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28 March 2019

Submission on the National Hydrogen Strategy Discussion Paper

Please find enclosed a submission by the Australian National University Energy Change Institute on the **National Hydrogen Strategy Discussion Paper**.

The ECI provides authoritative leadership in energy research, education and public policy through a broad portfolio ranging from the science and engineering of energy generation and energy efficiency, to energy economics, regulation, security, sociology and policy.

The Institute comprises more than 300 staff and PhD students from all seven Colleges of the University, and over $100 Million in infrastructure and facilities, supported by a major portfolio of external grant funding.

We hope that this submission is useful in informing your inquiry into the future prospects for a hydrogen economy in Australia.

Finally, we would like to thank you for the opportunity to meet with members of the Chief Scientist's National Hydrogen Taskforce on March 21st.

Please contact us at the above address should you have any queries regarding this submission.

Yours sincerely,

Professor Ken Baldwin,
ECI Director

Contributors: Dr Fiona Beck, Ms Tory Bridges, Associate Professor Paul Burke, Professor Kylie Catchpole, Associate Professor Llewelyn Hughes, Professor Frank Jotzo, Professor Yun Liu, Dr James Prest, Dr John Pye, Dr Igor Skryabin, Dr Matthew Stocks, Dr Robin Purchase, Dr Mahesh Venkataraman

Editor: Peter Dawson

A National Strategy for Hydrogen

Submission by the ANU Energy Change Institute (ECI)

Energy Change Institute (ECI)

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In this submission, please note that where a specified number of key points are requested (such as the three most important issues), we have highlighted them using red headings, with additional points in blue headings. We have used this prioritisation throughout the document. Note that the length of the response does not necessarily reflect the priority in each case.

The principal authors of each section are listed in the document.

Preamble

We maintain that a future hydrogen economy should be based on “clean” hydrogen, created using renewable energy sources. Hydrogen generated using fossil fuels (“dirty” hydrogen – formed from coal and natural gas and producing greenhouse gases) is not sustainable in the long term in a carbon-constrained world – particularly when carbon pricing impacts the world’s economies.

If “dirty” hydrogen is to be considered a low-emissions fuel, it needs to be coupled with carbon capture and storage (CCS), considerably increasing the expense and the technical requirements. Australia would need to implement CCS at an unrealistically rapid pace over the next 15-20 years to sequester the emissions from fossil-fuel-based “dirty” hydrogen generation if it is to meet the projected Australian export opportunity.[1] The CCS storage capacity required by 2040 to support the generation of “dirty” hydrogen is similar to the total capacity of all CCS facilities currently operating worldwide. Conversely, “clean” hydrogen is generated using heat or electricity from renewable sources and has no embedded carbon.

Although the submission relates primarily to hydrogen, it should be noted that hydrogen gas is itself only a part of the supply chain, with e.g. ammonia as another potential major energy vector.

Finally, currently a third of the emissions due to global energy use have no *commercially* viable alternative to fossil fuels. These include heavy freight, aviation, and industries like iron and steel, cement, chemicals and aluminium. To truly decarbonise, we need to find carbon-free energy vectors and fuels that can replace fossil fuels in a range of sectors. In some cases e.g. mineral ore reduction, hydrogen technology has the capacity to add enormous value to Australia’s exports. Hydrogen and its export applications are a key driver of the ANU Energy Change Institute’s Grand Challenge: *Zero-Carbon Energy for the Asia-Pacific.*[2]

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[1] See the ACIL Allen report: *Opportunities for Australia from hydrogen exports”,* 2018, for projected Australian export quantities.

[2] http://energy.anu.edu.au/eci-grand-challenge.

1. What do you think are the two or three most significant recent developments in hydrogen?

- ### The rapid reduction in renewable energy costs – which provide Australia with a comparative advantage because of its excellent renewable energy resource and large land area

Dr Fiona J Beck, Ms Tory Bridges, Dr Robin Purchase, Dr Mahesh Venkataraman

The most relevant development in hydrogen is the falling cost of renewable electricity (renewable energy) generation over the past ten years, driven by factors such as decreasing supply chain costs, improving technologies and increased competition.[3] The growth of the Australian renewable energy industry will be key to providing zero-carbon embedded electricity for green hydrogen generation.

The cost of renewable energy worldwide is reducing rapidly due to technology development, economies of scale and increasing industrial experience. Australia has some of the best solar and wind assets in the world, coupled with a large land area, and a skilled workforce. This gives Australia a comparative advantage in rapidly deploying large-scale zero-carbon hydrogen generation by electrolysis, powered with low-cost renewable energy.

Meeting the projected demand for Australian zero-carbon hydrogen exports[4] with electrolysis would require Australia to nearly double its domestic electricity generation by 2040. However, estimates suggest that due to the rapid growth of the renewable energy industry in Australia *it is feasible to provide this additional electricity with renewable energy*, if the growth of the renewable energy capacity continues at its current rate of 6.3 GW p.a.[5] Notably, this projection does not rely on any significant technology improvements or breakthroughs, and only a marginal increase in electrolyser efficiency over the next 20 years.

- ### The demand for (clean) hydrogen exports to nearby Asian markets (Japan, Korea now have their own hydrogen road maps) is a key driver

Associate Professor Llewelyn Hughes

Key Asian markets, centred on Japan and South Korea, have released long-term roadmaps, and are making substantial public investments, in support of the development of global supply chains for hydrogen. Companies are also showing a long-term commitment to hydrogen by developing and commercialising products that utilise hydrogen.

- ### Energy security drivers in Europe

Professor Frank Jotzo

Germany and other European countries are developing an interest in building up a hydrogen infrastructure as a zero-carbon option for energy in industry, transport and electricity supply (balancing intermittent renewables). These countries anticipate that they

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[3] See, for example, Lazard's Levelized Cost of Energy Analysis V 12.0. https://www.lazard.com/media/450784/lazards-levelized-cost-of-energy-version-120-vfinal.pdf
[4] ACIL Allen Consulting, "Opportunities for Australia from Hydrogen Exports," no. August, p. 47, Table 4.9, 2018.
[5] http://re100.eng.anu.edu.au/publications/assets/100renewables.pdf

would continue importing energy as part of a future low-carbon energy system, and have a strong interest to diversify sources of imports in order to improve energy security from a geo-strategic perspective. Hydrogen from Australia and other exporting countries could in part replace Russian gas.

- ## New clean hydrogen applications such as steel production and reduction of mineral ores

Dr John Pye

Hydrogen is being actively considered as a reducing agent for large-scale mineral processing. Specifically, the HYBRIT project in Sweden is aiming at commercial production of hydrogen-reduced iron by 2035, and is currently building a demonstration-scale system in Sweden[6]. This is in parallel with some other projects such as Siderwin and Boston Metals, which are using direct electrolytic reduction of iron ore.

Which process(es) are ultimately commercially successful cannot yet be predicted, but a study by Vogl et al[7] found that there may be as little as a 20-30% price differential for hydrogen-reduced steel compared to blast furnace steel based on present-day costs of electricity from wind/PV.

It may be that one of the largest and most beneficial uses for hydrogen produced from renewables in Australia could be in large-scale reduction of iron ore for steel production. This topic is one that is being considered in detail as part of the ANU Energy Change Institute's Grand Challenge: *Zero-Carbon Energy for the Asia-Pacific*.

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[6] LKAB/SSAB/Vattenfall, 2019. *Hybrit Development*. https://www.hybritdevelopment.com/

[7] Vogl et al, *Journal of Cleaner Production*, 2018. https://doi.org/10.1016/j.jclepro.2018.08.279

2. What are the most important safety issues to consider in producing, handling and using hydrogen in Australia?

- ### Review of safety regulation for hydrogen in various applications

  Dr James Prest

  Existing regulatory frameworks such as dangerous goods legislation and gas safety laws already cover the use of hydrogen. There are many existing Australian standards that are relevant to the transportation, storage and use of hydrogen. In addition, there are numerous international hydrogen safety and production standards. Australia must decide whether to adopt or modify these international standards.

  The International Organisation for Standardisation (ISO) has standards pertaining to hydrogen gas generators using water electrolysis.[8] These standards define the construction, safety and performance requirements of industrial, commercial and residential appliances using electrolysis.

  Standards Australia has not yet published a standard on hydrogen *production*. A search of the Standards Australia database in the Electrotechnology and Energy Sector suggests that hydrogen standards have not yet been made in Australia.[9] In this sense, Australia is lagging behind other developed countries. The British,[10] French,[11] Spanish,[12] Danish[13] and Netherlands[14] Standards Associations have all adopted at least one of the ISO standards on hydrogen generation.

  Australian transport legislation already covers hydrogen vehicles, for example the *Heavy Vehicle (Vehicle Standards) National Regulation 2013,* Part 9 Alternative Fuel Systems - s 108A regulates Hydrogen powered heavy vehicles.

  However, there is ambiguity and a lack of clarity about how natural gas safety legislation applies to hydrogen in the pipeline injection context.

  Our recommendation is to avoid reinventing the specialised regulatory frameworks for electricity and gas that are already in place on a national level. Instead, to the extent possible, we would suggest amendment of existing legislation and rules.

  Nevertheless, a fundamental choice for Australian law makers is whether there should be a stand-alone National Hydrogen Act passed by the Federal Parliament and whether new provisions should be inserted into the *National Gas Act* and *National Gas Rules* (noting that these apply through mirror legislation in the majority of the States). Because gas, particularly gas safety, is also regulated on a State and Territory basis it will also be necessary to encourage regulatory reform at the sub-national level.

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[8] ISO 22734-1:2008; ISO 22734-2:2011

[9] Standards Australia, Standards Development Public Portal, search conducted online 7.1.2018 at http://sdpp.standards.org.au/Committee.aspx?sector=Electrotechnology%20and%20Energy

[10] BS ISO 16110-2:2010.

[11] NF ISO 16110-1:2009

[12] UNE ISO/TR 15916:2007.

[13] DS ISO 22743-1:2008.

[14] NEN ISO 22734-1:2008.

As was noted in the 2017 South Australian *Hydrogen Roadmap*, a serious safety incident involving hydrogen may undermine the business case for hydrogen investment for several years. The complexity and difficulty of hydrogen transport issues is considerable. Robust and safe hydrogen delivery infrastructure will require significant attention to safety issues and requirements surrounding transport and leak detection.[15] However, Australian legislators and regulators will be able to manage these issues by drawing upon international standards and expertise.

- ## Need solutions for odourless supply and colourless combustion

Dr Igor Skryabin and Dr James Prest

Natural gas is typically odourised by adding tetrahydrothiophene mercaptans or sulphur-free odourising agents. This provides a warning smell intended to indicate to people when gas appliances are leaking or gas is otherwise escaping unburnt.

The legal requirement for odourisation of reticulated natural gas is universal in Australia. For example, in Victoria, the Gas Safety (Safety Case) Regulations 2018 (Vic) (ss.46) (made under the Gas Safety Act 1997 (Vic)[16]) require that gas must:

(a) have an odour which is distinctive and unpleasant; and
(b) have an odour level that is discernible at one-fifth of the lower explosive limit of the gas.

Since hydrogen is odourless (just like natural gas), it must be odourised for safety reasons and to comply with the regulations. An additional safety issue is that hydrogen flame is invisible.

Solutions for the problem of odourless supply and colourless combustion of hydrogen must be developed and reflected in relevant standards and regulations. The two main categories of options are adding specific substances to hydrogen distribution lines (chemical solutions) or deploying hydrogen sensor alarms and flame indicators (physical solutions).

Chemical solutions are potentially complicated by **three factors**: (i) fuel cells (e.g. in FC vehicles) can be damaged by substances added to hydrogen; (ii) a separation of hydrogen and added substances is possible when substances are injected far upstream from the point of consumption (e.g. household cooktop) and (iii) the regulatory requirements (i.e. gas quality guidelines and standards) restricting the addition of substances to the gas supply network.

Otherwise, physical monitoring solutions would require extremely high reliability of alarms.

A logical approach is for the National Hydrogen Strategy to examine the approaches to the odourisation question that have been applied overseas in markets that already have a high uptake of hydrogen, namely California and Japan.

The approaches to hydrogen safety however depend on the application and whether this is for the transport sector or for pipeline injection of hydrogen.

[15] U.S. DRIVE (United States Driving Research and Innovation for Vehicle efficiency and Energy Sustainability) Hydrogen Delivery Technical Team, (2017) *Hydrogen Delivery Technical Team Roadmap*, https://energy.gov/sites/prod/files/2017/08/f36/hdtt_roadmap_July2017.pdf

[16] https://www.esv.vic.gov.au/news/gas-safety-regulations-2018/

In relation to the transport sector, it is evident from overseas jurisdictions that the preferred approach is the use of sensors. For example the California Governor's Handbook on *Hydrogen Vehicle Fuelling stations in California* states that sensors are to be used instead of an odourisation approach:

"Hydrogen sensors are used to detect leaks and have been used to meet safety standards for decades. By comparison, natural gas is also odourless, colourless, and tasteless. In this case, a sulfur-containing odorant, called mercaptan, is typically added to make natural gas detectable by smell. Hydrogen fuel would not work well with odorants because they interfere with the fuel cell systems, so other safety measures, like sensors, are used.[17]"

- ## Need solutions for flashback issues with 100% hydrogen supply pipelines

Dr John Pye

Flashback is the propagation of a flame front back against the direction of flow. In conventional gas burners, this can lead to unsteady burning or possibly explosions. To prevent flashback, the gas velocity either needs to be much faster (about 10 times than for natural gas), or else the gas must travel through small 'quenching holes' that remove the heat from the flame and extinguish it before it can travel upstream. In both cases, the very different combustion properties of hydrogen[18] mean that a standard natural gas burner (such as a in a gas cooker or gas-fired hot water system) is not suitable for the combustion of hydrogen. Quenching holes in the case of hydrogen need to be so small that there becomes a risk of blocking.

Burners adapted to hydrogen seem to be an active area of research and development. Flameless catalytic combustion addresses the flashback issue as well as reducing the production of NOx gases[19]. Pre-mixing of air or flue gases before the burner, so that a leaner mixture is burnt, also appears to be an option for reducing the risk of flashback[20].

If an existing natural gas network were to be adapted to hydrogen, it would be critical to review all connected equipment to ensure that unsafe burners were removed or replaced.

- ## Marketing strategies for public acceptance of safety and useful applications

Dr Fiona J Beck, Ms Tory Bridges, Dr Robin Purchase, Dr Mahesh Venkataraman

For the hydrogen industry to successfully develop in Australia for domestic consumption and/or export, the support of the Australian public must be secured. Social license to operate must be obtained and subsequently maintained. Absence of public support, especially when expressed in protest movements, may lead to politically based constraints on projects and potential regulatory restrictions, which can cause project failures, economic losses and reputational damage to the industry[21]. Initial research into public

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[17] Governor's Office of Business and Economic Development (2015) Hydrogen Station Permitting Guidebook: Best practices for planning, permitting and opening a hydrogen fueling station, November 2015 http://www.businessportal.ca.gov/wp-content/Documents/ZEV/Hydrogen-Permitting-Guidebook.pdf

[18] Drell and Belles, 1957. *Survey of Hydrogen Combustion Properties.* NACA RM E57D24. https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19930089867.pdf

[19] Fumey et al, 2016. https://doi.org/10.1016/j.ijhydene.2016.03.134, http://www.arizonaenergy.org/AltEnergyClub/Heatin'%20with%20Hydrogen.pdf, https://bigccs.no/research/sp1-co2-capture/hydrogen-combustion/.

[20] https://arizonaenergy.org/AltEnergyClub/Cookin%27%20on%20Hydrogen.pdf

[21] C. Gallois, P. Ashworth, J. Leach, and K. Moffat, "The Language of Science and Social Licence to Operate," *J. Lang. Soc. Psychol.*, vol. 36, no. 1, pp. 45–60, Jan. 2017.

attitudes towards hydrogen[22] is an important first step and needs to be built upon and investigated further.

- ## Store and transport safely with a low cost: deliverable at ambient environment

  Professor Yun Liu

For large scale and safe application of hydrogen energy, hydrogen would ideally be stored and transported near room temperature and near ambient pressure to reduce safety issues. One alternative is to embed hydrogen in liquid organic hydrogen carriers which are treated as normal hazardous chemicals.

For current technologies for storage and transport, their safety issues will be different, such as:

- Metal Alloy Hydrogen storage: Stainless steel hydrogenation, cylinder leakage.
- High pressure cylinder hydrogen storage: leakage is big issue.
- Liquid-hydrogen storage and transport: temperature control, leakage.
- Ammonia: toxicity issues with leakage.

[22] D. V. Lambert and P. P. Ashworth, “The Australian public ’ s perception of hydrogen for energy,” 2018.

3. What environmental and community impacts should we examine?

• Initially there will be an increase in hydrogen emissions before 100% renewable electricity

Dr Fiona J Beck, Ms Tory Bridges, Dr Robin Purchase, Dr Mahesh Venkataraman

Generating hydrogen could lead to an increase in CO_2 emissions in Australia, depending on the technology employed. If hydrogen is generated with fossil-fuel based thermochemical methods (i.e. coal gasification or SMR), CO_2 is emitted during the process. Emissions can be mitigated with carbon capture and storage (CCS), however not all of the emitted carbon dioxide can be captured: some CO_2 will escape into the atmosphere, and additional CO_2 may be emitted due to the extra electricity needed to compress, transport and store CO_2. The efficiency of CCS depends on the technology that is used and the type of carbon emitting process, however, it is usually between 80-90%[23].

Alternatively, generating hydrogen with electrolysis *may also* lead to short term increases in CO_2 emissions, if the electricity used is not fully renewable. Fossil fuel electricity may still be required to meet the projected demand[24], even if the growth of the renewable energy capacity continues at its current rate of 6.3 GW p.a[25].

• CCS acceptance and feasibility for dirty hydrogen

Dr Fiona J Beck, Ms Tory Bridges, Dr Robin Purchase, Dr Mahesh Venkataraman

Australia would need to implement CCS at an unrealistically rapid pace over the next 15-20 years to sequester the emissions from fossil fuel based thermochemical hydrogen generation if it is to meet the projected Australian export opportunity. Currently, there are no large-scale CCS facilities operating successfully in Australia. The CCS storage capacity required by 2040 to support the generation of dirty hydrogen is estimated to be similar in capacity to the total capacity of *all* CCS facilities currently operating worldwide.

Initial research from University of Queensland[26] has indicated that the public has a negative attitude towards producing hydrogen from fossil fuels with CCS, when compared to producing hydrogen using renewables. There may be large-scale public opposition to hydrogen production methods that rely on fossil fuels and unproven CCS technologies.

• Domestic hydrogen price driven by exports (LNG lessons)

Associate Professor Llewelyn Hughes

If a major hydrogen export industry develops, Australia's domestic hydrogen price will be exposed to international price fluctuations. The history of linking of domestic gas with regional gas markets shows this could have an important impact on Australian consumers as the importance of hydrogen in the domestic energy mix increases.

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[23] N. Muradov, "Low to near-zero CO2 production of hydrogen from fossil fuels: Status and perspectives," *Int. J. Hydrogen Energy*, vol. 42, no. 20, pp. 14058–14088, May 2017.

[24] ACIL Allen Consulting, "Opportunities for Australia from Hydrogen Exports," no. August, p. 47, Table 4.9, 2018.

[25] http://re100.eng.anu.edu.au/publications/assets/100renewables.pdf

[26] D. V. Lambert and P. P. Ashworth, "The Australian public ' s perception of hydrogen for energy," 2018.

- ## Hydrogen generation/hub locations – benefit sharing with local communities (LNG lessons)

  Associate Professor Paul Burke

  Key hydrogen generation and export facilities would ideally be located in areas that are closest to Asian markets and that have a comparative advantage in zero-carbon energy. The development of the hydrogen industry is thus closely linked to the Northern Australia development agenda. Frameworks are needed for participation and benefit-sharing between investors and communities – particularly indigenous communities in Northern Australia.

- ## Retrofitting costs for domestic appliances is a burden on poor households

  Dr Igor Skryabin

  Australia has perhaps the world's strongest standards on gas appliances and their safety. Replacement of natural gas with pure hydrogen would require modification or replacement of domestic gas appliances. Overseas trials demonstrate that in most cases the domestic appliances can be modified.

  While initially only a small fraction of hydrogen (<15%) will be injected into existing gas networks, the switch from natural gas to pure hydrogen may not happen for at least a decade, during which there is time to prepare. At the switchover, existing assets will have to be replaced immediately. As with other massive technological changes (i.e. conversion from burning town gas to natural gas, replacement of resistive hot water heaters with heat pumps, replacement of analogue TV with digital), the expected decarbonisation of the Australian gas network is likely to create an additional burden on low-income households.

  Australian governments have developed and implemented in the past various forms of support for technological transition of low-income households. The support could be undertaken through the welfare system or, in the case of income-contingent loans, the tax system.

- ## Higher NO_x output at higher hydrogen combustion temperatures

  Dr John Pye

  Hydrogen, if used as an energy carrier in large amounts, would be likely to be used in a range of downstream energy transformations including in fuel cells for electricity production, in burners for production of heat, in engines as a fuel for stationary or transport energy, or as a feedstock for chemical processes.

  In the case of combustion of hydrogen, there is a risk of significant emissions of several different gaseous oxides of nitrogen, together referred to as 'NO_x'. These gases are significant atmospheric pollutants, causing smog, acid rain, and enhanced greenhouse effect. NO_x can be produced as a result of the combustion of fuels, including hydrogen, at high temperatures. At these high temperatures, the nitrogen in air (air is approximately 79% nitrogen by volume) starts to react with the oxygen, and forms NO_x compounds. Flame temperatures for hydrogen are higher than those for natural gas and many other fuels, and so there is an increased risk of so-called 'thermal NO_x' production.

Strategies for reducing NO_x production are available. These include catalytic combustion at lower temperatures, pre-mixing and delayed mixing of the fuel with the air, and recirculation of flue gases.[27]

If hydrogen is to be adopted as a replacement fuel for domestic, transport or industrial applications, it will be important to ensure that NO_x production can be limited, so that it does not cause additional environmental issues.

- ## Hydrogen catalyst life-cycle disposal issues

Dr John Pye

Equipment involved in energy transformations with hydrogen will likely utilise catalysts that improve reaction kinetics, lower the production of NO_x, or enhance product selectivity. In some cases, these catalysts may be rare materials which must be recovered at the end of the equipment lifetime. In other cases, the catalysts may be toxic materials which should not be allowed to pass out into the environment.

For example, a low-NO_x hydrogen burner has been proposed which uses silicon carbide with a platinum coating. Platinum is non-toxic but valuable. A water electrolysis cell has been proposed for hydrogen production which involves the metal vanadium. Vanadium is considered toxic in some forms, although it is safely used in small percentages in some grades of steel.[28]

It is not clear whether material toxicity/disposal requirements will be a barrier that limits the uptake of hydrogen technology, but this should be a consideration.

[27] https://www.greencarcongress.com/2018/11/20181109-toyotahydrogen.html, https://www.sciencedirect.com/science/article/pii/S0306261918300436
[28] https://doi.org/10.1016/j.apenergy.2018.01.042
https://www-sciencedirect-com.virtual.anu.edu.au/science/article/pii/0360319981900252
https://phys.org/news/2019-01-powerful-catalyst-electrolysis-harness-renewable.html

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

- ## Develop clean hydrogen market frameworks, regulatory systems and validation processes

Dr James Prest

As other markets (California, Germany, Japan) already have a considerable head start on Australia, it is difficult to say that Australia will pioneer market and regulatory frameworks for hydrogen. It may be more appropriate for Australian legislators to carefully study the experiences of other nations in order to develop appropriate regulatory and policy instruments for hydrogen in the Australian context.

A legislative definition of green hydrogen
Our analysis suggests that there is a need to legislate for a definition of 'green hydrogen'. This is necessary to create an incentive for the use of renewable energy in the production of hydrogen, rather than its production from steam methane reformation of natural gas, which is usually considered (at present) to be more cost-effective than renewably produced hydrogen. European approaches to this question emphasise the need for precision in terms of requiring the producer to give guarantees of origin, for example, to prove that a specified quantity of hydrogen was produced from a renewable energy source, whether this is required for disclosure to consumers, and whether a specified quantity of hydrogen was associated with specific levels of GHG emissions (e.g. in kg of CO_2-equivalent per MWh of hydrogen).[29] Since 2006, Californian legislation has required 33% of hydrogen to come from renewable sources.[30]

In 2017, a South Australian hydrogen study suggested the following definition of green hydrogen: "hydrogen that has been produced using energy from renewable sources or is net carbon zero energy through carbon capture and/or emissions offsets."[31] This definition, due to the reference to offsets, leaves the door open for production of hydrogen from steam reformation of natural gas and other fossil fuels. It is important that Parliaments and decision makers consider whether they wish to allow carbon offsets in the definition.

International hydrogen trade and certificate of origin schemes
A crucial aspect of regulatory and policy frameworks to promote renewable gas is certificates or guarantees of origin. This scheme involves creating a certificate for each unit of renewably-produced hydrogen and assures buyers that 'green hydrogen' is genuine, and the hydrogen has not been sold to someone else. Each certificate is given a unique identifier that traces back to the producer through the supply chain.

The market for hydrogen (and biomethane) will grow more rapidly in Australia if it becomes easier to match willing buyers of green hydrogen with its producers. This can be done either on a voluntary basis, or by combining the certificate of origin scheme with a quantity obligation that would be placed on the wholesale buyers of hydrogen. The latter is

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[29] Jansen, J. and Londo, M. (2015) *Briefing Paper on the Regulatory Context for Defining Green Hydrogen and its Certification*, paper for the EU under the CertifyHy grant funded project, European Commission.
[30] California Senate Bill No. 1505, adding Section 43869 to the Health and Safety Code of California.
http://www.leginfo.ca.gov/pub/05-06/bill/sen/sb_1501-1550/sb_1505_bill_20060930_chaptered.pdf
[31] Advisian and ACIL Consulting (2017) *South Australian Green Hydrogen Study A report for the Government of South Australia*, August, 130pp.

equivalent to a renewable portfolio standard used in the electricity market, for example the tradeable green electricity scheme that underlines Australia's federal Renewable Electricity Target (RET), and detailed in the *Renewable Energy (Electricity) Act 2000* (Cth).

It is conceivable that certificate of origin schemes and related incentive mechanisms could be designed to operate on an international basis, for example by agreement between Australia, Japan and South Korea. In such an international market, certificates of origin for green hydrogen could be traded amongst entities in each of the participating countries.

- ## Australia is a pathfinder for zero-carbon hydrogen export (particularly with rapid renewable energy deployment)

Professor Ken Baldwin

Australia is experiencing some of the highest renewable capacity growth in the world (>6 GW p.a.[32]) and already has a high renewable penetration (>20% rooftop household solar penetration, around 20% of NEM electricity). If current installation rates continue, Australia could reach 50% renewables by the mid 2020s. Australia has one of the longest (5,000 km), thinnest, least interconnected electricity networks in the world – and it is an island not connected to any other electricity supplier. If Australia can make the transition to >50% renewables well before 2030 and provide stable, reliable electricity, it will be an exemplar to the world of how to transform a previously fossil-fuel dominated electricity sector to renewables while keeping the lights on. If hydrogen production utilising Australia's enormous renewable resources can yield a profitable hydrogen export economy, then this will show the way to other nations perhaps less well-resourced in renewables, how to develop a hydrogen economy once hydrogen production becomes profitable for them. In this sense Australia has a competitive first-mover advantage.

- ## Implement trade agreements e.g. export forward contracts, to guarantee supply to Asian markets

Associate Professor Llewelyn Hughes

Justifying large up-front investments in hydrogen infrastructure requires a level of certainty that there will be sufficient demand. Certainty can be provided, in part, by using government to support the development of commercial arrangements that provide certainty to suppliers and purchasers.

- ## Develop an export infrastructure strategy building on existing LNG experience

Associate Professor Paul Burke

Australia has the chance to build off the experience of the LNG industry in the development of an export infrastructure strategy for hydrogen. Ideally, the hydrogen industry would itself make key required infrastructure investments. Any public investments would ideally be recovered from revenue raising instruments applied to the industry.

Public investments related to the hydrogen industry should be planned in a way that allows flexibility in how the investment can be utilised in the future. For example, public infrastructure investments could be located where they are of benefit to other industries (such as minerals). Flexibility is particularly important given demand-side uncertainties in the hydrogen market.

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[32] [32] http://re100.eng.anu.edu.au/publications/assets/100renewables.pdf

5. What are the top two or three factors required for a successful hydrogen export industry?

- **Drive down renewable energy costs and facilitate 100% renewable energy**
  Dr Fiona J Beck, Ms Tory Bridges, Dr Robin Purchase, Dr Mahesh Venkataraman

  The expansion of the electricity market and a move towards 100% renewable energy generation is necessary to support a successful zero-carbon hydrogen export industry. This would necessarily require significant infrastructure development, in addition to renewable energy installations, to accommodate the growth of the electricity network, including grid upgrades and storage (e.g. pumped hydro, batteries, and demand management) to balance the grid.

  However, hydrogen generation from electrolysis could play a significant role in grid stabilisation, providing grid firming services and a way to store electricity on many different time scales [6, p. 35][7, p. 41]. Electrolysers can act as variable loads, soaking up excess electricity when large amounts of renewable energy is being produced, and scaling back hydrogen production when demand exceeds supply (although see dot point 3, Q8).

  Stored hydrogen could also be used to compensate for seasonal changes in renewable energy production. More work is needed to prove that hydrogen generation could be a cost-effective method of grid balancing.

- **Consistent and predictable policy settings are essential across the renewable energy / hydrogen value chain**
  Professor Frank Jotzo and Associate Professor Paul Burke

  A renewables-hydrogen production system for export will require large investments, the payback on which will in part depend on policy settings. Reliable and predictable policy is essential to unlock large-scale private investment; by contrast, policy uncertainty will stymie investment. It will be particularly important to develop sound and stable rules for royalties and taxation of a hydrogen export industry. Policy applying to the hydrogen production and export industries should furthermore be consistent with policy applying in other parts of Australia's energy sector.

  The need for policy consistency includes the treatment of any greenhouse gas emissions that may arise from hydrogen production if this were to involve fossil fuels. Fundamentally, building a hydrogen production industry in Australia is compatible with national and international climate change goals only if it is 'green hydrogen', produced using renewable energy.

  Sound arrangements for taxation/royalties and investment for the public benefit

  A successful hydrogen export industry could be highly profitable. Profits beyond those required for an adequate rate of return on private capital investments should accrue to Australian governments, and thus the Australian community. Clarifying royalty/taxation arrangements at the outset is important to facilitate investment and to achieve a positive outcome for the community overall. Options should be systematically investigated, including the case for a resource rent tax (progressively higher taxation at higher levels of profitability), with possible re-investment in a sovereign wealth fund.

- ## Evaluate alternative techno-economic pathway value propositions – especially location of generation and access points, and storage and transport technologies

  Professor Ken Baldwin

  Given the number of alternative hydrogen generation, storage and transport technologies, a comprehensive range of different techno-economic pathways need to be evaluated to provide a comparative evaluation of future hydrogen economy scenarios. This also includes geographic issues, such as port locations relative to generation sites and hydrogen markets.

  In addition, hydrogen will also compete not only with other energy transport vectors, but with entirely different systems (such as undersea, HVDC cable export of electricity). So the viability of future scenarios should also be evaluated against other very different techno-economic alternatives.

- ## Understand the evolution of overseas policies e.g. carbon pricing, to avoid carbon-risk for hydrogen export

  Professor Frank Jotzo

  International demand for Australian produced hydrogen is likely to depend on technical, economic and policy factors in energy importing countries.

  Among policy factors, the most important aspect is the treatment of carbon emissions in importing countries e.g. carbon pricing, and the treatment of embodied carbon in imported energy. Carbon policies in importing countries will mean higher demand for traded hydrogen; any measures importing countries take on embodied carbon will mean a disadvantage to hydrogen produced from fossil fuels, including possible import penalties, restrictions or bans on hydrogen that incurred carbon dioxide emissions in production.

  To estimate possible demand scenarios and possible ranges for hydrogen prices, it is important to understand and quantitatively estimate the potential effects of such policies.

- ## Continue to provide research support e.g. through ARENA, to keep at the cutting edge of hydrogen research

  Professor Ken Baldwin

  Australia already has a strong research profile in the hydrogen economy, so continued investment in research across the hydrogen value chain is essential to capture the full opportunities provided by such research leadership.

- ## Cost and safety for hydrogen generation, storage and conversion

  Professor Yun Liu

  Lowering the cost of hydrogen is essential to replace current energy sources. The strategy for this to identify various hydrogen sources both locally and at large scale, develop safe storage techniques, and to minimise the energy dissipation during the hydrogen-electricity conversion. There is a further need to thoroughly solve the safety issue is by developing safety techniques, and better monitoring/alarm systems.

6. What are the top two or three opportunities for the use of clean hydrogen in Australia?

- ### New clean hydrogen applications such as steel production and reduction of mineral ores

  Dr John Pye

  - See Q1.

- ### Hydrogen fuel cell electric vehicles for long-range travel and heavy transport

  Dr Matthew Stocks

  Future low emissions transport will lean heavily on low emissions electricity. Direct electrification through battery storage is looking the most likely route for light vehicles. The solutions for long range, heavy transport, where Australia has a disproportional dependence relative to other countries, are still open. Hydrogen may play a significant role here due to its high energy-to-weight and the ability to replenish a tank rapidly, but needs to overcome efficiency, storage, transport and fuel cell cost challenges to be the solution of choice in comparison to direct electrification through batteries or catenary lines.

- ### Synthetic fuels and other carbon-intensive products e.g. ammonia, fertilisers

  Dr John Pye

  World production of ammonia is approximately 200 Mt/a. China is the largest producer, where ~70% production of ammonia is from coal, with high emissions. Ammonia production globally is a very significant contributor to CO_2 emissions; ammonia is the second-largest GHG-emitting chemical industry after the olefins industry. Ammonia is primarily used as a feedstock for fertiliser production, but also contributes to other important industrial chemicals including explosives and polymers.

  Converting renewably-produced hydrogen to ammonia gives Australia a great opportunity to access this large chemicals market, and to simultaneously make a large contribution to decarbonising the global chemical industry. Ammonia is far easier to transport than pure hydrogen, and already has a large market. In 2017, the IEA noted that ammonia production via electrolysis may already be competitive with fossil-based production in some areas[33]. Yara (in the Pilbara) is developing a pilot plant for this process, and many others are watching with interest.[34] This will be the first large-scale demonstration of electrolytic production of ammonia in the world, and is considered to a key topic for global innovation by the IEA[35].

  Ammonia may have far greater potential than just the 200 Mt/a for the chemical industry, by using it as an energy vector. In this case, the ammonia could be fed into fuel cells to produce electricity; it could be burnt as a fuel in power stations or in transport; or it could be converted back to hydrogen to open up a broader range of other downstream processes.

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[33] IEA, 2017. https://is.gd/BBbZwi

[34] https://www.yara.com.au/siteassets/about-yara/pilbara-documents-other/renewable-ammonia-factsheet.pdf

[35] IEA, 2019. https://www.iea.org/tcep/industry/chemicals/

CSIRO has been working on a palladium membrane process to extract hydrogen from ammonia. This could be a key part of a process for delivery of hydrogen to Japan and Korea, if ammonia itself is not immediately suitable for their energy needs.[36]

If ammonia were to be burnt directly as a fuel for heating, then 'fuel NO_x' would also be a concern; suitable low-NO_x burner technologies would need to be developed and used. It is not clear to what extent ammonia may be a feasible large-scale fuel to replace fossil fuels. It is also relatively toxic and requires careful handling.

[36] https://publications.csiro.au/rpr/pub?pid=csiro:EP179514, https://www.csiro.au/en/Research/EF/Areas/Low-emissions-technologies/Hydrogen-membrane

7. What are the main barriers to the use of hydrogen in Australia?

• Cost, and the absence of carbon pricing

Professor Frank Jotzo

Hydrogen for the Australian domestic market may face a cost disadvantage relative to other sources of energy, including oil and gas for transport, and direct use of renewable electricity, given the cost and energy loss involved in the hydrogen chain.

As discussed above, price is currently a barrier. A key component of the price barrier is the capital cost of electrolysis plants. These are currently at an early stage of commercial development and there is substantial opportunity for costs to reduce due to economies of scale, as well as increase in efficiencies. Since the barrier is capital cost, this means that any electrolysis systems should be run at high capacities, which in many cases may mean connection to the electricity grid. The limitation of capital cost also means that some applications are likely to become economic much later than others e.g. seasonal storage – where the electrolyser is run for only a fraction of the year – is likely to be economic relatively late compared to other applications.

A clear pricing signal on carbon emissions domestically would help encourage the growth of a domestic green hydrogen industry. Current thinking is focussed on an export model; the lack of local infrastructure means there is little in the way of a local market.

• Incumbent natural gas advantage

Associate Professor Paul Burke

The hydrogen industry faces substantial competition from incumbent energy industries, especially natural gas. Existing infrastructure and supply chain advantages, together with continued technological progress in fossil fuel extraction, will mean that hydrogen will not face a simple path to a high market share. Fossil fuel prices may fall if fossil fuels face market competition, undermining the competitiveness of zero-carbon hydrogen projects.

• Development of distribution infrastructure

Associate Professor Llewelyn Hughes

In addition to regulatory and legal systems, and storage facilities, adequate domestic infrastructure will be required to enable hydrogen produced using Australia's renewable energy resources to be distributed to the point of final consumption across the transport, industry, household, and power sectors.

• Development of storage and transport technologies

Professor Yun Liu

One of the main barriers to the use of hydrogen in Australia is to develop safe, scalable and low cost (including infrastructure) storage and transport.

- ## Potential community acceptance questions

  Dr Fiona J Beck, Ms Tory Bridges, Dr Robin Purchase, Dr Mahesh Venkataraman

  For the hydrogen industry to develop in Australia, whether for domestic consumption and/or export, the support of the Australian public must be secured. Social license to operate must be obtained and subsequently maintained by the hydrogen industry. Absence of public support, especially when expressed in protests and conflicts, may lead to politically based constraints on projects and potential regulatory restrictions, which can cause project failures, economic losses and reputational damage to the industry. This was recently experienced by the coal seam gas industry in the Northern Rivers region of New South Wales, where social license withdrawal occurred (spurred by local perceptions of sustainability, rural economies and questions about the local benefit provision). This recent example demonstrates that the importance of obtaining and maintaining social license to operate should not be underestimated. To give the Australian hydrogen industry the highest chance of success, appropriate time and resources need to be invested into education and genuine participatory processes.

- ## Development of regulatory and safety systems

  Dr James Prest

  There are a number of regulatory issues that need to be considered in order to grow a renewable hydrogen industry in Australia generally. Identifying and evaluating the nature of these issues depends on the sector of the hydrogen industry in question and the application of the technology that is proposed, including the scale of application and the precise location of application. Resolution of these issues is a necessary but not sufficient condition for industry development, as the business case for investment depends on many technical and economic considerations, including the extent and terms of any proposed public-private partnerships. The primary aim of legislative reform in this area should be to attempt to de-risk investment.

  There is an urgent need for the passage of framework legislation for hydrogen at both at state/territory and federal levels. This legislation would need to set out broad principles to reduce uncertainty for investors in the hydrogen energy field throughout Australia. It is well established and self-evident that regulatory uncertainty can undermine the business case for investment in energy technologies.[37]

[37] Barradale, Merrill Jones. "Impact of Public Policy Uncertainty on Renewable Energy Investment: Wind Power and the Production Tax Credit." Energy Policy 38, no. 12 (December 2010): 7698–7709. https://doi.org/10.1016/j.enpol.2010.08.021.

8. What are some examples where a strategic national approach could lower costs and shorten timelines for developing a clean hydrogen industry?

- **Drive down renewable energy costs and facilitate 100% renewable energy**
  Dr Fiona J Beck, Ms Tory Bridges, Dr Robin Purchase, Dr Mahesh Venkataraman

  - see Q5.

- **Market development and research is essential across the renewable energy / hydrogen value chain**
  Professor Frank Jotzo

  Coordination of the national research effort, such as for example through a CRC for Clean Hydrogen, would provide strategic direction to the national research effort. Continued support for ARENA will allow strategic investment in renewable power research and development.

  Support should cover the entire innovation spectrum, from basic R&D to market development approaches. For example, in R&D it is essential to maintain Australian leadership in hydrogen through near-term research in advanced catalysts as well as longer-term research in areas such as photo-electrochemical conversion and microbial conversion.

  An important component of developing a new industry that involves large up-front investments is to develop market perspectives, in this case helping ensure that there will be demand in importing countries. There are possible lessons to be drawn from the development of Australia's LNG export industry, where the viability of supply infrastructure (liquefaction trains and export terminals) depended on the establishment of import infrastructure. For hydrogen, large-scale production for export would need confidence that large scale hydrogen usage infrastructure will be developed in potential importing countries, and that this hydrogen demand will not be served by domestic production.

  Driving establishment of a domestic hydrogen using infrastructure, e.g. in long distance transport, may need demand-pull measures. Policies used to support the renewable energy industry may provide important lessons.

- **If electrolysers dominate, encourage dedicated renewable energy + storage PPAs for 24/7 hydrogen electrolyser generation, with merchant electricity going to renewable energy surplus (to minimise pressure on domestic electricity prices)**
  Professor Ken Baldwin

  The additional demand on the grid created by the development of an electrolysis-based hydrogen industry could create upward pressure on domestic electricity prices – similarly to any new electrification load growth e.g. for transport and electric vehicles. Electrolysers generally need to be operated continuously to be efficient, and hence need guaranteed

24/7 supply to enhance profitability. It is therefore unrealistic to expect that hydrogen generation will be based on "surplus renewable energy" – instead it will need constant supply. If this is achieved by new PPAs with renewable energy generators firmed using storage then there will be no extra demand placed on the grid, and any excess renewable generation could then be used for merchant participation in the market which could potentially put downward pressure on electricity prices.

- Encourage research into potentially disruptive hydrogen technologies

  Professor Ken Baldwin

  In many parts of the hydrogen value chain, there are as yet no clear technological winners. Further, it is possible that current leading technologies such as electrolysis may be challenged in the future by upcoming new technologies, such as direct generation from solar photovoltaics. For this reason, support for research into promising alternatives is important to establish the outcome of competitive research outcomes and learning rates.

- Evaluate alternative techno-economic pathway value propositions – especially location of generation and access points, and storage and transport technologies

  Professor Ken Baldwin

  - See Q5

- Develop clean hydrogen market frameworks, regulatory systems and validation processes

  Dr James Prest

  - See Q4.

- Extract hydrogen from waste products, biomass, by-products of chemical industry, and the environment

  Professor Yun Liu

  Hydrogen can also be extracted as a by-product from different sources, such as waste water/soil, biogas from plants, natural ammonia-rich environments, and hydrogen-by-products of the chemical industry.

9. What are Australia's key technology, regulatory and business strengths and weaknesses in the development of a clean hydrogen industry?

- Strengths:

    - ### Low renewable energy costs - an Australian comparative advantage

      Dr Fiona J Beck, Ms Tory Bridges, Dr Robin Purchase, Dr Mahesh Venkataraman

      Australia has vast renewable energy resources, including some of the best solar and wind assets in the world. Because of this Australia has the opportunity to rapidly develop a 100% renewable electricity market, and drive down renewable energy costs. There is a clear opportunity for Australia to take the lead in developing a hydrogen export industry based on renewable energy, which would demonstrate the feasibility of a truly zero-carbon approach to the world.

    - ### Highest per capita renewable energy deployment capacity currently being demonstrated

      Professor Ken Baldwin

      Australia is currently demonstrating the world's highest per capita renewable installation rate at 250 W per person p.a. – several times higher than our closest competitors. This will enable us to grow renewable energy for dedicated hydrogen production using electrolysers very rapidly, feeding into the pathfinder dot point, and enabling the neutral (or even reduced) pressure on electricity prices noted above.

    - ### Proximity to Asian hydrogen markets (Japan, Korea)

      Associate Professor Llewelyn Hughes

      A key strength of Australia in developing a clean hydrogen industry is our proximity to important markets in the Asia-Pacific region, beginning with South Korea and Japan. Japan, in particular, has been a long-standing importer of Australian energy resources, providing a key competitive advantage in the form of existing commercial and inter-governmental links.

    - ### Existing LNG experience, infrastructure and shipping supply lines

      Associate Professor Paul Burke

      Australia has the advantage of being a major LNG exporter, well linked to international shipping routes. Similarities between LNG and hydrogen exports – for example in terms of export infrastructure requirements – provides Australia with a competitive advantage over some other potential suppliers of zero-carbon hydrogen.

- ## Weaknesses:

  - ### Small domestic market

    Professor Ken Baldwin

    There is already a growing international economic market roadmap for export of Australian green hydrogen, whereas there is currently no planned domestic market. The small domestic market will be delayed by infrastructure conversion in any event (even if it does operate at a low <15% level in existing gas mains) until the switch to 100% hydrogen happens further down the track. This, in addition to the small scale of the Australian economy compared to our major trading partners, means that exports will continue to dominate the domestic hydrogen market as the key driver.

    However, while the transition will be driven by huge export opportunities, the domestic market could advantageously be developed in parallel with the export market to contribute to decarbonising Australian economy (piggy-backing on the economies of scale of hydrogen generation and distribution). The addition of a domestic market to the international market portfolio would also help spread some of the geopolitical risk associated with hydrogen export markets.

  - ### Lack of a clear regulatory framework for hydrogen gas

    Dr James Prest

    One of Australia's key weaknesses is a lack of a clear regulatory framework for hydrogen gas.

    One example issue is that hydrogen gas is presently outside the scope of the National Gas Law (NGL). Therefore, an amendment to the NGL to include reference to hydrogen may be appropriate and should be considered. By contrast, in Germany, national level legislation recognises hydrogen. According to Kreeft (2018) "Hydrogen and SNG produced through power-to-gas, if they are injected into a public gas network, are both covered under the definition of "gas" under Article 3(19a) of the EnWG, Energy Industry Act of 1935 *(Energiewirtschaftgesetz) , where* "Gas" includes Natural gas, biogas, liquefied gas as well as, if they are injected into a gas supply network, hydrogen, which has been produced by water electrolysis, and synthetically produced methane, which is produced from hydrogen produced by water electrolysis and the subsequent methanation thereof. In fact, the expansion of the definition of gas in German legislation represents an implementation of European law, particularly Article 1(2) of the EU 2009 Gas Directive "which determines that the European common rules on the internal market in natural gas also apply to "other types of gas in so far as such gases can technically and safely be injected into, and transported through, the natural gas system".[38]

    There are further legal uncertainties

[38] Kreeft, G.J. (2018*), 'Legislative and Regulatory Framework for Power-to- Gas in Germany, Italy and Switzerland*', STOrenewable energy&GO Project, Deliverable 7.3

- In the case of electricity: does the Federal renewable electricity support law apply to the production of hydrogen?
- In the case of hydrogen to gas: is it possible for hydrogen producers to apply to gain access to Natural Gas pipelines under the National Gas law? How can technical and safety limits on the injection of hydrogen into pipelines be complied with to prevent dangerous levels of pipeline injection?
- In the case of hydrogen to heat & electricity via residential fuel cells: can green hydrogen's contribution to reducing the GHG emissions of heating be incentivised under a Renewable Heat Incentive?
- In the case of hydrogen to synthetic methane (SNG) into Natural Gas Networks: how can gas pipeline access questions be resolved, given that under the *National Gas Law* and Rules, synthetic natural gas is outside the National Gas Law? To clarify, the National Gas Law only applies to *natural gas* and *processed gas* from natural sources.
- Specialised measures to incentivise hydrogen alone will raise public policy questions about incentivising competitor technologies such as battery storage and biogas. An alternative to enacting a specialised hydrogen-centric measure is to enact a generalised energy storage incentive in each Australian jurisdiction.

For hydrogen as an energy storage technology, it is evident that hydrogen-related regulatory issues will overlap with those facing other energy storage technologies. For example, if there were a generalised 'renewable energy storage incentive law' enacted, as in California, there would be an incentive for investment in the deployment of hydrogen as a storage technology. Hydrogen would compete on a level playing field with other storage technologies such as lithium batteries and flow batteries, or compressed air storage. It is possible for incentive laws to be designed with a multiplier or a 'carve out' for those technologies which are presently further from market competitiveness.

10. What workforce skills will need to be developed to support a growing clean hydrogen industry?

- ### Engineers

  Professor Kylie Catchpole

  The hydrogen industry has the potential to evolve quickly once demonstrated, and will require a skilled and specialised workforce.

  Australia should cultivate engineering expertise for the manufacture, installation and maintenance of hydrogen facilities.

  Australia's natural gas infrastructure could be re-purposed towards a hydrogen infrastructure, which will require retraining people with expertise in existing natural gas infrastructure.

- ### Hydrogen-safety trained workers

  Professor Yun Liu

  Professional training is needed on hydrogen safety, which can be linked to government measures to standardise hydrogen management, safety, regulation and monitoring.

- ### Expertise covering the whole hydrogen production chain from generation, storage, conversion to applications (coupled to research strategy)

  Professor Yun Liu

  The development of expertise in R&D across the hydrogen supply chain will foster the development of professional workers, engineers and academic staff in hydrogen generation, storage, conversion and applications.

11. What areas in hydrogen research, development and deployment need attention in Australia? Where are the gaps in our knowledge?

- Encourage research into potentially disruptive hydrogen technologies
  Professor Ken Baldwin

  - See Q8.

- Evaluate alternative techno-economic pathway value propositions – especially location of generation and access points, and storage and transport technologies
  Professor Ken Baldwin

  - See Q5.

- Develop clean hydrogen market frameworks, regulatory systems and validation processes
  Dr James Prest

  - See Q4.

- Establish several R&D centres in key technologies in the hydrogen industry export value chain
  Professor Kylie Catchpole

  R&D is currently reasonably well supported in Australia, but there are benefits in coordinating the research effort through mechanisms such as a Cooperative Research Centre, an ARC Centre of Excellence or other research clustering.

  For example, a Clean Hydrogen CRC would provide strategic direction to hydrogen research and could be focussed on developing deployable, market-ready hydrogen products such as vehicle fuel cells and catalysis plants, or new overseas transport and storage systems.

  If it had a hydrogen export focus, it would complement the Future Fuels CRC which is focused on domestic hydrogen distribution.

- Hydrogen storage and transport
  Professor Yun Liu

  The infrastructure requirements for handling and storage of hydrogen need to be explored, and the readiness for deployment in vehicles needs to be assessed. Infrastructure will almost certainly require government support.

- ## Direct ammonia production

  Dr John Pye

  Direct electrolytic production of ammonia from air and water is considered to be one of the 'holy grails' of electrolysis research, since it would supplant one of the largest present-day chemical industries, namely ammonia production by the Haber-Bosch process using hydrogen produced from steam methane reforming or coal gasification. If ammonia is really the desired end product, rather than hydrogen, then it can be noted that production of ammonia from hydrogen is fairly exothermic (indeed, previous ANU research by Keith Lovegrove made use of this reaction as a form of reversible thermochemical energy storage): hence, producing ammonia directly without going via hydrogen may present the opportunity for energy savings. As noted earlier, ammonia is also more immediately transportable than hydrogen.

  If successful, there would be large reduction in emissions compared to the current fossil-based process. It is not clear whether this direct electrolytic ammonia process will ultimately be feasible, however it is the topic of current active research, and some initial favourable results have been reported.[39]

  It should be noted that ammonia-fed fuel cells are also considered as the reverse process, and have been somewhat more successful.[40]

- ## Marketing strategies for public acceptance of safety and useful applications

  Dr Fiona J Beck, Ms Tory Bridges, Dr Robin Purchase, Dr Mahesh Venkataraman

  - See Q2.

[39] https://www.nature.com/articles/srep01145, https://www.nwo.nl/en/research-and-results/research-projects/i/58/28558.html

[40] https://www.ohio.edu/engineering/ceer/ammonia-electrolysis.cfm, https://nh3fuelassociation.org/wp-content/uploads/2017/11/NH3-Energy-2017-John-Hansen.pdf