

CSIRO Submission 19/670

Updating the Authority's Previous Advice on Meeting the Paris Agreement

Climate Change Authority

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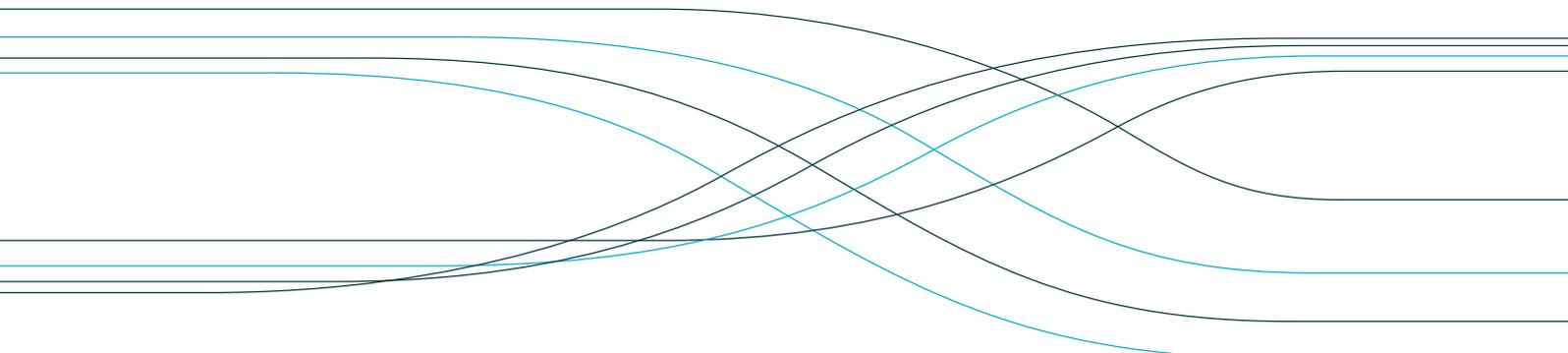


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Introduction

CSIRO welcomes the opportunity to contribute to the Climate Change Authority's consultation on updating the Authority's previous advice on meeting the Paris Agreement. As the national science agency CSIRO has limited its comments to scientific and technical matters that may inform policy advice by the Authority, in particular regarding the emerging role of hydrogen as low or zero emission energy source and battery research and technology.

CSIRO is developing technologies to support accelerated development of hydrogen production, storage, transport (including export) and utilisation for energy and transport applications. This work is aimed at facilitating a new export energy industry for Australia based on low emission and renewable hydrogen energy systems, which is also expected to support decarbonisation of domestic transport, power, and industry. In this regard, CSIRO is engaged with key industry groups in development of networks and standards to support technology and implementation strategies associated with infrastructure requirements for hydrogen based energy systems.

CSIRO has been active in battery research for decades. Our early work on lead-acid batteries and supercapacitors led to the development of the UltraBattery technology. Our current work looks at lithium battery technologies and new systems based on non lithium-ion batteries and ionic liquid electrolytes.

CSIRO has recently made public submissions on hydrogen and battery technology to Parliamentary inquiries on electric vehicles <https://www.aph.gov.au/DocumentStore.ashx?id=23f3578c-92a6-4f40-aa4b-008df3606fbf&subId=661202> and automated mass transport <https://www.aph.gov.au/DocumentStore.ashx?id=283f0677-cb8a-46b5-934d-9fef7a95afa9&subId=664553> and on hydrogen to the National Hydrogen Strategy Taskforce. This submission draws on those documents.

Hydrogen Energy Systems

Australia has access to vast energy resources of sun, wind, biomass, natural gas, and coal, all of which can be used (in some cases with water) to produce hydrogen and/or the desired chemical compound which can be used as a hydrogen carrier. Australia's significant resources mean it is well positioned to be an exporter of hydrogen and to make significant domestic use of hydrogen in transport and power generation, and to offset natural gas use in the gas network.

Deployment of hydrogen technology systems and infrastructure is gaining considerable momentum globally. As part of many global initiatives for emissions reduction from the energy sector, North Asia and Europe in particular are aggressively investigating adoption of hydrogen-based transportation and energy systems. If produced and transported at scale, hydrogen could be integrated into the future energy value chain to support low-emissions power generation, transport, food and agriculture, water, resources, heavy industry and more.

Australia's role and opportunities in emerging hydrogen energy industries have been considered in the context of scenarios for both domestic transport and stationary energy applications as well as from the perspective of Australia potentially becoming a major global exporter of renewable energy using various hydrogen carriers. The IEA has recently released a review and outlook for hydrogen energy systems at the global scale which indicates strong growth in the fuel cell electric vehicle market supported by rapid development in fuel cell availability for transport applications (http://ieahydrogen.org/pdfs/Global-Outlook-and-Trends-for-Hydrogen_Dec2017_WEB.aspx).

The Chief Scientist of Australia (Commonwealth of Australia, 2018) and CSIRO (Bruce *et al.*, 2018) have recently published detailed Roadmaps outlining possible future pathways for Australia in this emerging industry.

Renewable and decarbonised low emissions energy systems

Low or zero emissions hydrogen can be produced using currently-available technologies; however, as at 2014, 96% of global hydrogen supply was derived from fossil fuel feedstocks through syngas conversion processes based on natural gas or coal, produced on-site where needed in applications such as oil refining and chemicals production (<https://www.iea.org/publications/freepublications/publication/essentials5.pdf>, <https://www.iea.org/publications/freepublications/publication/TechnologyRoadmapHydrogenandFuelCells.pdf>).

To develop an impactful hydrogen export industry, supply chains must be developed to produce and distribute hydrogen from a range of processes including, but not limited to:

- water electrolysis driven by renewable electricity from solar PV, solar thermal, wind and hydro
- decarbonised fossil fuel sources (coal gasification or natural gas reforming with Carbon Capture and Storage)
- biomass and waste conversion
- thermal water decomposition processes using technologies such as catalytic solar thermal technologies.

Hydrogen-based energy systems also offer the potential to remove (or abate) pollutants such as sulfur oxides, particulate emissions and photochemical smog precursors as they replace the use of fossil fuels for transport, power, and industrial use.

Development of hydrogen energy systems to support various applications and associated value chains will be supported and enabled by focussed research, development, and demonstration. Current activities being undertaken by CSIRO and its partners across the hydrogen value chains include:

1. Developing new materials and technologies for reducing the cost of hydrogen (or carrier) production from renewables and low emissions fossil fuel pathways;
2. Identifying and applying novel, hybrid pathways (biological, chemical, physical) allowing integration of production processes with intermittent, distributed renewables;
3. Creating technologies to effectively extract hydrogen from relevant carriers at the point of use;
4. Generating the scientific knowledge required to support direct use of ammonia (and other hydrogen carriers) in engines, gas turbines, and fuel cells;
5. Understanding environmental, social, and practical implications of new renewable energy systems. For example, using new atmospheric and environmental chemistry and physics to support identification and management of potential impacts associated with increased uptake of new chemicals and fuels.

Hydrogen energy systems: creation of new energy value chains

The schematic diagram in Figure 1 shows an example of a value chain based on production of renewable hydrogen through electrolysis and/or gasification (with CCS) processes. These processes could be combined with new or existing technologies for the production of ammonia (or other carriers) enabling low emissions hydrogen production pathways to support development of zero emissions at point of use applications. This is an important step in the decarbonisation of energy and transport systems both domestically and in export markets.

CSIRO and other research and industry groups are exploring and developing new technologies across this value chain to support rapid expansion of the opportunity for the development of internationally traded renewable energy through hydrogen energy systems.

Enabling H₂ energy systems

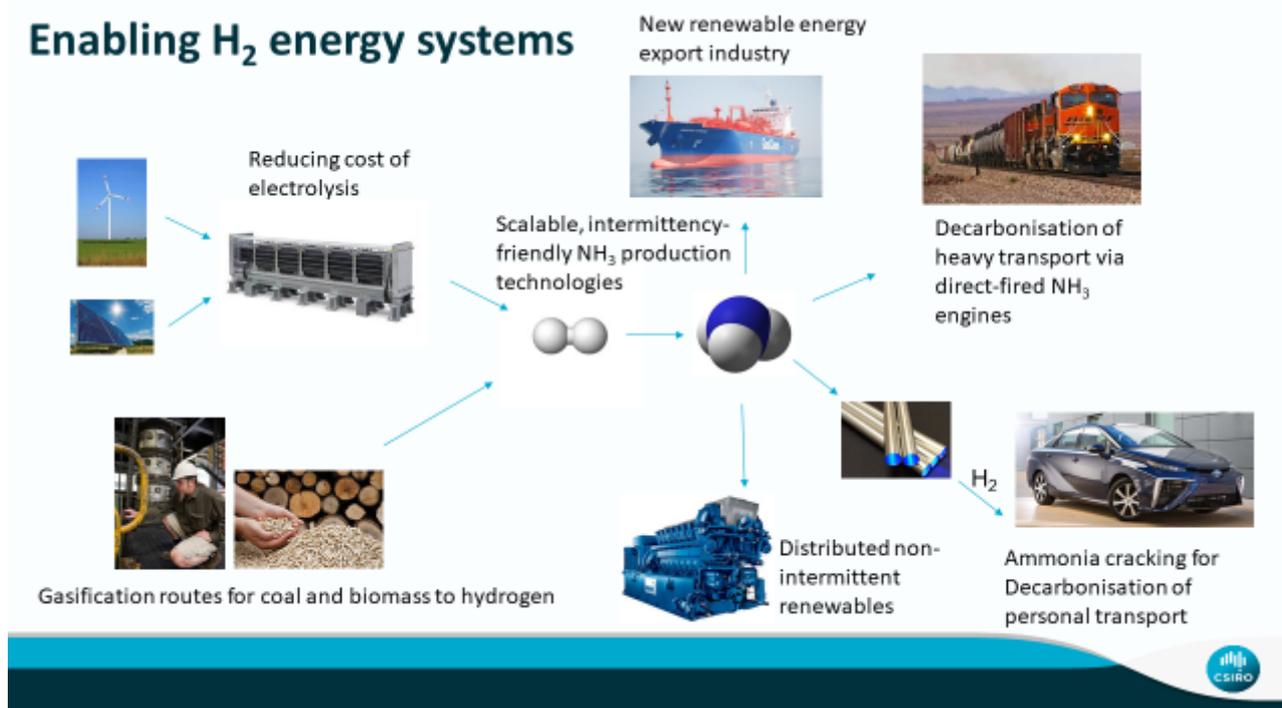


Figure 1: Example of hydrogen energy value chain based on renewable hydrogen production using ammonia as a hydrogen carrier (Source: CSIRO).

Research and technology development activities are focused on the three key aspects of this value chain: hydrogen production, storage and transport, and end use applications.

As noted above, hydrogen production is currently dominated by fossil fuel based energy routes, but will shift to include more renewable routes as renewable electricity is harnessed to drive electrolysis processes and other renewable energy sources, such as biomass and waste streams, are used to produce hydrogen.

The transport of hydrogen to distant markets represents a major challenge. In gaseous form, hydrogen has a very low energy density. Various projects around the world are looking at different hydrogen transport pathways that enable the energy density to be increased to the point to enable economically feasible transport. To enable efficient and economic transport of hydrogen, it is important to maximise gravimetric density (i.e., the weight percentage of hydrogen) and volumetric density (i.e., the mass of hydrogen per unit volume) of hydrogen carrier material. The most effective ways to increase hydrogen density are through liquefaction or conversion to liquid chemical forms with high hydrogen content.

Hydrogen requires significant energy input to liquefy. This is the reason why most of the hydrogen used in industrial and commercial processes is either manufactured at the point of use (such as in refineries and chemical plants) or transported as compressed hydrogen gas at about 200 bar. The volumetric density of gaseous hydrogen, even at a pressure of 200 bar, is very low, however, at just 20 kg/m³.

Liquid hydrogen is the transport medium being explored by Kawasaki Heavy Industries (KHI) and their collaborators in their Hydrogen Energy Supply Chain (HESC) project at Port Hastings in Victoria. The challenge with liquid hydrogen is the extremely low temperature required (-253°C at ambient pressure). This incurs a significant energy penalty, and places great demands on materials. Ship-based liquid hydrogen transport at scale has not yet been commercially demonstrated, and therefore is a critical outcome of the HESC project. This project also relies on CO₂ storage in the adjacent CarbonNet storage project to produce near-zero emissions.

There is extensive worldwide attention on a range of possible commercial hydrogen carrier materials. Traded commodity products containing high proportions of hydrogen such as methanol, methane (as compressed natural gas or LNG), methyl cyclohexane and other hydrocarbon carriers are being considered. Some of these alternatives, being hydrocarbons, can produce CO₂ on use and, depending on the source and application, may not be effective as suitable low, or zero, emissions energy carriers.

Ammonia (NH₃) is a carbon-free chemical which is 17% hydrogen by weight, and in liquid form, contains 120 kg/m³ by volume of hydrogen—about 70% greater than liquid hydrogen. Ammonia is also a liquid at ambient temperature and very mild pressures, similar to LPG. Ammonia production is one of the world's leading chemical industries with annual production of approximately 150 Mt per year (see <http://www.roperld.com/science/minerals/ammonia.htm> and <http://www.catalystgrp.com/wp-content/uploads/2018/04/PROP-Ammonia-Production-April-2018.pdf>). Unlike liquid hydrogen, there's an established distribution network of ships, trains, trucks and pipelines which could be utilised to help develop a new energy network based on renewable and low emissions energy stored in chemical form as hydrogen and transported as ammonia.

There are relatively-few technologies which enable ammonia to be used directly as a fuel, however, or converted back to hydrogen for use in proton exchange membrane (PEM) fuel cells such as those used in commercial fuel cell electric vehicles (PEM fuel cells require very high purity hydrogen). Research programs in Japan, USA and in Australia (including CSIRO) are developing direct-ammonia turbine technologies for large-scale power generation, and there are advanced programs developing direct ammonia fuel cells for high-efficiency stationary power generation. Suitably modified large-scale, low-speed internal combustion engine technologies are capable of being fueled directly with ammonia and offer real solutions to decarbonisation of marine and heavy rail.

Figure 1 illustrates the role of ammonia (NH₃) as a hydrogen carrier. As ammonia is already an extensively traded commodity product, the infrastructure, markets, and regulatory frameworks for international trade in ammonia are established. The inclusion of increasing amounts of 'renewable ammonia' (through inclusion of renewable hydrogen and nitrogen in existing and developing ammonia production technologies) in the market can be facilitated through existing industries and infrastructure systems. While major opportunities for direct use of ammonia in large stationary engines and transport systems are being developed, the immediate market opportunity is being driven by increasing development and deployment of fuel cell electric vehicles operated on pure hydrogen.

To access the rapidly growing hydrogen fuel cell vehicle fleet, however, it is necessary to extract high-purity hydrogen from ammonia close to the point of use. CSIRO's membrane technology has a key enabling role in this value chain as it can be used to purify hydrogen from ammonia (and potentially other hydrocarbon-derived feedstocks) to meet the stringent purity requirements of proton exchange membrane (PEM) fuel cells which are used in hydrogen fuel cell vehicles.

Hydrogen production

Global hydrogen production is currently 55 million tonnes per year (equivalent to energy content of 132 million tonnes of LNG) (Commonwealth of Australia, 2018), and it is mostly used to refine oil, produce ammonia and methanol, and for metallurgical applications and food production. Only around a million tonnes is used for energy applications, although almost all of the projected growth in global hydrogen use over the next 30 years is in these applications for mobility, power, and industrial energy.

Hydrogen is mostly produced from natural gas (NG) and coal. Around 50% of the global hydrogen is produced by NG steam reforming. The hydrogen production efficiency from this route is ~64% (lower heating value basis), and results in around 9 kg CO₂ per kg of hydrogen produced (Commonwealth of Australia, 2018). Globally black rather than brown coal has been the dominant fuel sourced for coal gasification. However, black coal gasification has challenges in an Australian context. Brown coal

gasification can achieve around 55% efficiency and the best figure quoted is around 20 kg CO₂ per kg of hydrogen produced (Bruce *et al.*, 2018).

Hydrogen produced from fossil fuels will thus require carbon capture and storage (CCS) to achieve zero CO₂ emissions. Australia’s black coal reserves are concentrated in NSW and Queensland where there are either no well-characterised, or only onshore CO₂ storage reservoirs (which carry a higher social licence risk) available. Hydrogen production via brown coal in Victoria’s Latrobe Valley which sits alongside a well characterised CO₂ storage reservoir in the Gippsland Basin represents the most likely thermochemical hydrogen production project. On the other hand hydrogen produced by electrolysis (splitting of water into hydrogen and oxygen) by using renewable sources of electricity will not contribute to direct CO₂ emissions.

There are two common types of technology currently used for electrolysis¹: alkaline solution (KOH) and PEM. The alkaline solution based electrolysis is a mature technology at large scale, but perhaps less suited to load ramping and variability than PEM systems. PEM based systems can respond more rapidly to variations in electricity supply, and therefore are considered more suitable for integration with intermittent energy sources. This technology is rapidly gaining maturity but is currently relatively expensive (yet on a strong cost improvement curve).

Both technologies require pure water supply and other balance of plant for separating gases from water. Each kg of hydrogen produced from water electrolysis requires 9 kg of water. Hydrogen compression to around 700bar is also required for refuelling of fuel cell electric vehicles. The cost of hydrogen produced from different pathways is shown in the **Table 1** below (Commonwealth of Australia, 2018).

Table 1 Hydrogen production technologies (Commonwealth of Australia, 2018)

Production Process	Primary Energy Source	Hydrogen Production Efficiency, %	Hydrogen Production Cost, A\$/kg	
			2018 Estimate	2025 Best Case Model
Steam – methane reforming with CCS	NG	64	2.30-2.80	1.90-2.30
Coal gasification with CCS	Coal	55	2.60-3.10	2.00-2.50
Alkaline electrolysis	Renewable Energy	58	4.80-5.80	2.50-3.10
PEM electrolysis	Renewable Energy	62	6.10-7.40	2.30-2.80

Note that for automotive applications, the compression cost per kg of hydrogen for refuelling of hydrogen cars will add around \$0.40 for 350 bar fill and \$0.70 for 700 bar fill (Kamiya *et al.*, 2015). There will also be additional cost associated with transport and distribution of the fuel to the refuelling station which are heavily scenario dependent.

There are many other technological approaches for hydrogen production from renewable energy. Solar thermal technologies, due to their high temperatures and scalability, are capable of being configured for hydrogen production and for the production of renewable fuels which can be used as hydrogen carriers. The levelised cost of fuel (LCOF), technical readiness and greenhouse gas (GHG) intensity projected to the year 2020 for the most prospective technologies are summarised in Table 2.

¹ Noting that solid oxide electrolysers, (that use a solid oxide, or ceramic, electrolyte to produce hydrogen gas), are not yet mainstream but aren’t far off.

Table 2: Projected 2020 levelised cost of fuel (LCOF), technology readiness level and greenhouse gas (GHG) intensity for key concentrating solar fuels technologies (Bruce *et al.*, 2018)

Process	Input fuel cost	Solar product gas LCOF	Technology readiness	GHG intensity
Conventional crude oil at \$100/barrel	\$16/GJ	–	Current technology	High
Solar gasification of brown coal	\$1/GJ	\$3.45/GJ	Medium	High
Solar reforming of natural gas	\$8.4/GJ	\$10.30/GJ	High	Medium
Solar gasification of biomass	\$8/GJ	\$9.75/GJ	Medium	Zero-low
Solar water splitting	Zero	\$29–46/GJ	Low	Zero

Gasification pathways using waste or biomass feedstock offer opportunities for hydrogen production, and when undertaken as part of a well-managed system, can also be low emissions (and often renewable) sources of hydrogen. There are also other emerging pathways at various levels of maturity, including biological-based fermentative processes and those using specialised materials to directly split water using the sun.

Hydrogen carriers

As noted above, liquefied hydrogen, ammonia and methyl cyclohexane (MCH) are examples of compounds that are being considered as suitable carriers of hydrogen for transport of hydrogen over long distances (by road or marine transport). The liquefaction of hydrogen consumes 20–30% of the original energy content of hydrogen, but its conversion back to usable form does not require as much additional energy as non-hydrogen carriers. While ammonia and MCH both require energy input during formation as well as during conversion back to hydrogen, there are advantages to their use that warrant consideration. Ammonia is carbon free when produced using renewable energy, and can be used directly to produce power or decomposed to produce hydrogen. It can be transported as liquid at near ambient conditions using well established infrastructure, and has a significantly higher volumetric hydrogen content than liquefied hydrogen. Australia is already an exporter of large quantity of ammonia (~1.8% of global ammonia export market) (Commonwealth of Australia, 2018).

Ammonia is currently produced by the Haber-Bosch process using hydrogen derived from fossil fuels (NG, fuel oil and coal), and is an energy intensive process requiring 9–15 MWh of energy per tonne of ammonia produced contributing to over 1% of global energy related CO₂ emissions (Giddey *et al.*, 2013 and 2017). Hydrogen produced by electrolysis with renewable electricity can also be used for ammonia production using the Haber-Bosch process. This provides an infrastructure stepping stone for possible introduction of increasing amounts of renewable hydrogen into existing systems. The energy input for this route has been suggested to be around 12 MWh per tonne of ammonia (<https://ammoniaindustry.com/australian-solar-ammonia-exports-to-germany/>). Recently, there has been a significant increase in worldwide effort to develop alternative ammonia production technologies to try and reduce this energy input and support more effective integration with intermittent renewable energy sources. One such technology is electrochemical synthesis based on the electrolysis of water, where the protons (H⁺ ions) produced by the splitting of water are made to react with nitrogen (supplied by an air separation unit (ASU)) to directly produce ammonia. This technology is still at an early stage of development with synthesis rates lower by two orders of magnitude than the commercial process (Hinkley *et al.*, 2016).

CSIRO is currently developing a metal membrane based process for ammonia production in a collaborative project with Orica, GRDC and ARENA, and is exploring novel alkaline based systems for ammonia synthesis through its Hydrogen Future Science Platform.

CO₂ Capture and Storage (CCS)

To produce hydrogen with low or zero emissions from fossil fuel sources will require CCS. The proposed KHI project to produce hydrogen from gasification of Victorian brown coal includes CCS in the project scope. This aspect of the project is being developed in collaboration with CarbonNET.

(<http://earthresources.vic.gov.au/earth-resources/victorias-earth-resources/carbon-storage/the-carbonnet-project>).

There are three cost aspects to CCS: technical, economic and social. The CarbonNet project is actively investigating all of these. Globally, according to the Global CCS Institute annual report (Global CCS Institute, 2017), there are 17 large-scale CCS facilities currently operating. To date over 220 million tonnes of CO₂ has been injected underground. The longest-running storage project is Sleipner, offshore Norway, which has been capturing and injecting CO₂ since 1996 and has injected over 17 million tonnes to date (<https://www.globalccsinstitute.com/projects/sleipner%2%A0co2-storage-project>).

Technical aspects: These include the transport of CO₂ from the production site and storage of CO₂ in the relevant reservoir. A number of selected sites in the offshore Gippsland basin are being surveyed for their capacity to store large volumes of CO₂ such as that expected from the KHI hydrogen project. Surveys include seismic and appraisal well drilling. Transport would be via pipeline to an offshore well (or wells) delivering compressed CO₂ for injection and storage into suitable geological reservoirs.

The US has an extensive network of pipelines transporting CO₂ from the source of generation to sites where the CO₂ is used for enhanced oil recovery. The CO₂ is injected and effectively pushes trapped oil towards production wells. The CO₂ is separated and reinjected, essentially a closed loop process. Consequently, technology around pipelines and transport is well understood, as is injection.

Economic considerations: There are a large number of cost estimates for the capture and storage of CO₂ from coal fired steam power stations, however, the capture costs are associated with combustion based processes where CO₂ is captured from a dilute flue gas are not transferrable to oxygen-blown gasification processes producing hydrogen where the CO₂ is produced as a high concentration, high pressure gas stream. In this situation, the CO₂ capture is integrated into the syngas processing component of the gasification plant. There are fewer cost estimates available for the cost of transport and storage alone as is required for hydrogen production. The most recent estimates come from the Australian Power Generation Technology Report (CO2CRC, 2015), which states “the cost for CO₂ transport, injection and monitoring is likely to vary between \$5/t and 14/t injected for cases involving short transport distances to storage formations with good characteristics”. This increases to be “almost \$70/t injected for cases involving the transport of small volumes of CO₂ over long distances to storage formations with poorer characteristics”. These estimates will vary according to the specifics of each project. The estimates exclude the cost of capture and compression, but include the cost of monitoring and verification. Regulators have a requirement for monitoring and verifying the quantity and spatial distribution of injected CO₂ for both social licence to operate (SLO) and greenhouse accounting purposes. The underlying concept for monitoring requires it to be scientifically valid and defensible while affordable.

CarbonNet are examining a number of injection sites. The costs for each site have been estimated as between \$6 and \$24/t CO₂ injected (CO2CRC, 2015).

Social license to operate: This is an important consideration in CCS projects, both onshore and offshore. The environmental benefits of storing CO₂ as an alternative to venting are not always obvious to local land-

users and communities. Consequently most project proponents, including CarbonNet, engage in early consultation with local landowners and communities.

Increasing the Scale of Hydrogen Production for Energy Applications

Ultimately hydrogen must be cost-competitive with other fuels in specific application areas if it is to achieve widespread adoption. Given the diversity of technologies involved in the range of different hydrogen value chains, there is no definitive answer to the question of what scale up of the industry is needed to achieve scale efficiencies and overcome cost barriers. A detailed answer which included realistic technoeconomic models, a proper research project would need to be undertaken to evaluate scale efficiencies and cost barriers.

CSIRO's National Hydrogen Roadmap (Bruce *et al.*, 2018) did give some consideration to this issue, as it is critical to the concept of 'market activation' in the emerging hydrogen space. For a hydrogen system based on electrolysis, the critical size is approximately 100 MW; and as mentioned, for the rest of the value chain it is more complex. A scale of 100MW is the first big step in cost reduction with most other technologies needing to be bigger than this to achieve significant impacts.

The complexity of this discussion increases as one considers the role of staged adoption, in particular in the gas pipeline and ammonia sectors. Here, existing, full-scale infrastructure can be used at (often a small) percentage of its capacity with hydrogen. In the case of natural gas injection, this has immediate and cost effective impacts on carbon emissions at very little relative cost, and there are few capital barriers to ongoing expansion.

There is an important role of research and development at scale in this matter, in particular in applications relying on new technologies or new integrations of existing technologies. Demonstration of new value chains is a key aspect of cost reduction, leading to technology de-risking as well as investor confidence. CSIRO is currently developing a large-scale research initiative to address the lack of industrial-scale RD&D in the hydrogen sector, which is being designed to be consistent with, and complementary to, related industry and government initiatives.

There is a need for infrastructure and coordinated efforts to provide a platform to assist technology development and pilot scale demonstration at the stage where relevant industry partners can begin to take prototype and proof-of-concept technologies to a scale that supports investment in appropriate design, manufacturing and applications initiatives. CSIRO is seeking to develop partnerships across the value chain to support the development of appropriate 'test-beds' or 'plug-and-play' development hubs to reduce the costs and risks (safety, emissions and by-products management etc) in conducting these pre-commercial pilot and demonstration activities.

CSIRO's National Hydrogen Roadmap (Bruce *et al.*, 2018) also made the point that the hydrogen industry in Australia (and more broadly) is no longer only constrained by technology development and now requires market activation activities. Research and development is, of course, going to have an important role to play as new pathways emerge and cost reductions continue; however, larger-scale, industrially-focussed initiatives are now needed to help the industry enter (and successfully traverse) the 'valley of death' - the technology stage that lies between small scale research and commercialisation, where costs are high but success is needed in order to support commercial scale deployment.

This would be assisted by collaboration and coordination at all levels of research, industry, and government.

CSIRO is developing a plan for increased investment in hydrogen activities, with a clear focus on supporting industrial scale collaborations to demonstrate key value chains and de-risk technology development and deployment. CSIRO is currently scoping a large scale program of work to support increased research activity

in hydrogen technologies, and also focus strongly on establishing collaborative RD&D infrastructure and facilities. These hubs will allow for significant leveraging of government, industry, and research funding, and provide the mechanism to allow the global demand for renewable hydrogen to have strong domestic impact: hydrogen for transport in Australia, for example, is almost entirely limited by the availability of the required infrastructure.

There are also benefits to be gained by partnering at an early stage between existing industries and new technology development initiatives to ensure that the technology options that are developed are compatible with existing industries and infrastructure in a practical way. For example, alignment with existing ammonia manufacturers is expected to be important in ensuring new ammonia production technologies (particularly those seeking to develop renewable hydrogen pathways) are able to leverage of existing business and market infrastructure to provide both a pathway to large scale impact as well as ensuring the new technologies have the necessary 'industry champions' to support investment, development and deployment at realistic industrial scale. The development of pilot scale technology development hubs such as those described above is intended to facilitate this scale of cooperation and coordination.

Battery Research and Technology

CSIRO has been active in battery research for many decades, and CSIRO's pioneering work in the lead acid battery/supercapacitor area is behind the development of the commercially-successful UltraBattery. This section summarises recent/current areas of activity regarding various battery research including lithium battery research, new battery technologies based on Silicon Carbide (SiC) and Gallium Nitride (GaN), (as opposed to Silicon (Si)), operating control and battery safety.

Lithium processing

Next generation lithium batteries will rely on use of lithium metal anodes for improving the energy storage capability of batteries. CSIRO has been developing the LithSonic™ technology which is a revolutionary method to produce lithium metal at low cost in an environmentally friendly way. The process uses a carbothermal reduction to generate lithium metal vapour, which is accelerated to velocities of 1000-1500 m/s through expansion in a supersonic nozzle. This results in quenching at greater than 1,000,000 °C/s and produces a fine metal powder. Preliminary estimates indicate production costs of less than half the existing technology without the release of toxic chlorine gas, as currently occurs in the electrolytic process. Capital cost is also expected to be significantly lower.

Optimisation and testing

An area of ongoing work for CSIRO is the control of lithium and lead acid battery systems. CSIRO has a long history of designing control optimisation techniques that decide how to best operate (charge/discharge profile) a battery, in order to get the best performance and lifetime extension.

CSIRO also has extensive experience in testing real-world battery systems, from residential scale to shipping container size, and extensive experience in the challenges and opportunities for lithium/lead acid chemistries. For example, in Newcastle, CSIRO is working on smarter use of lithium battery storage systems, coupled to solar with the aim of offsetting and reducing CSIRO's overall electricity consumption at the Newcastle site on a year by year basis.

CSIRO is working with a number of Australian SMEs to evaluate natural graphite materials for use in batteries. Previously CSIRO worked with Archer Exploration to investigate mined graphites from South Australia and their use in batteries. More recently CSIRO has been working with Hazer Group to evaluate their synthetic graphite for use as lithium ion battery anodes and has been conducting extensive experimental evaluation to show if these materials can be used for the targeted application. We have also begun to assess mined graphite from Strike Resources for the suitability of their materials in battery applications.

Beyond graphite, CSIRO is working with lithium producers, such as Lithium Australia NL and their subsidiary, VSPC, to assist them in turning Australia's valuable battery minerals into products such as cathode materials that can be used in lithium-ion batteries. CSIRO expects to broaden this effort to address other metals used in lithium batteries such as aluminium, copper, nickel, manganese and cobalt.

CSIRO has worked in partnership with Australian and overseas Universities to evaluate new anode materials, electrolytes and devices, such as the use of titanium dioxide as an alternative lithium ion battery anode.

Research has also been conducted on forensically testing batteries and advising manufacturers of the performance of their cells. CSIRO currently has various projects testing performance of different kinds of batteries for clients.

Applications

CSIRO is actively investigating lithium batteries for connection to photovoltaic (PV) generation for residential and light-commercial applications. As part of this work CSIRO is testing and evaluating commercially available lithium batteries under a range of different test conditions and developing a method to rapidly evaluate lifetimes of batteries connected to PV systems.

Funded by the Australian Renewable Energy Agency (ARENA) and the Victorian Government, CSIRO is working with partners to develop an Australian Standards submission for evaluating the performance of commercial batteries including lithium for connection to residential PV systems and light-commercial PV systems. At present, limited standards exist for commercial batteries targeted for PV connection and this causes confusion for Australian industry and consumers. Having a standardised and well-defined method for performance evaluation will eliminate this confusion and enable the industry to provide better quality technology and also eliminate any poor technologies which could come into the Australia market, potentially hampering the industry.

CSIRO is developing an experimental database of lithium and other battery technology performance under different charging/discharging conditions and temperatures to provide a reference for ongoing efforts into algorithm development for smart use of batteries for best performance.

Work us underway with a local arm of the Delta Group to help develop, test and evaluate their electric vehicle fast charging technology for lithium batteries. The technology utilises lithium batteries for energy storage from renewable power generation systems (currently PV) and enables rapid charging of electric vehicles.

Electric vehicle batteries are very expensive and, at their end of life, disposal of the batteries is required. However, there is still the ability to use these batteries for alternative, lower powered applications (such as PV generation storage). Relectrify is a start-up company that is developing technology which can enable this application to be realised. CSIRO is working in partnership with Monash University and Relectrify to host, train and mentor a PhD student to investigate the effect of high frequency currents on batteries. This is an area that has not been well explored and the partnership will generate needed information on the fundamental science. The results will also help Relectrify develop their battery reuse technology further.

End of life

Lithium battery recycling in Australia is very limited with only 3% of batteries sold currently being captured and sent for recycling off-shore. As volumes of waste batteries grow an emerging problem of landfill waste increase and hazards such as environmental chemicals leakage from pierced batteries or even fires may occur. CSIRO is developing a recycling technology designed for Australian conditions (environmental, geographic and economic) which may be able to recycle lithium batteries on-shore and grow the current

industry if the science is successful. CSIRO's technology is also investigating if alternative value can be captured from waste batteries and make the economics of recycling even more favourable.

Battery Safety

It has long been realised that lithium (Li) would be the most attractive candidate material for high performance batteries, because of its low density and highest electrochemical potential. Work on lithium batteries began in 1912 although it wasn't until 1991 that rechargeable Li batteries were commercially successful (https://batteryuniversity.com/learn/archive/lithium_ion_safety_concerns).

A key to the commercial introduction of the Li battery to the market was the use of graphite, a layered compound which is naturally occurring, as well as able to be prepared synthetically, and which can "intercalate" Li ions between the graphite planes. This was the "birth" of the modern rechargeable Li-ion battery as we now know it. The use of graphite meant that there was no need to plate lithium metal (the chemical reduction of lithium ions to metal that produces an electron) which is, and still remains, difficult to achieve in two-dimensions. When Lithium is plated, especially at high current densities, it can form three-dimensional or dendritic structures which can penetrate the separator between the terminals and cause short-circuit and fire.

Since the launch of the Li-ion battery there have been a number of high-profile recalls, including the recent Samsung smartphone battery recall (<https://www.samsung.com/au/news/local/samsung-electronics-australia-extends-recall-to-all-galaxy-note7-smartphones-in-australia/>). The most common reasons for these issues are:

1. An external heat source, e.g. a fire that ignites the battery.
2. A short (low resistance connection) between the terminals. This short may be the result of:
 - a. Compressing the terminals to reduce battery size. e.g. Samsung recall (<https://www.samsung.com/au/news/local/samsung-electronics-australia-extends-recall-to-all-galaxy-note7-smartphones-in-australia/>).
 - b. Contamination of production line. e.g. Sony recall (https://batteryuniversity.com/learn/archive/lithium_ion_safety_concerns).
 - c. Growth of dendrites (sharp metal filaments) that puncture the polymer separator between terminals due to "over-charging" of the device (which is one of the reasons that Li batteries took so long to develop).
 - d. Puncture of the battery. e.g. in a car accident.
3. Battery management system (BMS) problems where the BMS does not prevent:
 - a. Overcharging the battery
 - b. Under-discharging the battery.
 - c. Charging the battery too fast.
 - d. Discharging the battery too fast.
 - e. Loss of cooling to or overheating of the battery and the BMS not shutting down.

The BMS problems should not occur in a well-designed system that is correctly fitted and hence they are unlikely to be a problem where battery systems are sourced from a major manufacturer, but could be a problem from a small manufacture or a conversion kit manufacturer.

The short between terminals or electrodes is of much greater concern than the BMS. Major manufacturers like Sony (https://batteryuniversity.com/learn/archive/lithium_ion_safety_concerns) and Samsung (<https://www.samsung.com/au/news/local/samsung-electronics-australia-extends-recall-to-all-galaxy-note7-smartphones-in-australia/>) have had problems and it is not possible to guarantee that, in an accident such as an electric vehicle crash, the battery casing will not be punctured or compromised (for example by crushing or bending) which can lead to electrodes contacting and causing short circuit conditions. Also,

unscrupulous producers, and low-cost suppliers of batteries do exist, where appropriate safety features may be omitted (either on purpose or through poor battery knowledge) and again a smaller manufacturer or conversion kit manufacturer might be tempted to purchase these cheaper batteries which have a poorer safety record (https://batteryuniversity.com/learn/archive/lithium_ion_safety_concerns). Similarly, an external heat source igniting the battery cannot be controlled against.

To mitigate these uncontrollable eventualities of a short or external heat exposure there are three main approaches:

1. Choose a more expensive chemistry (per kWh of storage) from reputable manufacturers. There are a range of chemistries all commonly called lithium, lithium-ion, or lithium polymer, which are generic catch-all terms for any lithium battery chemistry. Some chemistries, which use electrode materials such as lithium-titanite and lithium-iron-phosphate, are largely benign when punctured but can be a more expensive option.
2. Install a fire suppression system.
3. Have a barrier between batteries to stop any fire spreading from battery to battery.

Option 1, the more expensive battery, is ideal, but not always possible for all manufacturers in mass market applications such as high volume automotive applications where economics plays a role.

A combination of approaches 2 and 3 is used by Tesla for example. Tesla claim that their implementation is five times safer than a conventional vehicle (which can also ignite) (https://www.tesla.com/en_AU/blog/tesla-adds-titanium-underbody-shield-and-aluminum-deflector-plates-model-s).

The only Australian lithium battery manufacturer, Energy Renaissance, have adopted approach 3 (fire barrier between batteries) (CSIRO, personal communication).

A final point of note is that a metal fire, in this case Lithium, is difficult to extinguish, e.g. once ignited it will continue to burn under water (for example, magnesium flares used by divers) (<https://www.bea.aero/docspa/2010/f-pk101208.en/pdf/f-pk101208.en.pdf> and <https://abc7news.com/automotive/fire-chief-tesla-crash-shows-electric-car-fires-could-strain-department-resources/3266061/>).

Post Lithium-ion Batteries & Ionic Liquid Electrolytes

Non lithium-ion batteries

One of the challenges of the lithium-ion battery is the never ending demand of end users to store more energy. For example, the more energy stored the greater the range of an electric vehicle or the longer the operational time of a smart phone. This needs to be balanced with the concomitant reduction or stabilisation of the battery and associated hardware volume. There are a number of different approaches being taken for current generation lithium-ion batteries:

1. **Increasing voltage:** Companies and researchers are trying to increase the voltage difference between the positive and negative electrode in order to increase the energy stored in the battery, typically by increasing the amount of lithium that can be extracted from the cathode (positive electrode). This is typically achieved through doping of different transition metal elements into the cathode. For example, the addition of small quantities of nickel and manganese to the LiCoO₂ cathode material increases the operating voltage from 4.2V, for example up to 4.7V for LiNiMnCoO₂ (NMC) batteries.
2. **Increasing electrode capacity through alloying or materials combinations:** To achieve higher energy, researchers and industry have developed, and are currently developing, new materials and combinations thereof in order to achieve this. As an example, today's state-of-the-art negative

electrodes (anodes) are a mixture of graphite and between 5 – 10 weight % Silicon particles. This enables greater energy storage than the conventional graphite negative electrodes through use of the higher storage capability of the silicon material. The much greater volume expansion (400%) of silicon going to lithiated silicon during the charging reaction inhibits their widespread use. Additionally, lithiated silicon is also known to be unstable in the presence of organic solvents (the basis of the electrolytes used in these devices), so researchers and industry are continuing to develop strategies and materials to allow them to be used safely even in abuse conditions (Arafat *et al.*, 2016). In both cases, the increase in energy stored in the battery can be the source of increased safety concerns especially under the conditions described above.

A number of these higher voltage cathode materials are commercially available at present, for example nickel-cobalt-aluminium batteries (NCA - Tesla) and nickel-cobalt-manganese (NMC – LG Chem, Samsung, Tesla etc.). CSIRO would estimate that batteries with substantial fractions of Silicon in the anode would be commercially available within the next 1 to 5 years with the continued level of R&D interest. However, these adaptations and improvements are pushing close to the theoretically maximum energy that lithium-ion batteries can provide. This is the rationale for development of new battery technologies such as lithium-sulfur which are considered as step-change technologies and can provide orders of magnitude increase in energy storage capability.

Batteries that utilise Lithium *metal* as the anode, are known as “beyond lithium ion” technologies due to the significant changes required in the materials to go in these devices. As indicated earlier, batteries that use Lithium metal as the anode, as opposed to graphite or composites thereof, have a 10 fold increase in specific capacity of the electrode (3800 mAh.g⁻¹ as compared to 375 mAh.g⁻¹, respectively). This significant increase in available energy at the anode requires a cathode with similarly matching capacity. To this end two devices have been of significant interest to researchers and industry, respectively: Lithium-Sulfur (Li-S) and ultimately Li-Air.

The Li-S device has a lithium metal anode, an electrolyte that is stable to lithium metal but only mildly soluble to sulfur and a cathode (positive electrode) that contains sulfur within an electronically conductive network. Typically, sulfur is infused into an electrically conductive network, such as carbon, where Li ions can react with the infused sulfur to form lithium polysulfides. These reactions can produce a specific capacity of ~1650 mAh.g⁻¹. In principle, these devices have a theoretical energy density of ~2200 Wh.kg⁻¹ (Bruce *et al.*, 2011), however, due to some of the issues noted below, this has never been achieved. The lithium sulfur battery has three main challenges to overcome:

1. Anode: dendrite formation which can cause short circuit or other safety issues
2. Cathode: poor sulfur capacity retention leading to poor battery performance
3. Electrolyte: polysulfide dissolution leading to leaching of sulfur from the cathode and deposition via transport through electrolyte into the anode causing poor battery lifetime

Historically any rechargeable battery system utilising lithium metal anodes has been limited due to the dendrite formation effect upon charging which leads to development of metallic needles which contact the cathode eventually and cause short circuits and in some cases fires. Using its experience in lithium metal batteries and ionic liquid electrolytes to prevent this occurring was the rationale for CSIRO’s Li-S battery development.

The key driver globally for Li-S batteries development at present is the push to increase the km per charge values for electric vehicles. As such there are a large number of research groups globally working on providing solutions to the cathode, anode and electrolyte problems. A number of these solutions are viable at a laboratory stage and are showing better performance, however translation to commercial success is limited due to the economics of scaling up to commercial production levels. As such continued research and development is needed to find solutions which are commercially acceptable. These systems are of

interest to vehicle manufacturers (Gao *et al.*, 2017) who are also funding research and development in Li-S battery development.

However, there are at least two commercial entities that have products being developed at a pilot plant scale for application to specific markets (UAVs and defence). The first is Oxis energy (UK) that have IP and pilot scale capabilities at present. They are targeting 500kWh systems for 2019. They have developed prototypes at 425 kWh at a 16Ah scale at present for high altitude pseudo satellite applications (<https://oxisenergy.com/news/press/>).

The second is Sion Power (USA) that again is close to commercialising Li-S batteries (www.sionpower.com). They are in the process of procuring manufacturing equipment and hiring at their Tucson plant. They currently have a Li-S battery of 500Wh/kg with 450 cycles lifetime.

In both cases, these devices offer energy density that is higher than is available in today's lithium-ion batteries, however, they both have extremely low cycle life - ~ 400 cycles as compared to Li-ion at > 2000 cycles - due to issues with the lithium anode and the generation of uncontained lithium polysulfides which leads to capacity loss and eventual cell failure (Barghamadi *et al.*, 2014).

CSIRO has been involved in the development of Li-S batteries since 2013 and in 2014 we were engaged with Boeing to develop a high energy battery. During the two years that this project ran for, CSIRO sought to develop:

- A Li-S device with an energy density of 600 Wh/kg at the 0.1 C rate
- A Lithium anode that had increased stability and cyclability
- A cathode and electrolyte where lithium polysulfide dissolution is mitigated.

As a consequence of this project, a number of prototypes were prepared for testing and evaluation by Boeing, however, due to changes of research focus at Boeing these cells were not further evaluated. CSIRO still continues to work on this technology due to our interest in lithium metal anodes and electrolytes that are stable with them. As part of this, CSIRO uses Ionic Liquid electrolytes (described below) due to their stability with lithium metal and are seeking to design cathode materials and improve electrolytes to reduce polysulfide dissolution which should improve capacity retention and enhance cycle life. CSIRO is still seeking to work with both local and international partners to develop the materials and concepts we have previously generated.

Since 2016, CSIRO has continued the cathode and electrolyte development with university collaborations (PhD, masters and honours students). Specifically CSIRO has focussed on cathode optimisation studies, use of CSIRO's Polymerised Ionic Liquid Blocks (PILBLOx) technology² to film cast ionic liquids onto cathodes to improve the cathode performance by reducing or limiting polysulfide migration into the electrolyte. CSIRO has also explored use of PILBLOx technology to modify the electrolyte to reduce or mitigate polysulfide dissolution to improve the lifetime and performance of the battery systems. This anode development research has also investigated the surface modification of lithium using ionic liquids and alternative fluorinated molecules to produce robust passivation films to improve cycling and safety in Li-S batteries. At present this work is ongoing with CSIRO seeking industrial partners to further progress the development.

Based on our understanding of the area, CSIRO estimates that Li-S batteries would be commercially available in the next 1 to 5 years for low cycle applications and if key research and development solutions are found then also for higher cycle applications within the next 10 years.

² Polymerised Ionic Liquid Blocks (PILBLOx) are solid materials for next generation devices (see Ionic Liquid electrolytes)

Ionic Liquid electrolytes

CSIRO has been working on ionic liquids and electrolytes thereof since 2002. Ionic Liquids are a novel class of materials that are comprised entirely of ions and as a consequence, have no vapour pressure across a range of temperatures. This minimises the risk of explosion and fire when used in batteries under abuse conditions. Ionic Liquid electrolytes are also a significant enabler for Lithium metal anodes, as Lithium metal offers an order of magnitude increase in energy density compared to graphite. However, the lithium metal anode, historically, has had a poor safety record due to interactions with the electrolyte. CSIRO's ionic liquid technology removes that issue and thereby potentially enables use of this material for batteries

CSIRO has portfolio of IP in the use and application of ionic liquid electrolytes for lithium (ion) batteries. CSIRO is currently in the process of licensing this IP to a number of ionic liquid manufacturers in order to allow them to manufacture, market, distribute and sell electrolyte formulations. CSIRO continues to work with its research and industry partners to develop new electrolytes with improved performance for both current lithium-ion solutions and beyond lithium.

To this end, CSIRO is developing PILBLox and has already scaled this material and it is now available for trial under a Materials Transfer Agreement. We will continue to develop the material over the coming year and seek partners to assist us in bringing this to the market and enable solid state battery technology.

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