Department of State Development, Manufacturing, Infrastructure and Planning

Gladstone and Townsville Hydrogen Opportunities Study

Part 1 Report | May 2020

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1. Introduction and rationale

1.1 Background

The world is moving to lower our non-carbon fuels to reduce carbon emissions in support of the Paris Agreement to limit the global temperature increase. To support this initiative, hydrogen is an attractive substitute fuel and, in particular, green hydrogen, produced without carbon emissions. Integration of renewable energy in the form of green hydrogen into Queensland's energy offering has the potential to provide economic, environmental policy and social opportunities.

In response to *Australia's National Hydrogen Strategy*[1], the State of Queensland released the *Queensland Hydrogen Industry Strategy 2019-2024*, a five-year plan to grow a sustainable hydrogen industry that supports renewable resources, creates jobs and strengthens Queensland's economy.

The strategy's vision is:

> *By 2030, Queensland is at the forefront of renewable hydrogen production in Australia, supplying an established domestic market and export partners with a safe, sustainable and reliable supply of hydrogen.*

Queensland is well placed for hydrogen production with a highly skilled workforce, an established export industry, ideal proximity to markets, significant biomass / renewable energy resources, plus the many existing and planned renewable energy projects underway[2].

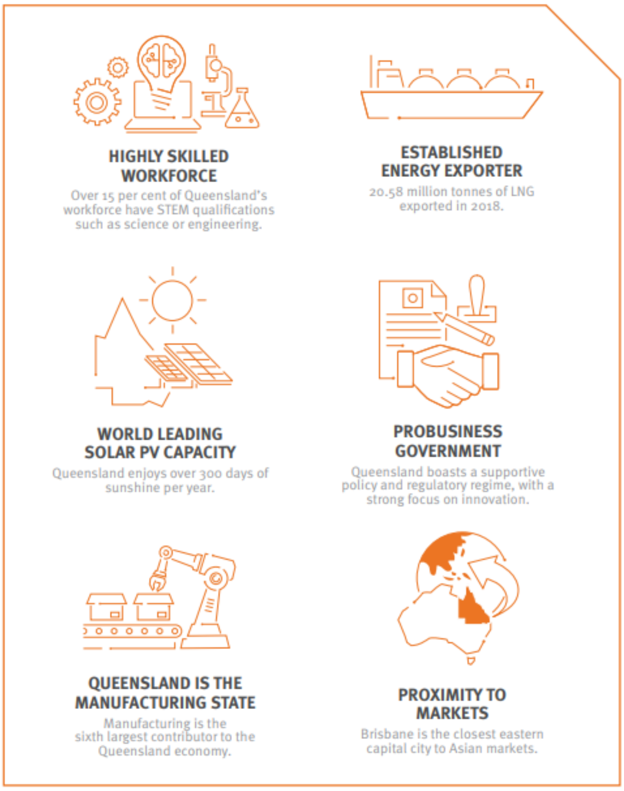

Figure 1 Queensland's Competitive Position

Source: DSDMIP 2019

1 COAG Energy Council Hydrogen Working Group 2019; World Energy Council 2019

2 Queensland Hydrogen Industry Strategy, State of Queensland 2019-2024

This study will build on the State's strategy, by investigating and identifying the land use planning, infrastructure and services required to support development of a hydrogen industry to inform Queensland State Government policy, and potential investors seeking hydrogen opportunities.

1.2 Purpose

The Gladstone and Townsville Hydrogen Opportunities Study will provide information for consideration by Government and assist with integrated land use and ports planning, infrastructure and services corridor planning and programming including the potential for common user infrastructure.

The overall study will consider a hydrogen industry development pathway from demonstration plants for domestic consumption and export. The study will also consider:

- The potential for transitional development from brown/grey hydrogen, blue hydrogen to green hydrogen
- The sources of blue and green hydrogen
- The integration with existing fossil fuelled and renewable electricity generation sites.

1.3 Scope of work

There are three main reporting stages that will form part of this study (see Figure 2). This report presents Part 1. The purpose of this stage is to develop an understanding of the current hydrogen setting in Queensland, Australia and the world.

The following tasks have been undertaken as part of Part 1:

- Collation and review of the available background information including published hydrogen roadmaps for Australia and Queensland, relevant port development plans, and planning instruments. This includes identification of factors that are considered important to assist the hydrogen industry to flourish
- Undertaking case study research of reputable scientific and engineering journals, and information published by technology vendors
- Preparation of concept hydrogen plan including block flow diagrams and schematics. This will set a baseline for further scenario development during Part 2: Market Assessment and Production Transition. The factors that are identified in Part 1 will assist in developing questions for the industry stakeholder engagement that will be undertaken in Part 2.

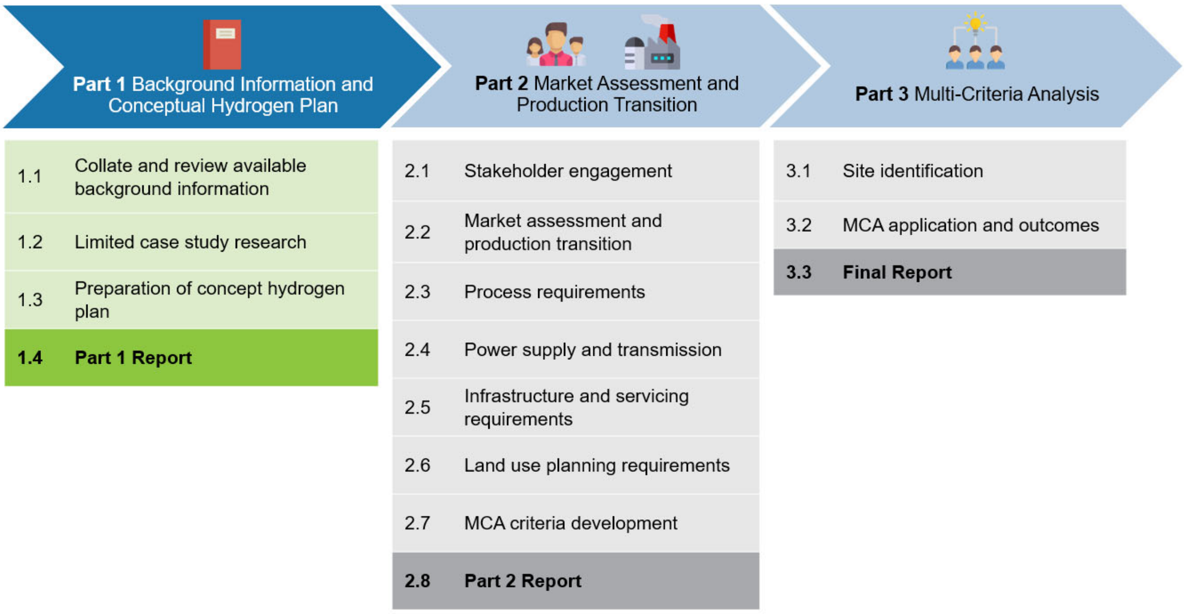

Figure 2 Study Methodology

1.4 Scope and limitations

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2. Hydrogen overview

2.1 Hydrogen production

Hydrogen is a carbon-free energy source, producing only water when combusted. Presently there are a number of processes for producing hydrogen. Figure 3 below represents the different types of hydrogen production, as well as potential end uses of hydrogen. Further detail on production methods and end uses is provided below.

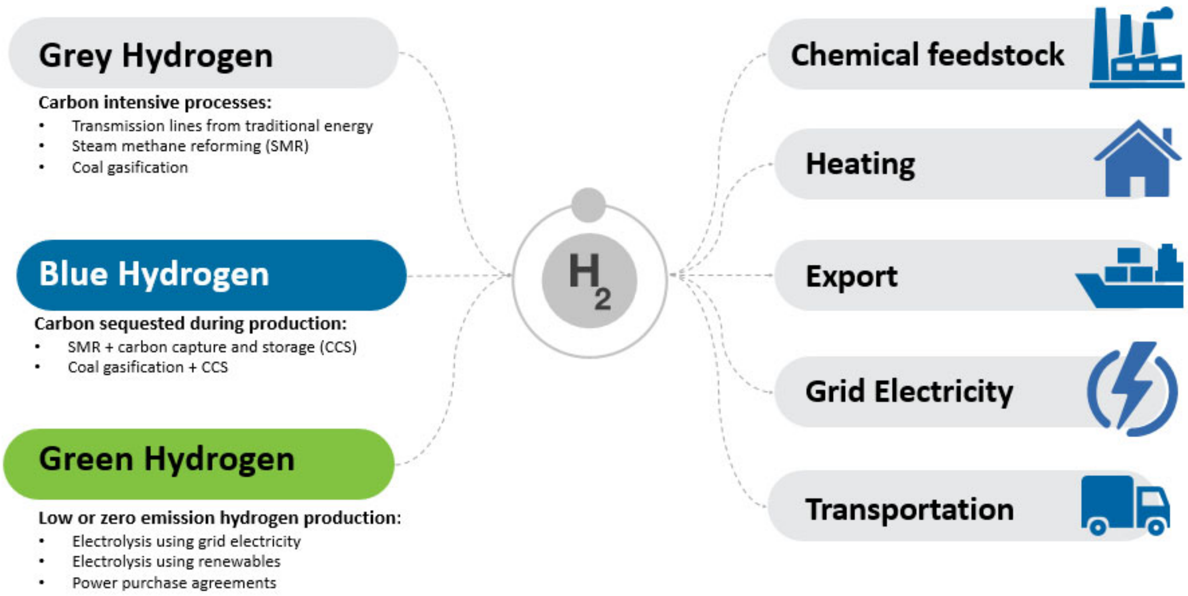

Figure 3 Hydrogen Production and Application

The most prevalent production processes are steam methane reforming and coal gasification, which are both fossil fuel dependent and carbon intensive. This process is commonly referred to as **grey / brown hydrogen**. The WEC and Hydrogen Council estimates that between 96% and 99% of hydrogen is currently produced using fossil fuels via carbon intensive processes, which may be attributed to the low cost of production, and the access to fossil fuels[3].

Blue hydrogen is grey / brown hydrogen where the CO_2 that is emitted during production is sequestered via carbon capture and storage, thereby reducing the CO_2 emitted during production.

Green hydrogen is the process of electrolysis to split hydrogen (H_2) and oxygen (O) from water (H_2O) and sourcing energy from renewable energy sources including wind or solar. This process has zero carbon emissions, however, has traditionally has a high cost of production and relies on availability of reliable renewable energy sources. Technological improvements and the growth of the renewable energy market are reducing costs to make this extraction method more competitive.

Figure 4 provides the breakdown of the crude conversion rate for the production of 1 kg of hydrogen. It demonstrates that the production of hydrogen using renewables, has zero emission outputs, with the use of traditional grid electricity and fossil fuels having the highest emission outputs per kg.

The Hydrogen Council highlights significant amounts of renewable energy is required to support the transition to decarbonised energy system[4]. Hydrogen technologies have the power to enable this

3 Innovation Insights Brief 2019

4 How Hydrogen Empowers the Energy Transition, Hydrogen Council 2017

transition to a zero or low-carbon energy system. Investments in Japan and Korea are rapidly developing technologies to assist in this decarbonisation of hydrogen production (green hydrogen).

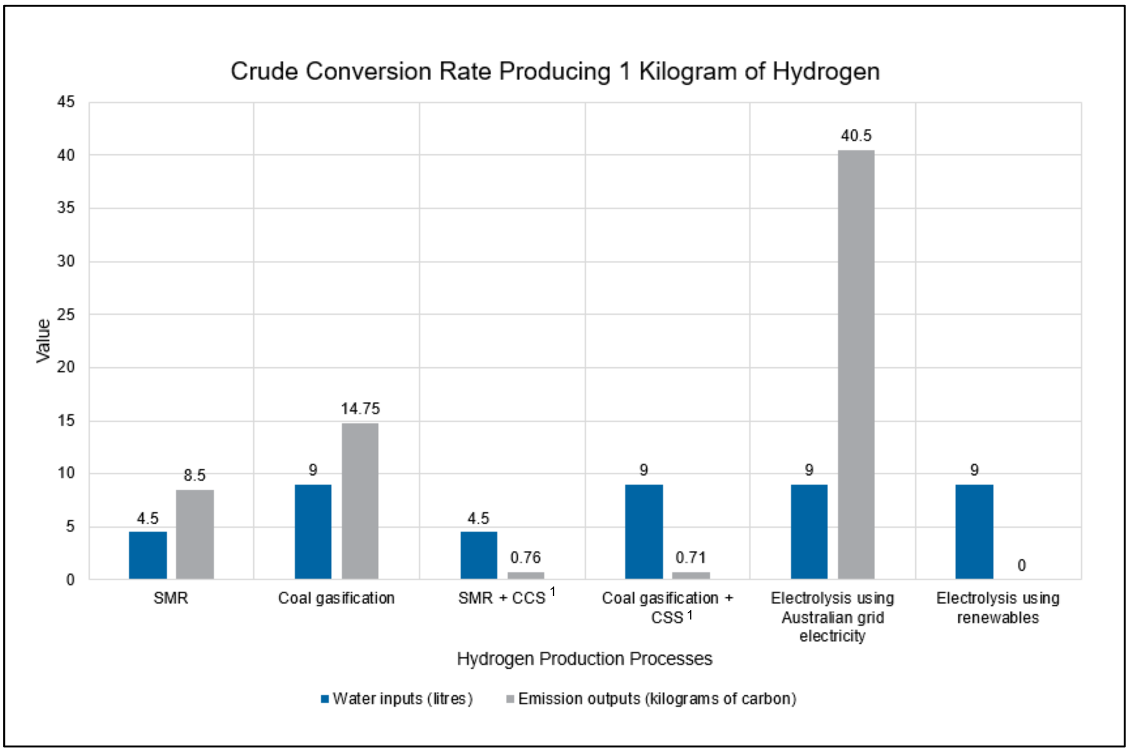

Figure 4 Inputs / Outputs to Produce 1 Kilogram of Hydrogen

Source: COAG Energy Council Hydrogen Working Group 2019

[1]Does not include energy required for sequestration.

2.2 Hydrogen use

Currently hydrogen is being mainly used for feedstock for industrial purposes including ammonia for fertiliser, as well as for food, electronics, glass and metal industries[5].

The potential applications for hydrogen are more diverse as compared to the current uses, which contributes to a more viable global and domestic hydrogen industry. A unique advantage of hydrogen is that it can service multiple sources on demand and, therefore, in practice a single hydrogen plant, could secure offtakes with a number of applications depending on available infrastructure, policy and demand profiles[6].

As illustrated in Figure 3 above, the outputs from hydrogen production could be applied to the following areas:

- Industrial/chemical feedstock:
  - Around the world, 90% of hydrogen production is used within the chemical industry, 50% of which goes towards ammonia production. Australia currently produces in excess of 2 million tonnes per annum (mtpa) of ammonia and this could rise to more than 350 mtpa of hydrogen as a feedstock for ammonia production from natural gas without CCS[7]. The global ammonia

5 Chemical Economics Handbook, IHS Market, 2018

6 National Hydrogen Roadmap, CSIRO 2019

7 Australian Hydrogen Strategy, COAG 2019

market was recorded as $48.65 billion (USD) in 2016[8], and expected to exceed 5% compound annual growth between 2019 and 2024[9]

- Transport:
  - The use of hydrogen as a fuel for transport is already financially viable in terms of the cost / kg, but is limited most notably by infrastructure barriers and technology (transport) availability. It is expected that the use of hydrogen in the transportation industry will proliferate rapidly once these barriers are overcome[3]
- Electricity Storage:
  - Electricity supply can be improved through the use of hydrogen in seasonal storage. This is most likely to benefit densely populated areas with high levels of demand on grids[3]. Hydrogen also offers the potential to provide frequency control services (load raise or lower).
- Industrial and Residential Heat:
  - It is possible for hydrogen to substitute natural gas in the residential and industrial heat supply chain as it can be directly burned to produce energy or heat. Currently, natural gas provides as much as 44% of cumulative household energy needs for as many as 70% of homes across Australia[10]. In most cases, hydrogen could use existing gas pipelines to heat buildings, cooking and providing hot water

    Hydrogen is also an alternative method of storing energy to fuel industry and households. Stored hydrogen using fuel cell technology is more cost-effective at scale, have a longer storage period and more tolerant of harsh conditions[11]
- Export:
  - There are opportunities for the export of hydrogen as other countries around the region seek alternative forms of energy. Australia is an established exporter with over 20.58 million tonnes of LNG exported in 2018 and Queensland is considered a precursor for the industry. The Queensland Gas Scheme, which commenced in January 2005 required electricity retailers and other liable parties to source 13% of the electricity they sell or use in Queensland from gas-fired generation[12].

8 Ammonia Market Size, Share and Trends Analysis Report, Grand View Research 2017

9 Ammonia Market – Growth, Trends, and Forecast (2020 – 2025), Global market Insights 2020

10 North Queensland levels of natural gas consumption may differ from national average

11 Hydrogen for Australia's Future, Hydrogen Strategy Group 2018

12 Minister for Mines and Energy, the Honourable Geoff Wilson 2007

3. Key hydrogen literature

A number of key bodies and working groups have been established in an attempt to guide the development of hydrogen as an alternative energy source. The following sections of the report provide an overview of the background strategies, studies, reports and papers that exists globally, nationally and locally in relation to the hydrogen industry.

3.1 Global perspective

The International Energy Agency (IEA), and the World Energy Council (WEC) are steering the strategic outlook for an emerging global hydrogen industry. The IEA's *Future of Hydrogen* report analyses the current state of play and offers guidance on the development of hydrogen, specifically identifying the barriers and opportunities for clean hydrogen production. The report identifies that clean hydrogen is encountering unprecedented political and business momentum, as indicated by the proliferation of hydrogen friendly projects and policies. The key inhibitor detailed in the report is the associated costs of accessing renewable energy sources and technology availability and, therefore, lowering costs will need to be a key focus to ensuring a green hydrogen future.

The WEC developed the *Innovation Insights Brief* (2019) (IIB) for strategic knowledge sharing to relevant stakeholders including policy shapers. The report recommends scaling up hydrogen production by establishing a greater role for hydrogen, reducing costs from economies of scale to stimulate commercial demand, and eliminating regulatory barriers and harmonising standards. The IIB presents a number of international case studies for hydrogen production in the emerging industries as discussed in Section 2.2 above.

The Hydrogen Council's *Hydrogen Scaling up (2017)* presents a vision of the long-term potential for hydrogen and a roadmap for deployment. This report presents an ambitious vision for hydrogen deployment which would include an aggressive push for scaling new technologies throughout the value chain and cross sector. This would require a high level of coordination and dialogue between investors, policy makers, and industry.

The level of interest from government, industry and international bodies is leading to an increased forecast in hydrogen demand and how the demand may be met by countries that are well placed to produce and export hydrogen. The IEA and WEC identify Australia as a potential 'green hydrogen production powerhouse'[13]. Australia has developed a number of key national strategies to respond to the growing acknowledgment that Australia is well placed to support the hydrogen industry.

3.2 A national hydrogen direction

A number of key scientific and governmental bodies within Australia have recognised that the national and international drive to decarbonise hydrogen production using clean energy resources is gaining momentum and is further supported by the development of technological advancements and increase market interest[14].

The *National Hydrogen Roadmap* (2019) was prepared by CSIRO with support from industry, government and consulting participants to provide a blueprint for the development of hydrogen in Australia. It provides detail on the current hydrogen state of play in Australia, and then explores the key areas of investment, with specific focus on the potential applications of hydrogen across the energy and industrial sectors. These were consistent with the outputs discussed in Section 2.1 above.

13 COAG Energy Council Hydrogen Working Group 2019

14 CSIRO 2018

The Australian Renewable Energy Agency (ARENA) commissioned *Opportunities for Australia from Hydrogen Exports* (2018), to identify the opportunities for Australia to export hydrogen as an energy source. The report is focused on production and export opportunity, specifically relating to 'clean hydrogen' which includes zero emissions hydrogen produced from renewable energy and low emissions hydrogen produced from fossil fuels.

The Council of Australian Governments (COAG) Energy Council set a vision for a clean and innovative, safe and competitive hydrogen industry in late 2018 in the National Hydrogen Strategy, with the aim of becoming a major global player by the year 2030. The *Australian and Global Hydrogen Demand Growth Scenario Analysis* (2019) was commissioned by the National Hydrogen Taskforce, an initiative that was established by the COAG Energy Council with the purpose of undertaking an Australian and global growth scenario analysis. The report analyses the global hydrogen industry, its development and growth potential, and the ways in which Australia can strategically position itself to best exploit potential opportunities. Various scenarios were created to model the range of possibilities within a timeframe to 2050.

The *National Hydrogen Strategy* (2018), commissioned by COAG Energy Council identifies key actions to a successful hydrogen industry in Australia through the establishment of the Hydrogen Working Group. One of the central actions identified in the *National Hydrogen Strategy* is the development of hydrogen hubs as a cost effective route to achieving efficiencies in production and scale. The advantages of establishing hydrogen hubs include:

- **Sector coupling:** Linking systems / markets to create new services and provide additional value. Grouping of complementary industries that may service or benefit from proximity to the hydrogen producer, such as industries with a high demand (mining). In this way, benefits are able to be shared amongst the different sectors and prices can be lowered
- **Decarbonising existing supply chains:** Locating hydrogen hubs in existing carbon-intensive industrial areas. This provides existing supply chains the option to take on more sustainable processes cost-effectively
- **Co-location:** Locating hydrogen production nearby to existing energy and resource sectors saves costs by utilising existing infrastructure
- **Centres of industrial and academic excellence:** Establishing a hydrogen hub may attract hydrogen investment to the regions.

Prospective hydrogen production regions of Australia (2019) was commissioned by Department of Industry, Innovation and Science to develop heat maps that show areas with high potential for future hydrogen production. The study is technology agnostic, in that it considers hydrogen production via electrolysis using renewable energy sources and also fossil fuel hydrogen coupled with carbon capture and storage (CCS). The heat maps presented in this work are synthesized from the national-scale datasets that are relevant for hydrogen production. These relate to available physical resources including:

- High wind speeds
- Continuous solar exposure
- Presence of coal and gas resources
- Proximity to existing port facilities, with sufficient berth availability, shipping channel depth access, tidal range and meteorological and ocean conditions that facilitate ship loading with limited potential for disruption

- Presence of directly supporting infrastructure including road corridors, power stations, and industrial estates
- Presence of indirectly supporting infrastructure including residential, commercial, education and hospital/medical facilities
- Skilled workers
- High land access and availability for industrial, parkland, primary production and other minimal land uses.

The *Australian Hydrogen Hubs Study* (2019) was prepared by ARUP for COAG Energy Council Hydrogen Working Group. The study considers the supply chain and infrastructure requirements to support the development of export and domestic hubs. The outcomes of the report were developed through targeted industry stakeholder consultation, and review of private and publically available datasets. The study built on the work undertaken in the *Prospective hydrogen production regions of Australia* report as detailed above. The outcome was the identification of 30 potential hydrogen export locations, supported by the identification of key criteria for the establishment of domestic hydrogen hubs or precincts.

In the list of potential sites for hydrogen export locations, Queensland had the highest number of sites identified, equal to South Australia, being:

- Abbot Point
- Brisbane (Bulwer, Gibson Island suggested)
- Bundaberg
- Gladstone
- Karumba
- Port Alma
- Townsville
- Weipa.

The *Australian Hydrogen Hubs Study* supports the identification of Gladstone and Townsville as appropriate locations for the development of hydrogen hubs.

3.3 Local strategy

The *Queensland Hydrogen Industry Strategy 2019-2024* (QHIS) highlights that renewable hydrogen has the potential to play a significant role in achieving identified renewable targets and will reinforce Queensland's position at the forefront of global climate action[15].

The Queensland Government has set a target to reach zero net emissions by 2050, with an interim target of 30% by 2030. These targets are supported by programs such as Solar 150, Renewables 400 and the establishment of CleanCo, the State's publically owned clean energy company, which are driving renewable energy investments through long-term revenue certainty.

QHIS was developed based on the outcomes and feedback from the *Advancing Queensland's hydrogen industry discussion paper (2018)* (discussion paper) as well as research on national and international trends and best practice in growing renewable hydrogen industries. The discussion paper identified five focus areas, which are addressed in the QHIS.

15 Queensland Hydrogen Strategy 2019-2024

The focus areas are as follows:

1. Supporting innovation
2. Facilitating private sector investment
3. Ensuring effective policy frameworks
4. Building community awareness and confidence
5. Facilitating skills development for a new technology.

The Gladstone and Townsville Hydrogen Study will support key actions identified within the QHIS, including:

- Focus Area 2 - through developing criteria that will assist in identifying potential hydrogen hubs and precincts, and supporting the development of an investor toolkit. As part of Part 2 and 3 of the study
- Focus Area 3 - through identifying current policy and statutory frameworks that would be relevant to a hydrogen industry in Queensland.

These are explored in the following sections.

3.3.1 State development areas

State development areas (SDAs) are clearly defined areas of land that are established to facilitate economic development in Queensland. They typically take the form of one of the following:

- Industrial hubs for development requiring larger footprints strategically located close to ports or major rail and road networks, e.g. LNG and mining industry in Gladstone, and freight and logistics in Bromelton, Cairns South and Townsville
- Infrastructure corridors for the co-location of infrastructure, e.g. rail lines, water and gas pipelines, and electricity transmission lines
- Major development sites, including tourism developments in Cairns and public works, e.g. the Queensland Children's Hospital.

Each SDA is subject to a development scheme that controls planning and development in an SDA. There are a number of strategically located SDAs in Queensland, including in Gladstone and Townsville, where there is significant interest in hydrogen due to its existing industrial demand, gas infrastructure, port access and skilled workforce. Additional SDAs that may be of benefit to the hydrogen industry through infrastructure delivery and ability to send for export, also exist in Abbot Point, Bundaberg, Callide Infrastructure Corridor, and the Stanwell-Gladstone Infrastructure Corridor.

SDAs may facilitate the targeted delivery of specific industries, such as hydrogen, through the development scheme and land use plan, which is the regulatory document that controls planning and development in the SDA. The development scheme can set the strategic direction of the SDA, through the identification of appropriate land uses, and infrastructure requirements.

3.3.2 Statutory

One of the key factors influencing the establishment of a successful hydrogen industry in Queensland is the ability for policy and regulation to facilitate the appropriate development scenarios.

There are a number of statutory pathways involved in establishing a hydrogen production facility in Queensland. The current approvals framework spans Commonwealth, State, and local regulatory authorities.

There are two approvals pathways available to proponents wishing to establish a hydrogen facility within Queensland. The approval pathways will be explored further in Part 2 of the study. Generally, approvals are required under the following legislation:

- Commonwealth approvals:
  - *Environment Protection and Biodiversity Conservation Act 1999*
- Overarching planning approvals:
  - *Planning Act 2016* or *State Development and Public Works Organisation Act 1971* or *Economic Development Act 2012*
- Specific assessable development approvals:
  - *Building Act 1975*
  - *National Greenhouse and Energy Reporting Act 2007*
  - *Environmental Protection Act 1994*
  - *Transport Infrastructure Act 1994.*

4. Case studies

4.1 General

Green hydrogen production has been identified in the literature (Section 3 above) as relatively immature in its establishment globally. Given this, the ability to review and provide meaningful outcomes from international case studies was limited. Many hydrogen projects are at the pre-feasibility / feasibility stage, or have developed a demonstration size plant. As such, the case studies below provide a high level analysis of the current projects that are underway globally, nationally and locally to assist in informing the establishment of a local hydrogen industry.

Much of the literature regarding Australia's ability to establish itself as a prominent exporter of hydrogen is centred on the success of the LNG industry in Queensland. Given this, a summary of the key learnings from the establishment of the LNG industry in Queensland is provided.

The case studies that are presented relate to the following;

- Japan's progress on achieving zero carbon hydrogen supply
- Hydrogen Energy Supply Chain (HESC) pilot project in Victoria
- The key learning from the LNG export industry in Queensland.

4.1.1 Global context

The Japanese Government is transitioning towards a 'hydrogen society'. The *Strategic Roadmap for Hydrogen and Fuel Cells* and Japan's 5th Basic Energy Plan support the expansion of hydrogen production and utilisations, and sets a target for a zero carbon hydrogen supply (aided by imports). Japan is also investing more than eight billion Yen in research and technology development, as well as demonstration projects.

The Japan Atomic Energy Agency has been developing a hydrogen production technology from temperature gas-cooled reactors. The effect of compositions and temperature on cell performance is being analysed. In an industrial-material facility, 10 litres of hydrogen could be produced per hour for eight hours. Longer-term demonstrations are scheduled for higher hydrogen production rates[16].

Relevance to the study: Although the technology in Japan is being developed to achieve zero carbon hydrogen supply, Japan's target of zero carbon hydrogen supply is forecast to be met via domestic and imported green hydrogen. This will influence potential exporters, such as Australia, to move towards a green hydrogen production model.

HyStock Green Hydrogen Park, Veendam, Netherlands

The HyStock[17] 1 MW power plant is located near Groningen with an adjacent 1 MW solar field and nearby wind farms in the North Sea. The plant is the first step in creating a hydrogen supply chain.

This power-to-gas installation is an important step in scaling up power-to-gas technology. EnergyStock is a partner in the HyStock project. EnergyStock operates a nearby underground gas storage facility which will provide buffer capacity and connection with the main gas and electricity infrastructure.

The 1 MW solar field consisting of approximately 12,500 solar panels is located at EnergyStock's site, with approximately 4,500 panels dedicated to the HyStock project.

16 Kasagara S. et al. 2017

17 World Energy Council, Bringing the North Sea Energy Ashore Efficiently, 2017; and EnergyStock, 'The hydrogen project HyStock', 2019, accessed 30 July 2019, refer to: https://www.energystock.com/about-energystock/the-hydrogen-project-hystock

The other 8,000 panels will be used to improve the 'green credentials' of the energy consumption of the gas storage facility. EnergyStock can store large quantities of blue and green hydrogen in salt caverns.

Most of the renewable energy (88 per cent) is delivered to the HyStock project via TenneT's high-voltage electricity grid, enabling energy conversion between the high voltage electricity network and the gas transmission network. In addition, a compressor fills cylinders with hydrogen so that it can be transported to end users.

Relevance to the study: This project shows the benefits of co-locating two renewable energy sources with underground hydrogen storage and good high voltage electricity network connections. Having two sources of renewable energy, grid connection and storage enables more continuous operation of the electrolysers and should improve the economics of the project.

4.1.2 Domestic context

The Australian Government is committed to accelerating the production and commercialisation of hydrogen, having already committed over $146 million to projects[18]. The government will also reserve $300 million from the Clean Energy Finance Corporation and $70 million from the Australian Renewable Energy Agency. The total package takes the commitments to over $500 million[19]. The hydrogen projects currently being undertaken in Australia include Adelaide's existing domestic gas networks, Victoria's trailing export supply chains, Canberra and Perth's pilot refuelling stations and Newcastle's seawater electrolysers. These projects are driven by building upon existing bilateral agreements within the Asian market. As the LNG importers, China, Japan and South Korea are now shifting their energy consumption towards hydrogen[20].

Victoria's Trialing Export Supply Chains

The Australian and Victorian governments have collaborated with Japan's Kawasaki Heavy Industries to demonstrate the feasibility of a hydrogen supply chain between Australia and Japan. Japan is identified as a prospective market due to of the size of the hydrogen market, scope to meet demand, policy support for hydrogen-related development, and existing trade relationships[21].

Victoria's Hydrogen Energy Supply Chain (HESC) pilot project commenced construction in Latrobe Valley in early 2019, with operations to start in 2020. The project seeks to demonstrate a production, transport and storage supply chain is viable to commercially operate between Australia and Japan in the 2030's. Leveraging from existing coal gasification technology, the pilot in particular seeks to maximise the technology for brown coal.

Coal gasification is the process of producing syngas, a mixture of predominantly carbon monoxide (CO) and hydrogen (H_2). The plant is expected to use 160 tonnes of brown coal from Loy Yang's Mine to produce up to three tonnes of hydrogen annually using this process. During gas refining, the carbon monoxide will be mixed with steam to react and produce additional hydrogen and carbon dioxide. The hydrogen will then be separated and refined for transport. The gaseous hydrogen will be transported via roads in high-pressure tube trailers to the liquefaction plant at the Port of Hastings, for eventual export to Japan[22].

The industry group Hydrogen Mobility Australia hopes this project will help build a hydrogen industry in Australia worth $1.7 billion from 2030[23].

18 COAG Energy Council Hydrogen Working Group 2019

19 Australia to be a World Leader in Hydrogen, Minister for Finance and Minister for Energy and Emissions Reduction 2019

20 ARUP Australia Pty Ltd 2019

21 Acil Allen Consulting Pty Ltd 2018

22 Hydrogen Engineering Australia 2020

23 ABC 2019

Relevant to the study: The HESC project is currently using coal to develop and produce grey/brown hydrogen for export to Japan. Based on the case study from Japan above, the demand for brown hydrogen may transition to green hydrogen demand into the future. The ability for hydrogen plants to be adaptable to changes in production techniques is important, and should be considered.

Australia's LNG Export Industry

Much of the literature describes hydrogen export as the greatest short-term opportunity for hydrogen production within Australia, with the success of the LNG industry in Queensland referenced as a precursor for the established export industry. Australia's LNG industry is an example of the possible time scale for establishing a new hydrogen industry for export.

Australia benefits from a competitive advantage in the LNG industry due to the abundance of gas basins (including the Bowen/Surat Basins in Queensland), established presence of supporting infrastructure and streamlined regulations, however there was a number of initial steps that were undertaken by Government, such as Western Australian Government underwriting the industry in 1979 to establish an export facility in Western Australia, which saw the first exports in 1989.

Queensland is considered a precursor for the industry. The Queensland Gas Scheme, which commenced in January 2005, required electricity retailers and other liable parties to source 13% of the electricity they sell or use in Queensland from gas-fired generation[24].

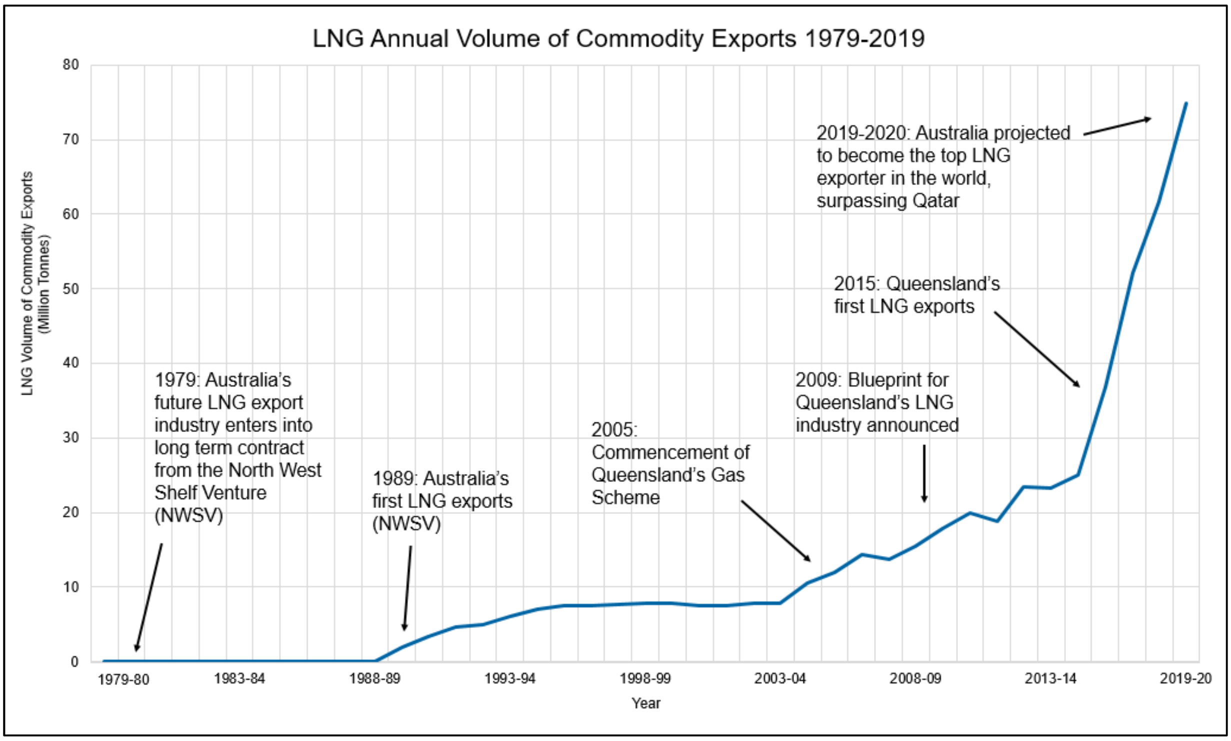

Figure 5 Australia's LNG Annual Volume of Commodity Exports 1979-2019

Source: Australian Government, Department of Industry, Science, Energy and Resources 2020

Relevant to the study: As is detailed in Figure 5, it was a decade from the release of the Blueprint for Queensland LNG industry in 2009, to 2019, where the volume of LNG export from Queensland rose from 20 million tonnes to 77 million tonnes per annum. The exponential increase in the LNG industry presented a number of challenges which have been acknowledged by the industry.

24 Minister for Mines and Energy, the Honourable Geoff Wilson 2007

If the hydrogen export market is to be compared with the LNG industry, a number of the key learnings from the LNG boom should be considered and adapted into policy.

Key learning from the LNG industry:

- Better manage the implications of concurrent projects so that the sharing of infrastructure, such as transport infrastructure, between the major projects can be achieved
- Take a long-term collaborative approach to working with local communities
- Understand the industry’s collective impact on local markets in regard to creating resource scarcities, and driving up costs
- Collaboration of key developers to ensure that new technologies and infrastructure is shared to minimise costs and better position Australia to compete more effective with the rest of the world[25].

25 The good, the bad and the ugly. The changing face of Australia’s LNG production, Deloitte 2015

5. Conceptual hydrogen plan

5.1 Overview

Hydrogen may be utilised as an energy supply in a range of domestic and international markets as a carbon-free fuel; however, it is not currently economically viable to transport hydrogen at atmospheric conditions due to the low energy content of hydrogen gas. Therefore, hydrogen carriers are required to make hydrogen transport economically more attractive. Each form of transport comes with its own set of advantages and disadvantages. Figure 6 illustrates the simplified process diagram for hydrogen carrier production, which is discussed in more detail below.

For Part 1 of the Study, the more likely carriers are defined. For each of these, the following will be defined in subsequent phases of the Study, helping to inform the better options:

- Process and technology risk for each option
- Process and logistics integration for each option
- Specific opportunities and disadvantages to each of the carriers
- Threshold capacity to produce an economically viable hydrogen carrier product; also, the typical scale(s) at which these products may be produced from a market and technology perspective.

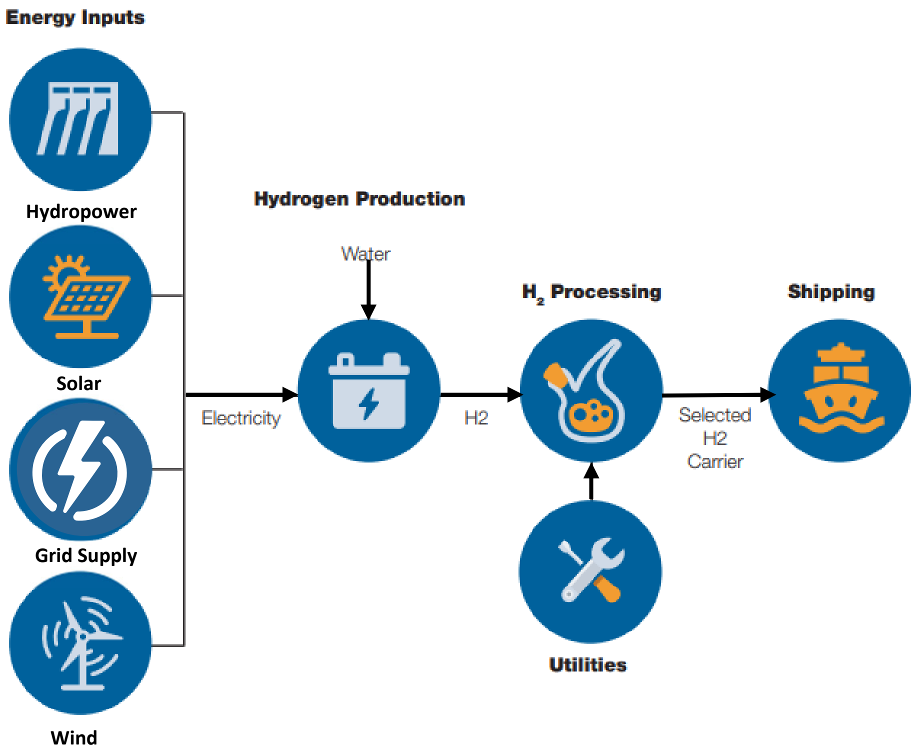

Figure 6 Simplified process diagram for hydrogen carrier production

5.2 Likely scenarios

The potential flow schemes for hydrogen production and hydrogen carriers are in Figure 7. Water electrolysis using renewable electricity is currently considered as a viable green hydrogen technology. Other technologies are either still in development or are not considered truly ‘green’, such as steam methane reforming with carbon sequestration, as it is still dependent on fossil fuel feedstocks.

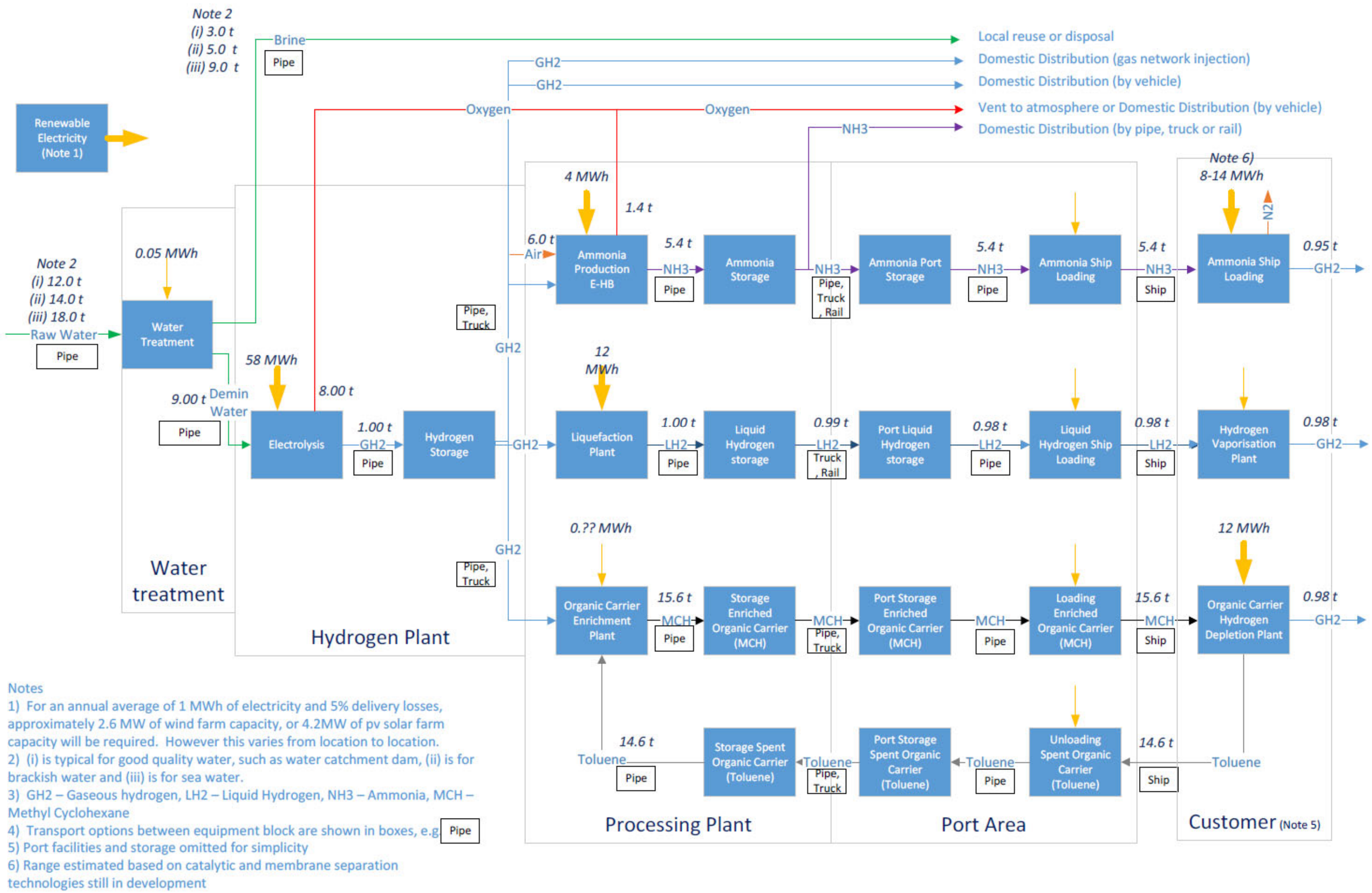

Figure 7 Flow schematic for production of hydrogen and hydrogen carriers

Demineralised water is required for water electrolysis to produce hydrogen; other technologies such as sea water electrolysis are not considered.

Hydrogen gas has a very low volumetric energy value and requires large volumes, even when compressed to high pressures. It takes approximately 14 litres of hydrogen compressed to 20 MPa to contain the same energy as 1 litre of diesel. This makes it economically unviable as a mode of transporting large amounts of energy from place to place, and in particular if the hydrogen is to be exported to other countries.

Therefore, once the hydrogen gas is produced at scale, it is converted into a hydrogen carrier, which stores hydrogen in a denser form. Of these, ammonia (as liquid; either under cryogenic conditions or compressed to liquid at ambient temperature), liquefied hydrogen (cryogenically cooled hydrogen) and methylcyclohexane (an organic hydrogen carrier) are identified by industry as the most likely candidates as carriers.

Ammonia is the most practical of these. The production technology is mature, ammonia has a relatively high liquefaction temperature (-33 ºC) and there is an existing global logistics network to import and export ammonia. It has to be split apart into hydrogen and nitrogen to be utilised, and the CSIRO is developing a membrane reactor technology to achieve this. Alternatively, ammonia can be directly utilised as fuel (e.g. ammonia turbines). A catalyst is required to produce ammonia through the Haber-Bosch process, leading to potential solid wastes.

Liquefied hydrogen has to be kept at extremely low temperatures (below -253ºC) to keep it in liquid state, but it is relatively easy to utilise once at market, with only vaporisation required prior to utilisation (similar to equipment utilised for liquid nitrogen re-vaporisation). The tankers, storage tanks and transmission infrastructure would have to be developed for liquefied hydrogen, although, it is expected that the industry would draw on LNG transport experience.

Organic carriers like methylcyclohexane (MCH) are less toxic than, for example, ammonia, and may, therefore, be more acceptable as hydrogen carriers. However, MCH, is produced through the hydrogenation of toluene, and toluene is toxic. MCH can be shipped at atmospheric conditions, which is advantageous, but then has to be dehydrogenated at market, which requires energy. In addition, catalysts are required for both the hydrogenation and dehydrogenation reactions, leading to potential solid wastes. The toluene may be recycled once dehydrogenated and returned to site utilising the same ships, but some will be lost due to inefficiencies and side reactions.

The industry is not developed enough to make a conclusion on the best carrier.

For the purpose of this Study, only centralised concepts are considered; that is, hydrogen production and conversion to a hydrogen carrier is conducted at the same site, rather than allowing for hydrogen export from site for conversion elsewhere. The hydrogen carrier is exported from site for storage at the port prior to shipping. Renewable power may also be generated at site (if the site is large enough) for generated remotely and imported.

The storage volume required is dependent on the capacity and frequency of ships to port.

In the following sections, hydrogen production via electrolysis, water treatment to produce demineralised water from raw water and conversion of hydrogen to the various considered carriers are briefly described.

5.2.1 Hydrogen production

Hydrogen will be produced through electrolysis of water, utilising a renewable power source such as wind or solar to supply power to the electrolysis units. Hydrogen production from electrolysis is currently the only green hydrogen production technology that is advanced enough to be considered in a commercial hydrogen production flow scheme.

There are two types of electrolyser units commercially available, these being alkaline and polymer electrolyte membrane (PEM) units. Although alkaline and PEM units are functionally similar, the electrolysis reaction in the stack is different, and this means each type have different characteristics and costs, which can provide relative advantages and disadvantages.

In a PEM electrolyser unit, water reacts at the anode to produce oxygen, hydrogen ions and free electrons. The electrons travel along the external electrical circuit to the cathode. The hydrogen ions travel across the solid polymer electrolyte to the negatively charged cathode. At the cathode, the hydrogen ions combine with the electrons from the external circuit to produce hydrogen gas. The typical electrode materials for PEM units are iridium and platinum for the anode and cathode respectively.

In an alkaline electrolyser the two electrodes operate in a potassium hydroxide (KOH) or sodium hydroxide (NaOH) electrolyte. Hydroxide ions from the electrolyte migrate to the positively charged anode to produce water, oxygen gas and free electrons (that travel in the external electrical circuit). Hydrogen gas and hydrogen ions are produced at the cathode by reduction of water. The typical electrode materials for alkaline units are nickel or iron and a carbon nickel alloy for the anode and cathode respectively.

Alkaline electrolysers require onsite storage of potassium hydroxide, which is a hazardous chemical and requires storage that meets regulatory requirements. The electrodes may be degraded during operation and require expensive maintenance and replacement. However, alkaline units are more mature than PEM units and information on operation and maintenance is more readily available, thus posing a lower technology and cost risk.

PEM electrolysers require expensive platinum group catalysts and membranes, which are both expensive to replace. While smaller units are better understood, reliability is still an unknown for larger units. PEM units can potentially operate at high pressure and have greater flexibility in operation and can therefore respond more quickly to load changes than alkaline units.

Alkaline units are generally more tolerant to water impurities than PEM systems, while PEM electrolysers require ultra-high purity demineralised water to prevent fouling and sedimentation formation of the platinum catalyst, which in turn reduces efficiency and increases maintenance cycles.

Both technologies have advantages and disadvantages attached to their selection. Overall, economic evaluation of the two technology types does not seem to favour either over the other. Both of these types of electrolyser units are still only available at relatively small scale, with the alkaline electrolysers being more widely used, and at larger scale. The units are modular, and consist of a number of modules (stacks) making up a specific unit module arrangement. This is the case for both alkaline and PEM technologies. Due to the typical plant capacities required to justify hydrogen product export, it is expected that a large number of electrolyser modules would be required. The largest typical water electrolysis unit at present is around 20 MW; these are built up of various arrangements of smaller stack modules.

5.2.2 Demineralised water

Electrolysers require relatively pure water as feed, called demineralised water. This is typically produced from a sustainable water source.

The high purity of water required for the hydrogen production process is similar to that required for high-pressure boilers, such as those used at large thermal power stations. Water purification is typically undertaken on site through the following treatment steps:

- Removal of particulate matter (filtration); including media filtration, in either a gravity or pressurised arrangement or membrane filtration (micro-filtration or ultra-filtration)

- Removal of organic species (responsible for colour); such as granular activated carbon filters or nano-filtration filters
- Desalination through reverse osmosis
- Demineralisation through ion exchange or electro-deionisation.

The specific flow scheme to produce demineralised water for hydrogen production depends on the quality of the source of raw water.

Brine (reject water) is produced from the process, which has to be treated or disposed.

5.2.3 Hydrogen carriers

The most likely hydrogen carriers include ammonia, liquefied hydrogen (cryogenic hydrogen) or organic hydrogen carrier such as methylcyclohexane. Of these, as discussed, ammonia is likely the most practical carrier.

These are discussed in the sections below. A brief comparison of the potential carriers are shown in Table 1 below.

Table 1 Comparison of potential hydrogen carriers

Carrier	Energy density (MJ/kg; MJ/L LHV)	Density (kg/m³)	H_2 density* (kg/kg)	Process to convert to carrier	Process to reconvert to H_2	Energy required to get to transportable state (MJ/kg)	Energy required to get to useable form (back to H_2)	Other issues
Gaseous H_2	119.96 (MJ/kg); 0.45 (MJ/L)	3.758 (@ an assumed 50 ºC and 50 barg)	1	Compression and cooling	None required, other than letdown to user pressure	7.67	Let down - generate energy	Low density - high volumes required. Flammable - storage of more than 50t at a site renders it a Major Hazardous Facility.
Liquified H_2	120.04 (MJ/kg); 9.67 (MJ/L)	80.54	1	Cooling to -255 ºC (cryogenic loops as per LNG analogy)	Utilise ambient conditions to regasify, have to manage operating pressure	42.51	Utilise ambient conditions to regasify	Insulation of equipment - temperatures are low enough to cause O2 in air to liquefy. Flammable if vaporised - Storage of more than 50t at a site renders it a Major Hazardous Facility.
Ammonia	18.9 (MJ/kg); 13.21 (MJ/L) or 11.18 (MJ/L)	698.8 (@ an assumed -35 ºC and ambient pressure) OR 591.5 (@ an assumed ambient temperature and 10.5 barg pressure)	0.151	Generate N_2 (usually via air separation which is a cryogenic separation, thus energy intensive). Compress N_2 and H_2 to 230 barg and pre-heat to 450 ºC. Catalytic reaction (Haber-Bosch process).	Catalytic decomposition of NH_3 - membrane reactor (CSIRO) or PEM technology.	9-11.25 MJ/kg NH3; thus 59.6-74.5 MJ/kg H2	26 MJ/kg H2 theoretically; probably around 38-40 MJ/kg in practice	Ammonia toxicity. Storage of more than 200t at a site renders it a Major Hazardous Facility.
MCH	43.38 (MJ/kg); 32.28 (MJ/L)	744	0.132	Hydrogenation reaction of toluene (toluene presents some issues of its own - storage and transport a challenge), catalytic reaction at around 170 ºC and 10 barg.	Catalytic dehydrogenation of MCH at around 350 ºC and 1-3 barg.		~43.4MJ/kg H2	Toluene has to be stored and is toxic. Should toluene be shipped back to be reused? How to separate by-products and what to do with by-products?

*Mass of recoverable hydrogen as a proportion of the carrier mass.

5.2.4 Ammonia

Ammonia production is a mature technology; there are many large plants of >100,000 tpa ammonia production around the globe. Due to the complexity and nature of the process, it benefits from scaling and larger facilities are more economically attractive due to much lower unit costs.

Ammonia is produced by reacting hydrogen and nitrogen. Nitrogen is typically produced from a cryogenic air separation unit. It is compressed and pre-heated together with hydrogen before it is routed to a catalytic reactor for ammonia synthesis. This is known as the Haber-Bosch reaction.

The preferred operation for the plant would be at high capacity factor with a stable production rate. Only a small amount of buffer storage would be required between the electrolyser and the ammonia plant because both would be operating as base loads with high capacity factors. Ammonia would be stored as a liquid in pressurised tanks for loading into tanker trucks for transportation to customers. Alternatively, ammonia is shipped in cryogenic tankers (for export). It may also be transmitted through an ammonia pipeline.

The production of ammonia is exothermic, and typically, a number of catalyst beds with cooling and recycling is utilised to prevent the catalyst from over-heating and sintering. A per pass conversion of approximately 15% is expected, with an overall conversion of 95 to 98%. The Haber-Bosch process typically operates at 400-700ºC and 100 to 300 barg.

To separate the produced ammonia from unconverted gases before recycle, the temperature of the reactor effluent is reduced to a low enough temperature via a refrigeration cycle to liquefy the ammonia at high pressure. Ammonia can thereafter be removed by adiabatic high pressure flash separation.

The unconverted separated gases are recompressed via a recycle gas compressor and re-heated via a heat exchanger, with the reactor effluent being utilised as the hot stream.

Ammonia is an attractive power storage medium since it can be liquefied at relatively high temperatures and/or low pressures. Therefore, storage is simple and cheap compared to hydrogen or other power storage media. In addition, transport of ammonia is relatively cheap.

Ammonia has a high toxicity, but its production and handling is well-known. Another safety aspect is that at high pressure and temperature, ammonia is capable of forming an explosive mixture with air.

Separation distances from ammonia storage are stipulated in AS 2022 Section 3, which recommends that a storage tank with a volume between 100 and 400 m^3 be located 150 m away from factories and buildings. However, within adequately fenced industrial sites that have good and continuous security and supervision, the separation distance may be reduced within the premises up to a factor of 4 with the approval of the regulatory authority (that is, instead of a 150 m separation distance it becomes 37.5 m). More tanks could be utilised, and the separation between tanks should allow for access for maintenance, inspection and emergencies.

5.2.5 Liquefied hydrogen

Liquefaction of hydrogen requires very low temperatures. Typically, two or more refrigeration cycles are required to liquefy the hydrogen. The Claude cycle is the basis for all large scale hydrogen liquefaction plants, while small scale plants (typically up to 3 tpd) utilise a Brayton refrigeration cycle using helium as refrigerant. The Claude cycle combines the refrigeration loop with expansion by turbines and finally via a Joule-Thompson valve.

One of the most important aspects of hydrogen liquefaction is the energy consumption. Liquefaction consumes more than 30% of the energy content of the hydrogen to cool it to below its liquefaction point of -253ºC.

Liquid hydrogen is stored in specially vacuum insulated cryogenic tanks. The choice of materials of construction for liquefaction and storage as well as insulation material is very important when designing a cryogenic hydrogen system. Some amount of hydrogen will be lost due to heat gain which causes evaporation or 'boil off' of liquefied hydrogen.

The initial capital investment for a new storage facility is high due to the need for liquefaction equipment as well as storage. The operating costs are also high due to the energy-intensive liquefaction process. Larger plants with higher liquefaction capacities cost more initially, but the cost of hydrogen and the energy needed to liquefy hydrogen decreases per kilogram of hydrogen liquefied. Typical liquefaction capacities can range from 100 kg/h to 10,000 kg/h and typical on-site storage capacities can range from 115,000 kg to 900,000 kg. In the United States, the total liquefaction capacity is about 69,000 tpd).

5.2.6 Organic hydrogen carriers

Methyl cyclohexane has a lower toxicity than ammonia. It has a reasonable hydrogen capacity at 6.1wt%. Compared to liquefied hydrogen, it remains a liquid at a wide range of temperatures, from -95 ºC to 101 ºC, making it significantly easier to transport than liquid hydrogen and ammonia.

Toluene hydrogenation is a reversible catalytic reaction. Hydrogenation to methyl cyclohexane (MCH) is exothermic and takes place at around 8 barg and 220ºC, while dehydrogenation of methyl cyclohexane is endothermic and occurs at a temperature of around 380ºC for adequate conversion. Therefore, when considering MCH as a hydrogen carrier, identification of energy sources at the delivery side is important. In addition, the conversion to and from toluene is not complete, so that by-products that are formed have to be considered and handled.

The hydrogenation process is integrated with the rest of the plant to allow for minimal variation in feed quality as well as acceptable turndown.

MCH and toluene are flammable materials, and this risk should be considered when determining the plant layout. Toluene has a severe interaction with some materials so that the plant layout (in particular storage) and materials of construction are important considerations.

6. Key findings and next steps

6.1 Hydrogen success factors and development scenarios

The review of the available literature, case studies and production of the conceptual hydrogen block diagram identified that the success of the hydrogen industry for both the export market and domestic uses will be reliant on the availability of a number of interrelated criteria (Figure 8), grouped broadly into the following categories:

- **Physical** requirements to support production, including proximity to ports for export, land mass, and infrastructure
- **Technology** advancements / availability
- **Environmental** impacts on the receiving environment, and more broadly the use of fossil fuels for production
- **Financial / economic** drivers for local and international investment
- **Risk** to surrounding land uses, sensitive receptors, and the environment
- **Statutory** limitations or agility to respond to emerging technologies and trends in land use
- **Community perception / stakeholder expectations** in regard to risk to human health, impact on the environment, creation of jobs and industry.

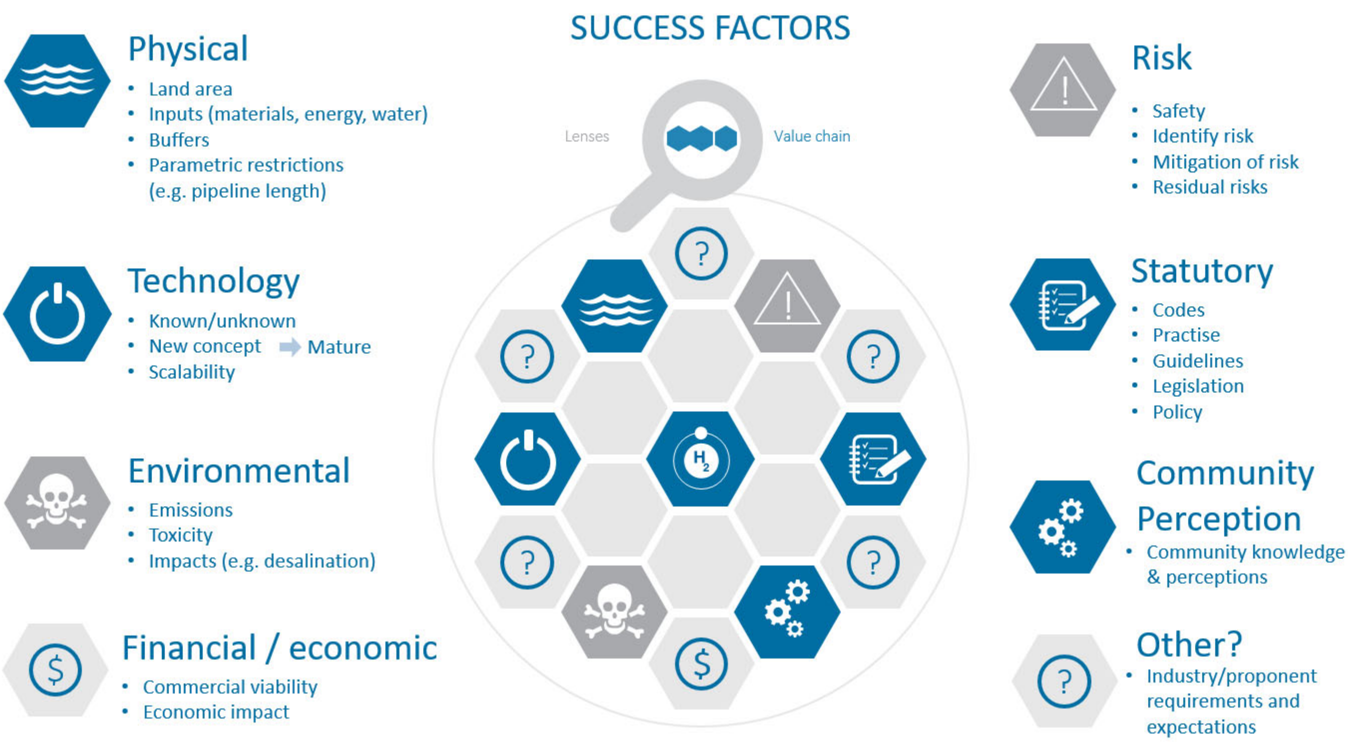

Figure 8 Hydrogen industry inputs

In this part of the Study, the detailed components of each success factor are not known. Part 2 of the Study will identify, develop and refine the inputs for each of the above factors to inform the identification of criteria that can be applied spatially to identify potential land areas to support hydrogen production and export.

Part 2 of the Study includes the following tasks:

- 2.1 Market assessment and production transition – which will identify the **financial / economic** drivers for local and international investment the development of production and growth scenarios
- 2.2 Process requirements – which will identify the inputs for the **technological, environmental, risk and physical** factors by determining the likely process derivatives (technically/economically/utilities demand, particularly water), plot plan considerations, and required connections
- 2.2A Power supply and transmission – which will identify **physical** and **technological** factors such as power supply and transmission requirements, including renewable energy
- 2.3 Infrastructure and servicing requirements – will identify **physical**, **technological and environmental** factors which will define plant utility connections, transport infrastructure requirements and port facilities
- 2.4 Land use planning requirements – will identify the **physical**, **statutory** and **environmental** factors through an analysis of land suitability and capability, appropriate land zoning, environmental constraints and other specific preconditions for hydrogen plant locations and operations
- 2.5 Stakeholder consultation – will identify the **community** and **industry (other)** factors that through consultation with industry and agency stakeholders. The stakeholder engagement will inform and provide perspective on the above tasks and factors.

The identification of the above factors will result in a suite of criteria that will form the basis for the multi criteria analysis which will be applied in Part 3 of the Study.

6.2 Next steps

Based on the outcomes of this Part 1 report, the following are the recommended next steps which form part of Part 2 of the Study.

- Workshop with the DSDMIP to agree on the Part 1 report findings
- Develop a suite of questions to be presented to the identified industry and state agency stakeholders
- Undertake the tasks identified above in Section 6.1 including the outcomes from the engagement
- Synthesis the findings from tasks 2.1 - 2.5 to develop the criteria to be developed into the MCA
- Workshop with DSDMIP to agree on the criteria and application process.

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