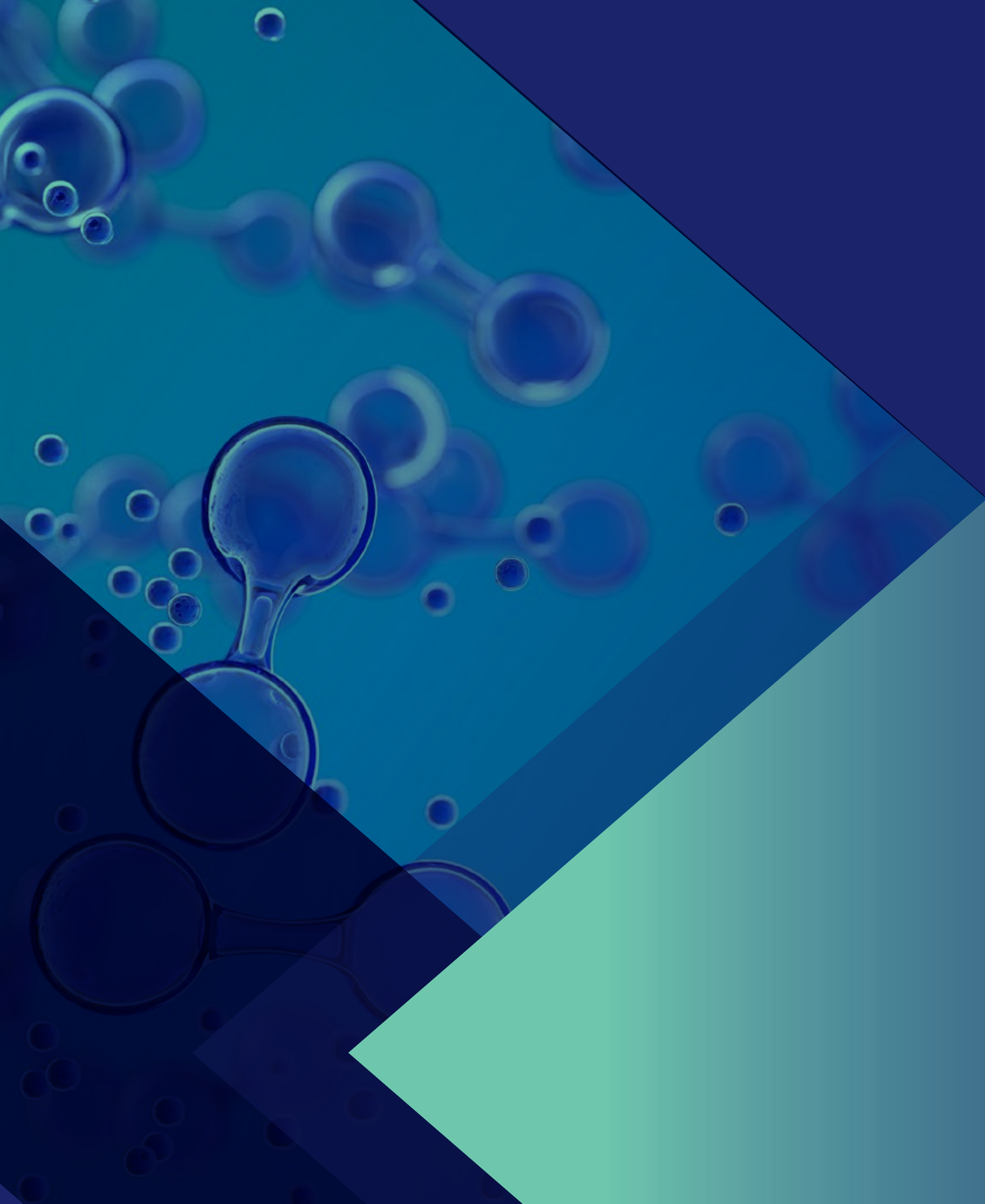
Schools and further education institutions need to collaborate with industry to create relevant courses to train the future generation of industry professionals. Existing industry workers need to be supported to transition existing skillsets. This can be through formal and on-the-job training or micro-credentials, etc. Fundamentally, consistency across the training spectrum, particularly to foster quality health, safety and environmental credentials across the Australian workforce, is necessary. To do this, a coordinating body that can define the type of skills required is essential. This body would need to work closely with educational institutions to then define the curriculum.

Table 21 HETS supply chain recommendations

Focus area	Identify (Now – 2025)	Develop (2025 -2030)	Adapt (2030 -2040)
Equipment	• Identify opportunities early and begin to invest in manufacturing capability for Australian suppliers across several supply chain nodes. Australia could draw upon its advances in novel electrolyser technologies. In addition, there are untapped reserves of platinum and iridium[72] which could be used to secure these essential materials for electrolysers, as well as High Purity Quartz reserves[64] that could meet the growing demand for silica for manufacturing of solar cells. • Hydrogen electrolyser production capacity: To drive down the construction cost of electrolysis plants, undertake the design and development of low-cost electrolyser modules for domestic fabrication. • Partnerships between CRCs, engineering businesses, and fabricators with suitable skillsets (e.g., oil and gas equipment, pressure vessels, HV electrical, SCADA) • Use advanced manufacturing principles - Design for Manufacture and Assembly (DFMA), Lean manufacturing, Industry 4.0, etc. - for whole-of-life cost reduction. • Secure supplies of crucial raw materials (e.g., platinum group metals) and other high-value components.	• Leverage early investment to build out capability in the supply chain, with the government absorbing intensive capital via innovative commercial models. • Build advanced manufacturing capacity for low-cost electrolyser modules: develop tooling/jigs/robotics, advanced test stations, QA/QC procedures, ICWs, etc. • Shore up materials supply, e.g., in extractive and materials processes and key component suppliers. • Reassess the capability of international suppliers across the supply chain to identify potential areas where Australia could invest in developing local capability.	• Continue to develop and expand world-class advanced manufacturing and assembly facilities. • Expand into international markets where Australia has a competitive advantage. • Roll out low-cost electrolysis plants. • Continue to improve advanced manufacturing capability and capacity.
Technology	• Ramp up investment in research and development of novel and emerging electrolyser and fuel cell technologies to improve asset lifetimes, efficiency, cost, etc. Early investments offer large long-term payoff potential. • Undertake a detailed evaluation of Australian technologies within other attractive supply chain nodes, for example, in hydrogen storage, salt cavern technology, alternative carriers, MCH conversion technology, and in transport, MCH and liquid hydrogen tankers. • Accelerate investment into nearer-term technologies close to commercial viability to bridge the gap. This includes technologies with high TRL ratings, such as liquid hydrogen storage tanks and tankers for distribution.	• Increase or focus funding on pilot-scale demonstrations and early commercial technologies. • Leverage early investments by exploiting opportunities for promising technology trials and demonstrations. • Continue investment in novel electrolysis and fuel cell technology developments. The key to successful R&D is prolonged and reliable funding. • Pivot the use of funding from technologies that are now commercially viable to others that are close to commercial viability.	• Upscale commercial developments and exporting to global markets. • Refine technologies and position as a technical expert in a certain technology. • Commercialise new technologies and create a local competitive advantage. • Continue investment in novel technologies position Australia as a leader in hydrogen technology development.

Focus area	Identify (Now – 2025)	Develop (2025 -2030)	Adapt (2030 -2040)
Services	• Begin to invest in roles that will support the hydrogen supply chain, such as professional, scientific, and technical services, as well as construction and manufacturing. These will be pivotal in supporting technology development and providing general support to the HETS supply chain. Undertake a wider supply chain component assessment to identify specific support roles and ensure funding is targeted. • Gain support from the government (state and federal) within the H&S and environmental regulations to initiate a regulated and governed hydrogen economy. • Where it does not exist already, undertake a detailed investigation into individual supply chain nodes to identify Australian raw inputs, skills, and capabilities. Grow investment in workforce upskilling to develop manufacturing, construction, professional, scientific, and technical capability. This can be done by implementing early workforce upskilling and transition pathway plans nationally. Ensure there is a collaboration with educational institutions, and relevant courses and micro-credentials are developed (and continue to be developed) to facilitate the transition. • Communicate workforce transition pathway options with clear transition goals.	• Continue to up-skill workers to promote manufacturing of developing technologies. • Increase or focus funding on developing services that will best support the hydrogen supply chain and bolster Australian capability.	• Embed training into all new and existing staff programs to ensure workers become technical experts. • Expand world-class education facilities and export these services globally. Become a trusted adviser to the global supply chain. • Regularly review workforce and skillset requirements and continually update these.

Focus area	Identify (Now – 2025)	Develop (2025 -2030)	Adapt (2030 -2040)
Other	Risk • Undertake a detailed risk assessment to reduce the likelihood of imbalances and bottlenecks within the supply chain. Analysis should include technology risks, material risks, skills risks, concentration risks, and spatial risks. • Understand and invest in regulatory framework development. Engagement • Undertake engagements with stakeholders, including industry across Australia, to gain a greater understanding of technological advancement and stimulate collaboration within the market. • Engage with international suppliers to derive lessons learnt from other countries to accelerate development in Australia. Economic analysis • Undertake a revised economic analysis within 1-2 years as the hydrogen market develops, and when improved, benchmarking and returns to scale estimates may provide a more accurate picture of the future. Further economic analysis could consider the wider supply chain, such as additional supporting jobs in training and education, for example. • Map industry capability and correlate with demand clusters. Consider establishing new clusters where there is greater capability.	HETS Supply Chain Development Plan • Develop a holistic supply chain program and plan to aid the coordination of investment and provide investor and wider stakeholder confidence within the hydrogen market. The plan should include a roadmap to achieve national supply chain goals, measurable steps to realise these goals, a partner engagement plan and a governance plan to track the development of the supply chain and enable adaption as the market develops. Invest and Engage • Continue investment in regulatory framework development and identify and resolve gaps with support from Government. • Build strong supply chain partnerships with international suppliers. • Stimulate collaboration within the market – promote positivity and enthusiasm within the hydrogen supply chain.	Reassess • Review supply chain progress against a holistic programme and plan key performance indicators and assess actions to address areas of improvement. • Undertake a detailed risk assessment to reduce the likelihood of imbalances and bottlenecks within the supply chain. • Undertake a revised economic analysis as the hydrogen market develops, and improved benchmarking and returns to scale estimates are likely to provide a more accurate picture of the future.



Appendices

Appendix A – Scope extents and supply chain information

Item	Comment
Water	Infrastructure requirements to source and deliver water for treatment/purification are not to be considered.
Water treatment	Water treatment requirements for electrolysis feedstock and cooling requirements to be considered.
Renewable energy generation	Dedicated renewable energy generation required for hydrogen production as modelled by the NHIA Central Demand Scenario to be considered – this will be done at a high level based on previous economic information.
Fossil fuel energy	Not to be considered.
Biomass feedstock	To be considered, but noting that biomass feedstock is typically a by-product of other processes and will be utilised opportunistically rather than via dedicated production. Additionally, biomass-to-energy or biomass-derived products (fertilisers, resins, etc.) would not typically be produced via a hydrogen route.
Nitrogen generation	Not to be considered – most likely generated on-site at ammonia processing.
Water purification	There is a water scenario in H_2 white paper that was produced for DISER. This will be used as a baseline.
Electrolysis	The level of electrolyser capacity required is specified in the NHIA Central Demand Scenario. Will make high-level assumptions regarding electrolysis type (PEM, etc.).
Anaerobic digestion or gasification	To be considered as part of a biomass feedstock production route.
Hydrogen compression	NHIA Central Demand Scenario does not anticipate that hydrogen will be compressed for movement or distribution. Power requirements for compression will be considered consumable, but renewable energy sources to provide this power will not be considered.
Hydrogen storage	Salt cavern and MCH storage will be considered as defined by the NHIA Central Demand Scenario.
Fuel cell production	NHIA has this modelled as a demand (export or domestic) – I.e. a point at which hydrogen is consumed. Will consider this as a demand and will not consider downstream manufacturing associated with fuel cells.
Hydrogen liquefaction	The NHIA Central Demand Scenario does not identify any liquefaction. Will make an assumption regarding the percentage of exported hydrogen that is liquified and used accordingly. No domestic hydrogen is liquefied – we will not consider domestic regasification.

Item	Comment
Alternative carrier production	Will consider ammonia production only – MCH is considered as part of storage and will not consider methanol or synthetic NG. Assumed value as per NHIA scenario.
Hydrogen combustion systems	Hydrogen combustion systems, in particular for high-heat users, include large gas-fired burners, air mixing, nozzles, specialised valves, and flue gas handling.
Dispensing / refuelling	Export and domestic demands are to be considered based on the demand assessment performed (Frontier) for the NHIA Central Demand Scenario. Development of industries (assets and operations) to generate demand will not be considered – hydrogen is assumed to be consumed at the point of demand.
Distribution	Construction of hydrogen pipelines to be considered based on the outcome of the NHIA Central Demand Scenario. Port and shipping requirements to facilitate export to be considered. NHIA scenario considers that road transport will be almost completely replaced by pipeline by 2040 – will consider at a high level. Electricity transmission infrastructure to feed electrolysers will not be considered.
Oxygen co-product	Not to be considered.

Data used for supply chain mapping

The data used to generate the supply chain assessment is summarised below:

- Demand for hydrogen, including location and demand type, were taken from the 'Hydrogen demand forecasts report' (May 2021) developed by Frontier Economics as part of the NHIA Study.
- Production and movement data were generated by Arup on the NHIA as part of the 'Low Emissions Central Demand' Scenario in the year 2040. The model assessed the most cost-effective way to meet demands throughout Australia through the production, storage and distribution of hydrogen.
- Information on current and announced hydrogen projects were provided by Bloomberg New Energy Finance (BNEF) and the CSIRO.
- A wide variety of sources were consulted relating to technical information at each node of the hydrogen supply chain, as noted throughout the report.
- The 'Hydrogen Industry Workforce Development Roadmap 2022-2032' developed by the Queensland Government Department of Employment, Small Business and Training (DESBT) was used to identify key roles and skills for critical nodes.
- Detailed information relating to the construction and supply of electrolysers has been sourced from the US Department of Energy report "Water Electrolysers and Fuel Cells Supply Chain | Supply Chain Deep Dive Assessment".

Distributed renewable energy generation for each state and region.

SOLAR AND WIND GENERATION BY STATE

Total	Solar GW	Wind GW
NSW Total	**22.57**	**12.55**
New England	5.26	4.66
Northwest NSW	6.49	0.00
Sydney	0.35	0.31
Central-West Orana	5.92	4.28
Wollongong	4.55	3.30

Total	Solar GW	Wind GW
NT Total	**3.34**	**5.22**
NT	0.43	0.68
Tennant Creek	2.90	4.54

Total	Solar GW	Wind GW
TAS total	**1.58**	**3.86**
Northeast TAS	0.52	0.66
Northwest TAS	0.68	2.71
Tasmania	0.38	0.49

Total	Solar GW	Wind GW
SA Total	**9.03**	**7.81**
Adelaide	0.79	0.65
Mid-North SA	1.59	1.72
Leigh Creek	3.27	2.68
Portland	3.20	2.62
Regional SA	0.17	0.14

Total	Solar GW	Wind GW
WA Total	**17.51**	**16.22**
Goldfields	0.40	0.47
Perth	0.56	0.65
WA Mid East	4.44	4.81

WA South West	2.72	3.19
WA Mid West	2.12	2.40
Regional WA	0.09	0.10
Port Hedland	0.23	0.14
WA Pilbara Inland	6.95	4.44

Total	Solar GW	Wind GW
QLD Total	**11.25**	**14.97**
Gladstone	0.03	0.04
Fitzroy	3.09	3.49
Regional QLD	0.22	0.26
Far North QLD	0.60	2.57
Northern QLD	0.76	0.89
Darling Downs	6.12	7.18
Mt Isa	0.05	0.06
Mt Isa	0.38	0.48

Total	Solar GW	Wind GW
VIC Total	**17.03**	**15.03**
Melbourne	8.60	9.70
Murray River	4.04	0.66
Regional VIC	0.28	0.05
Western VIC	1.42	1.60
Geelong	2.69	3.03

Appendix B – Economic analysis

MODELLING INPUTS

Key modelling cost assumptions

Assumption	Value	Source
Weighted average cost of capital (WACC)	5.9%	Standard modelling assumption
USD/AUD exchange rate	0.78	Reserve Bank of Australia - 10-year average exchange rate

Variable costs – NHIA model inputs (real terms)

Cost item	Value	Description
Purified water	0.002	Cost per litre
Methane	8.21	Cost per kg of hydrogen
Dedicated renewable electricity	0.031	Cost per kW
Carbon capture and storage	0.27	Cost per kg of hydrogen
Toluene	1.05	Cost per kilogram
Fuel	6.00	Cost per GJ
Truck movements	2.98	Cost per kilometre per kilogram

Capital costs – NHIA model inputs (real terms)

Cost item	Value	Description
Ammonia production	1.25	Cost per kg of ammonia
Blue hydrogen	8.29	Cost per kg of hydrogen
Compression	6,987.83	Cost per kW of compression
Electrolysis	1,181.90	Cost per kW of electrolysis
Liquefaction	8.36	Cost per kg of liquefied hydrogen
MCH (production)	0.11	Cost per kg of MCH produced
MCH (storage)	1.25	Cost per kg of MCH storage
MCH (regasification)	0.23	Cost per kg of MCH regasified
Pipelines	1,692,411.29	Cost per km of pipeline
Salt cavern storage	7.07	Cost per kg stored in salt caverns
Solar PV	776.51	Cost per kW of installed solar
Wind	1,683.21	Cost per kW of installed wind

SUMMARY TABLES

Outputs – annual turnover by node in 2040

Node	Domestic turnover ($m, annual)	Total turnover ($m, annual)	Domestic proportion (%)
Ammonia	2,800-3,500	3,300-4,000	86%
Blue H_2 / biomass	800-900	1,100-1,400	68%
Compression	1,900-2,400	2,200-2,700	87%
Electrolyser	6,800-8,400	8,000-10,000	83%
Liquefaction	1,200-1,500	1,400-1,700	88%
MCH	35-45	45-55	82%
Pipeline	4,000-5,000	4,200-5,100	98%
Salt caverns	90-120	100-120	94%
Solar PV	7,200-8,700	8,000-10,000	87%
Trucks	N/A	N/A	N/A
Water supply	500-600	500-600	100%
Wind	14,000-17,000	16,000-20,000	86%

Note: Domestic is the revenue that is spent on domestic goods and services.

Outputs – annual GVA by node in 2040

Node	Direct GVA ($m, annual)	Wider GVA ($m, annual)	Total GVA ($m, annual)
Ammonia	1,800-2,200	700-900	2,500-3,100
Blue H_2 / biomass	300-400	300-400	600-800
Compression	1,000-1,300	700-900	1,700-2,100
Electrolyser	5,000-6,200	1200-1500	6,300-7,700
Liquefaction	700-800	400-500	1,100-1,300
MCH	10-15	20-25	30-40
Pipeline	2,700-3,300	800-1,000	3,500-4,300
Salt caverns	60-70	25-30	80-100
Solar PV	4,600-5,700	1,800-2,200	6,400-7,800
Trucks	N/A	N/A	N/A
Water supply	300-400	100-200	400-500
Wind	9,500-11,500	2,800-3,400	12,000-15,000

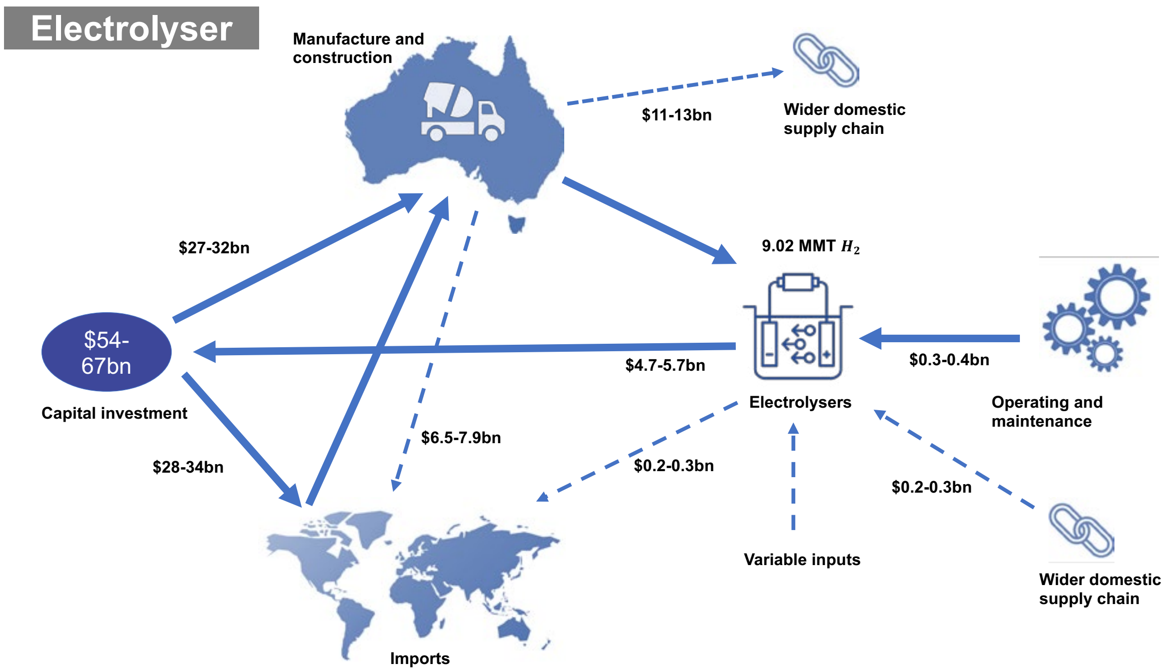
Note: Direct is activities relating to annual fixed and variable operations (O&M). Wider includes indirect supply chain activities related to O&M activities and activities related to capital construction and installation annualised by the assumed lifetime of the capital.

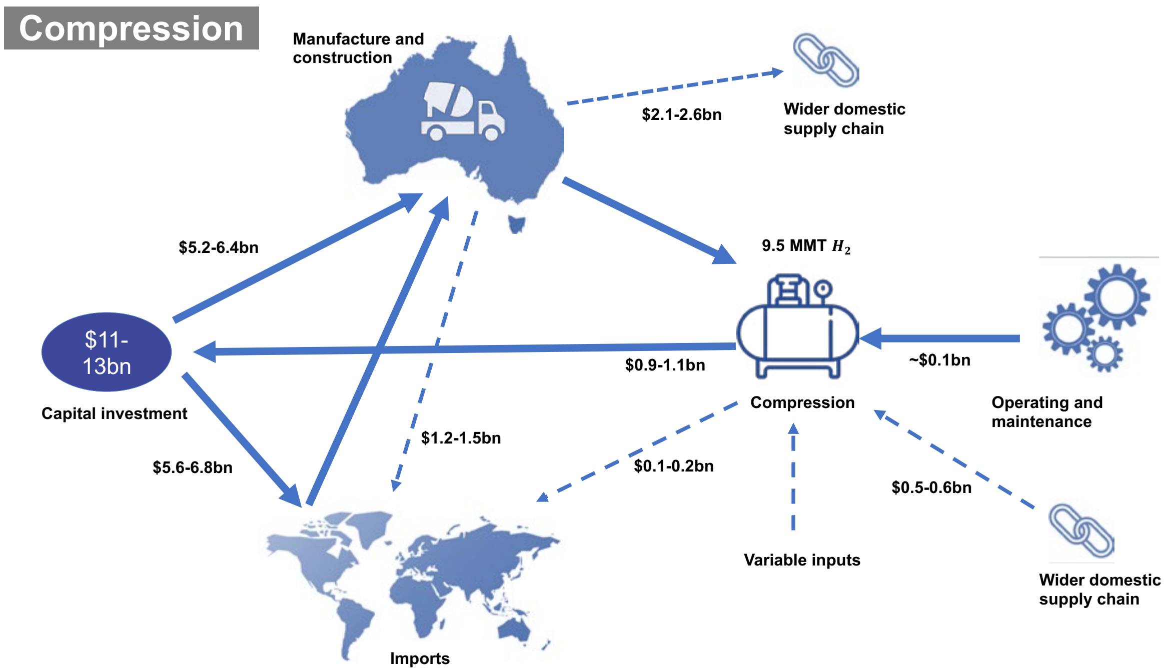
Outputs – Annual employment by node in 2040

Node	Direct employment (FTE, annual)	Wider employment (FTE, annual)	Total employment (FTE, annual)
Ammonia	2,400-2,900	3,600-4,400	5,900-7,200
Blue H_2 / biomass	400-400	1,800-2,200	2,200-2,700
Compression	700-900	2,400-2,900	3,100-3,800
Electrolyser	2,800-3,400	8,300-10,000	11,000-13,500
Liquefaction	900-1,100	1,500-1,800	2,400-2,900
MCH	15-20	45-55	60-70
Pipeline	2,700-3,300	4,200-5,200	6,900-8,400
Salt caverns	60-70	100-200	190-240
Solar PV	800-1,000	9,200-11,000	10,000-12,000
Trucks	N/A	N/A	N/A
Water Supply	700-800	300-400	1,000-1,200
Wind	2,600-3,200	14,000-17,500	17,000-20,500

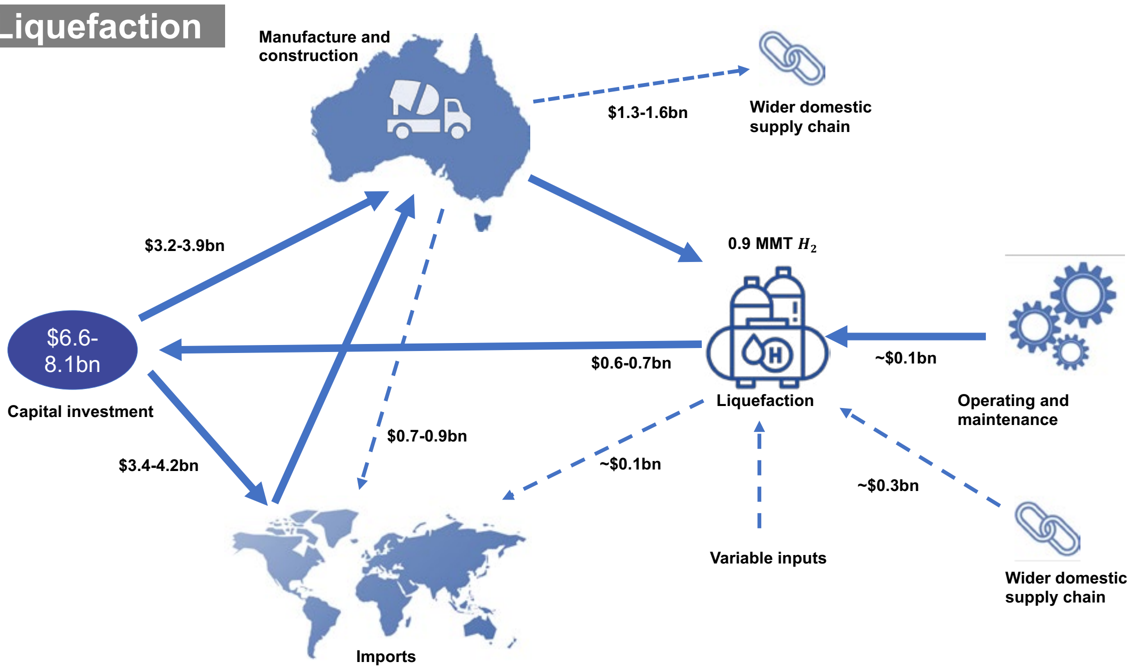
Note: Direct is activities relating to annual fixed and variable operations (O&M). Wider includes indirect supply chain activities related to O&M activities and activities related to capital construction and installation annualised by the assumed lifetime of the capital.

ECONOMIC FLOWS BY NODE

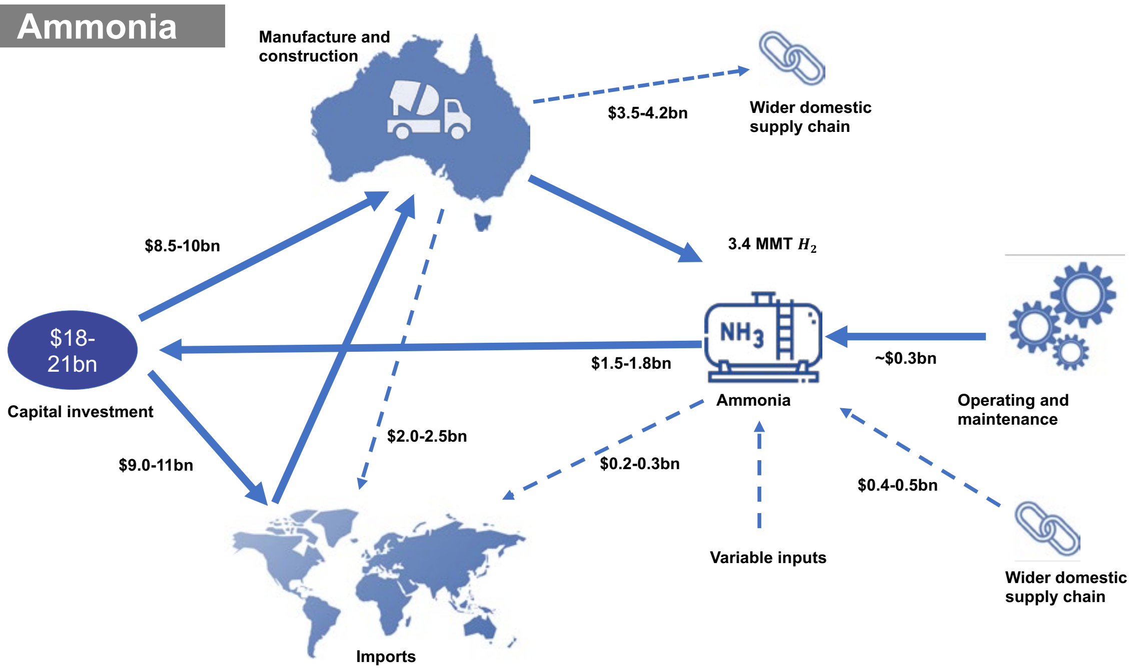


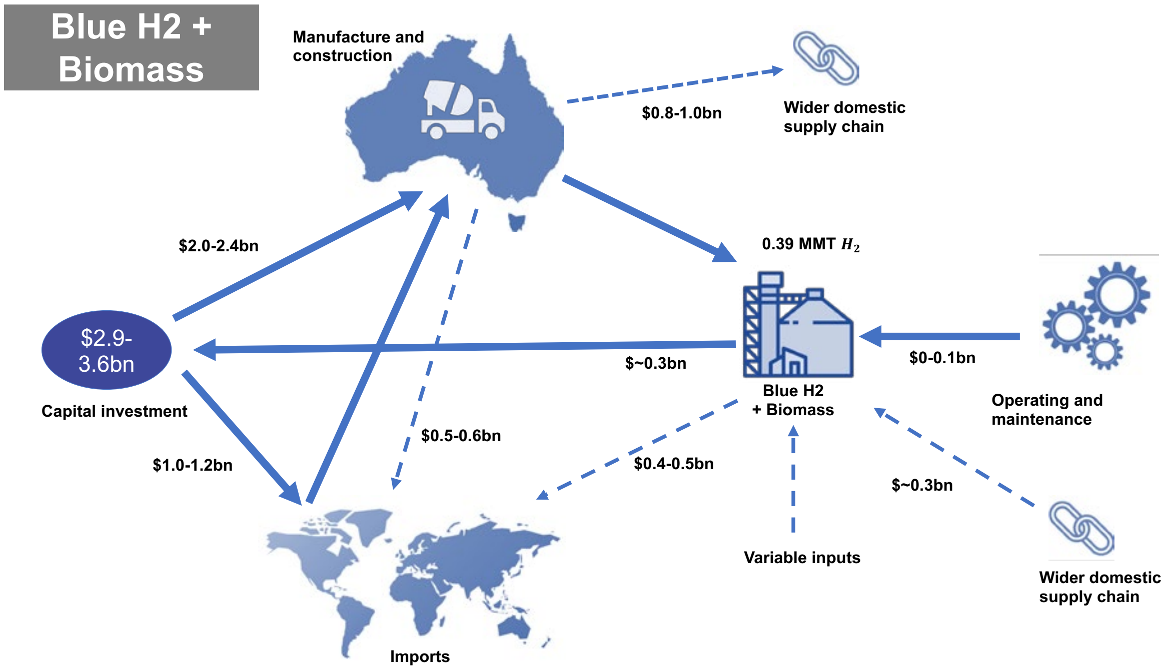


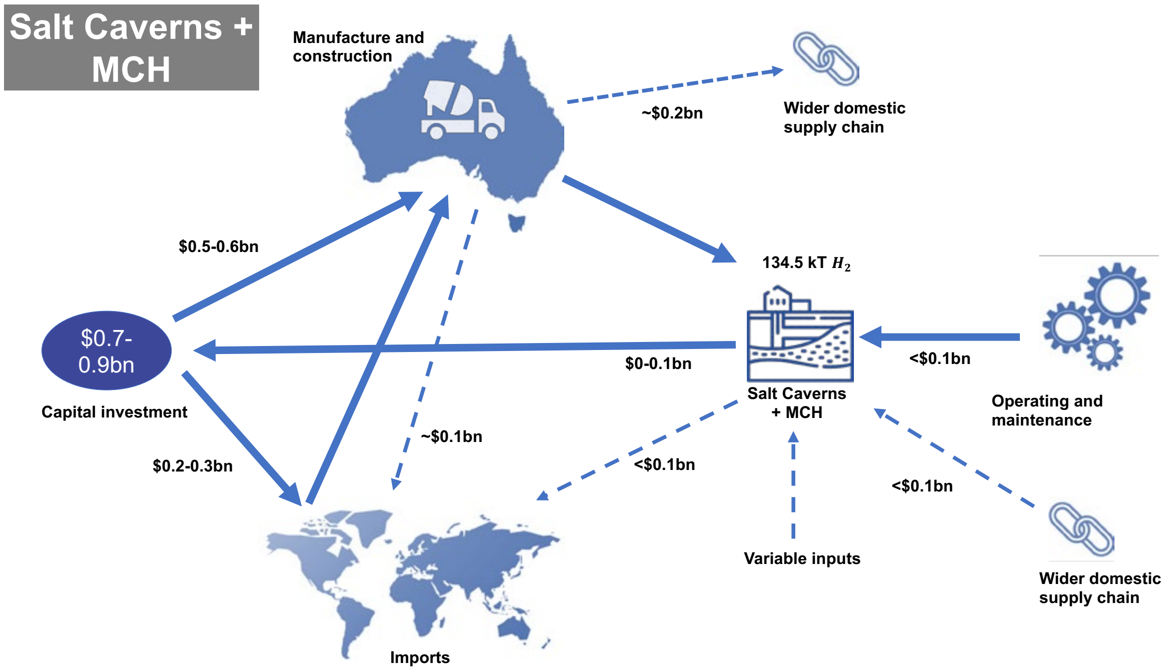
Liquefaction

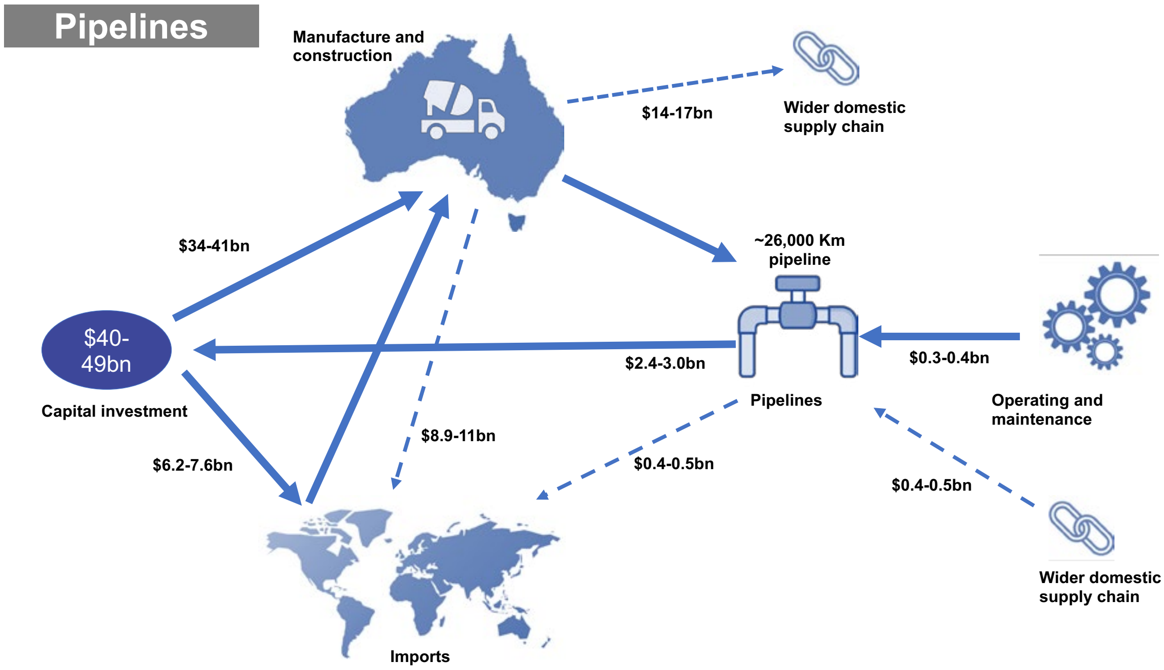


Ammonia

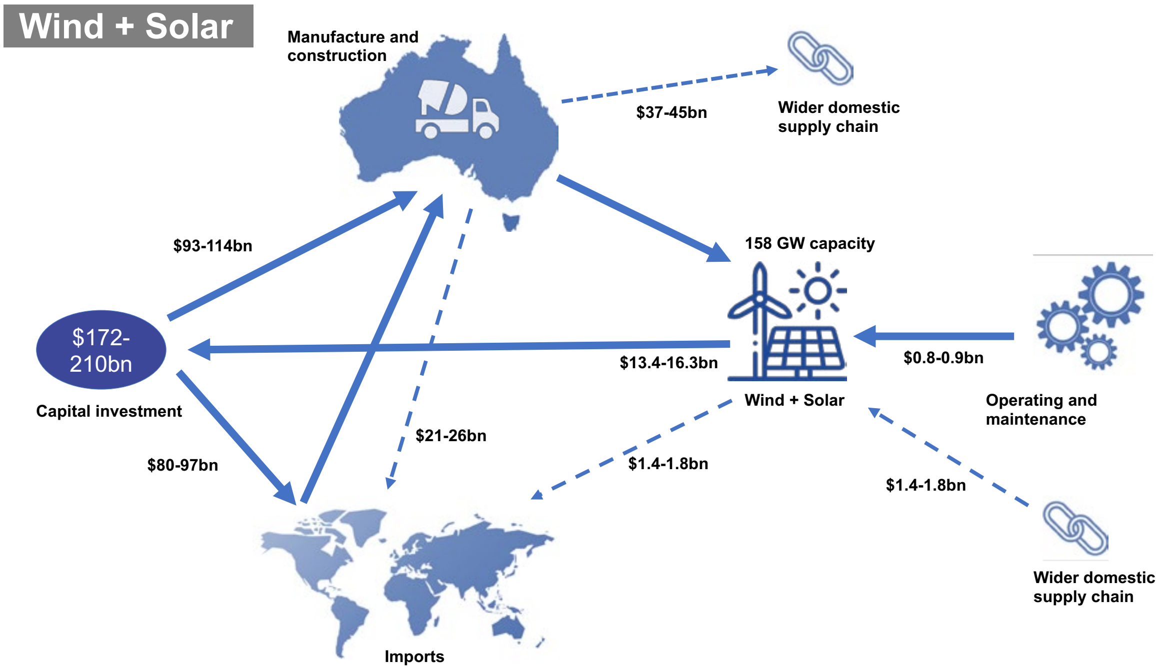



Blue H2 + Biomass
Manufacture and construction
$0.8-1.0bn
Wider domestic supply chain
$2.0-2.4bn
0.39 MMT H_2
$2.9-3.6bn
Capital investment
$~0.3bn
$0-0.1bn
Blue H2 + Biomass
Operating and maintenance
$0.5-0.6bn
$1.0-1.2bn
$0.4-0.5bn
$~0.3bn
Variable inputs
Wider domestic supply chain
Imports


Salt Caverns + MCH
Manufacture and construction
~$0.2bn
Wider domestic supply chain
$0.5-0.6bn
134.5 kT H_2
$0.7-0.9bn
Capital investment
$0-0.1bn
<$0.1bn
Salt Caverns + MCH
Operating and maintenance
~$0.1bn
$0.2-0.3bn
<$0.1bn
<$0.1bn
Variable inputs
Wider domestic supply chain
Imports



Pipelines
Manufacture and construction
$14-17bn
Wider domestic supply chain
$34-41bn
~26,000 Km pipeline
$40-49bn
Capital investment
$2.4-3.0bn
$0.3-0.4bn
Pipelines
Operating and maintenance
$8.9-11bn
$6.2-7.6bn
$0.4-0.5bn
$0.4-0.5bn
Wider domestic supply chain
Imports



Wind + Solar
Manufacture and construction
$37-45bn
Wider domestic supply chain
$93-114bn
158 GW capacity
$172-210bn
Capital investment
$13.4-16.3bn
$0.8-0.9bn
Wind + Solar
Operating and maintenance
$21-26bn
$80-97bn
$1.4-1.8bn
$1.4-1.8bn
Wider domestic supply chain
Imports

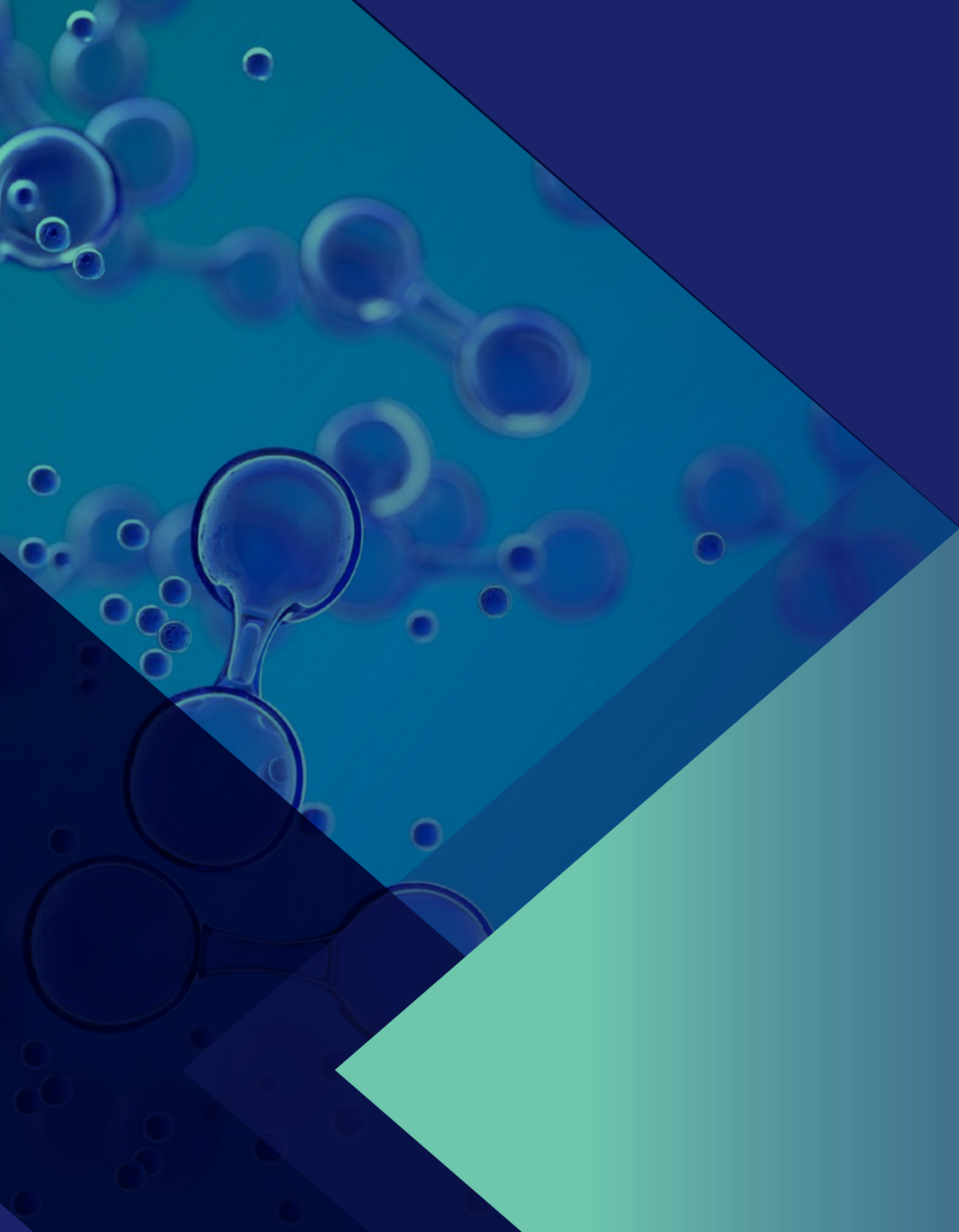
Appendix C – Industry capability and capacity

Technology Readiness Level (TRL)

TRL score definitions[73]

TRL rating	Concept	Definition
1	Initial idea	Basic principles have been defined
2	Application formulated	Concept and application of solution have been formulated
3	Concept needs validation	Solution needs to be prototyped and applied
4	Early prototype	Prototype proven in test conditions
5	Large prototype	Components proven in conditions to be deployed
6	Full prototype at scale	Prototype proven at scale in conditions to be deployed
7	Pre-commercial demonstration	Prototype working in expected conditions
8	First of a kind commercial	Commercial demonstration, full-scale deployment in final conditions
9	Commercial operation in relevant environment	Solution is commercially available, needs evolutionary improvement to stay competitive
10	Integration needed at scale	Solution is commercial and competitive but needs further integration efforts
11	Proof of stability reached	Predictable growth

73 Source: IEA ETP Clean Energy Technology Guide, https://www.iea.org/data-and-statistics/data-tools/etp-clean-energy-technology-guide



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