HYDROGEN FOR RENEWABLE ENERGY EXPORT: BROADENING THE CONCEPT OF HYDROGEN SAFETY

Roberts, D[1]., Munnings, C[2]., Giddey, S[2]., and Hayward, J[3].
[1]CSIRO Energy, Brisbane, QLD, AUSTRALIA
[2]CSIRO Energy, Melbourne, VIC, AUSTRALIA
[3]CSIRO Energy, Newcastle, NSW, AUSTRALIA

ABSTRACT

Recently we have seen hydrogen (re)emerge as an important component of widespread decarbonisation of energy sectors. From an Australian perspective, this brings with it an opportunity to store, transport, and export renewable energy—either as liquefied hydrogen or in a carrier such as ammonia. The growth of the hydrogen industry to now include the power and transport sectors, as well as the notion of hydrogen export, has broadened the range of safety considerations required and seen them extend into the realm of the consumer for the first time.

Hydrogen, as well as ammonia and other carriers such as methanol, are existing industrial chemicals which have established protocols for their handling and use in the chemicals sector. As their use in energy and transport increases, especially in the context of widespread domestic use, their handling and use by inexperienced people in less-controlled environments expands, shifting the risk profiles and management systems required. There is also the potential for novel hydrogen carriers, such as methylcyclohexane/toluene, to reach commercial viability at industrial scale.

This paper will discuss some of these emerging applications of hydrogen and its carriers, and discuss some of the technological innovations under development that may accompany a new energy industry—with some consideration given to their potential risks and the required safety considerations. In addition, we will also provide an overview of global activity in this area and how new standards and regulations would need to be developed for the adaption of these technologies in an Australian context.

1.0 AUSTRALIA'S RENEWABLE HYDROGEN POTENTIAL

The most common pathway for renewable hydrogen production is electrolysis from renewable electricity. Australia has some of the world's best onshore wind resources, and in 2014-2015, 11 TWh of electricity from wind energy was produced annually in Australia [1]. The majority of this wind energy contributes to meeting electricity demand in Australia's National Energy Market (NEM). The majority of offshore wind resources are along the southern coastline.

On average, Australia is home to the world's greatest solar irradiation, at 9.7 kWh/m2/day. All of Australia's current electricity demand could be met through a solar array 50 km x 50 km [1] (2,500 ha). Therefore, given the size of Australia, there is the potential to produce vast quantities of electricity from solar to power electrolysers to produce hydrogen.

Australia also has world class ocean renewable energy resources, including wave and tidal, particularly in the southern oceans and King Sound in North West Western Australia for tidal energy. Central Australia is home to 'hot rock' geothermal resources more than 4 km below the surface, however, the technology to extract this resource is at a low technology readiness level.

Other renewable pathways for hydrogen production include conversion of waste and biomass. Lignocellulosic biomass, which could be used to produce hydrogen via gasification, is estimated to have an availability of 100-115 Mt per year by 2030 [2]. The types of lignocellulosic biomass considered in this study include crop stubble, grasses and forest plantations. There are also technologies emerging for conversion of other waste streams to hydrogen via various biological pathways.

The total global demand for hydrogen is currently 55,000 kT. This is projected to increase by between 15,804–82,105 kT by 2040 [2]. In order for this demand to be met solely by Australian solar PV, 325–1,700 GW of capacity and 910,000–4,730,000 ha of land would be required. Note that the size of WA is 264.6 million ha, thus less than 2% of land in WA would be needed. This increase in hydrogen production would represent an increase of between 30-150% over the next 2 decades compared to

current hydrogen production and usage. Currently only 3-5% of hydrogen is product electrolytically so this would result in at least an order of magnitude increase in hydrogen production from electrolysis. Hydrogen is currently produced globally mainly in centralised facilities using natural gas as a feedstock. A shift to using electrolysis combined with renewables will have implications from a production safety perspective, most likely lowering the risk associated with production as there are no high temperature or pressure processes involved. The main risks are electrical, which are well known and relatively simple to mitigate.

2.0 AUSTRALIA'S CARBON-FREE HYDROGEN POTENTIAL

These significant renewable resources, combined with the large emerging demand for hydrogen energy applications, means that renewable hydrogen production from the resources discussed above is a topic of significant interest. It is expected, though, that while the costs of exploiting these resources continues to decrease, some of the early hydrogen production is likely to be from gas, and perhaps to a lesser extent, coal. These pathways offer cost-effective hydrogen production and opportunities for deployment of infrastructure supporting large-scale opportunities, which can pave the way for increased penetration of renewable hydrogen as costs continue to fall. Safety aspects of these approaches are, generally, likely to be consistent with the industrial practices already established around the world in the fertiliser and chemicals industries.

Australia is, of course, endowed with gas and coal resources, and these are already being used in some early industrial-scale hydrogen projects. As most export markets are already suggesting that carbon-free hydrogen is a requirement at any stage of the developing hydrogen industry, however, these pathways also rely on safe and effective carbon storage solutions.

Australia has some world-class CO_2 storage sites, some which have been operational at a demonstration scale for some time, and some which are under planning and development. There are some well-documented (and fairly well understood) safety aspects associated with long-term geological storage of CO_2, mainly around stability and leakage, and it is likely that these will become relevant for an emerging hydrogen energy industry.

We are already seeing natural gas infrastructure being used for demonstration projects for injection of hydrogen at small concentrations. If successful, these will almost certainly lead to higher concentrations of hydrogen, which for the first time since town gas was discontinued, will bring hydrogen into people's homes. This will require education, awareness, and training. In particular, there are concerns around increased flammability limits which could lead to lower volumes of gas leakage resulting in an explosive mixture or a flammable gas mixture with a significantly lower ignition energy. This may require a review and potential changes to current safety practices such as hazardous area classification that rely on restricting ignition sources. This approach is less appropriate for the use of hydrogen due to the low ignition energy compared with natural gas. If this approach is not updated then it is likely that there will be a significant increase in cost in relation to the implementation of this safety standard due to the high cost of intrinsically safe equipment for us with hydrogen.

3.0 PRODUCTION OF HYDROGEN AND POTENTIAL CARRIERS OF HYDROGEN FOR EXPORT

Hydrogen is used extensively around the world as an industrial feedstock, mostly produced by natural gas reforming, and mainly used for ammonia production and in refineries for producing lighter oil fraction. Only a small percentage of hydrogen is produced by electrolysis of water. However, with rising interest in the export of renewable energy and decarbonisation of the various industrial sectors, water electrolysis using renewable electricity is increasing in popularity, as is the use of hydrogen in energy and transport sectors.

The technologies under consideration are alkaline solution, polymer electrolyte membrane (PEM) and solid oxide electrolyte (SOE) based electrolysis. Alkaline solution based electrolysis is the most mature and SOE the least mature technology. PEM based electrolysis, though less mature than alkaline solution based electrolysis, offers several advantages such as excellent response to intermittent renewable energy sources and smaller footprint, and is close to commercialisation with systems now available at MW scale. These electrolysers typically can produce hydrogen up to 35 bar pressure with electricity consumption of 54-58 kWh per kg of hydrogen produced [3]. The PEM electrolysers can be operated with electricity from the grid when in excess or directly from renewables. Hydrogen produced from the renewables can either be stored for local consumption for stationary or automotive applications, or exported to other countries. Different electrolysis technologies bring with them different safety risks, and these need to be managed in an appropriate way.

The export of hydrogen will require it to be converted into a suitable exportable form. The major exportable forms of hydrogen or hydrogen carriers being considered are liquefied hydrogen, ammonia (NH_3) and methylcyclohexane (MCH – C_7H_{14}). A significant energy input is required for conversion of hydrogen into any of these forms. Hydrogen liquefaction requires compression and cooling (to -253$_o$C) and this process can consume 20-30% of the energy content of hydrogen in addition to the boil-off losses during transport [4,5]. Further, the infrastructure for the intercontinental transport of liquid hydrogen is almost non-existent. However one big advantage of liquid hydrogen export is that there are minimal further losses expected at the point of use for stationary or automotive applications. A project is currently underway to convert brown coal from Latrobe Valley of Victoria, Australia to liquid hydrogen and export to Japan [6].

Ammonia is mostly produced from natural gas using Haber-Bosch process, and consumes around 8-10 MWh of energy per tonne of ammonia [7]. However the conversion of hydrogen (once produced from renewables or fossil fuel) to ammonia requires less than 1/4$_{th}$ of this energy. Ammonia is considered an excellent hydrogen carrier due to its high hydrogen energy density (5.8 kWh/kg), existing infrastructure for storage and export, and emission-less processes for end-use [8]. However, compared to liquid hydrogen, ammonia requires reconversion back to hydrogen (ammonia cracking) that leads to further energy losses.

The hydrogenation of toluene to produce MCH offers hydrogen storage of 6.2 wt% and hydrogen energy density of 2.1 kWh/kg. MCH and toluene being liquid under ambient conditions provides an excellent route for the export of hydrogen in the form of MCH. MCH is then dehydrogenated at the point of hydrogen use, and returned back to the exporting country as toluene. This route seems to be quite attractive, but has two major drawbacks: both hydrogenation and dehydrogenation processes are carried out a high temperatures (200-300$_o$C) and dehydrogenation process consumes a significant amount of energy (~0.6 kWh/kg); and the additional costs associated with the shipping of toluene back to the country of origin [9]. This route is currently being demonstrated for exporting hydrogen from Brunei to Japan [10].

All these hydrogen carriers will require special safety regulations for their production, storage, export and reconversion back to hydrogen due to the concerns such as flammability, corrosive and toxic nature of ammonia and toxic nature of MCH.

4.0 NEW UTILISATION PATHWAYS FROM HYDROGEN AND CARRIER EXPORT

The export of hydrogen, in particular as carriers such as ammonia, introduces new utilisation pathways that will further broaden the notion of 'hydrogen safety' in the context of new hydrogen energy systems. Given that ammonia is seen as an attractive hydrogen carrier (especially in the Australian context) there have emerged some direct ammonia utilisation pathways for the production of electricity. These become attractive when the export market has sectors other than mobility targeted for decarbonisation. Large-scale ammonia turbines are at the late stages of development, and we are already seeing cost-effective technologies for ammonia fuel cells that offer smaller-scale, distributed applications for ammonia-to-power.

There is also the opportunity for direct use of ammonia in reciprocating engines. While an old concept, new science and technology development is supporting the use of ammonia in modern, slower-speed diesel engines. These have the potential to decarbonise shipping, and possibly rail, significantly distributing the movement and utilisation of ammonia across land and sea.

This broadening of the notion of 'hydrogen energy' from fuel cells for mobility to a range of distributed and larger, industrial scale applications extends wider than the energy and transport sectors. The prospect of decarbonised ammonia in the agriculture sector is creating considerable interest, as is the linking of the fertiliser and energy needs of agriculture sector via renewable hydrogen and ammonia. There are many examples of sector coupling such as this, which points to the potential hydrogen has to decarbonise industries where it has traditionally been difficult. However, this brings with it new users and industries that have not had relevant safety experience.

4.0 CONCLUSIONS: IMPLICATIONS FOR AN EMERGING HYDROGEN ENERGY INDUSTRY

As hydrogen generation and use moves from an industrial process to one involving large-scale storage and transportation in an energy context, particularly with a significant increase in the utilisation of hydrogen by consumers, we will see the risk profile associated with hydrogen change. This will be further complicated by the use of chemical carriers for hydrogen storage and distribution—especially in the context of renewable energy export. There is the possibility of increased movements of ammonia, methanol, compressed or liquefied hydrogen, and other carriers in urban areas, and the introduction of new bulk materials being shipped in harbours and the open ocean

There will also be a changing risk profile resulting from production and use of hydrogen in less controlled environments such as domestic properties and also within the automotive sector. Although the risks of hydrogen are will understood there has been little preparation or consideration been given to the use of hydrogen and hydrogen mixes in these environments. There may need to be significant changes made to building codes, installation practices and product safety standards to ensure hydrogen can be safely used within the home by untrained members of the general public. Some progress has already been made with a number of standards already in place, in particular within the automotive industry. These standard included SAE J2799 and J2601 which relate to the safe refuelling of car, heavy commercial vehicles and fork lift trucks.

REFERENCES.

[1] Geoscience Australia (2019) Australian Energy Resources Assessment (https://aera.ga.gov.au)

[2] Crawford D F, O'Connor M H, Jovanovic T, Herr A, Raison RJ, O'Connell DA & T Baynes (2016) A spatial assessment of potential biomass for bioenergy in Australia in 2010, and possible expansion by 2030 and 2050, GCB Bioenergy, 8, 707-722

[3] ACIL Allen Consulting for ARENA (2018) Opportunities for Australia from Hydrogen Exports

[4] Giddey S, Badwal SPS, Ju H (2019), Polymer electrolyte membrane technologies integrated with renewable energy for hydrogen production, In Current Trends and Future Developments on (Bio-) Membranes – Renewable Energy Integrated with Membrane Operations; Elsevier Inc., Pages 235-259.

[5] Badwal SPS, Giddey S, Munnings C (2018), Emerging technologies, markets and commercialisation of solid electrolytic hydrogen production, Wiley Interdisciplinary Reviews: Energy and Environment, 7, e286.

[6] Giddey S, Badwal SPS, Munnings C, Dolan M (2017), Ammonia as a renewable energy transport media, ACS Sustainable Chemistry & Engineering, 5, 10231-10239.

[7] Hydrogen for Australia's future, Commonwealth of Australia, 2018.

[8] https://hydrogenenergysupplychain.com/about-hesc/.