ENERGY TRANSITION HUB an Australian-German innovation partnership

Australia's Hydrogen Future

A Research Report

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The global shift to a net-zero emissions economy presents genuine opportunities for Australia and Germany

ENERGY TRANSITION HUB

About the Australian-German Energy Transition Hub

The Energy Transition Hub is a collaborative venture supported by the Australian Department of Foreign Affairs of Trade and the German Federal Ministry of Education and Research. It brings together researchers, industry experts, government, and communities to address energy transition challenges across a range of disciplines. Core partners are the University of Melbourne, the Australian National University, Potsdam Institute for Climate Impact Research, Münster University's Centre of Applied Economic Research, and the Mercator Research Institute of Global Commons and Climate Change.

The Hub's research aligns with four themes and includes such focii as reform to energy markets; regulation and policy to support low-carbon energy investment; technical aspects of the transition to a renewables-intensive electricity supply; roadmaps to effective and sustainable deployment of negative emissions technologies; and creating new industry trade and export opportunities. It aims to maximize economic and geopolitical opportunities for Australia and for Germany through research and academic-public sector-industry collaboration. The Hub will bring together more than 60 Australian and German researchers with industry partners and government bodies. If you are interested in becoming a partner of the Hub, please contact us (Rebecca.burdon@unimelb.edu.au). We welcome industry, government and civil society partners in exploring the energy transition and its opportunities, incorporating technical, economic, policy and social dimensions.

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Key points

Technological breakthroughs in hydrogen technology, low cost renewables, and Japan's hydrogen import target, have driven renewed interest in hydrogen's role as an energy carrier and export opportunity. A 'hydrogen economy' will address some of the most intractable problems of climate change. Examples include the substitution of coal with hydrogen as a reductant for iron production, seasonal electricity storage, and transport fuels for heavy vehicles, ships and aircraft. The utility value of hydrogen is its versatility as an energy carrier, storage medium, and chemical. Hydrogen intermediates between electricity, mobility, heat and work, but involves an 'energetic trade-off' between versatility and efficiency.

This research report synthesises the recent literature, explores the concept of the 'hydrogen economy, and includes four 'what if' hydrogen scenarios up to 2050. Under the 'Global Leader' scenario, all domestic industrial coal consumption, roughly half of natural gas, and 40% of petroleum would be substituted for electricity and hydrogen. The substitutions would roughly triple Australia's electricity demand.

The potential for hydrogen exports is vast, whether the hydrogen is exported as hydrogen or ammonia energy, or embodied in steel, non-ferrous metals, and other energy intensive products. Australia's renewable resources, access to Asian markets, and established trading relationships are key competitive advantages.

- Hydrogen technology is ready for 'market activation' due to low cost renewables and technological advances
- A hydrogen economy is the outcome of a dual electrification-hydrogen strategy
- Hydrogen addresses some of the most intractable problems of climate change
- There is vast potential for hydrogen exports, either as energy resources or embodied in energy intensive products

Executive summary

A conjunction of events has driven renewed interest in hydrogen's role as an energy carrier in Australia. Technological breakthroughs in hydrogen technology, low cost renewables, and Japan's decision to adopt a hydrogen import target, has created a groundswell of interest. The release of the South Australian hydrogen roadmap in September 2017 was followed by the announcement of the Future Fuels CRC in April 2018. August and September 2018 saw the release of the ACIL Allen exports report, CSIRO hydrogen roadmap, Finkel briefing paper, and ARENA announcement of $22.1 million in funding across 16 projects. This research report synthesises the reports and recent literature, and explores the concept of the 'hydrogen economy'. It includes four 'what if' scenarios up to 2050 to estimate the renewable energy resources that would be needed to produce hydrogen in Australia.

In 1972, John Bockris coined the term 'hydrogen economy' to describe a 'medium of energy transport' that encompassed the 'energetic, ecological and economic aspects of this concept'. In the recent CSIRO hydrogen roadmap, Dr Larry Marshall described future development in hydrogen as a 'moonshot', and Dr Alan Finkel argued that the 'long-held dream of meeting energy needs with clean hydrogen is becoming a reality'.

A hydrogen economy will address some of the most intractable and challenging problems of climate change. Examples include the substitution of coal with hydrogen as a reductant for iron production, seasonal electricity storage, and transport fuels for heavy vehicles, ships and aircraft. However it will require sustained investment with limited payoffs in the short run. In the medium to long term, a hydrogen economy will exhibit increasing returns to scale. Learnings and cost declines in the core hydrogen infrastructure will translate to improved efficiency and cost improvements across multiple use cases.

Commercially viable niche applications have already emerged, and many energy supply firms, multinational manufacturers and service firms are investing in the hydrogen fuel cycle. Research groups and commercial enterprises are coalescing into collaborative groups and industry bodies. But a hydrogen economy is not inevitable. Hydrogen is often framed around narratives of energy independence, the 'inevitability of the hydrogen economy', and notions of progress. Perhaps the biggest challenge is grounding those rhetorical visions in concrete business models that are marketable and profitable.

The utility value of hydrogen is its versatility as an energy carrier, storage medium, and chemical reducing agent. Hydrogen intermediates between electricity, mobility, heat and work. The versatility may open up possibilities for production, linkages, and applications that may not be immediately apparent. However, hydrogen involves an 'energetic trade-off' between versatility and efficiency. The versatility derives from the multiple conversion and reaction pathways, into and out of, elemental hydrogen. Each conversion reduces the end-use energy available, and many of the conversions are highly irreversible chemical processes with constrained efficiency. For some energy pathways, it is simply not worth the efficiency trade-off.

One of the key opportunities for Australia is that Japan and South Korea have signalled their intention to import hydrogen from low-emission processes. Furthermore, the prospect of a new hydrogen export industry has created a rare alignment of interests across groups with divergent positions on energy and climate policy. European and Asian hydrogen equipment manufacturers and service firms have already identified Australia as a preferred destination for investment. Australia has established energy trading relationships with Japan and South Korea, the technical know-how, and the natural resources to accelerate development. No offtake agreements have been secured to date, and annual exports would not be expected to reach $1 billion before 2030. Should hydrogen progress to being a globally significant energy carrier, ACIL Allen concluded that the value of Australian exports could surpass $10 billion by 2040. Supplying this volume of export hydrogen would require roughly 70 TWh of electricity if produced via the electrolysis route. If an export market were to develop, it would enable a domestic market to achieve economies of scale more rapidly than relying on a gradually evolving local market. A domestic hydrogen market is dependent on an export market to achieve economies of scale, but an export market could evolve independently of domestic developments.

The 'what if' scenarios are focused on substitution possibilities for end-use energy rather than an assessment of primary energy for electricity generation. Under the 'Global Leader' scenario, which is the most techno-optimistic hydrogen scenario, all industrial coal consumption, roughly half of natural gas, and 40% of petroleum would be substituted for electricity and hydrogen. Based on current end-use consumption, the substitutions would result in a tripling of Australia's electricity demand to 710 TWh.

The CSIRO Roadmap argues that technological developments have reached a sufficient level of maturity that the narrative is ready to shift to 'market activation'. Achieving a price outcome with specific applications is necessary, but not sufficient for realising the benefits of a hydrogen economy. There is already commercial activity in passenger vehicles, forklifts, remote area electricity storage, and ammonia production. A key challenge is developing an overarching narrative that encompasses a broader socio-economic perspective. Hydrogen needs to be understood as a system rather than a collection of marketable technologies.

A hydrogen economy is an open-ended and multi-decadal project without an off-the-shelf template for implementation. It will require collaboration across research institutions, commercial organisations, and governments. It requires, to borrow Edward De Bono's phrase, 'parallel thinking', that can identify and capture the momentum and alignment of interests, while being mindful of the challenges.

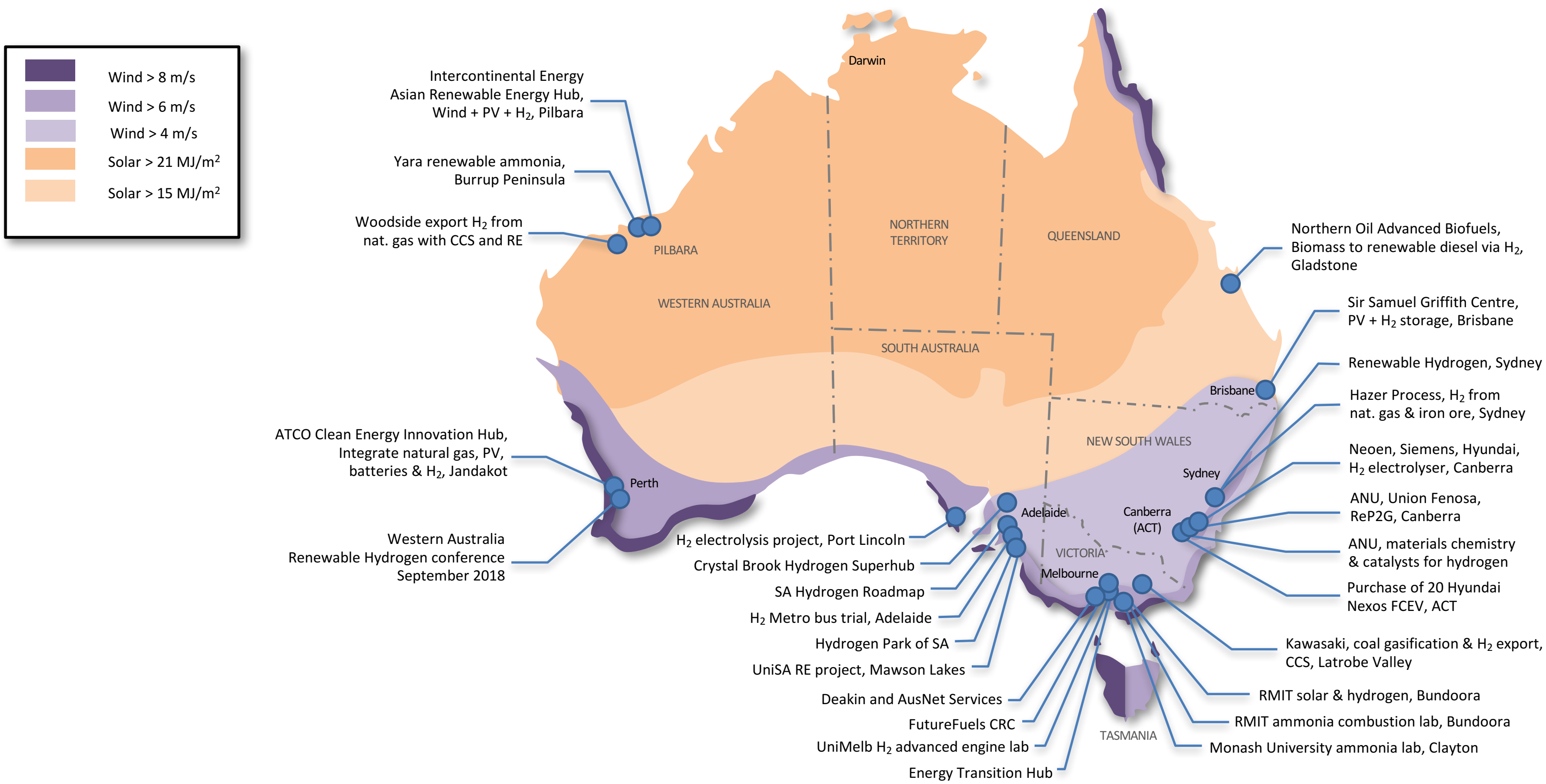

Figure 1: Australia current hydrogen projects and recent activities, Nov. 2018.

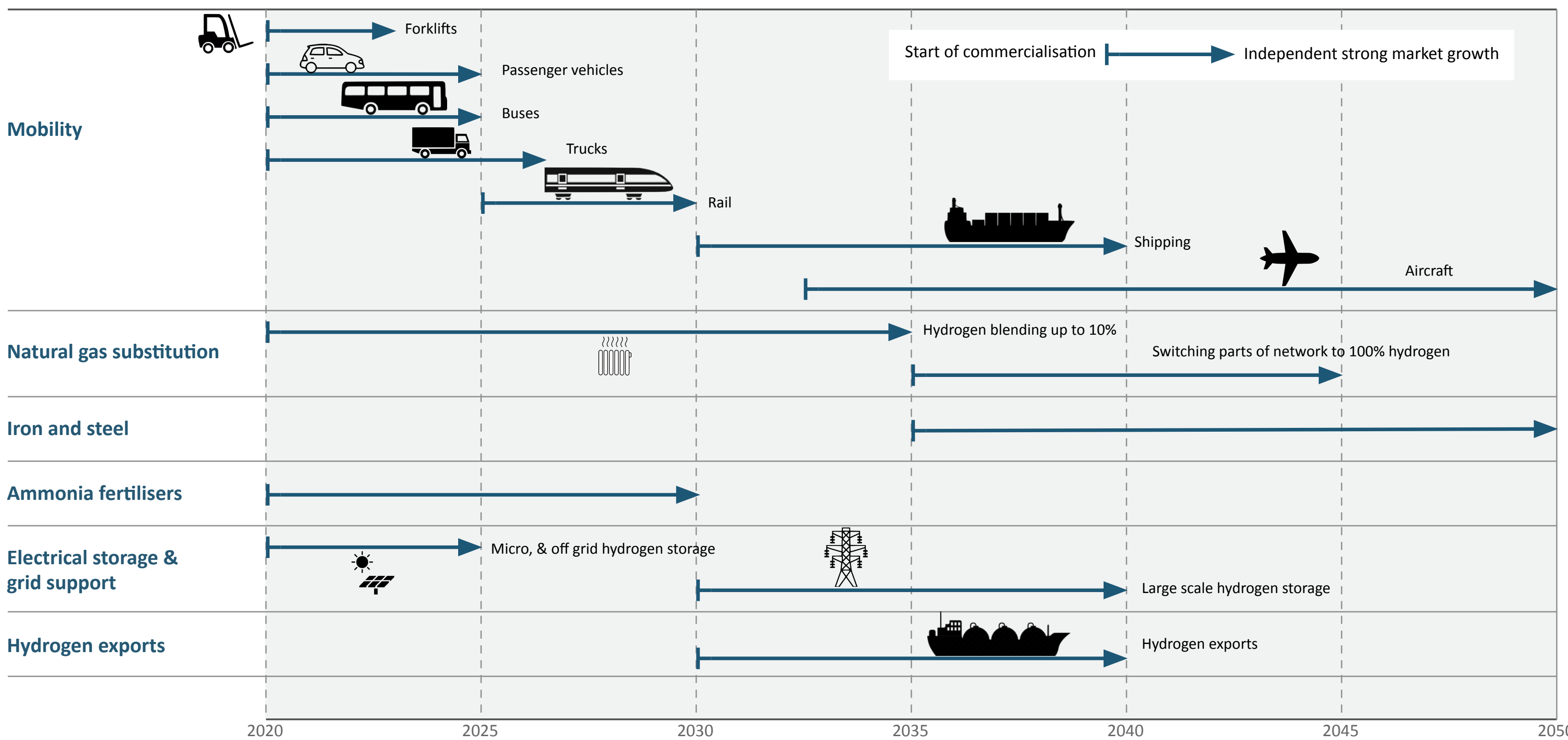

Figure 2: Indicative hydrogen deployment for the 'Global Leader' scenario. Left end of line indicates the approximate year of first commercial applications in Australia. The right end indicates the approximate year of strong market growth. Figure based on Hydrogen Council (2017, exh.7)

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1 Introduction

1.1 The promise of the hydrogen economy

The description of a hydrogen economy as a moonshot is an apt metaphor for several reasons. NASA adopted liquid-hydrogen technology in the early 1960s for the upper stage rocket for the Apollo space mission. NASA also chose the then cutting-edge hydrogen fuel cell for the primary source of electricity for the Apollo Command Module. Despite needing to overcome several technical challenges, the decision to pursue hydrogen was later seen as a key competitive advantage of the United States space program and the overall success of the Apollo 'moonshot' (Dawson & Bowles 2004).

By the 1970s, hydrogen's properties as an energy carrier were being explored for general transport, chemical, and metallurgical uses. John Bockris coined the term 'hydrogen economy' to describe a 'medium of energy transport' that encompassed the 'energetic, ecological and economic aspects of this concept' (Bockris 1972). Bockris's vision was that low-cost power, originally via atomic power but later from renewable power (Bockris 2013), would be converted into hydrogen via electrolysis, and distributed for use in trucks, cars, ships, trains, aircraft, along with chemical and metallurgical uses. However technical challenges, high cost, and fossil-based incumbency hindered progress towards a hydrogen-based energy system.

Hydrogen based pathways comprise hydrogen, or hydrogen carriers. These gaseous or liquid fuels intermediate between electricity, mobility, heat and work. Proposed hydrogen carriers include methane (CH_4), ammonia (NH_3), methanol (CH_3OH), and methylcyclohexane ($CH_3C_6H_{11}$). Energy systems based on the respective compounds have been referred to as the 'hydrogen economy' (Bockris 1972), 'ammonia economy' (Avery 1988), 'methane economy' (Gloor 2004), 'methanol economy' (Olah 2005), and large-scale MCH (Chiyoda Corporation 2014).

Interest in hydrogen continued to occur sporadically in response to policies, such as California's Zero Emission Vehicle Law of 1990 and the US Hydrogen Posture Plan of 2006 (US DOE 2006). But critics of 'hydrogen hype' critiqued the 'rhetorical visions' of the ideal of the universal chemical-energy converter, pointing to the ongoing challenges and the high cost of enabling the hydrogen economy (Eisler 2009, Sovacool & Brossmann 2010).

Several factors have converged to drive renewed interest in hydrogen globally. These include the significant fall in the price of renewables, the need for a broader suite of non-fossil energy carriers to address climate mitigation in response to the Paris Agreement, and ongoing improvements in hydrogen-based technologies. From an Australian perspective, the demand-pull from Japan, and to a lesser extent, South Korea, has created an opportunity for rapid up-scaling that would not otherwise be available from domestic demand. Japan intends to demonstrate a liquefied hydrogen supply chain by the mid-2020s for commercialisation around 2030, with an intention of importing 300,000 tonnes annually (METI Japan 2017). The recent World Energy Council report, on the potential global market for hydrogen, identified Australia as a potential 'giant' (Frontier Economics 2018). Australia's vast resources, favourable investment environment, and established trade relationships with prospective buyers were identified as key strengths.

Although policy responses to hydrogen have waxed and waned, research and development has persisted in the background. The recent announcement of the successful hydrogen fuelling of fuel cell electric vehicles (FCEV) with '99.9999% pure hydrogen' (Service 2018, Ginn 2018) is a recent example of the steady progress of hydrogen technologies.

Many of the technical challenges have been addressed or resolved, and elements of the hydrogen value chain are now considered mature technologies. Hydrogen-enabled technologies are currently characterised by a state of 'high technology readiness', but 'low commercial readiness', requiring 'market activation' (Bruce et al. 2018).

Recognising the future commercial value of the hydrogen supply chain, many energy supply firms, multinational manufacturers and service firms are investing in the hydrogen fuel cycle. Japanese firms, including Mitsubishi and Mitsui, are investing along the full hydrogen value chain through so-called 'trading houses'. Major European engineering firms, including Siemens and Thyssenkrupp, are investing in hydrogen technologies. Japan and South Korea have identified the hydrogen pathway as complementing emission goals while supporting industry. Policy commitments have created market-pull for potential hydrogen exporters (Bruce et al. 2018).

But the 'hydrogen economy' is held back by several factors (Hydrogen Strategy Group 2018). Consumers and enterprises will only purchase hydrogen-enabled vehicles and equipment if the full hydrogen supply chain is enabled, but supply chain investors will not commit to the large investments without certainty of demand. Unlike the early roll-out of battery electric vehicles (BEVs), which could piggy back onto the existing electrical network, FCEVs require the simultaneous roll-out of hydrogen fuelling stations and commercially available vehicles.

In some cases, hydrogen-based technologies may be near, or approaching, cost competitiveness, but technological lock-in, political-economic resistance, and currently a fragmented and diffuse industry act as barriers (Andrews & Shabani 2014). There is widespread recognition that price competitiveness of hydrogen-based technologies requires economies of scale, and these can only be reached with directed market activation and policy intervention (Bruce et al. 2018). Furthermore, without a recognition of climate risks and environmental externalities, hydrogen-based technologies may always struggle to compete with fossil fuel based technologies in some areas.

1.2 Prospective roles of hydrogen in an energy transition

Early interest in hydrogen was focused on finding a substitute for petroleum-based fuels. In the current situation, hydrogen-enabled energy supply chains potentially address some of the most intractable or long-term challenges of decarbonisation.

Energy source/carrier	Consumption (PJ)	%
Electricity	838	21.1
Natural gas	887	22.4
Coal	214	5.4
Petroleum	2,028	51.1

Table 1: Australian end-use energy consumption 2015-16. Derived from Office of the Chief Economist (2017).

Globally, electricity comprises between 18% and 38% of total primary energy use, depending on the stage of the transformation process and energy accounting methodology (IEA 2016, Palmer & Floyd 2017). Electrification of energy supply is a key decarbonisation strategy, however the provision of the full suite of global end-use energy services will require a diverse range of energy carriers. A hydrogen economy should be seen as a dual electrification-hydrogen strategy. Five of the major roles that address difficult challenges include:

1. **Iron and steel production**

   Steel is produced via two main routes: the blast furnace-basic oxygen furnace (BF-BOF); and electric arc furnace (EAF). The BF-BOF route produces steel from iron ore, coke, limestone, and recycled steel. Coke serves as both the energy source and reductant. The BF-BOF process emits about 2 tonnes of CO_2 per tonne of steel (Junjie 2018). The EAF route uses electricity to melt recycled steel, and therefore the emissions intensity is dependent on the emissions intensity of electricity supply. About 75% of global steel is produced with the BF-BOF route.

   Currently, the most viable pathways to decarbonsing steel production are via either carbon capture and sequestration, or hydrogen direct reduction (H-DR) (Vogl et al. 2018). Hydrogen reduction is being investigated in several countries (Fischedick, Joyashree, Acquaye & Allwood 2014). In principle H-DR can be near-zero emissions, although the decomposition of calcium carbonate, comprising a minor share of CO_2 emissions in the BF-BOF route, will still contribute to emissions.

2. **Mobility**

   Battery electric vehicles (BEV) are making steady progress as a viable option for light duty transport. However, absent significant breakthroughs in electro-chemistry, many transport tasks are unlikely to be fully supplanted by battery technology. These include rail, heavy transport, sea and air, and longer range vehicles. Fuel cell electric vehicles (FCEV) are likely to complement BEVs and hybrids in a market with a more diverse range of vehicle drive trains (Bruce et al. 2018, Andrews & Shabani 2012).

3. **Seasonal storage**

   As electrical grids progress towards full decarbonisation, large scale or seasonal storage may be required. Batteries, pumped hydro, and energy storage in concentrated solar thermal can provide storage services, but are not likely to be able to provide seasonal storage. The only feasible seasonal energy storage technologies include hydrogen or synthetically produced hydrogen carriers, such as methane, ammonia, methanol, or methylcyclohexane (MCH).

4. **Substitution of natural gas**

   Natural gas is used for residential and commercial space and water heating, and process heat for industry. Some of these tasks can be cost-effectively shifted to electric, especially low-temperature heat. However, it is may be more feasible to undertake a complete conversion of natural gas to hydrogen. During a ramp-up of hydrogen production, the existing natural gas networks and appliances can readily accommodate a 10% hydrogen blend, and appliances are certified for use with a slightly higher blend (Hydrogen Strategy Group 2018).

5. **Ammonia for agricultural fertilisers**

   Ammonia is composed of nitrogen and hydrogen and produced with the Haber-Bosch process. The major source of hydrogen for Haber Bosch is methane steam reforming from natural gas, followed by oil/naptha reforming and coal gasification. In a shift away from fossil fuels, the most viable pathway is ammonia production via electrolysis and Haber-Bosch (Institute for Sustainable Process Technology 2017).

2 Hydrogen primer

2.1 The physical basis for hydrogen as an energy carrier

Hydrogen energy is frequently discussed as a *technology*, but a prospective hydrogen economy is an ecosystem encompassing a suite of technologies, transformations and linkages between primary energy sources and end-uses. This section briefly explores the properties of hydrogen as an energy carrier, its strengths and weaknesses.

2.2 Water, hydrogen and oxygen

The rationale for a hydrogen-based energy system is due to the properties of hydrogen, oxygen and water.

1. Water, hydrogen and oxygen are abundant and essentially unlimited from the perspective of human civilisation. The Earth's atmosphere is composed of 21% oxygen and the oceans cover 71% of the Earth's area. Free hydrogen is not common in nature, but elemental hydrogen is the most common element in the universe.

2. The combination, or decomposition of water from hydrogen and oxygen is environmentally benign. The Earth's atmospheric oxygen was produced almost entirely by the photosynthetic decomposition of water, energised by sunlight.

3. There are several processes that can drive the reactions between hydrogen (and hydrogen carriers) and constituents, enabling several synthesis and use pathways. Hydrogen can be oxidised by combustion for heat and motion, or fuel cells for electricity. Hydrogen can be carried by carbon, for example as the methane molecule, or by nitrogen, as the ammonia molecule. The choice of hydrogen carrier depends on whether there is a need to capture and re-use carbon as carbon dioxide, or the avoidance of carbon entirely from the energy supply chain.

4. The oxidation of hydrogen, and the hydrogen carriers, is strongly exothermic. The double bond of the O_2 molecule is much weaker than comparable bonds, and the formation of the stronger bonds in CO_2 or H_2O results in a strongly exothermic reaction. In oxidation reactions of hydrogen and hydrocarbons, oxygen is actually more important to the reaction energy.

5. Although 'hydrogen energy' is dependant on oxygen and water, only the hydrogen component needs to be actually stored and transported where the carrier is the hydrogen molecule. Hydrogen is the lightest element in the periodic table, and comprises only 11% of the molar mass of water. Since the specific energy of 'hydrogen energy' only accounts for the mass of hydrogen, the apparent specific energy is nearly an order of magnitude greater than if the oxygen was also accounted for. Nonetheless, even where the oxidiser must be carried, such as rockets, hydrogen has been commonly used as a propellant.

2.3 Hydrogen as a parallel energy network

Contemporary energy supply in the advanced economies consist of three essentially parallel and mostly isolated energy networks.

1. Firstly, there is a global petroleum supply chain. The petroleum value chain begins with crude oil, but the refining process enables many end-use products with widely differing properties. Petroleum is an energy stock, essentially composed of the flow of millions of years of 'stored sunlight'. Petroleum is a liquid fuel that can be transported by shipping tanker, pipelines, and road tanker at a local level.

2. Some regions also possess a reticulated natural gas network. Natural gas may be locally sourced or imported via LNG, and fed into local networks. The primary use of gas is for various heat applications, including industrial process heat, space heating, and hot water. Gas can also be combusted in engines, turbines for motion or electricity generation, and as a chemical feedstock for industrial processes.

3. Electrical grids comprise regional systems that are interconnected by electrical transmission networks, and fed into local distribution networks. It is usual to discuss electricity as an energy source, but more accurately, it is an energy carrier and a power *flow*. Other than electrostatics, electricity is not storable *per se*. Storage requires conversion to electro-chemical, chemical, potential, or kinetic energy, then re-conversion back to an electrical flow.

4. In a fully enabled hydrogen economy, hydrogen production and distribution would form a fourth energy network, except that it would link with the other networks as part of an integrated system. During the establishment phase of a transition, niche use-cases would be implemented that link in with the most economical and useful hydrogen applications.

   The establishment of a hydrogen network could be compared with the mid-nineteenth century establishment of British railways. Railways represented a transportation network that operated in parallel, and linked in with, the road, inland water, and sea-based transport. Rail substituted for, and complemented, the existing transport networks. The overall effect of rail was to significantly improve the efficiency and availability of freight and people movements. The inherent benefits of rail persist today. The two outstanding examples are bulk freight shipments, and inner urban passenger movements. Despite a commuter cost recovery of only 20 to 25% (Department of Infrastructure and Urban Development 2014), Australian urban rail is considered essential to productive and liveable cities (Walker 2010).

2.4 Challenges of hydrogen as an energy carrier

There are many challenges to the realisation of a hydrogen economy —

1. As the lightest element, hydrogen has a low volumetric density, requiring very high pressure or liquefaction for storage and transport, or conversion to high volumetric density hydrogen

carriers. Compression, liquefaction, and expansion incurs an energy cost. For comparison, the volumetric density of hydrogen at 700 bar (typical for motor vehicles) is 5.6 MJ/L, compared to petrol at 34 MJ/L.

2. A major barrier is the so-called chicken-and-egg problem. Hydrogen end-uses can only be enabled with supply and infrastructure, but investment for infrastructure will only be enabled with sufficient demand. Economies of scale require an acceleration of deployment.

3. The capital cost of electrolysers is currently prohibitive. However, assuming a learning rate of 10 to 15% (per doubling of cumulative production), the cost is expected to decline significant with mass deployment. If hydrogen were to be widely deployed, we would expect a production expansion of roughly 2 orders of magnitude over the next one to two decades.

4. The cost of electrolysis is mostly a function of 3 elements: the cost of electricity; the capital cost of electrolysis; and the capacity factor of the electrolyser. Wind and solar PV are the lowest cost sources of low-emission electricity, but the capacity factor of both is less than optimal from the perspective of electrolysis. In some regions, a combined wind-solar system may offer an improved outcome. The highest capacity factor will be obtained using grid electricity, but will incur networks costs. Matching electricity supply with electrolysis, subject to emissions, cost, and availability constraints will be a challenge.

5. The location of RE, electrolysis and shipping will usually require a trade-off between optimising the cost of hydrogen production versus transport. For example, some of the most favourable locations for solar are in arid regions, remote from available shipping ports.

6. Based on the current price of hydrogen, there are few use cases with a compelling economic case. The commercial use cases, such as forklifts or non-electrified rail, are viable due to a broader cost-benefit evaluation. Mobility applications offer the best prospects in the near term. Unlike emerging technologies that are able to capture value from exploiting market niches and the 'early adopter' market, many hydrogen-enabled technologies currently face an infrastructure hurdle.

7. The capability of multiple pathways adds to the versatility of hydrogen, but the need for multiple conversion processes reduces the overall conversion efficiency. Some of the conversion processes are highly irreversible chemical processes, which places an upper bound on conversion efficiency.

   Hydrogen involves an 'energetic trade-off' between versatility and efficiency. For some energy pathways, it is simply not worth the efficiency trade-off. However, the concept of efficiency also depends on how efficiency is being measured, the boundaries of the analysis, and the specific application.

8. One of the frequently proposed hydrogen applications is storage of electricity. But for short term storage, the efficiency of substitutes, including batteries and pumped hydro, is much higher

than for hydrogen. The utility value of hydrogen electricity storage lies in long term, rather than short term storage.

9. Via electrolysis, one kilogram of hydrogen requires 9 kilograms, or 9 litres, of deionised water. At scale, the volume of water is significant and may be a constraint if electrolysis plants are located in arid regions. For example, the Australian NEM supplies around 200 TWh of electricity per annum. If this magnitude of electricity was used to produce hydrogen with an efficiency of 54 kWh per kilogram of hydrogen, around 20 gigalitres of water would be used. For comparison, Melbourne uses around 450 gigalitres per annum.

10. All energy production and transport systems contribute life-cycle environmental impacts when the full value chain is considered. The life-cycle performance of electrolysis pathways depends mostly on the source of electricity. In principle with renewable energy, the impact will be much lower than the use of fossil fuels. If grid electricity is used, the global warming potential may be double that of steam methane reforming (Mehmeti et al. 2018, table 2).

11. Hydrogen and its carriers are reactive and flammable, and therefore carry safety and environmental risks. Hydrogen has a wide flammability and detonability range, and low ignition energy. Offsetting this is a high buoyancy and diffusion rate in the event of an accident (Najjar 2013). Hydrogen and its associated chemical compounds are widely used in industry, however establishing safety codes and standards for the widespread use of hydrogen is still a work in progress (EERE 2015). There is currently no commercial experience with shipping molecular hydrogen.

    The willingness or otherwise of communities to accept the risks associated with energy carriers is not straightforward. Motorists do not seem unduly concerned about sharing the road with petrol tankers carrying 40,000 litres of petrol. Air travellers board aircraft of which half the take-off weight is jet fuel. Nonetheless, a hydrogen economy will carry risks and community concerns that need to be worked through.

    Different jurisdictions apply different regulations, and the introduction of hydrogen and its carriers to transport routes will require addressing regulatory barriers. For example, ammonia is frequently discussed as a prospective hydrogen carrier in Australia, but some jurisdictions may not approve the widespread distribution of ammonia.

12. A prospective hydrogen economy should be understood as an ecosystem encompassing a suite of technologies, transformations and linkages between primary energy sources and end-uses. A conceptualisation of hydrogen as simply a storage technology invites comparisons with alternative storage devices, such as batteries, which risks creating an overly narrow perspective. Similarly, the framing of 'BEV versus FCEV' as a 'Beta versus VHS' argument misses the complementarity of different technologies.

13. Hydrogen addresses several intractable energy-climate problems but the future value of a 'hydrogen solution' will usually be higher than the current value. For example, without a current

need for seasonal storage, a hydrogen solution to storage will tend to be undervalued based on current needs.

14. Wind and solar are modular technologies. This property has proven beneficial for rapid learning effects and cost declines. Deployment has benefited from short lead times, access to finance, and the capability of building at any scale. Hydrogen shares some of the benefits of modularity, but aspects of a 'hydrogen economy' will require large scale projects, co-ordination, and strategic management.

    A comparative example is the prospective expansion of high voltage transmission for enabling geographic diversity of wind and solar resources. To date, there are few examples of 'wide area' renewables integration even though it nearly always features as a key strategy in scenario analyses. The risk for hydrogen is that modular components are deployed but the absence of an overarching architecture inhibits the full capability of hydrogen.

3 Efficiency of hydrogen supply chains

3.1 Efficiency with respect to system boundaries

The low efficiency of conversion pathways between electricity and energy end-uses is a major weakness of hydrogen. However, the concept of efficiency also depends on what is being measured, the boundaries of the analysis, and the specific application. Many processes in nature are not particularly 'efficient', but are nonetheless 'effective'. Howard Odum argued that many biological processes could be understood as systems that selected for maximum power rather than efficiency (Hall 2004).

Two examples include an efficiency of conversion of sunlight into biomass of 1-2% (Aresta et al. 2013), and a metabolic efficiency of cycling of 20 to 25% (Ettema & Lorås 2009). If the entire metabolic and industrial system, from sunlight, through plant growth, food production and distribution, and final conversion of food to mechanical motion was considered, the 'efficiency of cycling' would evaluate to much less than 1%.

With respect to passenger vehicles, the well-to-wheels efficiency of FCEVs is estimated at 27% (Li et al. 2016). For comparison, the equivalent efficiency of internal combustion cars is 15 to 20% (Li et al. 2016, Damiani et al. 2014). Rather than accounting for efficiency, motorists are more concerned with the price of fuels at the pump and the value that the vehicle provides. Most people willingly trade-off owning a heavier vehicle for the additional safety and comfort of cars versus the reduced fuel costs of motorbikes. Similarly, fuel cell vehicle users will assess the value proposition of hydrogen with respect to the distance travelled per dollar, rather than the electricity required to produce the hydrogen.

3.2 Direct and indirect efficiency

In general, direct electrification is more energy efficient and cost effective than using a hydrogen-based solution. Furthermore, there are many non-hydrogen storage types that are suitable for short-term (<2 hours) storage. However, in cases where large scale storage is required, the benefits of conventional electrical storage diminish. One way to explore the efficiency of storage is with the concepts of *direct* and *indirect* efficiency.

The conversion efficiency of electrical storage, as it is usually understood, refers to the round trip *direct* efficiency. For example, lithium-ion batteries and pumped hydro storage (PHS) possess a round trip efficiency of 80 to 85%. In contrast, the round trip direct efficiency of electricity via electrolysis and fuel cells is around 34% (Bruce et al. 2018).

'Indirect efficiency' is an imprecise concept, but refers to the overall life-cycle efficiency, including the embodied energy of the storage devices. A high embodied energy of the physical storage system implies a low energy-return-on-investment (EROI), and therefore a low indirect efficiency. At the limits, a low EROI indicates that an energy system may be energetically unviable in the sense that net-energy return is too low. The importance of evaluating the EROI increases when the time-scale over which the storage operates widens.

In order to contextualise storage efficiency, table 2 provides a matrix of the two types of efficiency, with examples of a relatively low and a relatively high efficiency for both types.

1. **Pumped hydro storage (PHS)** has a high round trip efficiency, and a low embodied energy, relative to the energy throughput. Not surprisingly, nearly all electrical storage to date has been (PHS), comprising 97% or 142 GW of global power capacity (US DOE 2016).

2. **Hydrogen** electricity storage has a low round trip direct efficiency. However, the embodied energy of conversion and storage devices is low relative to the energy throughput, representing a relatively high indirect efficiency.

3. **Batteries** have a high direct efficiency but are energy intensive devices, representing a relatively low indirect efficiency.

4. **Biofuels** possess a low direct efficiency with respect to combustion pathways, and extremely low when the photosynthetic efficiency is included. Furthermore, the embodied energy of the supply chain is high (Carneiro et al. 2017), resulting in a low indirect efficiency.

Indirect \ Direct	High	Low
High	Pumped hydro storage	Hydrogen electrolysis and fuel cells
Low	Batteries	Biofuels

Table 2: Examples of direct versus indirect efficiency.

3.3 Storage capacity and geometric scaling

Storage devices that separate the *conversion* hardware from the *storage* hardware are more readily scalable. In many cases, geometric scaling enables a proportionality between investment and storage capacity that is greater than unity. For example, the energy storage capacity of pumped hydro scales roughly to the square of the dam wall height, independently of the pump, turbine and generator. Similarly, the storage capacity of a cylindrical gas or hydrogen storage vessel scales to the square of the diameter, independently of the engine or fuel cell.

On the other hand, examples of integrated devices, which do not separate the conversion and storage hardware include standard batteries and super-capacitors.

4 Scenarios

4.1 Introduction

Four 'what if' scenarios were developed to address the following questions —

1. What are the quantity, quality and cost of renewable energy resources needed to produce hydrogen in Australia?

2. What is the techno-economic feasibility of the synthesis pathways and what are the major drivers? What are the barriers?

3. Which technologies are most likely to be a part of the hydrogen future, and what are the interactions between these technologies and other energy sources and carriers?

The assessment was based on the current and projected technological developments in the reports given in table 3, and guided by the IPCC 'Shared Socioeconomic Pathways' (SSPs). The SSPs are based on five overarching global narratives describing socioeconomic trends, and are intended to span a broad range of plausible futures.

A challenge with developing energy scenarios is that there is a natural tendency to assume that it is possible to seamlessly overlay a new system on top of the incumbent system. Given the high degree to which modern economies are tied to energy systems, there are risks that scenarios can under- or over- state the costs and benefits. For example, scenarios can understate the degree to which technologies, synergies and innovative business models develop, and therefore understate the opportunities and benefits that might arise. On the other hand, the economic, energetic, social, and environmental costs can be understated, and therefore unintended blockages prevent the realisation of the projected scenarios.

Furthermore, forecasting technological change is inherently difficult and uncertain. Amara's Law, which is a re-statement of the hype cycle, states that *we tend to overestimate the effect of a technology in the short run and underestimate the effect in the long run* (Saffo 2015).

As such, the scenarios are intended to be reference points for further exploration rather than probabilistic projections of how the future might unfold.

4.2 Scenario descriptions

The four scenarios are described as —

1. **Business as usual (BAU)**

   BAU is the most techno-economically conservative scenario, with an assumption of little innovation in hydrogen enabled pathways. The scenario aligns with the IPCC socio-economic narrative of 'SSP5 Fossil-fuelled Development ' (Riahi et al. 2016).

2. **Near Term Solutions**

Assumes that there is moderate innovation in hydrogen technologies and system, and progress is made towards enabling hydrogen-based pathways. It assumes that some near-term cost-effective solutions are adopted. The socio-economic narrative is 'SSP2 Middle of the Road' (Riahi et al. 2016).

3. **World Best Practice**

   Assumes that there is strong global progress in hydrogen, and that Australia adopts world's best practice. The cost learning curve of hydrogen solutions persists such that hydrogen becomes competitive with alternative solutions. The socio-economic narrative is 'SSP1 Sustainability – Taking the Green Road' (Riahi et al. 2016).

4. **Global Leader**

   The most techno-optimistic hydrogen scenario. Similar to 'World's Best Practice' except that Australia is a global leader in hydrogen generated from renewable energy. The socio-economic narrative is 'SSP1 Sustainability – Taking the Green Road' (Riahi et al. 2016).

Publication	Author/s
Opportunities for Australia from Hydrogen Exports	ACIL Allen Consulting (2018)
Technology Roadmap Hydrogen and Fuel Cells	IEA (2015, 2017*a*)
National Hydrogen Roadmap	Bruce et al. (2018)
Decarbonising Australia's gas distribution networks	ENA (2017)
Basic Hydrogen Strategy Japan	METI Japan (2017)
Hydrogen Scaling up - A sustainable pathway for the global energy transition	Hydrogen Council (2017)
The role of hydrogen in a global sustainable energy strategy	Andrews & Shabani (2014)

Table 3: Recent hydrogen reports that underlie the hypothetical scenarios.

4.3 Deployment timeline

Figure 3 is a stylised depiction of the deployment timeline of hydrogen end-uses for the 'Global Leader' scenario, beginning 2020. The left end of the arrow indicates the period of the start of commercialisation, with the line indicating the period of early market development. The right end of the line indicates the period in which the technology achieves rapid take-up.

Figure 4 illustrates end-use energy for Australian for 2015-16, disaggregated by industry and households. In order to focus on the potential for substitution of non-electric consumption by 2050, the substitution possibilities are estimated by:

1. End-use consumption, rather than primary energy consumption. This is to focus on substitution possibilities for electrification and hydrogen rather than electricity generation. Coal currently dominates electricity primary energy and an ambitious hydrogen policy would presumably include a phase-out of coal that does not incorporate carbon capture well before 2050.

2. The end-use consumption for 2015-16 was used for 2050. Clearly, end-use consumption will be different in 2050. Future end-use consumption can be modelled by extrapolating elements of the Kaya Identity, including population, economic growth, and energy intensity of the economy.

For the 'Global Leader' scenario given in figure 5, assuming all hydrogen is produced by electrolysis, and assuming 64 $kWh_e/kg\ H_2$ for production, compression and transport of hydrogen, equates to 397 TWh_e per annum. This is equivalent to 130 GW of renewable capacity at 0.35 capacity factor.

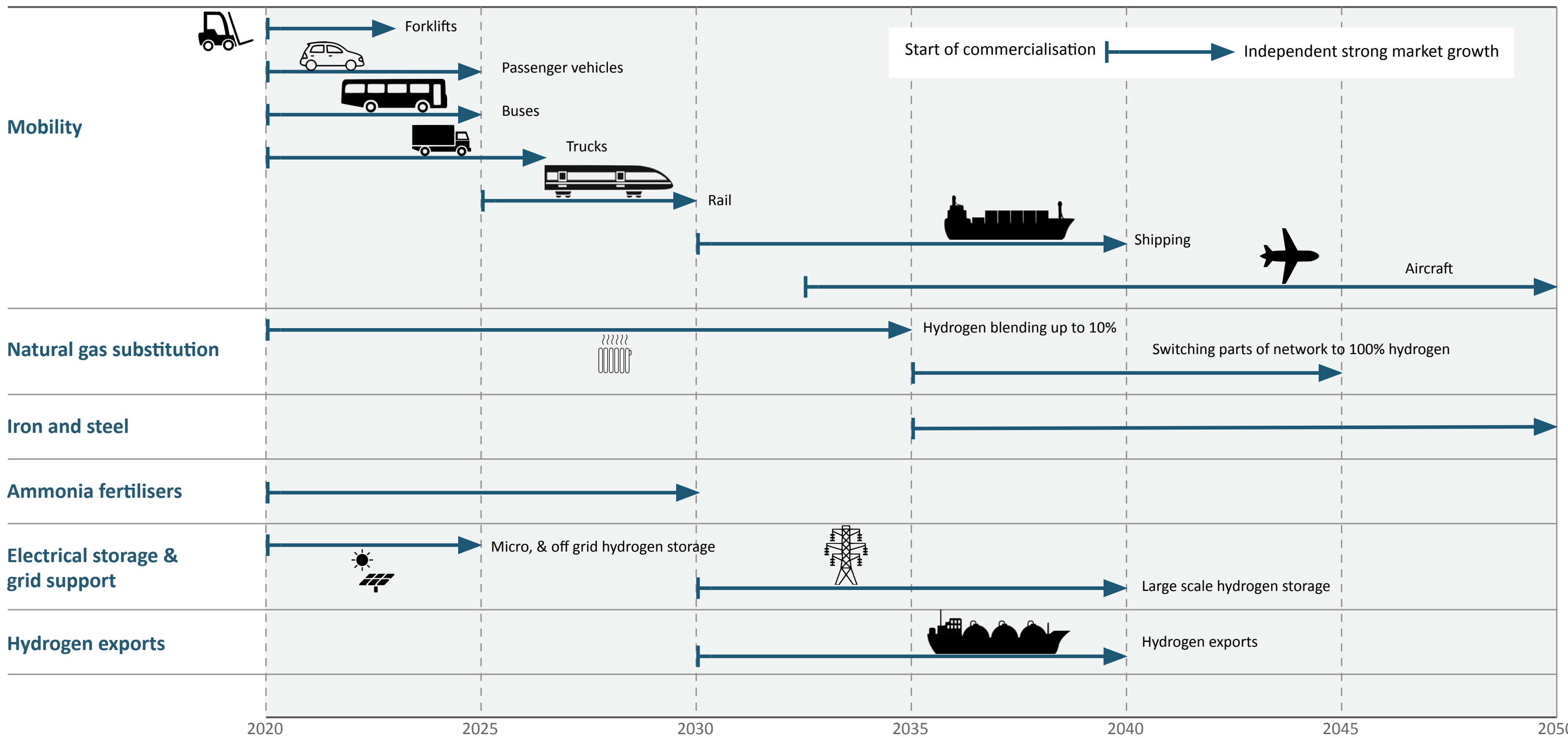

Figure 3: Indicative hydrogen deployment for the 'Global Leader' scenario. Left end of line indicates the approximate year of first commercial applications in Australia. The right end indicates the approximate year of strong market growth. Figure based on Hydrogen Council (2017, exh.7)

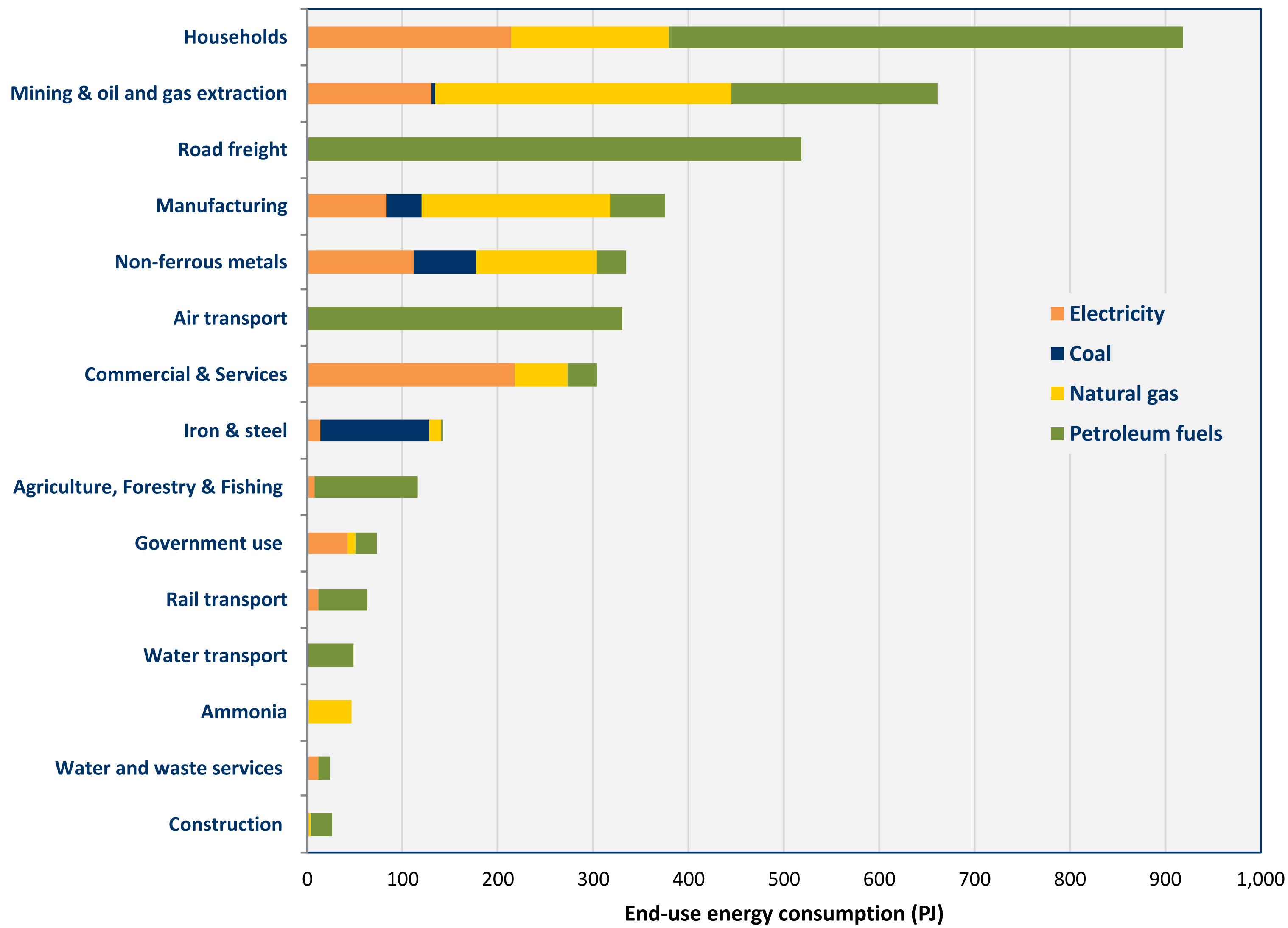

Figure 4: Australia energy end-use for 2015-16. Note table is end-use energy, not primary energy. In 2015-16, all ammonia production was for agricultural fertilisers, industrial chemicals and explosives.

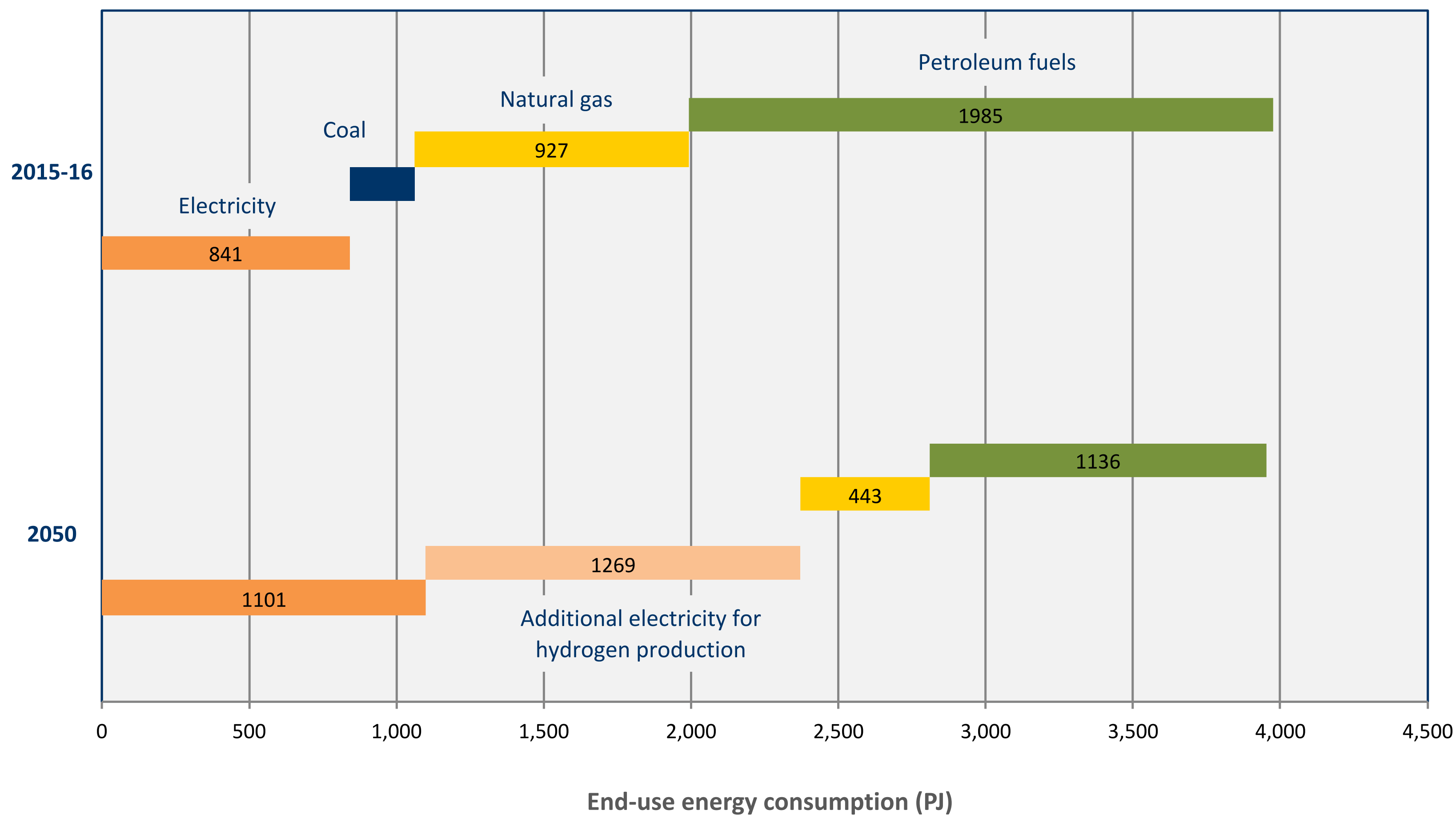

Figure 5: Australia energy end-use for 2015-16 and 2050 based on ‘Global Leader’ scenario. End-use in 2050 is based solely on electrification and conversion to hydrogen for the end-use in 2015-16. End-use substitution conversions have been adopted, including petroleum-to-electricity of 3.5 and petroleum-to-hydrogen of 2.0. Note table is end-use, not primary energy.

4.4 P2X as a realisation of a hydrogen economy

Power-to-X (P2X) is an implementation of the hydrogen economy concept. A long term realisation of hydrogen as an energy carrier will likely encompass all or most of the elements of P2X. From the expression 'P2X', 'power' refers to electricity, and 'X' refers to any one of a number of hydrogen carriers. The associated expressions, Power-to-gas (P2G), Power-to-Liquid (P2L), and Power-to-Chemicals (P2C), refers to gaseous fuels including hydrogen and methane, liquid fuels for mobility, and basic chemicals for industry respectively.

The three compounds most commonly associated with P2X are methane, ammonia and methanol. Germany has been the leading proponent of methane (Moore & Shabani 2016), ammonia is often associated with North American (NH3FA 2018) and Australian groups including Monash University (Mott 2018), and methanol is usually associated with the Hungarian and American chemist George Olah (Olah 2005).

Methane and methanol are carbon-based hydrogen carriers, and therefore tied to carbon-based infrastructure. The carbon carrier is generally CO or CO_2, derived either from fossil fuels, industrial processes, or biomass. The use of carbon can be taken as either an asset or a disadvantage. For example, the German Kopernicus Project notes that 'it is better to find sensible uses of carbon dioxide rather than pump it into the air' (Federal Ministry of Education and Research 2016). The concept of carbon capture and utilisation (CCU) is based on the potential for CO_2 to provide a feedstock for urea, methanol, carbonates, and many other compounds (Aresta et al. 2013), essentially recycling CO_2 before it is released to the environment. On the other hand, ammonia is a nitrogen-based hydrogen carrier that is not tied to carbon, which proponents argue is one of ammonia's key advantages.

The term 'sector coupling' is often applied to P2X and was originally associated with the German Energiewende. In Germany, it refers to the concept of combining electricity, heat and mobility. Since wind and solar photovoltaics produce electricity, the concept of sector coupling would enable those renewable energy technologies to supply a broader range of energy services, rather than just electrical services (Palzer & Henning 2014).

A related concept is combined heat and power (CHP), often referred to as co-generation. CHP is conceptually similar to sector coupling except that it relates to a specific installation, rather than a regional system as a whole. All heat engines produce waste heat but CHP plants include the appropriate hardware to utilise the heat as an economically useful resource, supplying water at 100 °to 180 °C. The major challenge with CHP installations is establishing an optimal balance between electricity demand and heat demand, such that the benefit of on-site heat production is greater than the (usual) additional levelised cost of electricity production compared to grid sourced electricity. The trigeneration concept is the utilisation of hot water to drive an absorption chiller to supply chilled water for air conditioning or refrigeration.

The co-generation concept can also refer to the application of fuel cells for simultaneous heat and electricity production. For example, the Japanese residential 'ENE-FARM' fuel cell units utilise natural gas for electricity generation and hot water. There are currently around 200,000 units deployed in Japan. The ENE-FARM generation capacity ranges from 0.3kW to 1kW of electricity, and 200 litres of hot water at 65 °C (Japan LP gas Association 2018). The ENE-FARM program is a public-private partnership with broader goals than optimising the financial cost of energy supply. It is difficult to establish the precise cost of ENE-FARM units, but they appear to be relatively expensive. In 2009, the government subsidy was JPY 1.4 million per unit (AUD 18,000) or half the unit cost, declining to JPY 500,000 (AUD 9,000) in 2015 (H2 International 2015).

In Germany, the Callux demonstration project was a pilot program with a similar fuel cell product. It concluded in 2015 with the installation of 500 systems (IEA 2017*a*).

Figures 6 and 7 provide a high-level overview of the P2X concept, based on methane and ammonia based PtG respectively.

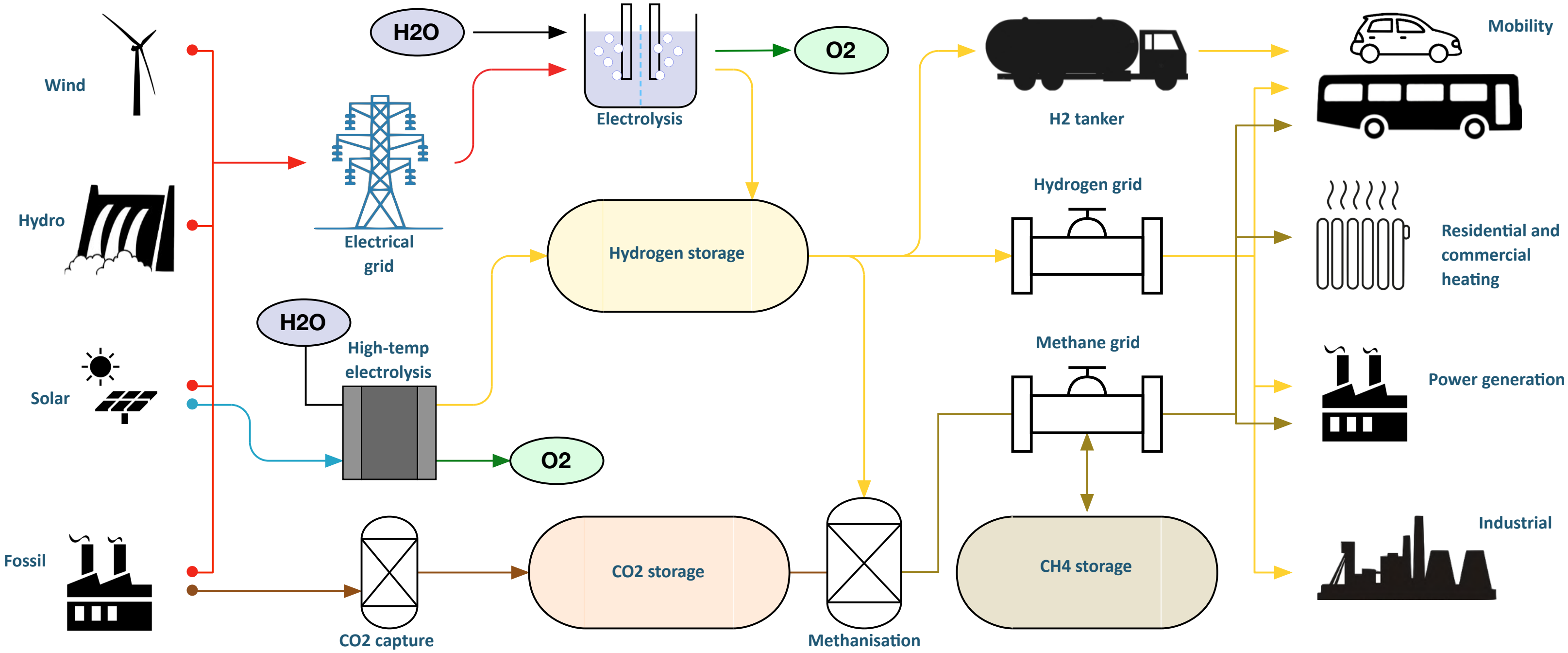

Figure 6: Schematic of methane based PtG.

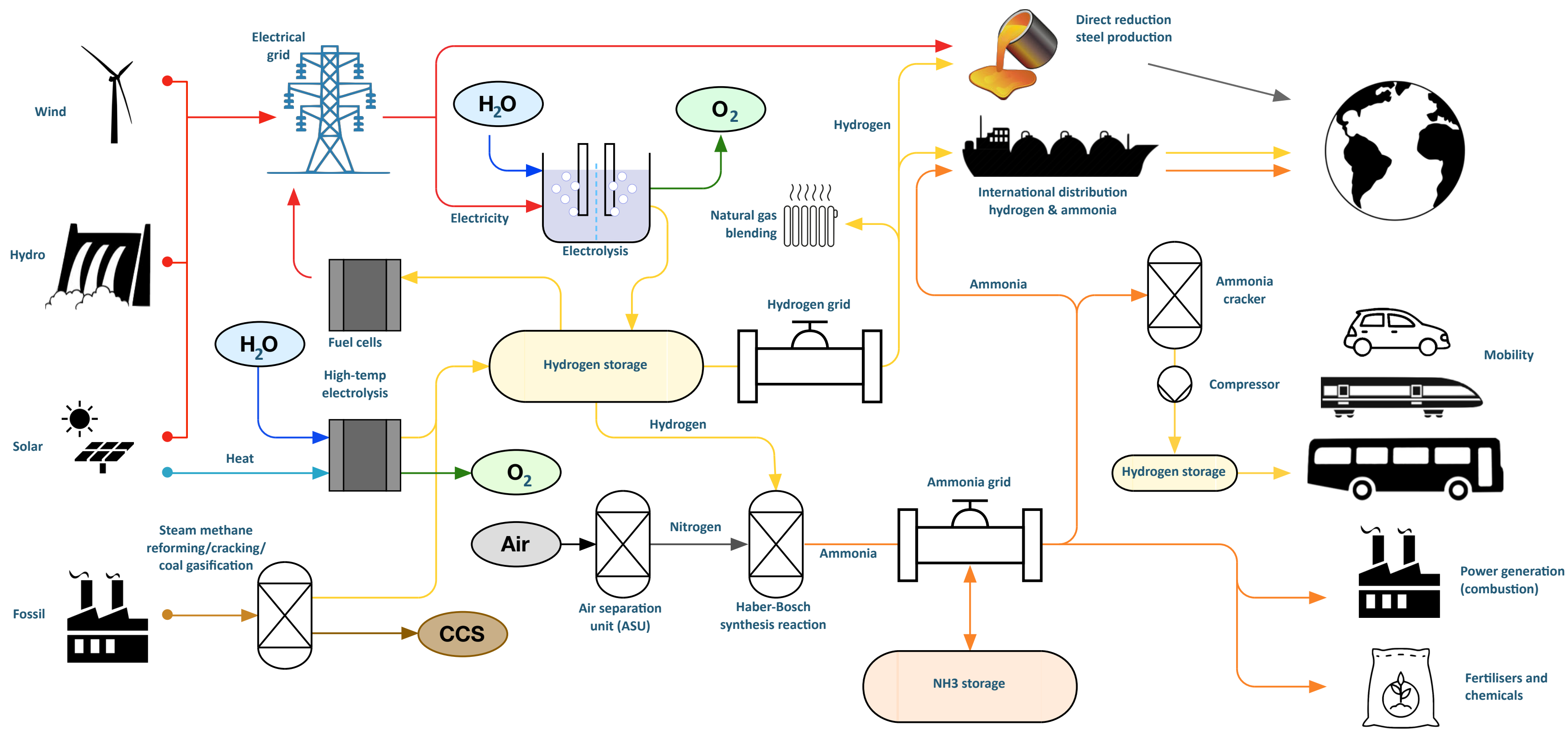

Figure 7: Schematic of ammonia based PtG.

5 Hydrogen production

5.1 Introduction

Hydrogen can be produced by one of two broad methods.

1. **Electrochemical**

   Electrochemical cells refers to the class of devices that directly generate an electric current from a chemical reaction, or vice-versa. It includes galvanic, primary (non-rechargeable batteries), secondary (rechargeable batteries), voltaic, electrolytic and fuel cells. An electrolytic cell, or more commonly, electrolyser, uses electricity to drive a non-spontaneous redox reaction, dissociating water into hydrogen and oxygen.

   The three common types of hydrogen electrolyser include —

   (a) Polymer electrolyte membrane (PEM), in which the electrolyte is a solid specialty plastic material. These operate at 70 to 90 °C. The cost of PEM electrolysers are currently slightly higher than for alkaline but have significant scope for cost reductions. In the context of variable renewable energy, their capability of fast response is an advantage.

   (b) Alkaline electrolysers (AE) operate via transport of hydroxide ions (OH^-) through the electrolyte from the cathode to the anode with hydrogen being generated on the cathode side. These operate at 100 to 150 °C. Alkaline are the most commercially mature and physically robust devices.

   (c) Solid oxide electrolysers are the least mature. These use a solid ceramic material as the electrolyte that selectively conducts negatively charged oxygen ions (O_{2-}) at elevated temperatures. These operate at 700 to 800 °C.

   In addition, there are research undertakings on other electrochemical devices that may lead to commercial development in the future, including electro-synthesis of ammonia (Zhou et al. 2017). Over coming decades, there is likely to be a diverse range of electrolysers deployed based on application and cost. Key attributes of electrolysers include output pressure, operating temperature, purity of output stream, and operational flexibility.

   The emission intensity of electrolysis is dependent on the emission intensity of the electricity supply. The cost of electrolysis is mostly a function of 3 elements: the cost of electricity; the capital cost of the electrolyser; and the capacity factor of the electrolyser. Wind and solar PV are the lowest cost sources of readily scalable low-emission electricity in Australia. Furthermore, if renewable energy and electrolysis were to be co-located, the cost of network services may be reduced or eliminated. On the other hand, some of the geographic locations that are optimal from the perspective of renewable generation may be less than optimal from the perspective of construction and running costs, and hydrogen distribution. Furthermore, the capacity factor of wind and solar is less than optimal from the perspective of electrolysis.

A second strategy is the use of technology diversity (e.g. wind + solar + biomass) to improve the capacity factor of the electrolysis plant. The benefit of stochastic smoothing is dependent on a negative temporal correlation between the technologies (i.e. if a region were to be windier at night-time and winter, wind and solar would exhibit a negative correlation). In general, wind and solar in a given region tend to be weakly or uncorrelated rather than strongly negatively correlated.

A third strategy is locating the electrolysis plant to minimise the logistics costs of hydrogen, and securing low-emission grid electricity with a power purchase agreement (PPA) rather than physically co-locating renewable electricity plants. This will incur network costs.

A fourth strategy is the same as the third except that a price ceiling on electricity purchases is set. Depending on the penetration of renewable energy, a low price may signal that there is surplus renewable electricity generation. The resulting capacity factor of electrolysis would be expected to fall significantly (Bruce et al. 2018, table 3), thereby amortising the capital cost of electrolysis over fewer units of production.

In summary, matching electricity supply with electrolysis, subject to emissions, cost, and availability constraints will be a significant challenge. Falling electrolyser prices will enable progressively lower capacity factors.

2. **Thermochemical**

   Thermochemical processes refers to processes that create products by reactions involving heat. In relation to hydrogen production, the three dominant processes are steam methane reforming, oil/naphtha reforming, and coal gasification (Weger et al. 2017, table 2). The CO_2 emissions intensity of these processes is estimated at 54, 71, and 107 kg CO_2 per GJ hydrogen respectively. For comparison, the National Greenhouse Emission Reporting (NGER) figure for combustion of natural gas is 51.2 kg CO_2-e per GJ (Australian Department of the Environment 2015).

   All of these technologies can potentially be coupled to CCS, which would reduce the emissions by 80 to 90%. Despite its slow progress, CCS remains a live option in IPCC (Clarke et al. 2014), IEA (IEA 2017*b*, p.34) and other international energy agencies. The recent delay with CCS injection at the Gorgon LNG facility (Doyle 2018) is a reminder of the practical challenges of CCS and its immature status in Australia. Emerging technologies include methane cracking, which is CO_2 free, instead producing a solid carbon or graphite as a by-product; chemical looping; and Concentrating Solar Fuels (Bruce et al. 2018, p.68).

   According to ordinary carbon accounting principles, any emissions associated with fossil-fuel based hydrogen production will be attributed to Australia, leading to so-called emissions displacement or carbon leakage (Jiborn et al. 2018). This is already the case with respect to Australia's exports of LNG and coal. The main difference is that only the emissions associated with extraction, transport and processing are attributed; the emissions associated with combustion are attributed to the destination country. In the case of hydrogen, the emissions associated with energy conversion, which are equivalent to combustion emissions, will be attributed to Australia. Although destination countries may signal an intention to favour low-emissions production, the territorial-based accounting methodology doesn't create an incentive to lower emissions. This will naturally raise questions in both Australia and destination countries as to the political and financial implications with respect to carbon accounting.

5.2 Cost of hydrogen production

Nearly all hydrogen production currently occurs within industrial facilities, usually as part of a larger production process in a refinery or chemical plant. Most hydrogen manufacturing in a petro-chemical plants is via either steam-methane reforming or steam-naphtha reforming. A ramp up of hydrogen as an energy carrier will require dedicated production supply systems. Therefore it can be difficult to apply current costs within a petro-chemical facility to retail prices for a different production and logistics system.

Current refuelling stations in California retail hydrogen at an average of AUD$19 per kg, and in Germany, AUD$15 per kg (EUR9.5 per kg). Retail prices are expected to fall substantially as the number of refuelling stations and their utilisation increases (Hydrogen Strategy Group 2018).

The target Australian 'free-on-board' (FOB) cost (delivered to the departure port) for the export market is $2-3/kg (Bruce et al. 2018, p.xix). Japan has set a target 'cost insurance and freight' (CIF) price (total including shipping) of 30 JPY/Nm^3 for 2030, and an ambition in the 'later future' (e.g. 2050) to reach a price of 20 JPY/Nm^3 (METI Japan 2017). At an exchange rate of 80 JPY to 1 AUD, 30 JPY/Nm^3 is equivalent to AUD4.40 per kg, and 20 JPY is AUD2.90 per kg. The long term preferred price outcome is that the CIF price of hydrogen is comparable with LNG. Tables 4 and 5 list the current Australian costs of production (excluding compression and storage) from Bruce et al. (2018).

	Grid connected	Dedicated RE	Curtailed electricity
Average electricity cost (c/kWh)	6	6	2
Average capacity factor (%)	85%	35%	10%
LCOH ($kg)	$\sim$ $ 6.60/kg	$\sim$ $ 11/kg	$\sim$ $ 26/kg

Table 4: Levelised cost of hydrogen (LCOH) for PEM electrolysis. From Bruce et al. (2018, table 3)

	Steam methane reforming	Black coal gasification
LCOH ($/kg)	$ 2.27 to 2.77/kg	$ 2.57 to 3.14/kg

Table 5: Levelised cost of hydrogen (LCOH) for thermochemical processes. From Bruce et al. (2018, table 5)

5.3 RE costs

Renewable energy electricity prices are a key determinant of the competitiveness of low emission electrolysis. The CSIRO Roadmap RE costs are derived from the CSIRO Low Emissions Technology

Parameter	Comments
Electrolyser cost	$968 PER kW
Capacity factor	95%
OPEX	$19/kW/yr
Financed life	20 years
Discount rate	7%
Electricity cost	4 c/kWh
Production cost	$2.4 per kh H_2

Table 6: Levelised cost of hydrogen (LCOH) for PEM electrolysis for 'best case' for 2025. Calculated from Bruce et al. (2018, Appendix.C)

Roadmap (Campey et al. 2017), and the Australian Power Generation Technology Report (Electric Power Research Institute 2015). Bruce et al. (2018, p.15) considers grid connected electrolysis but it is not clear how transmission or network costs have been incorporated into electricity costs. The costs presented in ACIL Allen exports report are derived from the CSIRO Roadmap, and given in table 7.

A related source for RE cost estimates is the Australian Energy Market Operator (AEMO) Integrated System Plan (ISP). The ISP was recommended by the Finkel Review. It includes wind and solar cost assumptions up to 2050 based on CSIRO, and internal AEMO estimates.

Historically, growth of energy technologies tends to follow an 'S', or logistic growth curve. In the first stage, growth is slow but increasing; in the second, growth is exponential; in the third, growth slows to linear, and finally, the growth slows, before asymptoting towards a maxima. However, the logistic curve is more evident in hindsight than foresight, limiting its utility for future cost projections. Wind power and solar PV are currently growing exponentially.

From 1990 to around 2012, the exponential doubling time of solar PV was 2.0 years, and since 2012, has slowed to 2.5 years. The selling price of solar PV shows a learning rate of 20% (per doubling of cumulative capacity) (Louwen et al. 2016, fig.3).

The doubling time of wind power has widened from around 3 years in the late 1990s to 5 years currently. The learning rate of wind power, defined as the cost per kW, has been estimated at 12% (per doubling of cumulative capacity) for studies up to 2010 [table 1](Rubin et al. 2015). The ACIL Tasman report appears to show a strong capital cost decline for solar PV but a modest reduction for wind. With respect to levelised cost (LCOE), Wiser et al. (2016) identified several cost reduction drivers for onshore wind, including increases in capacity factor and operating life, and reductions in capital and operating cost.

Technology	2018	2025	2030	2040
Large solar PV	6.0	4.0	3.9	3.4
Onshore wind	6.8	6.9	6.8	6.1

Table 7: LCOE of large solar PV and onshore wind (cents/kWh), from ACIL Allen Consulting (2018, table 4.3).

5.4 Summary

A challenge for Australian policy makers is optimising a deployment pathway that enables cost-effective hydrogen in the short run, but that supports electrolysis in the long run. From the perspective of transitioning towards an integrated hydrogen economy in Australia, the electrolysis pathway makes the most sense. Furthermore, the renewable-electrolysis pathway locks onto Australia's strengths, and the capability of modular electrolysis deployment more closely replicates renewable deployment. In contrast, thermochemical processes are integrated industrial facilities that rely on economies of scale.

However, given the much lower current cost of steam methane reforming (SMR) and coal gasification with CCS, thermochemical pathways may provide an entry point for developing commercially viable hydrogen infrastructure and permitting more rapid up-scaling in the medium term. Should an international export market develop, several countries will be jostling for first mover advantage with implications for market share.

Given the different stages of cost-learning of renewable-electrolysis versus thermochemical, there are risks in both directions — the mature thermochemical processes may be overtaken by rapid cost reductions of renewable-electrolysis; or alternatively, up-scaling of renewable-electrolysis may take longer, or achieve more modest cost reductions than anticipated.

One policy approach would be that buyers (or regulators) would require a target CO_2 intensity for hydrogen, regardless of production method, and allow markets to decide. Another is to preference electrochemical production methods on the assumption that this will turn out to be the most credible long-term pathway.

6 The export opportunity

6.1 Natural resources

6.1.1 Non-renewable

Australia is one of only three OECD energy exporting nations in net terms (IEA 2012). Australia is a major exporter of coal at 10,687 PJ, liquefied natural gas (LNG) at 2,865 PJ, and uranium at 3,300 PJ (in equivalent terms) in 2016-17 (Department of the Environment and Energy 2018). In net terms, Australia is only 38% self-sufficient in petroleum fuels, although crude oil production from the north-west shelf is exported to the closer Asian refineries. Figure 8 depicts Australia's major renewable and non-renewable energy resources.

6.1.2 Renewable

Australia has significant wind resources. The southern part of the continent lies in the path of the westerly flow known as the roaring 40s (Coppin et al. 2003). Strong low pressure systems may cover the entire southern half of Australia, while weaker systems skim the southern coasts. Northern Australia experiences monsoon and trade wind systems.

The Australian continent has the highest solar radiation density of any continent (Geoscience Australia 2010). Solar resources are greater in the northwest and centre of Australia, although the populated eastern seaboard resources are very good. The annual solar radiation falling on Australia is approximately 58 million petajoules (PJ), approximately 10,000 times Australia's annual energy consumption (Geoscience Australia 2010, p.261).

6.2 LNG development

The development of the LNG industry is considered a useful template for how a hydrogen export industry might proceed. Much of the experience gained from the production, storage and transport of LNG will be transferable to an emerging hydrogen export industry. Furthermore, there are already established trading relationships with the major prospective hydrogen importers.

The LNG export industry began in 1989 in western and northern Australia. Demand increased significantly from 2004, and further in the period 2009 to 2011 when commitments to build seven more large LNG plants were announced. Australia is now the second largest exporter after Qatar, and expected to rival Qatar exports and also a projected rapid expansion of US exports (IEA 2017*c*, fig. 9.7). Japan has been the largest importer of Australian LNG, and since 2016, exports volumes to China and South Korea have increased significantly. For the year 2017-18, the value of exports was AUD 29.9 billion following investment of around AUD 200 billion since the mid 2000s (Cassidy & Kosev 2015).

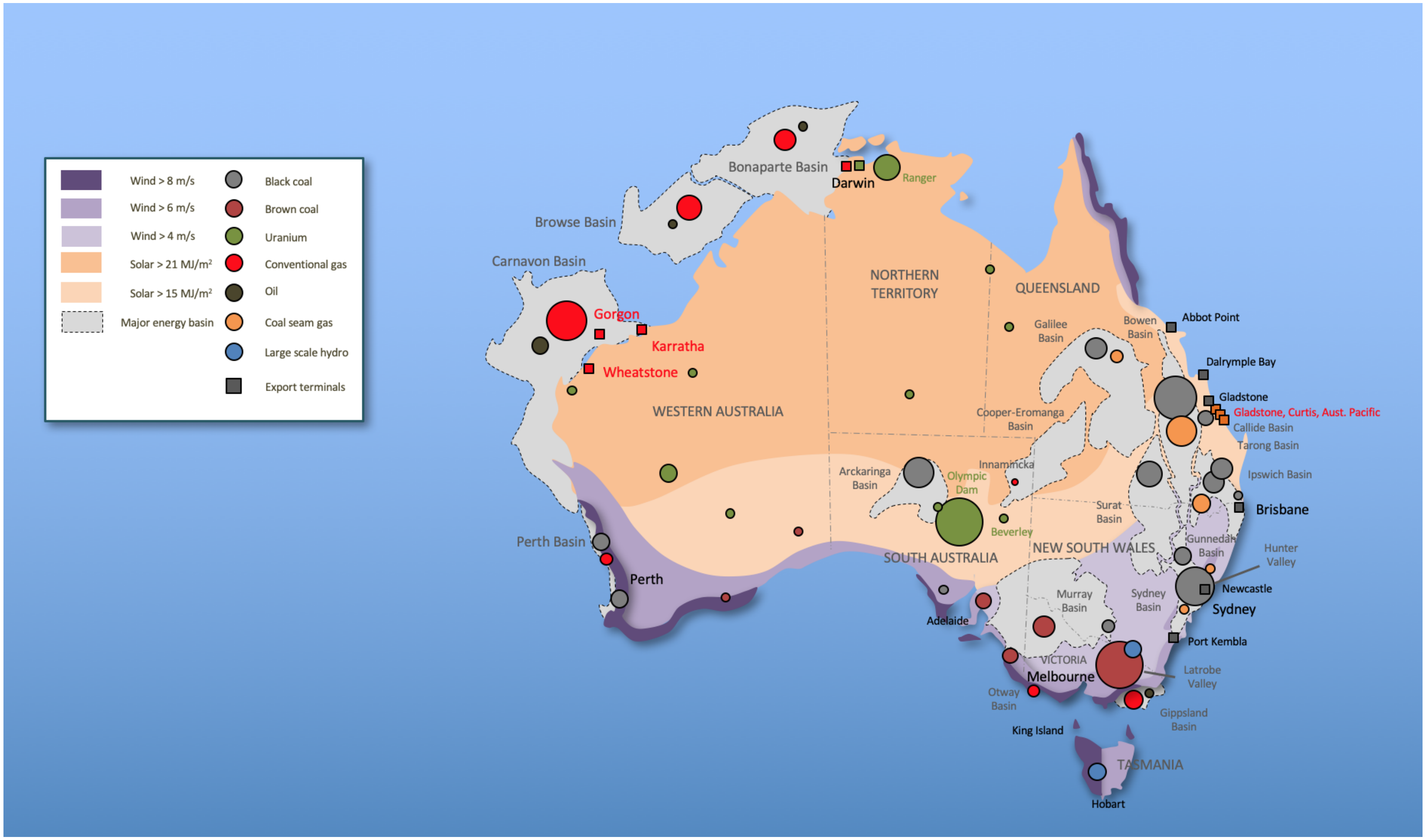

Figure 8: Australia's renewable and non-renewable energy resources and major export terminals. Sources: Geoscience Australia (2010, 2018), Coppin et al. (2003)

6.3 Estimates of export potential

ACIL Allen (ACIL Allen Consulting 2018) were engaged by ARENA to identify the opportunities for Australia to export hydrogen. Four countries were identified as being early prospective markets for Australian exports, including Japan, Republic of Korea, Singapore, and China. ACIL Allen modelled a range of scenarios under a broad range of assumptions. As such, scenario outcomes should be taken as internally consistent outcomes rather than probabilistic scenarios. Nonetheless, it is clear that the sheer scale of an international hydrogen export market would be vast, should hydrogen become a globally significant energy carrier. A reasonable appraisal of Australia's strengths and weaknesses suggest that Australia is well positioned to gain a meaningful market share of destination country imports.

The ACIL-Tasman report focused on hydrogen exports for energy use only, and excluded hydrogen use for ammonia fertilisers and industrial uses, such as steel making. The four target countries were identified on the basis of market size, existing policies, existing trade relationships with Australia, and the scope for those countries to meet demand with their own production.

The countries most likely to compete with Australia for a prospective hydrogen market include Norway, Iceland, USA, Middle Eastern and North African countries and Brunei. It is expected that only some of this hydrogen will be produced from clean energy, although Japan has indicated that only low-emission hydrogen will be sourced.

There is already early activity in the hydrogen international trading space, including:

1. Norway is progressing a demonstration project to deliver liquefied hydrogen produced from renewable energy. The project is supported by Japan's Mitsubishi Corp. and Norway's Statoil (Reuters 2018).

2. Woodside have signed a memorandum of understanding (MOU) with the state-run Korea Gas Corporation (KOGAS) to strengthen cooperation in the hydrogen sector (Song-hoon 2018).

3. Kawasaki Heavy Industries (KHI) are the lead proponents of the Latrobe Valley project to convert Victorian lignite into liquid hydrogen for export (Yoshino et al. 2012, Commonwealth of Australia 2018)

4. The Japanese AHEAD group are constructing a hydrogenation plant in Brunei to convert hydrogen sourced from steam methane reforming to MCH. The MCH will be shipped to Japan for de-hydrogenation, and is the first international hydrogen supply chain project (AHEAD 2017).

ACIL Allen scenario	Country	Potential exports (PJ) 2030	2040
Low	Japan	21.9	47.1
	Republic of Korea	4.8	12.9
	Singapore	0.5	1.5
	China	1.4	10.7
	ROW	0.5	2.4
	Total	29.1	74.6
Medium	Japan	44.2	102.3
	Republic of Korea	9.4	28.1
	Singapore	0.9	2.7
	China	4.5	23.7
	Rest of world	1.3	5.4
	Total	60.3	162.2
High	Japan	96.4	237.7
	Republic of Korea	20.1	68.4
	Singapore	1.8	7.5
	China	9.5	55.7
	Rest of world	2.8	12.7
	Total	130.7	382.0

Table 8: Australia's potential exports of hydrogen. From ACIL Allen Consulting (2018, table 4.9)

Hydrogen production	Electricity (35% c.f.)		Steam methane reforming		Coal gasification (lignite)	
(PJ)	(TWh)	(GW)	(PJ)	(kt)	(PJ)	(kt)
10	5	1.7	14	256	22	2,131
20	11	3.5	29	513	43	4,263
50	27	8.7	72	1,282	109	10,656
100	53	17	144	2,565	217	21,313
200	107	35	289	5,129	435	42,626
500	267	87	722	12,824	1,087	106,564

Table 9: Electricity, natural gas or lignite required to supply given hydrogen production. Generation capacity given for 35% capacity factor and assuming 64 $kWh_e/kg\ H_2$ for production, compression and transport; methane assume 13 $MJ/Nm^3\ H_2$ for steam methane reforming plus 20% energy use for CCS; coal given for lignite at 10.2 GJ/t and 4.6 kg H_2/GJ coal (Burmistrz et al. 2016) plus 20% energy use for CCS.

	Annual CIF value ($ million)	
	2030	2040
Low	1,072	2,623
Medium	2,225	5,703
High	4,822	13,430

Table 10: Annual CIF (landed) value ($ million) of Australia's potential hydrogen exports. Source ACIL Allen Consulting (2018, table ES5)

6.4 Transport

The volumetric density of compressed hydrogen is too low to be practical to transport internationally. Currently, the three main options are liquefied hydrogen, ammonia, or methylcyclohexane (MCH). All incur energetic costs. Bruce et al. (2018, p.87) estimated liquefication at 9 $kWh_e/kg\ H_2$, which equates to 27% of the LHV value of hydrogen.

The MCH cycle is the most common of the several liquid organic hydride cycles (Alhumaidan et al. 2011). Organic hydride cycles are based on reversible catalytic hydrogenation-dehydrogenation reactions. In the MCH cycle, toluene is hydrogenated with hydrogen to produce MCH, which is transported, then dehydrogenated back to toluene and hydrogen. An advantage of the MCH route is that it is compatible with existing energy and refinery infrastructure. A disadvantage is that a toluene round trip would require shipping the toluene back to the hydrogen source country after dehydrogenation at the hydrogen destination country.

6.5 Summary

In the event of hydrogen becoming a globally significant energy carrier, the potential export market for Australian low-emission hydrogen fuels is vast. A reasonable appraisal of Australia's strengths and weaknesses suggest that Australia is well positioned to gain a meaningful market share of destination country imports.

7 Mobility

7.1 Passenger vehicles

Battery electric vehicles (BEV) are making steady progress as a viable option for light duty transport. However, absent significant breakthroughs in electro-chemistry, many transport tasks are unlikely to be fully supplanted by battery technology. These include rail, heavy transport, sea and air, and longer range vehicles. Fuel cell electric vehicles (FCEV) are likely to complement BEVs and hybrid vehicles in a market with a more diverse range of vehicle drive trains (Bruce et al. 2018, Andrews & Shabani 2012). For lighter, and shorter range vehicles, BEVs will be a more cost effective petroleum substitute than FCEVs. One Chinese-based analysis suggested that the current cross-over point for FCEV versus BEV is 500 km of range (Caixin Net 2018).

In the 2018 KPMG Global Automotive Executive Survey, FCEVs have replaced BEVs as the 'key trend until 2025' (Bacellar 2018). Although the BEV market is much larger and leads the FCEV market by several years, the automotive majors are nonetheless anticipating a significant role for FCEVs.

Passenger FCEVs currently achieve around 100km per kg of hydrogen, and increased range is simply enabled with a larger fuel tank. From a motorists' perspective, the hydrogen filling operation is similar to LPG filling, taking several minutes. Taking into account the entire weight of storage, conversion and ancillary devices, the Honda Clarity FCEV drive train has around 5-times the specific energy as the Nissan Leaf BEV drive train (Pollet et al. 2012).

The current cost of FCEVs are much higher than for BEVs, but the price difference is projected to narrow with increasing production. Several countries have set FCEV targets (see table 11). At current FCEV production, fuel cell cost is estimated at USD300 to 500 per kW. Economies of scale are projected to reduce the cost to USD60 per kW at an annual production of 100,000 vehicles (IEA 2015, p.31).

	2020	2025	2030
US	13,000	40,000 (2023)	
Japan	40,000	200,000	800,000
France		5,000 (2023)	20-50,000 (2028)
China	5,000	50,000	1,000,000
Netherlands	2,000		
Korea	10,000	100,000	630,000

Table 11: National FCEV targets. Source IEA (2018)

The first FCEV generally available in Australia will be the Hyundai NEXO, with an expected price of around $100,000 (Brogan 2018). In the United States, a Toyota Mirai is available for sale at USD$57,500 (IEA 2017*a*). In California, there were just over 1,600 registered FCEVS in April 2017 (IEA 2017*a*). Worldwide, three models of FCEV are commercially available, and ten more are due for release by 2020 (Hydrogen Council 2017, p.37). The most significant cost component is the fuel cell system. IEA (2015, table 12) list the fuel cell system costing USD30,200, and comprising half the vehicle cost for the reference vehicle. Assuming a learning rate of 20%, the US DOE expects the cost to decline to USD4,300 in 2030. As a small market and an importer, the Australian market will depend on overseas developments in vehicle models and costs.

Compared to a petrol car using 8 litres per 100 km at $1.40 per litre, an equivalent FCEV costs the same per 100 km with a retail hydrogen price of $11 per kg (Hydrogen Strategy Group 2018). Current refuelling stations in California sell hydrogen at an average of AUD$19 per kg, and in Germany, AUD$15 per kg (EUR9.5 per kg). Retail prices are expected to fall substantially as the number of refuelling stations and their utilisation increases (Hydrogen Strategy Group 2018).

The only public hydrogen station in Australia is the Hyundai station at Macquarie Park. A station is planned to open in Canberra to support the proposed deployment of 20 FCEVs by 2019-20 (ACT Government 2018). Hobsons Bay City Council in Melbourne also recently announced a short trial of Toyoyta Mirai's.

Fuelling stations are likely to be built, owned, and operated under joint ventures between conventional petrol station operators, vehicle OEMs, with Governments underwriting the initial demand risk (Bruce et al. 2018, pp.41-42). The current cost of hydrogen refuelling stations in California is USD2.1 to USD3 million (IEA 2017*a*).

Future projections of vehicle stock can only be a calibrated guess. For this briefing, US, Japan and EU estimates were taken from IEA (2015, p.36) as reference data for strong growth of non-ICE vehicles. These were subjected to Australian actual vehicle sales and stock data up to 2018, and extrapolated with strong growth of BEV, FCEV, and hybrid to give sales of 100,000, 40,000, and 100,000 vehicles per annum respectively in 2030, with strong growth continuing for BEV and FCEV. In 2050, ICE, BEV, FCEV, and hybrid comprise 12%, 31%, 40% and 18% of new sales respectively. The value of imported passenger vehicles totalled $22.8 B in 2017 (DFAT 2018).

Scenarios for passenger vehicles are given in table 12. Figure 9 gives the resulting stock for 2018 through 2050. The figure illustrates the classic stock-and-flow outcome — despite rapid growth of non-ICE vehicles, the long turnover time of the stock slows the change in stock compared to sales. The average age of passenger vehicles in Australia is 9.8 years (ABS 2015), with the age distribution following a logistic curve (Mitchell 2002). Around half the vehicle stock at any time is more than 8 years old.

Scenario	Comments	BEV	FCEV	Hybrid-ICE
BAU	Gradual uptake of BEVs, low FCEV, bias towards hybrid instead	6%	5%	10%
Near term solutions	Gradual uptake of BEVs, medium FCEV, less hybrid	12%	10%	15%
World best practice	Strong uptake of BEV, followed by FCEV	15%	15%	15%
Global leader	Large scale uptake of electric, bias towards FCEV	18%	20%	13%

Table 12: Scenarios of passenger vehicles in 2050. Proportion estimates based on US, Japan and EU estimates from IEA (2015, p.36). Retaining the historic 4% attrition (scrapping) rate equates to a passenger vehicle stock of around 20 million in 2050.

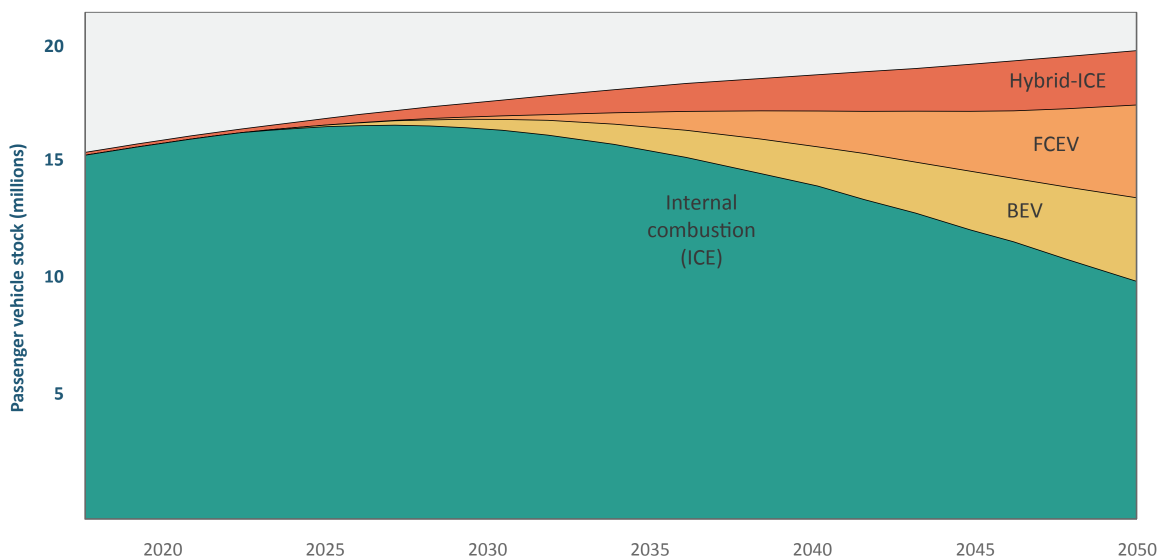

Figure 9: Stock of passenger vehicles for the Global Leader scenario. Stock based on a decline of passenger vehicles per-capita from 0.62 to 0.57 as a result of urbanisation and alternative transport options. Assume population increases to 35.9 million in 2050.

7.2 Heavy vehicles

For heavy and longer range vehicles, the high specific energy of hydrogen and hydrogen carriers is expected to be a key enabler. Of the forms of transport suitable for hydrogen, rail has seen the highest levels of activity globally (Bruce et al. 2018, p.44). Alstom has supplied hydrogen 'hydrail' trains to the UK and Germany, with other manufacturers following. In Europe, 'green' hydrogen is currently almost twice the cost of diesel, but is nearly twice as efficient and offers zero emissions (Rail Engineer

2018). In Australia, of the 33,000 km of rail, only 10% is electrified (Department of Infrastructure and Regional Development 2014), offering substantial opportunity to begin to plan a hydrogen rail strategy.

Most of the interest in hydrogen mobility has focused on fuel cells, however internal combustion (IC) remains a live option in hydrogen use, mostly notably for heavy vehicles. The main benefits of IC are a much lower capital cost per kW of power, the capability of using lower purity fuels, and proven durability.

In Australia for 2014, the road transport sector consumed 488 PJ of diesel fuel (Office of the Chief Economist 2017) to deliver 196 billion tonne-km of road freight, giving 2.5 MJ per tonne-km. Using an estimate of 1.0 MJ of hydrogen per tonne-km to allow for the higher end-use conversion efficiency, an electrolyser efficiency of 54 kWh per kg H_2 (Bruce et al. 2018), and adding 10 kWh per kg H_2 for compression and storage gives 105 TWh of electricity to power the entire road transport sector.

The average age of light rigid, heavy rigid, and articulated trucks is 11.1, 15.7, and 11.9 years respectively (ABS 2015). The value of imported 'goods vehicles' totalled $8.8 B in 2017 (DFAT 2018).

7.3 Aircraft

For large commercial aircraft, no serious alternative to jet propulsion has been identified (Sims et al. 2014, 8.3.2.2). Fuel switching is considered the most likely non-petroleum pathway, including 'drop in' biofuels, or in the longer-term, hydrogen. Some low-emission pathways retain fossil fuelled aviation and employ carbon capture and sequestration elsewhere to achieve emissions goals (Blanco et al. 2018). Since Australia does not lead production of commercial airliners, it will be technological follower and buyer, and not expected to significantly influence their trajectory.

From the physics of aerodynamics, the range of aircraft can be approximated by the specific energy of the fuel, and efficiency of conversion to power (MacKay 2008, eq.C32). For a modern wide-body airliner such as the Airbus A380, with a fuel load of 50% of the take-off weight, the range can be estimated at around 13,000 km. Fossil-based, synthetic, and biomass-derived liquid fuels possess a specific energy around an order of magnitude greater than the medium term prospects for commercial batteries (Eftekhari 2018).

7.4 Warehousing

The earliest strong application of hydrogen mobility has been forklifts, with Toyota and Plug Power globally supplying 15,000 fuel cell forklifts to date (Hydrogen Council 2017, p.38). Hyster-Yale recently introduced fuel cell (FC) models into the Australian market (HMA 2018). Since warehouse forklifts operate indoors, avoidance of combustion gases is a strong driver of electric drive. Compared to battery, FC models have much shorter fill times, improved logistics around refuelling or battery storage, and the fuel cell stacks have a longer operational life than batteries under comparable conditions.

7.5 Petroleum use

Policies directed towards broadening mobility fuel options need to be considered in the context of current petroleum expenditures, the significant trade deficit of petroleum fuels, and the vulnerability of Australia to supply shocks. In 2017-18, Australia consumed 60,415 ML of petroleum products, at an estimated value of $55 billion (excl.taxes and duties), or 3.3% of GDP.

In the years following the first oil crisis of 1973, Australia's domestic supply of oil increased with the development of the Gippsland Basin, followed by the Carnavon and Bonaparte Basins in the 1980s and 90s, and later Browse. Nearly all oil imports were refined locally. By the 1990s, Australia almost achieved oil self-sufficiency.

Since 2000, the trend has reversed, with a widening gap between production and consumption — Australia is now 38% self-sufficient in petroleum. Furthermore, Australia has been steadily increasing imports of refined fuels rather than local refining of imported crude. Australia's 8 major refineries have been reduced to 4, with the prospect of further closures. As a member of the OECD, Australia is obliged to comply with a 90 day strategic reserve. However reserves are limited to commercial holdings, which have been estimated at 21 days for diesel up to 54 days in aggregate.

7.6 Summary

The Hydrogen Council expects mobility to lead a prospective transition to hydrogen (Hydrogen Council 2017, Exhibit 7). In Australia, high vehicle price and a lack of hydrogen fuelling are currently the key barriers (Bruce et al. 2018). Forklifts have been the earliest strong application, with passenger vehicles, trains, and heavy vehicles expected to follow.

8 Iron and steel production

8.1 Global and Australian production

Global steel production was 1,689 million tonnes in 2017 (World Steel Association 2018). Global steel production greenhouse emissions, including direct and indirect emissions, were estimated at 2.6 $GtCO_2$ in 2006 (Fischedick, Joyashree, Acquaye & Allwood 2014). From an economic and mass perspective, iron ore is by far the most important base metal, with USD225 billion of global sales in 2014, with a metal content of 1.4 billion tonnes. Copper at USD130 billion and 18.7 million tonnes, and aluminium at USD90 billion and 49.3 million tonnes were the second and third most important base metals respectively (IMF 2015). Nearly all iron ore is converted via the pig iron route using metallurgical coal as the reductant (World Steel Association 2018, p.18), however natural gas and hydrogen can also serve as a reductant.

Australian crude steel production was 5.3 million tonnes in 2017, or 0.3% of global output. Australia also imported 4.8 million tonnes of finished steel products (World Steel Association 2018). Australia was the leading producer of iron ore, with 40% of global output. Australia is also a major producer of metallurgical coal, with exports of 172 million tonnes in 2017. There are two producers of crude steel in Australia: BlueScope Steel and Liberty OneSteel (formerly Arrium Steel), operating steelworks in Port Kembla, NSW, and Whyalla, South Australia, respectively (Commonwealth of Australia 2017).

8.2 Steel production

Steel is produced via two main routes: the blast furnace-basic oxygen furnace (BF-BOF); and electric arc furnace (EAF). The BF-BOF route produces steel from iron ore, coke (made by heating metallurgical coal in the absence of oxygen), limestone ($CaCO_3$), recycled steel, and forced air. Coke (C) serves as both the energy source and reductant. The $C + O_2 \rightarrow CO_2$ reaction is exothermic, producing heat which drives other reactions. As the CO_2 moves through the furnace, some of it reacts with the coke, producing carbon monoxide (CO). The CO undergoes several reactions with iron oxides, producing metallic iron. At the same time, calcium carbonate undergoes a decomposition reaction, producing calcium oxide (CaO) and carbon dioxide (CO_2). The calcium oxide is alkaline and neutralises the acidic oxides, including SiO_2, Al_2O_3, and Fe_2O_3, which float on the heavier molten iron in a furnace. The BF-BOF process emits about 2 tonnes of CO_2 per tonne of steel (Junjie 2018). About 75% of global steel is produced with the BF-BOF route.

The EAF route uses electricity to melt recycled steel or direct reduced iron (DRI), and therefore the emissions intensity is dependent on the emissions intensity of electricity supply.

Although the BF-BOF route dominates the production of primary steel, many alternative processes have been explored. In the most recent IPCC review, four low emission production routes were identified as the most promising (Fischedick, Joyashree, Acquaye & Allwood 2014): top-gas recycling applied to blast furnaces with carbon capture; HIsarna with carbon capture (a smelt reduction technology); direct reduction with natural gas or hydrogen; and electrolysis (e.g. Allanore et al. (2013)).

Other potential candidates include biomass-based reduction and alkaline electrolysis (Junjie 2018). Currently, the most viable pathways to decarbonsing steel production are via either carbon capture and sequestration, or hydrogen direct reduction (H-DR) (Vogl et al. 2018). Hydrogen reduction is being investigated in several countries (Fischedick, Joyashree, Acquaye & Allwood 2014). In principle H-DR can be near-zero emissions, although the decomposition of calcium carbonate, comprising a minor share of CO_2 emissions in the BF-BOF route, will still contribute to emissions.

The H-DR process is projected to have a higher capital cost than the BF-BOF route, but competitive with low-emission alternatives, including BF-BOF with carbon capture (Fischedick, Marzinkowski, Winzer & Weigel 2014). In their scenario-based model for Germany, Fischedick et al. expects H-DR to be the most profitable technology by around 2040, even without a carbon price.

A similar proposed H-DR process is the Hybrit process under development by the Swedish-Finnish steel company SSAB, with an expected cost 20 to 30% higher than their reference case (SSAB 2017). The estimated electricity consumption for the hydrogen electrolysis and the electric arc process is 3,488 kWh per tonne of steel. SSAB have announced plans for a pilot plant, with an intention for a full scale commercial plant in 2035

8.3 Electricity consumption of H-DR

Australian crude steel production was 5.3 million tonnes in 2017, and 4.8 million tonnes of imported finished steel products (World Steel Association 2018). Using the Hybrit electricity consumption estimate and taking a production of 5.3 million tonnes per annum would equate to 18.5 TWh of electricity, equivalent to around 6,000 MW of renewable power at 35% capacity factor.

8.4 Innovation in Australian iron and steel

The Australian steel industry has a reputation for innovative products and design (Commonwealth of Australia 2017, p.18). Collaboration between steel manufacturing and downstream steel product manufacturers has contributed to the development of specialised steel products, including military products, products for high-rise construction, refinery and petrochemical equipment. Much of the innovation occurs in downstream processing and use of steel products, such as steel coating technologies and cold-formed steel for building framing. The key Australian steel research focal point is the Australian Council Research Hub for Australian Steel Manufacturing at the University of Wollongong. Partners include BlueScope Steel, Arrium, Bisalloy Steels, Lysaght, and the Australian Steel Institute (Commonwealth of Australia 2017, p.19).

8.5 Substitution of steel

Although steel has substitutes in some applications, it possesses several important properties that contribute to its essential role in industry, construction, mobility and other applications. Depending on the alloying components and heat treatment, steel can be produced as soft, malleable, hard or brittle. The steel alloy families are defined as: carbon steels; low-alloy (mild) steels; high-strength steels; tool steels; and stainless steels. Steel can be forged, rolled, cast, and machined. Mild steel can be readily welded *in-situ*.

Steel is recyclable and the end-of-life recycling rate has been estimated at a between 70 to 90% (UNEP 2011, table C1). Because of increased use over time, and long in-use lifetimes, the recycled *content* of steel is less than the recycling *rate*. Iron is one of 18 elements that has a recycling rate above 50%. Depending on the country, national end-of-life recycling rates are up to 90% for steel (Smil 2016). Since recycling is much less energy intensive than virgin product, the maximisation of recycling is an important strategy for minimising energy use and emissions. Improving functional recycling by separation and sorting processes provides a means to improve the grade of recycled content (UNEP 2011).

In construction, steel possesses several properties that improve its compatibility with concrete. Steel binds well to concrete, and steel's high tensile strength complements concrete's high compressive strength. The most important compatibility is that both materials possess a similar thermal expansion coefficient, which is critical to reducing cracking and fatigue of structures.

8.6 Barriers to hydrogen processes

Although the Australian iron and steel industry has invested in ongoing incremental improvements to the production process, the BF-BOF remains the dominant pathway for primary steel production. Traditional iron and steel plants rely on economies of scale and established technologies. The approach to innovation in the primary production processes has mostly been evolutionary rather than revolutionary, although alternative processes have been explored from time to time.

An example was BHPs Boodarie Iron Plant in the late 1990s. The plant was located about 20 kilometres south of Port Hedland in Western Australia (BHP 2005). It used FINMET technology to convert iron ore fines into iron briquettes. Iron ore fines are less expensive than lumped iron ore, in part because they cannot be used in blast furnaces without further processing. The FINMET process produces direct reduced iron (DRI) by reacting fine iron ore with reformed natural gas in a series of fluid bed reactors. The DRI is briquetted into dense, high quality iron briquettes (Honeyands et al. 1997). The plant was abandoned in 2005 due to persistent commissioning difficulties, large cost overruns and significant operational issues (BHP 2005). The eventual gross write-down was 2005AUD 2.5 billion

In Australia, the barriers to new entrants are high (Aravanis 2017). The metallurgical industry is characterised by large investments in long-lived assets. Improvements tend to be incremental and gradual rather than revolutionary. The final product is a commodity in a highly competitive and globalised market. Australian producers are known for preferring a strategy of 'fast following' rather than taking the role of a disruptive technological leader. In common with many large and established industries, firms invest in research activities in order to stay informed and up to date with leading edge technologies. Knowledge of potential technological disruption is critical to protecting the balance sheet of public companies.

The failure of BHP's Boodarie Iron plant, using the innovative FINMET technology (BHP 2005), possibly set back the prospects for a major shift from the BF-BOF route. Furthermore, given the challenging competitive environment of the Australian crude steel industry, the prospects for major investments in alternative crude steel routes is currently low.

8.7 Summary

1. In the absence of policy, there is unlikely to be substantial investment in hydrogen-based iron and steel production in Australia. The international Hydrogen Council proposed government support for large scale pilot plants, and a long-term regulatory framework based on national action plans once the technologies are proven (Hydrogen Council 2017).

2. There is uncertainty around the potential global market for 'green steel'. However, a viable Australian industry could be possible, providing it was globally competitive, based simply on the sheer scale of global steel relatively to Australia's likely production capacity.

3. Demand for low-emission steel will be influenced by the evolution towards low-emission building products and materials, carbon markets, and trends.

4. A new process would introduce a new value chain, different vendors and possibly different clients with different needs. A new business model and set of operating practices may need to be introduced based on the new process and markets.

5. Apart from the iron element, carbon is currently the most important element in conventional iron and steel making. There is a need to understand ore reduction mechanisms and reactions in the absence of carbon (SSAB 2017).

6. Elements of the hydrogen chain are commercial, however the hydrogen supply chain is not yet mature, contributing to technical and economic risks. Assuming that hydrogen is adopted for non-steel making applications first, this is not likely to present a challenge.

8.8 Scenario outline

Scenario	Comments
BAU	No change to crude steel production. BF-BOF plants are retired and either not replaced or replaced with modern equivalents.
Near term solutions	New crude steel plants are higher efficiency, including natural gas. Some hydrogen blending.
World best practice	First successful pilot plant in 2040, and commercial scale plants by 2050, producing 5 million tonnes per annum.
Global leader	First successful pilot plant in 2035 and complete shift to H-DR by 2050, producing 10 million tonnes per annum. Prospect of significantly increasing 'green steel' exports.

Table 13: Scenarios of crude steel production.

9 Seasonal storage

9.1 Scenario modelling

Much of the analysis on electricity system transformations derives from energy-economic optimisation models. Modellers preselect a portfolio of eligible low-emissions technologies, and adopt an optimisation routine. The routine evaluates a least cost solution that satisfies a supply-demand balance based on historical climate data. Various forms of storage may be included to improve the availability factor of variable renewables, along with geographic diversity. Natural gas or biofuels are commonly adopted as a dispatchable and flexible supply technology that can 'fill the gaps' during low wind and solar insolation conditions e.g. AEMO (2013), Elliston et al. (2014), Elliston & Riesz (2015), Lenzen et al. (2016). Modellers generally aim to minimise the consumption of natural gas and biofuels.

As electrical grids progress towards full decarbonisation, unsequestered natural gas will need to be phased out and the scalability of biofuels is uncertain. Nationally-based optimisation models that rely on variable renewables, but without natural gas or biofuels, typically require large scale or seasonal storage, e.g. Palzer & Henning (2014), Preston (2015), Aghahosseini et al. (2016), Clack et al. (2017).

9.2 Potential storage solutions

Batteries, pumped hydro, and energy storage in concentrated solar thermal can provide storage services, but are not likely to be able to provide seasonal storage. Presently, the only feasible seasonal energy storage technologies are hydrogen or synthetically produced hydrogen carriers, such as methane, ammonia, methanol, or methylcyclohexane (MCH).

The main barriers to the use of hydrogen carriers for electricity storage are a low electricity round-trip efficiency, and high capital cost (Giddey et al. 2017). For short term storage (sub-daily), batteries, pumped hydro, and other storage devices have a much higher direct efficiency and will remain more cost effective for the foreseeable future. Conventional hydro can be conceptualised as a form of storage over longer time scales. However storage capacity is governed by other factors, especially irrigation demand, environmental flows, and inflows that are governed by climate variability. In the case of the Snowy Hydro Scheme, electricity generation is secondary to water release obligations (Snowy Hydro 2018).

If hydrogen were to be widely deployed, with the cost of hydrogen infrastructure amortised over multiple uses, the scalability advantages of hydrogen would alter the market dynamics. For multi-day or longer storage, few non-hydrogen storage technologies are feasible, and therefore a direct cost comparison with short-term storage is not meaningful.

9.3 Remote area power systems (RAPS)

Remote area power systems (RAPS) are electricity supply systems that are located outside of the supply grid. They may also be adopted in rural areas where the cost of network connection may be prohibitive. Some RAPS systems power remote telecommunications, radio beacons or other functions. RAPS systems in Australia are usually diesel, solar PV or diesel-solar hybrid systems. Battery or hydrogen storage enables the reduction of diesel fuel, or complete elimination of the diesel generator. Reliance on diesel generation incurs both fuel costs and maintenance costs.

For storage up to several days, batteries possess a higher round trip efficiency and lower costs. Hydrogen provides the capability of multi week, or longer, storage by simply sizing the storage tank appropriately. Hydrogen based RAPS systems are financially competitive with diesel-PV-hybrid and PV-battery systems (Shabani & Andrews 2015). In Australia, hydrogen-based storage is currently a niche market.

10 Substitution of natural gas

10.1 Shifting natural gas to electric loads

Natural gas is used for residential and commercial space and water heating, process heat for industry, and a feedstock for chemical processes. Some of the heating tasks can be cost-effectively shifted to electric or solar thermal, especially low-temperature heat (<100 °C). Although uncommon in Australia, high temperature heat pumps are available for industrial process heat up to 100 °C, and units that can provide provide steam at 120 to 165 °C are available in Japan (Jutsen et al. 2017). In principle there is no industrial heating process that cannot be electrified, and electric solutions may offer ancillary benefits (Lord 2018, p.27). Other electric-based heat sources include resistance heating, induction, infra-red, microwaves and electric arc.

For those loads for which natural gas is retained, it may be feasible to undertake a complete conversion of natural gas to hydrogen. The 'H21 Leeds City Gate' project in Leeds, UK has shown that a conversion may be cost-effective compared to electrification (Sadler 2016).

10.2 Peak loads

An important attribute of reticulated gas networks is that they perform the dual roles of distribution and storage. High pressure regional gas networks may contain days, up to weeks, of gas supply, referred to as 'linepack'.

Natural gas constitutes 24% of end-use energy use in Australia. Switching Victoria's residential space heating from natural gas to high-efficiency electric heat pump would approximately double Victoria's peak electricity demand (AGIG 2018, Palmer 2012) even though residential comprises only 37% of overall Victorian natural gas consumption (DELWAP 2018).

There is already a precedent for such a change in Australia. Following the development of the Gippsland Basin, natural gas was introduced into Victoria in 1969, and one million appliances were converted from town gas to natural gas (Proudley 1987). The conversion in Melbourne took place over a 20 month period, ending in December 1970. Adelaide, Brisbane and Sydney also undertook conversions. Town gas typically comprised 50 to 60% hydrogen (ENA 2017).

10.3 Efficiency of electric versus natural gas/hydrogen

Depending on application, the coefficient of performance (COP) of heat pumps is typically 2.5 to 4, giving an end-use efficiency of 4 to 5 times that of natural gas combustion. The highest COP residential heat pump available in Australia is 5.9 (Daikin Australia 2018).

Based on Australia's current primary energy mix for electricity generation, much of the end-use efficiency gain is lost when the efficiency of thermal generation is taken into account. Based on the mix in 2013-14, 2.6 to 2.9 MJ of primary energy are used to generate 1 MJ of electricity, depending on energy accounting methodology (Palmer 2017).

Traditionally, the price of natural gas has been much lower than electricity in Australia. Although both gas and electricity prices have risen significantly in recent years, a gas price of 1.5 cents/MJ is equivalent to 5.4 cents/kWh, or around a fifth to a quarter of the typical household or commercial price of electricity on a MJ basis. Given the falling costs of renewable electricity, the comparative cost advantage of natural gas would be expected to decline in the medium to long term.

Since the introduction of natural gas in the early 1970s, it has contributed the largest fuel share for space heating. Fuel price has been a major factor, however other factors have contributed to a preference for gas heating including comfort, cold weather performance, stratification, and airflow (Palmer 2012).

A prospective shift from natural gas to hydrogen, produced via electrolysis, requires a detailed analysis of the respective energy pathways and end-use performance. In general, direct use of electricity is much more efficient than indirect use via electrolysis and hydrogen. Hydrogen substitution for natural gas should ideally be limited to use cases where it is impractical to substitute for electricity. But as noted with respect to peak loads, natural gas networks are much more cost effective with respect to supplying peak loads, and the capability of multi-day to multi-week storage overcomes the costs of variable renewables integration.

10.4 Natural gas blending

In the meantime, the existing natural gas networks and appliances can readily accommodate a 10% hydrogen blend, and appliances are certified for use with a slightly higher blend (Hydrogen Strategy Group 2018), permitting a ramp-up of hydrogen production. For steel pipelines, the potential for steel embrittlement places an upper limit of 20 to 30%, depending on steel type and system pressure (IEA 2015, p,23). 10% of Victoria's annual gas consumption of 200 PJ (excluding power generation consumption) would require 9 TWh of electricity based on an electrolyser efficiency of 54 kWh per kg H_2. This is equivalent to around 3,000 MW of renewable power at 35% capacity factor in Victoria dedicated to hydrogen production.

10.5 Substitution of natural gas with hydrogen

In 2016-17, industry used 745 PJ and residential 166 PJ of natural gas. To replace half of Australia's 2016-17 gas consumption, at a conversion of 54 kWh per kg H_2 equates to 205 TWh, or around the annual generation of Australia's NEM, excluding additional consumption due to compression and storage. This is equivalent to around 67 GW of renewable generation at 35% capacity factor.

10.6 Scenario outline

Scenario	Comments
BAU	Some pilot plants and small scale blending of hydrogen into natural gas networks.
Near term solutions	Larger scale blending of up to 15% hydrogen into natural gas networks.
World best practice	Large scale hydrogen blending throughout Australia. Some small regions are changed-over to 100% hydrogen.
Global leader	Half of Australia's natural gas supply is replaced with hydrogen. Hydrogen blending continues in other areas.

Table 14: Scenarios of hydrogen substitution for natural gas.

11 Ammonia for agricultural fertilisers

11.1 Ammonia use

The principle elements of living organisms are carbon, hydrogen, oxygen, and nitrogen, roughly in the dry mass proportions C_5:O_3:H_1:N_1. Although the atmosphere contains 78% nitrogen, the N_2 molecule is non-reactive and commonly the most important factor that limits crop growth (Smil 2004). Traditional farming relied on intensive recycling of organic wastes and cultivation of leguminous plants to ensure adequate reactive nitrogen in soils. The industrial synthesis of nitrogen-carrying ammonia was enabled by the Haber-Bosch process, which expanded rapidly from the 1920s. In global agriculture, nitrogen, as ammonia, is one of the three key nutrients. World supply of ammonia was estimated as 172 million tonnes in 2017 (FAO 2015). Taking an average efficiency of ammonia production of 36 GJ/t (Tavares et al. 2013) equates to 6.3 EJ, or 1.1% of global primary energy supply of 566 EJ (BP 2018). Smil (2004, cht.8) estimated that by 2050, Haber-Bosch fixation of nitrogen could account for 60% of global nutrition.

11.2 Production

Globally, the major source of hydrogen for the Haber Bosch process is natural gas using the methane steam reforming process, followed by oil/naptha reforming and coal gasification (Weger et al. 2017). In 2016, Australia produced 1.3 million tonnes of ammonia (USGS 2017) for agricultural fertilisers, industrial chemicals and explosives. In Australia, natural gas is the primary feedstock, representing around 70% of ammonia production cost (McGregor 2018). Therefore accessing the lowest cost gas is a primary factor when establishing new plants (Fazzino 2017). The current delivered price for large industrial users is around $7 and $10 per GJ in Western Australian and the East Coast respectively (Snow et al. 2017), which is 2 to 3 times the current US price.

In a long term shift away from fossil fuels, the most viable pathway is ammonia production via electrolysis and Haber-Bosch (Institute for Sustainable Process Technology 2017). Using a conversion efficiency of 10 kWh per kg ammonia via the electrolysis or prospective electrochemical synthesis pathways (Giddey et al. 2017) would require 13 TWh of annual electricity to produce Australia's current annual ammonia use, equivalent to around 4,300 MW of renewable power at 35% capacity factor.

In a European study, the cost-competitive electrolyser-based production of ammonia will require a 70% decline in electrolyser capital cost, and access to relatively cheap electricity (Institute for Sustainable Process Technology 2017). The high capital cost of electrolysers requires operation with a sufficiently high capacity factor to amortise the cost of capital.

11.3 Scenario outline

Scenario	Comments
BAU	First successful pilot plant in 2019, and commercial scale plants by 2025, producing 25% of Australia’s 1.3 million tonnes per annum. Yara have already signalled their intention to develop a renewable ammonia plant for fertiliser and chemical feedstocks (Brown 2018).
Near term solutions	First successful pilot plant in 2019, and commercial scale plants by 2025, producing 50% of Australia’s 1.3 million tonnes per annum.
World best practice	First successful pilot plant in 2019, and commercial scale hydrogen-based plants by 2025, producing all of Australia’s 1.3 million tonnes per annum.
Global leader	First successful hydrogen-based pilot plant in 2019, and commercial scale plants by 2025. In 2050, all of Australia’s 1.3 million tonnes per annum is hydrogen-based, with exports a further 1.3 million tonnes of ‘green ammonia’.

Table 15: Scenarios of fertiliser and industrial ammonia production.

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