ENERGY TRANSITION HUB an Australian-German innovation partnership

National Hydrogen Strategy- Submission

Submission to the COAG Hydrogen Working Group National Hydrogen Strategy Discussion Paper

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1. Executive Summary

The Australian-German Energy Transition Hub (the Hub) welcomes the COAG Hydrogen Working Group request for information to support the National Hydrogen Strategy. The Hub concurs with the state and territory governments' view that hydrogen production and use creates an opportunity for Australia to lead in the emerging global markets for low- and zero-emissions energy, and energy intensive goods.

The Hub supports the principles underpinning the National Hydrogen Strategy (COAG, 2019, p. 5). The main points the Energy Transition Hub seeks to make in this submission are:

- Hydrogen technology is ready for 'market activation' due to low-cost renewables, technological advances, and the demand emerging in major export markets.
- A hydrogen economy is not inevitable – it is the outcome of a dual electrification-hydrogen strategy, supported by effective policy.
- There is vast potential for hydrogen exports, either as energy, ammonia or chemical feedstock resources or embodied in energy intensive products. The development of an export market for these products will support the emergence of an Australian hydrogen industry and could support domestic use.
- Australia's hydrogen strategy is best developed using a whole-of-system approach to energy production and consumption, rather than defining a hydrogen outcome as an independent end-point in itself. The key reasons for pursuing hydrogen are to decarbonise energy services and chemical feedstocks that are difficult to electrify and to export renewable energy. The role of hydrogen should be considered within the context of the full energy value chain, from primary energy through to the delivery of final energy services and energy intensive goods.
- Consumers in Australia could benefit from grid-connected hydrogen production assets that provide demand flexibility to the electricity system. Consumers in Australia may also benefit from mobility applications such as hydrogen-powered vehicles. The low round-trip efficiency of hydrogen powered light duty vehicles compared to an electric alternative may mean hydrogen use in the transport sector is limited to rail, buses and long-haul trucks in the near term.
- Australia will benefit from supporting renewable hydrogen pathways in the medium to long term. 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. The renewable-electrolysis pathway for hydrogen production taps into Australia's comparative advantages – world leading wind and solar resources - and provides the greatest opportunities

for Australia to lead in large-scale production and use of hydrogen in a zero-emissions world. Coal gasification and steam methane reformation could have lower production cost than electrolysis in the short- to medium-term but must be cost effectively combined with carbon capture and storage (CCS).

This submission is structured to respond to five of the policy questions in the National Hydrogen Strategy Discussion Paper. A brief description of the Energy Transition Hub and its work program and research capabilities in relation to hydrogen is provided below.

About the Energy Transition Hub

The Hub is a bilateral initiative for applied research on energy transition opportunities. It brings together an increasing number of research organisations – currently, seven in Australia and six in Germany - that are central to energy transition in both countries. The Hub addresses policy, socio-economic, system integration and technical dimensions of a transition to zero-carbon energy systems. Its work is highlighting the economic opportunities for Australia in a zero-emissions world economy.

The Hub is supported by the Australian and German governments, and industry participants in both countries. It is designed to foster close links between industry, governments, communities and the research sector.

The Hub's capabilities and work programs relevant to the evolution of the hydrogen sector in Australia include:

- Global, and Australian energy systems modelling incorporating scenarios for global hydrogen demand and Australian hydrogen production, export and consumption. Our modelling uses five leading European and Australian energy-system models developed and managed by Hub institutions (REMIND, REMIX, DIETER, MUREIL, and OpenCEM). This modelling suite enables the Hub to explore:
    - Long-term scenario planning, including using the REMIND integrated assessment model, which integrates energy, the carbon cycle and economic systems. REMIND incorporates all major energy sources and is being expanded to include hydrogen as an energy vector. It allows us to conduct a global analysis of low-emissions pathways and explore the role of hydrogen in various scenarios.
    - Australian energy system analysis using least-cost capacity and dispatch optimisation models MUREIL and OpenCEM. These tools enable the Hub to develop least-cost scenarios of future electricity system configurations, which include hydrogen and other storage, subject to emissions, engineering and resource constraints.
- The links the Hub provides across several initiatives in Australia and Germany, including:

- The $10m ANU initiative on "Zero-carbon energy for the Asia-Pacific", which will explore possibilities for new export industries, such as hydrogen, to deliver cheap, clean energy for Australia and the region.
- The German Kopernikus projects 'Power-to-X' and 'ENavi', flagship projects of energy transition research dedicated to hydrogen, power-to-X and energy transition across sectors.

2. What are significant recent developments in Hydrogen?

The Hub considers that significant recent developments in hydrogen include:

- Costs across the hydrogen value chain dropping sufficiently that hydrogen can begin to be deployed commercially as an energy source.
- The active interest in developing a global demand and supply chain for hydrogen demonstrated by Japan, South Korea, and others including Germany, in which Australia is seen as a major potential source of supply.
- Commercialisation opportunities and commercial interest in developing hydrogen for a range of applications including transport, electricity storage and grid support, production of ammonia, and zero-emissions steel using green hydrogen as a reductant instead of coke.

Cost reductions along the hydrogen value chain

There is an expectation that hydrogen will be commercially competitive in several applications in the near future, and in others in the medium term. The concept of the 'hydrogen economy' was coined in 1972, but it is only in recent years that the cost of the complete value chain has dropped sufficiently that hydrogen can begin to be deployed commercially. The major factors driving the change in the costs of hydrogen value chain include:

- The dramatic fall in the cost of solar and wind electricity, and
- The steady improvement in the commercial status of electrolysers, fuel cells and supporting infrastructure (Bruce et al., 2018).

As hydrogen technology is brought into use, further rapid declines in cost are expected. Early stage commercial development is driven by viable market niches. Cost declines are driven by economies of scale, learning by doing, standardisation, network building and other scale effects. The cost learning rate, or the cost decline per cumulative doubling of installed capacity, is typically 10 to 20% for electrolyser and fuel cell technology (Wei et al, 2017). For every 100 fold increase in the deployment of hydrogen technology increases capital cost declines of around 50 to 80 per cent can be projected (Wilson, 2012).

These projected cost declines do not guarantee that all potential uses of hydrogen will prove financially viable but underscore the value of driving early stage development. The most significant cost declines, in absolute terms, will occur during early stage deployment.

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 may offer the greatest benefits. The renewable-electrolysis pathway utilizes Australia's high-quality wind and solar resources, and the capability of modular electrolysis deployment more closely replicates renewable deployment. The lower current cost of steam methane reforming (SMR) and coal gasification with CCS, means thermochemical pathways may be seen as providing an entry point for developing commercially viable hydrogen infrastructure and permitting more rapid up-scaling in the medium term.

Development of global demand for hydrogen

Hydrogen is projected to play a major role in meeting demand for energy in a zero-emissions world by the middle of this century. The implementation of hydrogen demand and supply technologies is only an emerging research field in the global integrated assessment models, such as the REMIND model that the Hub works with. Several of the initial results are providing some indication of the increasing global demand and its timescales in the context of a world that moves to implement the Paris Agreement targets.

Global and regional hydrogen use in the 1.5°C and 2°C scenarios from the IPCC Special Report on 1.5°C Scenario Database[1] is illustrated Figure 1 and Figure 2 using box-whisker plots. The boxes represent the interquartile range including the median value. Whiskers show the full range including any outliers. The number of samples used per category is shown on the top of the box-whisker plots.

The figures illustrate that in scenarios in which the world pursues action consistent with limiting warming to 1.5 °C above pre-industrial levels, the share of global energy demand supplied by hydrogen is several times larger than in a 2°C world. These scenarios also indicated that in both the regional and global setting:

- Hydrogen is a long-term proposition with a long gestation.
- The share of hydrogen is increasingly important in strong abatement scenarios and categories.
- Hydrogen comprises a meaningful but not majority share of final energy in both regional and global scope.

[1] https://data.ene.iiasa.ac.at/iamc-1.5c-explorer

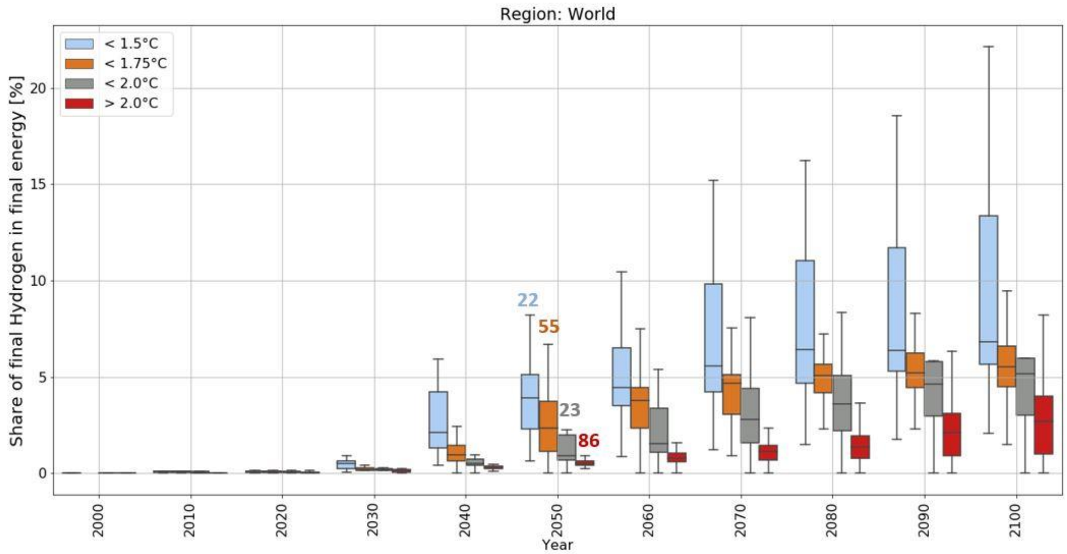


Figure 1: Global demand for hydrogen for final energy use in scenarios used in the IPCC Special Report on 1.5 degrees. The number of analyzed scenarios per scenario class is indicated by the numbers around year 2050. The scenarios are classified by their likelihood to limit global mean temperature increase to below 1.5°C, below 1.75°C, below 2.0°C or lead to warming in excess of 2.0°C. Source: Analysis by the Energy Transition Hub using the database of scenarios from IPCC SR 1.5 report

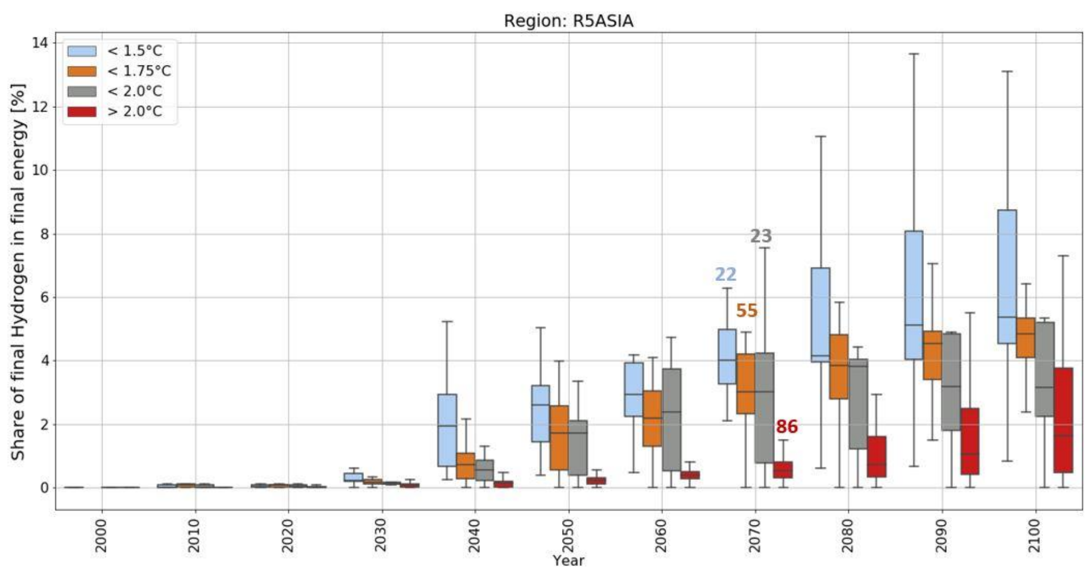


Figure 2: Demand in the Asian region for hydrogen for final energy use in scenarios used in the IPCC Special Report on 1.5 degrees. Source: Analysis by the Energy Transition Hub using the database of scenarios from IPCC SR 1.5. Scenario classifications as in Figure 1.

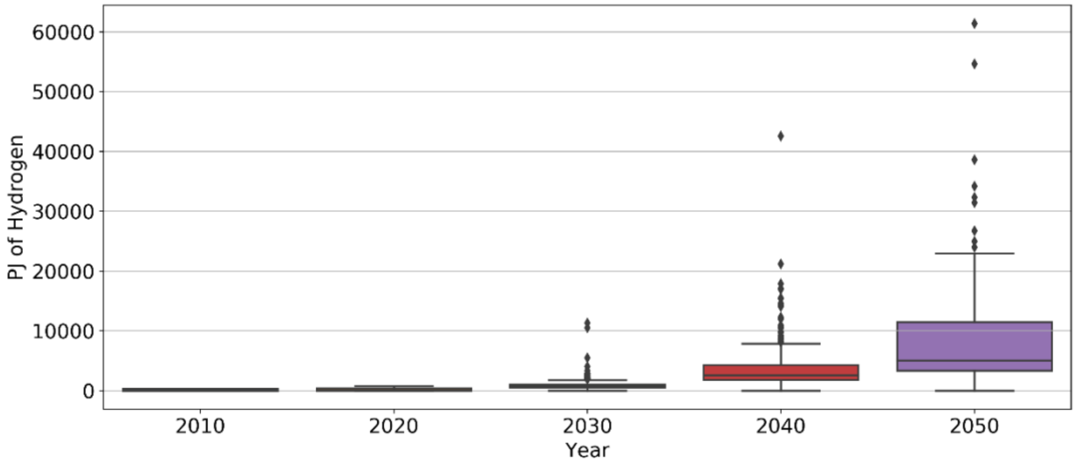


Figure 3: Global demand projection for hydrogen calculated in scenarios used in the IPCC Special Report on 1.5 degrees, Source: Analysis by the Energy Transition Hub using the database of scenarios from IPCC SR 1.5

In absolute terms, the global projected demand of hydrogen over several decades is illustrated in Figure 3. The box-whisker plots in the figure are accumulated over 400 scenarios that were generated by integrated assessment models and reported in IPCC SR15. The plots suggest that the demand for hydrogen could increase significantly between 2030 to 2050. In 2050, although the demand in most of the scenarios stays within 20,000 PJ, a couple of scenarios – represented by the outliers in the box plots – suggest 55,000 PJ or more. The scenarios are broadly comparable with ACIL Allen, 2018 (Figure 2.1, page 7), showing a similar growth rate in demand.

One of the most important developments for Australia's hydrogen sector is that Japan and South Korea, amongst others, are implementing strategies to drive their imports of hydrogen from low-emission processes (Palmer, 2018; Trencher, 2019). Singapore and China are also identified as early prospective markets (ACIL Allen, 2018; Burmistrz, 2016). An Australian domestic hydrogen market is dependent on an export market to achieve economies of scale. Australia has established energy trading relationships with Japan and South Korea, the technical capacity, and some of the infrastructure and natural resources important to accelerating development of hydrogen-based exports. Japan and others see Australia as an important potential source of hydrogen (Trencher, 2019). Should hydrogen progress to being a globally significant energy carrier, ACIL Allen, 2018 concluded that the value of Australian exports could surpass $10 billion by 2040. 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.

Near-term commercialisation prospects for hydrogen applications

Commercially viable niche applications have already emerged, and many energy supply firms, multinational manufacturers and service firms are investing in the hydrogen fuel cycle (Palmer, 2018). Research groups and commercial enterprises are coalescing into collaborative groups and industry bodies. But a hydrogen economy is not inevitable. There is widespread recognition that price competitiveness of hydrogen-based technologies requires economies of scale, and these may not be reached without directed market activation and policy intervention (Bruce et al. 2018). Without a recognition of climate risks and environmental externalities, hydrogen-based technologies may struggle to compete with fossil fuel-based technologies in some areas.

Energy Transition Hub research (Palmer, 2018) developed four scenarios to consider:

- What quantity, quality and cost of renewable energy resources are needed to produce different quantities of hydrogen in Australia.
- The techno-economic feasibility of the synthesis pathways and the major drivers and barriers.
- Technologies that are most likely to be a part of the hydrogen future, and the interactions between these technologies and other energy sources and carriers.

Indicative deployment timelines possible for different applications in the most ambitious of these four scenarios - in which Australia becomes a 'global leader' in hydrogen production and use - are illustrated in Figure 4. The left end of each line indicates the approximate first year of first commercial applications in Australia. The right end indicates the approximate year of strong market growth. The figure illustrates a range of applications that are or could be commercial in the 2020s. In the scenario depicted in

Figure 4:

- Some transport applications could be commercial by the 2020s, starting with niches such as forklifts, but including passenger vehicles, buses, and trucks, followed by rail from around 2025.
- Natural gas substitution could start from the 2020s initially incorporating a small percentage of hydrogen, followed by appropriate upgrading of networks to carry 100% hydrogen.
- Australian hydrogen-refining of steel is depicted in Figure 4 as having commercial applications from the mid 2030s. Pilot projects are already emerging in other countries. With appropriate support, these could commence in Australia, even if full-scale commercialization and provision of zero-carbon steel may be only likely to emerge after 2030.

- Ammonia fertilizers, and the large global market for these products, offers a near term opportunity for hydrogen trade in the form of ammonia, using existing and upgraded infrastructure.
- The first seasonal and shorter-term electricity storage from micro-grid hydrogen pilot applications are coming onto the market. There is a possibility for larger scale deployment from 2030 onwards.

Under the 'global leader scenario' that underpins the timelines for commercialisation illustrated in

Figure 4, industrial coal consumption, roughly half of natural gas, and 40% of petroleum would be substituted for electricity and hydrogen by 2050.

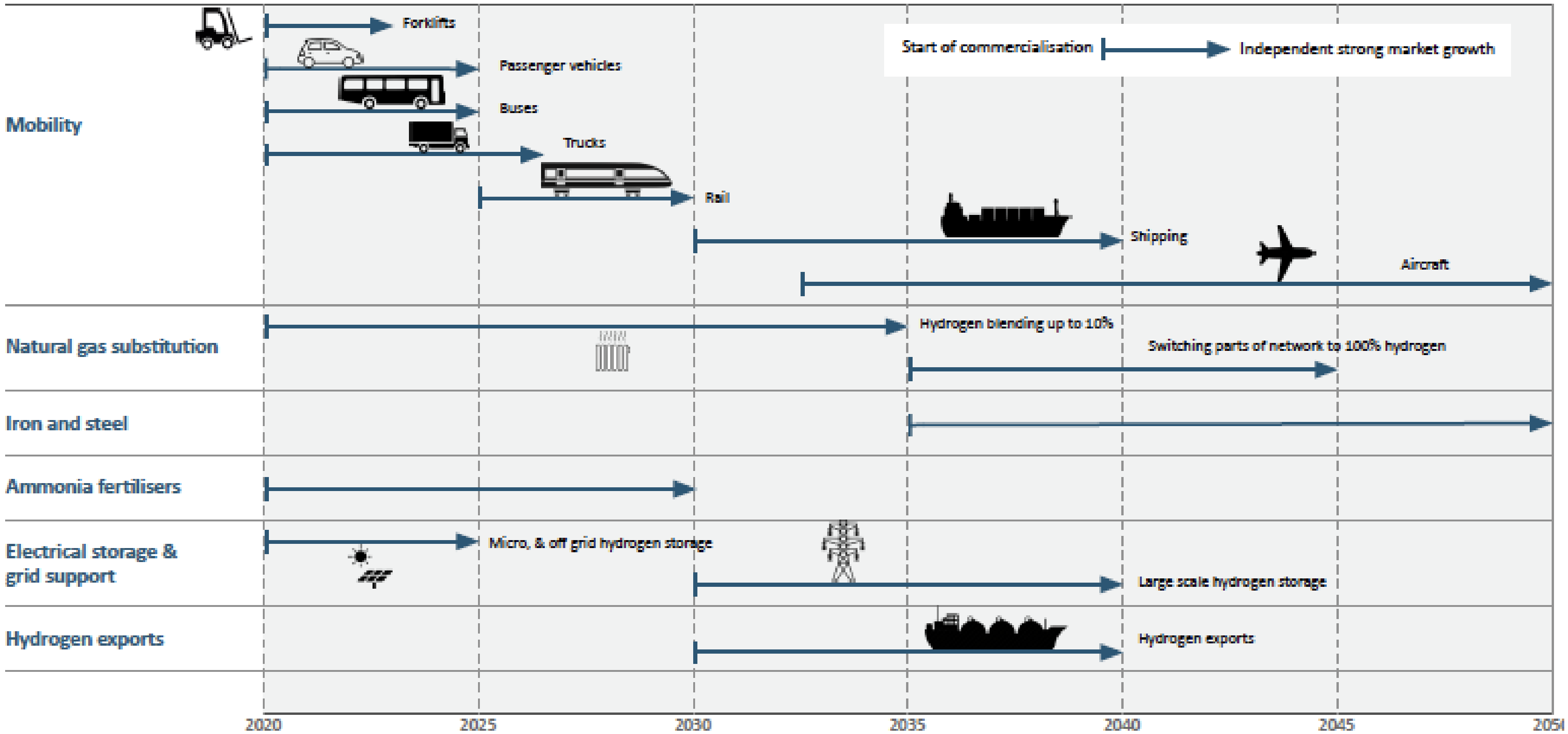


Figure 4: Indicative hydrogen deployment for the 'global leader scenario' for Australia. Graph source: Energy Transition Hub, Palmer, 2018

3. How can Australia influence and accelerate the development of a global market for hydrogen?

There is a range of barriers to the development of a global market for hydrogen and a domestic hydrogen sector. The Hub considers action by Australia, in conjunction with countries that represent major potential markets, is important in assisting to accelerate the development of a global market and supporting Australia’s position as a major supplier in that market.

In the early stage of development, construction of supply infrastructure risks being constrained by a lack of hydrogen demand, and vice-versa. Countries and states such as Japan, California, Germany and South Korea are addressing this dilemma by strong policy, and government supported development. In countries that are likely to be importers, efforts may focus on hydrogen use, industrial development, and other elements of the value chain. Australia’s comparative advantage will be in hydrogen production, and the associated deployment of production and distribution assets. Also, a large potential for hydrogen in Australia is indirect by using it in on-shore energy intensive industrial production, such as steel refining, in order to supply zero-emission energy-intensive materials. Australia can support initiatives to accelerate the development of a global hydrogen market by, amongst other things:

- Working with governments and industry to support pilot projects and the development of global supply chains across a range of feasible pathways including hydrogen, ammonia, steel, and other energy intensive materials.
- Adopting policies that support hydrogen pathways that maximise Australia’s comparative advantages, especially production of renewable hydrogen and export of energy materials using green hydrogen. Australia could adopt emission intensity target(s) for hydrogen production, while supporting a technology neutral approach.
- Participating in international forums and standards development agencies.

Hydrogen-based solutions will be supported globally and within Australia by policies that ensure market prices reflect the benefits in the form emissions reductions, pollution and possibly energy security. At present, hydrogen-based solutions are replicating services that are already provided by another energy carrier. Some of the hydrogen-based solutions might at this stage carry higher technology risks and cost. At this early stage in the hydrogen commercialisation cycle, few hydrogen-based solutions can successfully compete on price alone, in the absence of prices on carbon or other pollutants. Stable and predictable policies that reflect the benefits of transitioning to hydrogen from higher emitting energy sources and processes will support the development of the global market and Australian supply into that market.

4. Hydrogen research, development and deployment: Where are the gaps in our knowledge?

The appointment of the COAG Hydrogen Working Group, and its focus on identifying gaps in the research, barriers and changes required to support the production and the use of hydrogen in the future, is a positive development.

Many of the research groups currently working on hydrogen are technology focused, supported by forums for knowledge sharing. This work needs to continue and be supplemented by additional research on possible technology learning curves in an Australian context to better inform assessments of future costs and what hydrogen pathways may emerge. The Hub is commencing a program of work on these issues, as are several other Universities and research institutes (e.g. the aforementioned ANU work program or the University of Melbourne's Hydrogen Strategy under leadership of Prof. Chris Goodes). Improved understanding of technology learning curves will help guide the development of standards, and regulations that support and do not inhibit particular pathways, and any targeted industry support.

A broader whole of system focus is also required. The development of a national hydrogen strategy should be informed by an understanding of the impact of different scenarios for changes in the global demand for hydrogen, and the impact of deploying hydrogen production in different forms and locations on the Australian energy system as a whole. The magnitude of the change and expansion of Australia's energy systems means this should be a key part of the information base used to inform any national hydrogen strategy. Estimates of the energy required to produce quantities of hydrogen that correspond to high export and domestic use scenarios are outlined below.

Table 1 provides estimates of the electricity, natural gas or lignite required to supply hydrogen production in quantities commensurate with the export potential considered in ACIL Allen 2018. Producing a quantity of green hydrogen consistent with the ACIL Allen, 2018 high demand scenario (382 PJ of hydrogen by 2040) would require an approximate doubling Australia's electricity generation capacity by 2040.

Possible energy requirements associated with the potential substitution of hydrogen for other end-use energy sources in Australia are illustrated in Figure 5 and Figure 6. These are based on the 'global leader' scenario that underpins the deployment timelines illustrated in Figure 4 . It assumes all hydrogen is produced by electrolysis and 64 kWhe /kg H_2 is required for the production, compression and transport of hydrogen. Under these assumptions, this level of hydrogen substitution equates to 397 TWh_e per annum, equivalent to 130 GW of renewable capacity at 0.35

capacity factor. This is approximately twice as much as the currently installed generation capacity in Australia.

Table 1: Electricity, natural gas or lignite required to supply hydrogen production

Hydrogen	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	107	35	289	5,129	435	42,626
500	267	87	722	12,824	1,087	106,564

Source: Palmer, 2018. Generation capacity given for 35% capacity factor and assuming 64 kWh_e/kg H_2, for production, compression and transport; methane assumes 13 MJ/Nm^3 H_2 for steam methane reforming plus 20% for CCS; coal given for lignite at 10.2 GJ/t and 4.6 kg H_2/GJ coal (Burmistrz et a. 2016) plus 20% for CCS

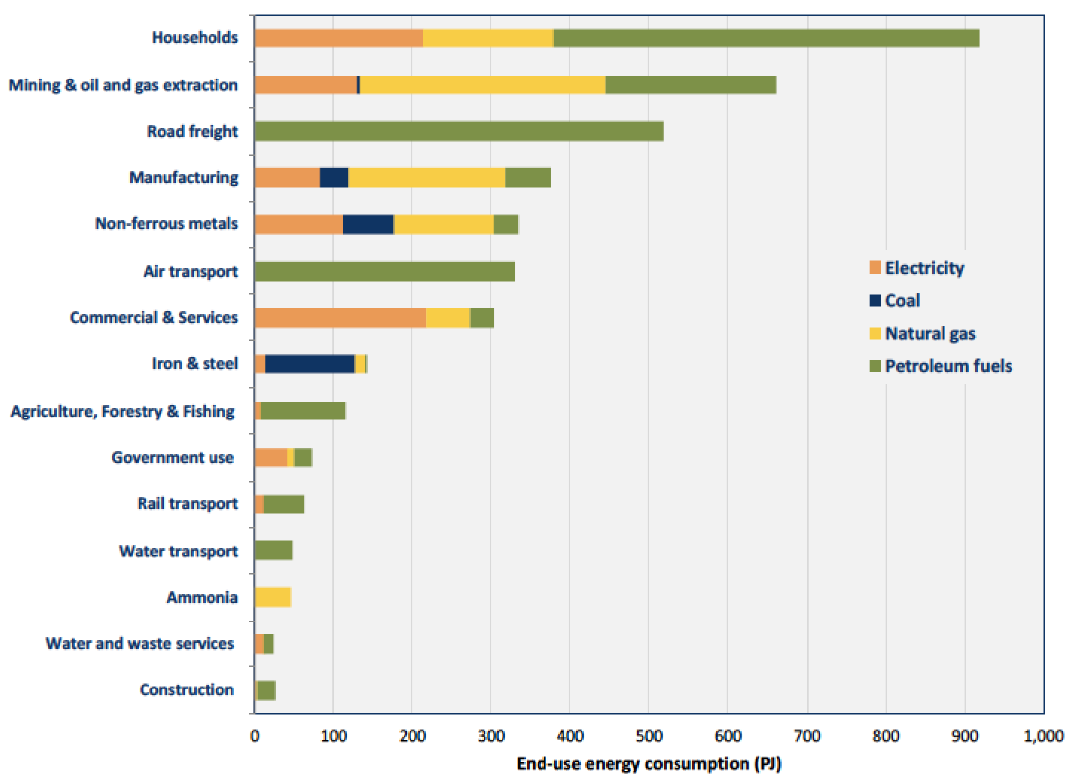


Figure 5: Australian energy end-use (2015-2016). Source: Palmer, 2018

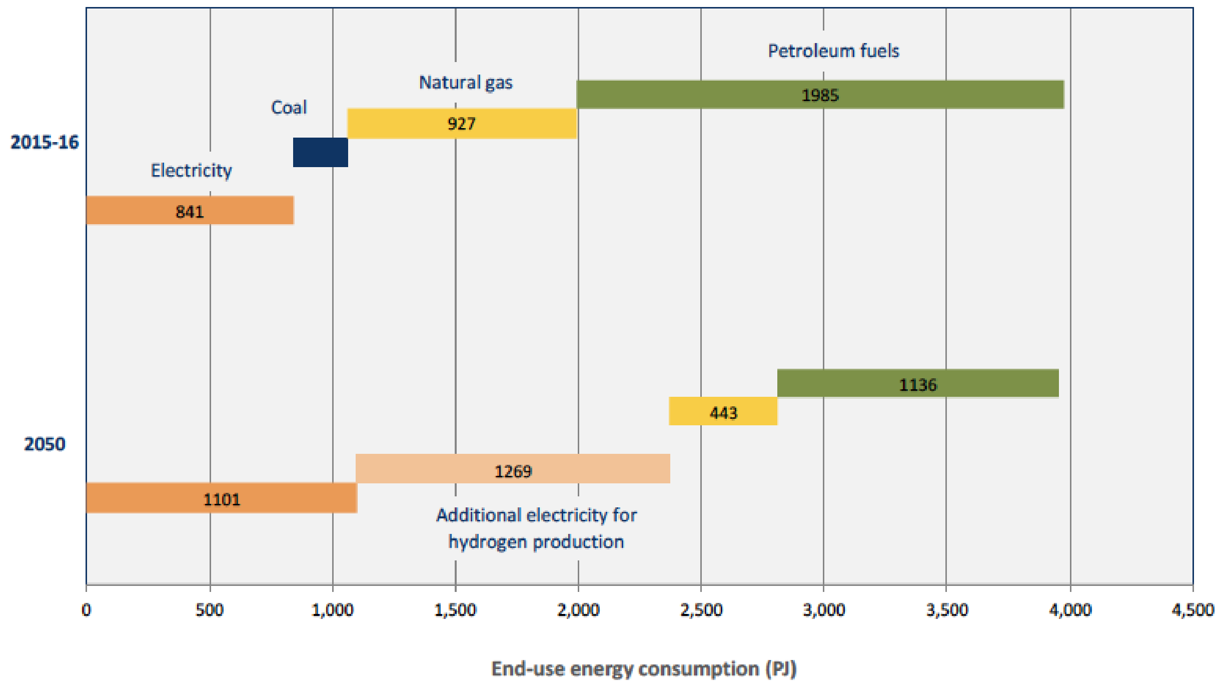


Figure 6: Australian energy end-use substitution possibilities by 2050 in a global leader scenario. End-use energy in 2050 is based on electrification and conversion to hydrogen for the energy end-use in 2015/16. The petroleum-to-electricity end-use conversion adopted is 3.5. The petroleum-to-hydrogen end-use conversion adopted is 2.0. It is assumed that under an ambitious hydrogen policy, coal that does not incorporate carbon capture and storage would be phased out well before 2050. Source: Palmer, 2018.

The example represented in these figures uses end-use energy consumption in 2015/16. 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.

Using global and Australian energy systems modelling that incorporates hydrogen will complement the technology focus of much of the current hydrogen research in Australia, and enable Australia's strategy and policies to be informed by:

- Long-term scenario planning which integrates global energy, the carbon cycle and economic systems. Integrated assessment models (such as the REMIND model) of the major energy sources are being expanded to more comprehensively include hydrogen as an energy vector. Use of these models will allow Australia to analyse trade and energy flows under different low-emissions pathways, and explore the role of hydrogen in various scenarios.

- Australian energy system analysis using least-cost capacity and dispatch optimisation models that include hydrogen as a potential generation and demand source. This type of modelling will enable a national hydrogen strategy to consider the least-cost scenarios of future electricity system configurations, which include hydrogen and other storage, subject to emissions, engineering and resource constraints. This can be used to explore the impact of future pathways for Australian hydrogen production, export and consumption on the optimal location and type Australia's generation and storage capacity and transmission and distribution infrastructure.

5. Opportunities for the use of clean hydrogen in Australia

There are hydrogen projects emerging across Australia. Figure 7 provides a map of current projects.

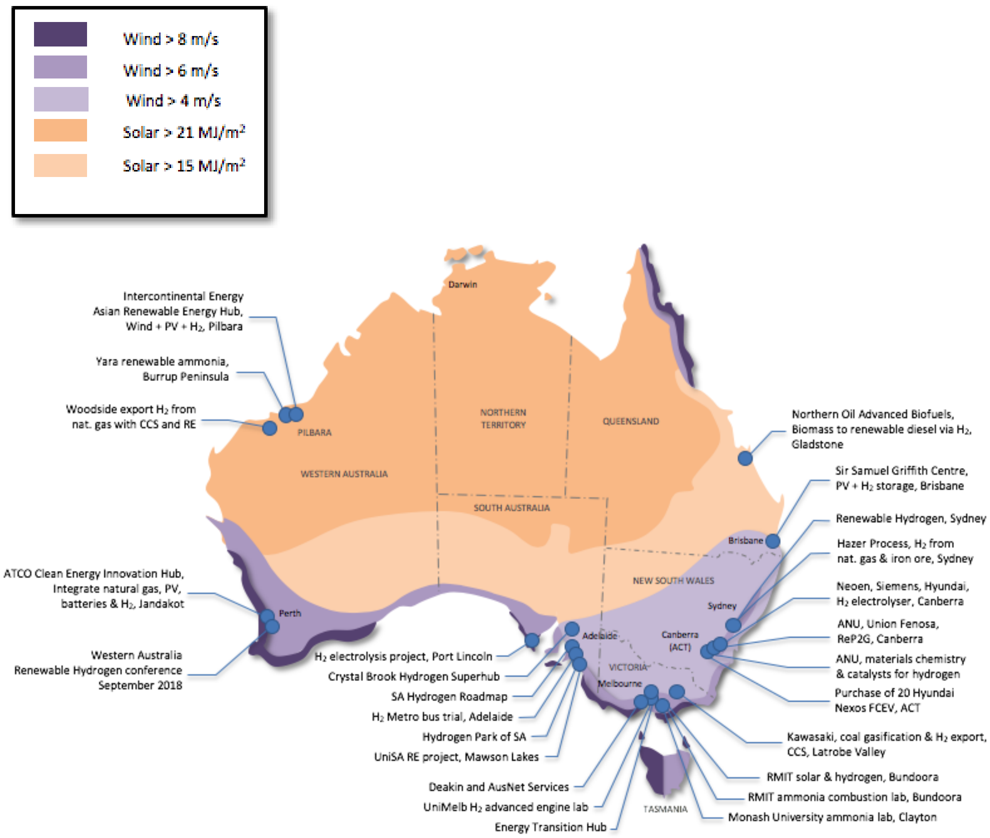


Figure 7: Current hydrogen projects in Australia. Source: Palmer, 2018

The national strategy adopted for hydrogen can influence whether hydrogen is developed primarily as an enabler of exports of energy intensive goods and renewable energy from Australia, or also as an enabler of a domestic decarbonisation strategy with direct benefits for end-users. Export and domestic market benefits could go hand in hand, or could emerge as alternatives, depending in part on the location of hydrogen production and distribution assets. For example, an export focused large-scale, grid-connected deployment of electrolysers, new transmission lines and new renewable energy supplies could create demand-side flexibility for the electricity grid with low curtailment of renewables. This demand side flexibility would lower electricity prices to the benefit of Australian end-users and energy-intensive industries. Domestic markets may not secure these or other benefits if hydrogen production assets are located in proximity to the best renewable resources, away from major electricity grids, and focused solely on producing for export markets.

Three early stage opportunities for the use of clean hydrogen in Australia include:

- **Green ammonia for fertilisers, industrial feedstock and the beginnings of a green synthetic fuel:** The Norwegian chemical company, Yara International, has announced a partnership with ENGIE to build a pilot 'green' ammonia plant in the Pilbara based on a 100 MW solar array, with capacity to produce 80 tonnes per day of ammonia. Ammonia can be used as a feedstock for agricultural fertilisers, industrial chemicals and explosives. Since ammonia boils at -33.3ºC, it is easily liquefied under moderate pressure and temperature. Liquefied ammonia may become an important hydrogen carrier in the future.
- **Remote area power systems (RAPS)**: RAPS systems are deployed in remote locations that lie outside of the geographical boundaries of grid electricity. Smaller systems currently power remote telecommunications, radio beacons, and monitoring stations. Larger systems power mining sites and island communities. RAPS systems in Australia are usually diesel, or diesel-solar-wind hybrid systems. Hydrogen-based systems can obviate the need for large battery storage systems where storage capacity beyond several days of capacity is required. The substitution of batteries and diesel generators with hydrogen storage can improve system reliability and reduce maintenance costs.
- **Substitution of diesel for passenger rail:** Hydrogen powered trains provide electrified rail services without overhead wires. The Alstom Coradia iLint was the first commercial hydrogen train to begin passenger operation, starting in September 2018. Four German states have collectively ordered 40 trains. Eversholt Rail in the UK has announced a rolling stock conversion to hydrogen, and Ontario is engaging Alstom and Siemens to produce concept designs for hydrogen trains. There are around 20 countries actively exploring the 'hydrail' concept. Hydrogen trains are more expensive than equivalent diesel-electric trains but expected to have lower operating and fuel costs. Australia has substantial non-electrified regional rail, providing an opportunity to begin to plan a hydrogen rail strategy. Rail requires few filling stations and may provide an early entry point for hydrogen mobility and building expertise.

As mentioned above, refining steel using green hydrogen as a reductant instead of coke is another major opportunity for the use of clean hydrogen in Australia given the proximity of high-quality iron ore resources to high-quality wind and solar resources, and port facilities. Pilot projects are being built in Sweden and Germany, but none have been announced as yet in Australia.

The expected timing, output and scale of investment and support associated with the European zero-emissions steel pilots provide an indication of the time and investment that could be required to develop operations in Australia. The Swedish-Finnish steel company, SSAB, is a leader in this space. Its pilot plant is expected to have a capacity of 500,000 tonnes a year of steel. SSAB has stated that the pilot plant will run tests between 2020 and 2024 and then scale up to a demonstration plant, and broader implementation of the technology between 2030-2040. The total cost of the pilot is expected to be around AUD 210 million. The Swedish Energy Agency will contribute more than AUD79 million toward the pilot phase and the three owners, SSAB, LKAB and Vattenfall, will each contribute one third of the remaining costs. The Swedish Energy Agency also contributed SEK 60 million to the pre-feasibility study and a four-year-long research project.[2]

[2] https://www.ssab.com/company/sustainability/sustainable-operations/hybrit

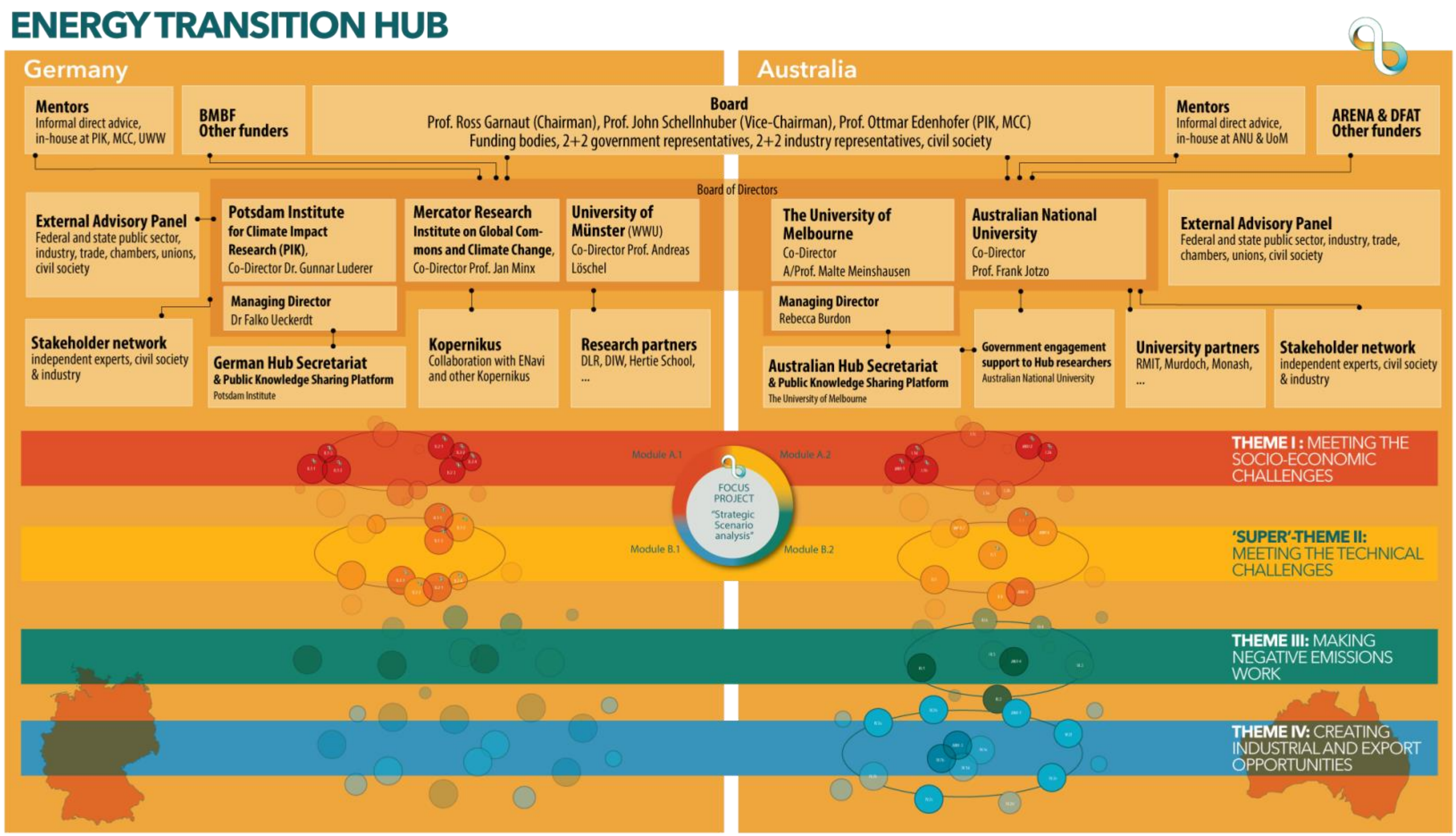
6. Australia's technology, regulatory and business strengths and weaknesses in the development of a clean hydrogen industry

Australia has significant advantages in the development of a clean hydrogen industry including its:

- Proximity to and existing trading relationships with countries that are implementing strategies to drive a transition towards hydrogen, including Japan, South Korea, Singapore and China.
- High-quality wind and solar resources and ability to deploy renewable energy resources in a way that supports both domestic energy needs and a hydrogen export industry.
- Capacity to provide sound regulatory settings and a stable investment environment, provided policy can deliver the consistent and predictable signals needed to support the scale of investment required to develop a hydrogen industry.

Important technology and business strengths include the capacity, skills and regulatory lessons from recent developments in the LNG industry. Hydrogen is considered a product that aligns with the competencies of the LNG industry and the LNG industry is widely considered a template for how a hydrogen export industry might proceed. Hydrogen liquefaction and distribution infrastructure will broadly replicate the engineering, scale, costs and risks of LNG infrastructure, although substantially higher energy-costs are related to hydrogen liquefaction. In the end, those liquefaction related energy costs might give a competitive advantage for ammonia as a hydrogen carrier.

One challenge to be addressed arises from the attribution of production emissions associated with fossil-fuel based hydrogen production. International carbon accounting principles mean any emissions associated with fossil-fuel based hydrogen production will be attributed to Australia. Although importing countries may signal an intention to favour low-emissions production, the territorial-based accounting methodology does not create an incentive to produce hydrogen using low-emissions processes. Apart from that question of who accounts for emissions, the larger issue related to fossil-fuel derived hydrogen is that it might undermine the public acceptance at the start, thereby preventing a large growth potential for hydrogen in a zero-emissions world.



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