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CSIRO Submission 18/635

The use and manufacture of electric vehicles in Australia

Senate Select Committee on Electric Vehicles

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Table of Contents

Executive Summary

CSIRO conducts a range of research related to electric vehicles. This includes battery research as well as the infrastructure requirements associated with developing electric vehicle transport systems, and the role of hydrogen technologies in hydrogen fuel cell electric vehicles. We note also that a useful UK roadmap for electric vehicles is available (Advanced Propulsion Centre, 2018) which covers many of the issues the committee is concerned about and in CSIRO's view is technically sound (though UK oriented).

Factors to be considered when developing electric vehicle technologies include:

- New power switching devices based on silicon carbide and gallium nitride as opposed to silicon
- Battery safety
- Manufacturing cost
- Opportunities for hydrogen energy systems
- Battery storage and application of post lithium-ion and ionic liquid electrolyte technologies
- Infrastructure safety
- Role of transport and stationary energy in meeting emissions reductions targets.

To address these considerations and to enable the realisation of the potential benefits of electric vehicles, CSIRO has an active research and development portfolio including:

- Developing next generation lithium batteries using lithium metal anodes (e.g. CSIRO LithSonic technology)
- Designing and optimising battery systems, and their applications
- Battery recycling
- Options for low emissions and renewable fuels for transport applications

CSIRO is also developing technologies to support accelerated development of hydrogen production, storage, transport (including export) and utilisation for fuel cell electric vehicle systems. This work is aimed at facilitating a new export energy industry for Australia based on low emission and renewable hydrogen energy systems. 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 such as fuel cell electric vehicles.

Introduction

CSIRO welcomes the opportunity to contribute to the Select Committee on Electric Vehicles' inquiry into the use and manufacture of electric vehicles in Australia. We also welcomed the invitation to appear before this Committee at a public hearing held on Friday 17 August 2018.

In this submission we have sought to answer the questions taken on notice at that hearing and also provide additional information regarding CSIRO capabilities, current relevant activities and topics related to the questions raised in the hearing.

We have organised our submission, including responses to the questions taken on notice at the hearing, against key themes as follows:

Theme	Asked by / Hansard page number	Question
CSIRO electric vehicle research	Senator Tim Storer and Senator Kim Carr (p. 46)	**Dr Harris:** We would be prepared to now prepare a submission. We now have the information and we can prepare a submission to the inquiry on notice. **CHAIR:** I'd like to invite you to do so.
Battery research and technology	Senator Kim Carr (pp. 46–48)	**Senator KIM CARR:** I'd be interested to know, given your expertise in this field, as to what your view is about the likely developments in battery technology as far as electric vehicles are concerned. Do you have an assessment in terms of what you expect will happen in terms of the movement from the current battery technology that's in predominant use compared to, for instance, hydrogen and what's referred to as solid-state batteries? **…** **Senator KIM CARR:** I'm particularly interested in what your projections are, in regard to your assessment—it's analysis I'm looking for—in terms of what you consider to be the directions of the technological development for batteries. In your submission, when you get to write that, can you attend to that? **Dr McLean:** Yes, absolutely. **Senator KIM CARR:** The committee's been told that by 2015 the development of these particular technologies will revolutionise the existing AC power grid. It will transform the grid so that we'll be able to adapt the entire approach to the electric vehicles system, right through from the charging to the operations of vehicles. Would you agree with that assessment? **…** **Senator KIM CARR:** It's been put to us that this will include the issue you mentioned of battery charging but also motor drivers, the actual drive train of the vehicle itself. Would you agree with that assessment? **…** **Senator KIM CARR:** In your submission, if you could provide us with that technical advice as to the CSIRO's assessment—and that's not irrefutable. It's contestable. All of this is. We have to look to people who have some technical impartiality when it comes to the assessment of these questions

SiC and GaN power devices	Senator Kim Carr (pp. 46–48)	**Senator KIM CARR:** What can you tell me about silicon carbide and gallium nitride based switching systems?
Battery safety	Senator Kim Carr (p. 48)	**Senator KIM CARR:** Thank you very much. Do you do any assessment on safety issues? I know CSIRO is currently involved in a number of safety disputes in other areas, but do you do any assessment on electric vehicle safety questions? **…** **Senator KIM CARR:** In your submission can you look at the issue of safety as well please?
Manufacturing cost of electric vehicles	Senator Kim Carr (p. 48)	There is another issue I'm concerned about, given the manufacturing unit has expertise in this field. There is an argument that the production process for electric vehicles is actually cheaper than for conventional vehicles because of the different method—rather than the current production line for a conventional vehicle, which is best summed up perhaps by the Toyota method, the Scandinavian method. Do you have any assessment on whether or not that is the case in terms of changing the business model for the production of vehicles?
Hydrogen energy systems	Senator Kim Carr (pp. 48–49)	**Senator KIM CARR:** I would be interested if your submission could cover that question as well—the comparison in terms of future technological development. The Chief Scientist has issued a paper this morning on the deployment of hydrogen. He is arguing that it is actually a more efficient and more effective means for the electrification of the transport infrastructure. Your assessment of that paper would be very useful.
Post lithium-ion batteries and ionic liquid electrolytes	Senator Patrick (pp. 49–50)	**Senator PATRICK:** … There are a few technologies you are working on. Lithium sulphur batteries, for example, with two times to five times the energy density sounds quite exciting. How long have you been working on that particular technology? If you were asked to place an estimate on when you think that would be in production and in the commercial market what timeframe would you expect? **…** **Senator PATRICK:** When would you project it becoming a commercial product? **…** **Senator PATRICK:** Scientists never want to commit to that. I understand that. I have an R&D background, running an R&D seller, so I know how hard it is. Is it a year, two years or 10 years? That is what I am trying to understand. There is another technology, ionic liquids, that you are working on. Once again, you've worked on it for some time. Is it likely to go to market shortly? **…**. So maybe the ultimate question is: noting all of the requirements for a car, when are we likely to see a change in technology?
Infrastructure safety	Senator Patrick (p. 50)	**Senator PATRICK:** And the Europeans generally have really good safety regimes. I presume that it's a much more expensive recharging station than an electric-charging station. Would that be fair?

Role of transport and stationary energy in meeting emissions reductions targets	Senator Rice (p. 51)	**Senator RICE:** I know we're running short of time. I look forward to seeing a comprehensive submission, and having you back to then discuss some of the issues raised in that submission would probably be the best way of proceeding. I am also interested in covering the role of potentially hydrogen-fuelled vehicles here in Australia, with the hydrogen economy—hydrogen is an export industry—and also your new technology of being able to store hydrogen as ammonia and use that as a storage medium. The only other area that I was interested in was CSIRO's *Low emissions technology roadmap* that you developed last year. Are you able to answer a couple of questions about the role of transport in that? **Dr Harris:** I'm not sure! **Senator RICE:** Essentially, it was basically setting out a road map for reaching 26 per cent reductions by 2030—our Paris target—and then I think net zero by 2050. I'm interested in what role decarbonisation of transport plays vis-a-vis stationary energy in that road map. **Dr Harris:** I would have to review that and get back to you. I'm happy to put that in a submission. That was a set of scenarios, and the scenarios were there to paint various pictures. They weren't meant to be predictions. I would be happy to review that and include that in the submission. **Senator RICE:** Reflecting upon the importance of decarbonisation of transport in meeting our emission targets. **Dr Harris:** Sure.

CSIRO Electric Vehicle Research

Introduction

CSIRO conducts a range of research related to electric vehicles and the infrastructure requirements associated with developing electric vehicle transport systems, including the role of hydrogen technologies in hydrogen fuel cell electric vehicles. CSIRO has a portfolio of research and capabilities relevant to electric vehicles and, for example, hydrogen membrane technologies which are the first of their kind worldwide.

With respect to hydrogen, CSIRO is developing technologies to support accelerated development of hydrogen production, storage, transport, export and utilisation for fuel cell electric vehicle systems. With the global market for hydrogen expected to grow over coming years, and Australia's extensive natural resources amenable to hydrogen production (refer to the recent Chief Scientist briefing paper for COAG Energy Council and CSIRO's Hydrogen Roadmap published recently (Commonwealth of Australia, 2018; Bruce *et al*., 2018)), this CSIRO work is contributing to the prospect of a new export energy industry for Australia based on low emission and renewable hydrogen energy systems. This technology would co-exist with battery electric vehicle technologies, and existing transport options, in Australia's future transport fleet.

CSIRO is working on technologies relevant to electric vehicles and alternative fuels by:

- looking at the potential benefits of transition to renewable and low emissions fuels for transport applications including work relevant to Fuel Cell Electric Vehicles (FCEV) and battery Electric Vehicles (EV);
- supporting the development of relevant supply chains including hydrogen fuels, and second-life applications and recycling for batteries;
- activities throughout the entire value chain of lithium batteries, from mining and resource production, battery development, battery applications and second-life and end-of-life management;
- developing ionic liquids as an electrolyte to improving battery safety, and next-generation batteries using lithium sulphur that could halve the weight of a current car battery; and
- developing renewable technologies, cleaner coal utilisation technologies, smart grid and load management all of which can be utilised to find targeted solutions to the concerns of how increased electric vehicle use could impact electricity network infrastructure.

We also note that a useful UK roadmap for electric vehicles is available (Advanced Propulsion Centre, 2018), which covers many of the issues the committee is concerned about and in CSIRO's assessment is technically sound (though UK oriented).

Battery Research and Technology

CSIRO has been active in battery research for a number of years. With regards to lithium battery research, the following information summarises recent/current areas of activity.

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.

CSIRO has been developing ionic liquid electrolytes for lithium metal batteries for a number of years and is now in the process of commercialising the technology. Ionic Liquids can be used as an alternative electrolyte material in batteries, as they are non-volatile and non-flammable, potentially offering safety improvements in lithium (ion) batteries. Ionic Liquid electrolytes are 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 continues to develop this technology and newer materials based on polymerised ionic liquids, with partners at Deakin University, to enable all solid-state-batteries.

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

Devices

CSIRO is continuing development of a lithium-sulfur battery technology. The lithium-sulfur battery can offer 2-5 times more energy density then the most advanced lithium-ion battery due to the theoretically increased energy density limits of the sulfur cathode. This technology poses a number of materials challenges which CSIRO has spent a number of years exploring.

CSIRO has been developing a textile based flexible battery for a number of years (since 2009) and a technology based on lithium-ion chemistry and ionic liquid electrolytes has been developed and patented. CSIRO is currently working with partners to scale up the technology and to explore commercialisation options.

CSIRO is developing a lithium microbattery to power small sensors such as those used to monitor the behaviour of bees, medical sensors and implantable devices, micro robotics etc. All of these applications require high power but at very small size. Conventional batteries are far too large to be used in these applications.

CSIRO has been working with PMB Defence in South Australia for a number of years, including in relation to technology improvements to their lead acid battery technology for submarines as well as to assist the company in the understanding and adoption of lithium-ion batteries for submarines and other military applications.

To support these efforts, CSIRO has established a small prototyping capability to assist to scale-up our own technologies as well as support Australian and international industry to take up lithium technologies.

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.

Safety testing

CSIRO is soon to commission a testing facility that will test operating residential lithium battery systems to various real-life scenarios, investigating safety and installation risks associated to lithium battery systems.

Additional information

CSIRO, as the host organisation together with its University partners and Business Events Sydney, will host the 21st International Meeting on Lithium Batteries (IMLB) in Sydney in 2022. This meeting is the largest meeting of its type in the world, with more than 1500 delegates attending to discuss all aspects of lithium technology. This will be an exciting opportunity for Australia to showcase both its R&D contributions and Industry within the lithium battery value chain.

Electric Vehicle Technology

SiC and GaN Power Devices

Power switching devices are an integral part of all modern electric vehicles (EVs), with their primarily use in the motor controller and battery charger (both fast and slow chargers). New devices based on Silicon Carbide (SiC) and Gallium Nitride (GaN), as opposed to Silicon (Si), are emerging. These new devices switch more quickly and hence have lower switching losses, primarily because the switching transient is shorter. These lower losses give greater efficiency which in turn means less cooling is required. A useful reference document is the UK Towards 2040 roadmap (Advanced Propulsion Centre, 2018), section 9 of which deals with Power Electronics.

The net effect is:

1. Motor inverters and chargers are smaller and lighter, with an approximately 40% volume reduction (Mishra, 2013) for the chargers and about half this, 20%, for the motor controller. The weight reduction will be about half the volume reduction, i.e. 20% for chargers and 10% for motor controllers). The improved power semiconductors help the chargers more than the motor controllers because the increased switching frequency allows a reduction in size and cost of inductors and capacitors as well as the cooling. This is not true for the motor converter which only sees the benefit of improved cooling.
2. Efficiency is improved; this effect is small, about 2% (because the efficiency of Si power devices is already good – therefore there is little room for improvement). Current power electronics are at least 95% efficient and the new devices can save about half their loss, hence 40% volume reduction, and hence an efficiency improvement of at most 2.5%.
3. The cost of devices is falling (Town, 2015) particularly for GaN based devices, and therefore EV costs will fall by about 0.06% per year. The effect of falling power device cost on a vehicle cost is small since the cost of power switches is only a small part of the overall vehicle cost. The cost of the power electronics is only 2% of vehicle cost (https://drive.google.com/file/d/0B20d92QYF8ZTVUUtWDhxb1I0YU0/view), and therefore the predicted 3% per year cost reduction of the power electronics (Advanced Propulsion Centre, 2018) amounts to 0.06% per year for the vehicle.

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 from a major vehicle manufacturer, but could be a problem from a small manufacture or 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, 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 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 (who plan to start limited production next March), 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/).

Manufacturing cost of electric vehicles

The cost of a vehicle is approximately 47% materials, 21% direct labour, and 32% other (https://www.statista.com/statistics/744910/cost-breakdown-of-car-production-by-segment/). Comparing an electric vehicle (EV) to a conventional vehicle, the materials and labour will change but the other costs will remain essentially the same. The net cost difference between a conventional car and an EV is that the cost of an EV is around $11,000 more at present (https://www.ucsusa.org/sites/default/files/attach/2017/09/cv-factsheets-ev-incentives.pdf?_ga=2.108452610.1630188791.1517413160-1434713090.1436805699). That difference is the cost of the EV drivetrain, ($19,000), minus the cost of a conventional drivetrain. However, over time this cost difference will diminish and both The Union of Concerned Scientists (https://www.ucsusa.org/sites/default/files/attach/2017/09/cv-factsheets-ev-incentives.pdf?_ga=2.108452610.1630188791.1517413160-1434713090.1436805699) and UBS (https://drive.google.com/file/d/0B20d92QYF8ZTVUUtWDhxb1I0YU0/view) predict price parity in 2023. This reduction in cost is primarily due to a decrease in battery costs and a much smaller effect of reduced electronics costs.

Taken together, this information suggests that after 2023 EVs could be expected to be cheaper to produce than conventional vehicles.

Automation of battery plants is key to being able to produce batteries 24/7 to deliver volume to the market. Such plants are likely to support skilled jobs due to the need to design electrode mixtures, coating techniques and component assembly processes.

Hydrogen Energy Systems

Australia has access to vast energy resources through sun, wind, biomass, natural gas, and coal, all of which can be used as feedstock to produce hydrogen (H_2) and/or the desired carrier feedstock. Australia's significant resources mean we are well positioned to be an exporter of H_2, and to make significant domestic use of H_2 in transport and power generation and potentially to offset natural gas use in the gas network.

Deployment of hydrogen 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 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 and through the use of a range 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 have recently released a review and outlook for hydrogen energy systems at the global scale which indicates strong growth in the FCEV 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 at scale, 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 (https://www.iea.org/publications/freepublications/publication/essentials5.pdf, https://www.iea.org/publications/freepublications/publication/TechnologyRoadmapHydrogenandFuelCells.pdf).

To achieve carbon reduction objectives, and develop an impactful hydrogen export industry, supply chains must evolve to derive feedstock from a range of processes including:

- decarbonised fossil fuel sources (coal gasification or natural gas reforming with CCS)
- biomass and waste conversion
- water electrolysis driven by renewable electricity from solar PV, solar thermal, wind and hydro
- 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, particulate emissions and photochemical smog precursors.

Development of hydrogen energy systems to support fuel cell electric vehicles and associated value chains will be supported and enabled by focussed R&D. Current activities being undertaken by CSIRO and its partners to increase the efficiency of H_2 production, storage, transport and utilisation. These 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 processes. These processes could be combined with existing coal and gas based hydrogen production technologies (with CCS) to achieve large scale low emissions hydrogen production pathways to support development of zero emissions at point of use applications enabling decarbonisation of energy and transport systems both domestically and in export markets.

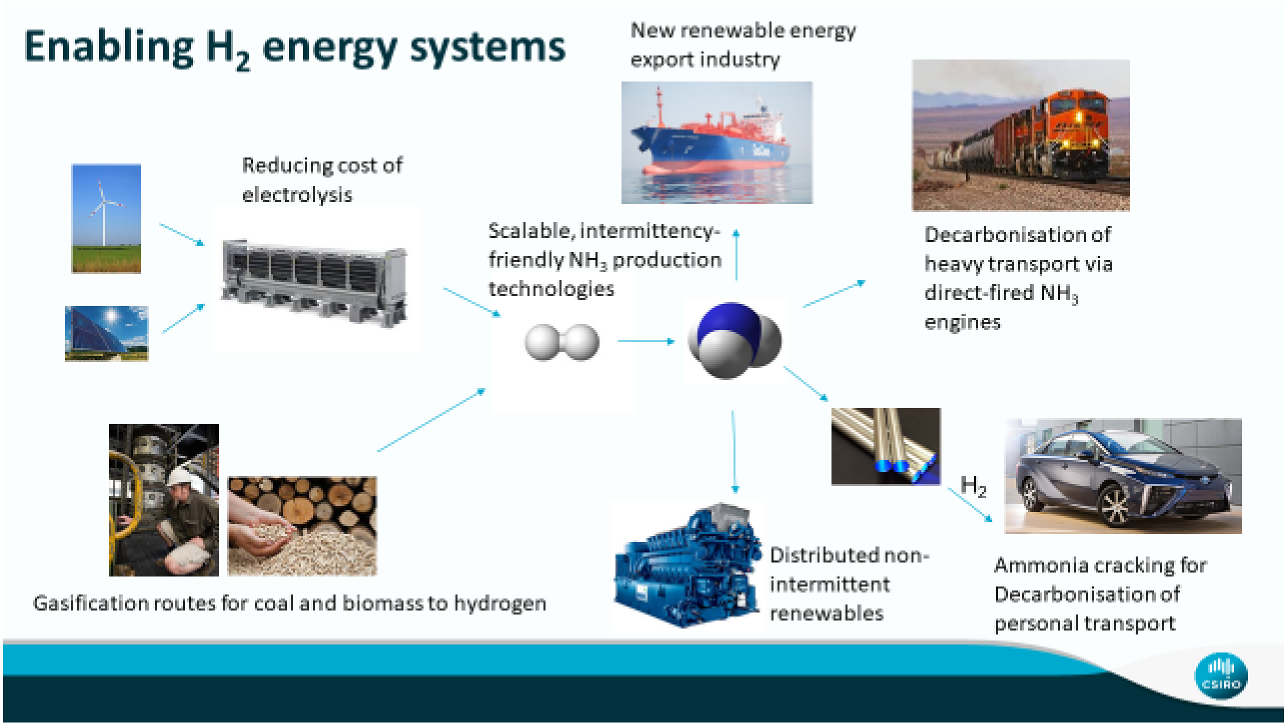


Figure 1 Example of hydrogen energy value chain based on renewable hydrogen production using ammonia as a hydrogen carrier (Source: CSIRO).

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.

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 energy routes, but will shift towards more renewable routes as renewable electricity is harnessed to drive electrolysis processes and other renewable energy sources.

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 maximize gravimetric density (i.e., the weight % of hydrogen) and volumetric density (i.e., the mass of hydrogen per volume). Hydrogen is the lightest gas, and requires significant energy input to liquefy. This is the reason that currently most of the hydrogen used in industrial and commercial processes is either manufactures at the point of use (such as in refineries) or transported as compressed hydrogen gas at about 200 bar. The volumetric density is very low, however, at just 20 kg/m^3.

Liquid hydrogen is the transport medium being explored by Kawasaki Heavy Industries in their HSEC project 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. This aspect, the international, ship-based transport of liquid hydrogen at scale, is a primary aim of the KHI HESC project.

There is extensive worldwide attention on a range of possible commercial hydrogen carrier materials. Other traded commodity products such as methanol, methane (as compressed natural gas or LNG), methyl cyclohexane and other hydrocarbon carriers are being considered. Many of these alternatives, being hydrocarbons, produce CO_2 on use and, depending on the source, may not be practical as suitable low, or zero, emissions energy carriers.

Ammonia (NH_3) is a carbon-free chemical which is 17% hydrogen by weight, and in liquid form, contains 120 kg/m^3 by volume of hydrogen. This is about 70% more 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.

Where ammonia suffers in comparison to liquid hydrogen, is in the technologies which enable it to be used directly as a fuel, or converted back to hydrogen for proton exchange membrane (PEM) fuel cells. Research programs in Japan, USA and in Australia (including CSIRO) are developing direct-ammonia combustion technologies for large-scale power generation or propulsion. There are also advanced programs developing direct-ammonia fuel cells for high-efficiency stationary power generation. However, to access the rapidly growing hydrogen fuel cell vehicle fleet, it is necessary to extract high-purity hydrogen from ammonia close to the point of use.

Figure 1 illustrates the use of ammonia (NH_3) 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, the immediate market opportunity is being driven by increasing development and deployment of Fuel Cell Electric Vehicles operated on pure hydrogen.

CSIRO's membrane technology potentially has a key enabling role in this value chain as it can be used to purify H_2 from ammonia and 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 tonne is used for energy applications. Hydrogen is mostly produced from natural gas (NG), oil and coal. Around 50% of the global hydrogen is produced by NG steam reforming. The hydrogen production efficiency from this route is ~ 64% (low heat value basis), and results in around 9 kg CO_2 per kg of hydrogen produced (Commonwealth of Australia, 2018). Brown coal can achieve around 55% efficiency and the best figure quoted is around 20 kg CO_2 per kg of hydrogen produced (Bruce *et al.*, 2018). Therefore hydrogen produced from fossil fuels will require carbon capture and storage (CCS) for zero CO_2 emissions. 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 CO_2 emissions. Two types of technologies are used for electrolysis – alkaline solution (KOH) and PEM. The alkaline solution based electrolysis is a mature technology. PEM based technology can respond more rapidly to the variations in electricity supply, and therefore is considered more suitable for renewable energy sources. This technology is rapidly gaining maturity but is currently relatively expensive. Both technologies require pure water supply and other balance of plant for separating gases from water, and hydrogen compression to around 880 bar for automotive applications. Each kg of hydrogen produced requires 9 kg of water. 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 dependant.

Solar thermal technologies are also capable of being configured for hydrogen production and for 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**.

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

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 intercontinental 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 additional energy. Ammonia and MCH both require energy input during formation as well as during conversion back to hydrogen. Ammonia offers number of favourable attributes such as a carbon free fuel that can be used to produce power or decomposed to produce hydrogen, can be transported as liquid at near ambient conditions using well established infrastructure, 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 conventionally produced by the Haber-Bosch process using hydrogen 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, and contributes to over 1% of global energy related CO_2 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. 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.

CO_2 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 CC facilities currently operating. To date over 220 million tonnes of man-made CO_2 has been injected underground. The longest-running storage project is Sleipner, offshore Norway, which has been capturing and injecting CO_2 since 1996 and has injected over 17 million tonnes to date (https://www.globalccsinstitute.com/projects/sleipner%C2%A0co2-storage-project).

Technical aspects: These include the transport of CO_2 from the production site and storage of CO_2 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 CO_2 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 CO_2 for injection and storage into suitable geological reservoirs.

The US has an extensive network of pipelines transporting CO_2 from the source of generation to sites where the CO_2 is used for enhanced oil recovery. The CO_2 is injected and effectively pushes trapped oil towards production wells. The CO_2 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 CO_2 from coal fired steam power stations, however, the capture costs are associated with combustion based processes where CO_2 is captured from a dilute flue gas and are transferrable to oxygen-blown gasification processes producing hydrogen where the CO_2 is produced as a high concentration, high pressure gas stream. In this situation, the CO_2 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 CO_2 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 CO_2 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 CO_2 for both social licence to operate (SLO) and greenhouse accounting purposes. The underlying concept for monitoring requires it to be scientifically valid and defendable while affordable.

CarbonNet are examining a number of injection sites. The costs for each site have been estimated as between $6 and $24/t CO_2 injected (CO2CRC, 2015).

<u>Social license to operate:</u> This is an important consideration in CCS projects, both onshore and offshore. The environmental benefits of storing CO_2 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.

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 (as noted earlier). Simply, within the EV context, the more energy stored is directly proportional to the range of the vehicle. 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 $LiCoO_2$ cathode material increases the operating voltage from 4.2V, for example up to 4.7V for $LiNiMnCoO_2$ (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 then 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 S and a cathode (positive electrode) that contains S within an electronically conductive network. Typically, S is infused into an electrically conductive network, such as carbon, where Li ions can react with the infused S 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 CSIRO’s experience in lithium metal batteries and ionic liquid electrolytes to prevent this occurring was the rationale for our Li-S battery development.

The key driver globally for Li-S batteries development at present is electric vehicles to increase the km per charge values. 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 showing better performance, however translation to commercial success is limited due to the economics of scaling up to commercial production levels. As such continued R&D 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 R&D 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 2 years that this project ran for, we 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, we use Ionic Liquid electrolytes (described shortly) due to their stability with lithium metal and we seeking to design cathode materials and improve our 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 we have focussed on cathode optimisation studies, use of CSIRO's Polymerised Ionic Liquid Blocks (PILBLOx) technology[1] to film cast ionic liquids onto cathodes to improve the cathode performance by reducing or limiting polysulfide migration into the electrolyte. We have also explored use of our PILBLOx technology to modify the electrolyte to reduce or mitigate polysulfide dissolution to improve the lifetime and performance of the battery systems. Finally we have continued out anode development work by investigating 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 still continuing and CSIRO is actively seeking to engage with new industrial clients to further progress the development.

Based on our understanding of the area, CSIRO would estimate that lithium-sulfur batteries would be commercially available in the next 1 to 5 years for low cycle applications and if key R&D solutions are found then also for automotive applications within the next 10 years.

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. 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.

[1] Polymerised Ionic Liquid Blocks (PILBLox) are solid materials for next generation devices (see Ionic Liquid electrolytes)

Infrastructure Safety

Cost of refuelling infrastructure safety: There are internationally recognised standards for all aspects of both refuelling and recharging infrastructure. As far as we are aware there have been no persistent major safety issues with either refuelling or recharging infrastructure. In terms of the major hazards associated with refuelling they largely relate to the handling of high pressure gas and the potential to create a hazardous (explosive) atmosphere. In terms of recharging a vehicle there are concerns around electrocution but this is very unlikely due to the communication protocols and connectors used in commercial charging stations. The major hazard with fast charging any battery system is always fire. This is very well managed within commercial charging stations with very few instances of cars catching fire during charging.

Relative cost of charging and refuelling infrastructure requirements: It is difficult to give a definitive answer to this issue as there are many unknowns. The cost of electric vehicle charging infrastructure is significantly lower than that of hydrogen refuelling infrastructure. The cost of a 50 kW DC fast charging station for an electric vehicle is in the order of $60,000 AUD (https://arena.gov.au/assets/2018/06/australian-ev-market-study-report.pdf). The cost of a refuelling station is typically in the order of $2-10 million AUD (Bruce *et al*., 2018; Commonwealth of Australia, 2018). The upper end of this range applies to stations that include on-site production of hydrogen using grid-connected electrolysis.

This infrastructure cost is not directly comparable as the two technologies are used in very different manners. Battery EV charging takes longer and is mainly done at home or work with infrequent fast charging of the vehicle on long journeys. The comparatively slow charging rates means that there is a requirement for significantly more charging stations compared to traditional refuelling infrastructure. Estimates from the Clean Energy Finance Corporation (https://www.cefc.com.au/media/files/australia-set-for-surge-in-electric-vehicles-and-infrastructure-in-just-four-years-new-modelling/) suggest that around 28,400 publicly accessible DC fast charging stations would be required to cater for a high penetration (100% of the light vehicle market) of battery electric vehicles. This is significantly higher than the approximately 6400 conventional fuelling stations currently in Australia. The total installed cost of such a network was estimated to be around $1.7 billion AUD. This estimate does not include the cost of home recharging stations, public slow charging stations or work place charging stations. We are unaware of any accurate estimation or modelling of how many slow charging stations would be required.

In nations with more developed EV markets, such as the UK, the ratio of publicly accessible fast charging stations to slow charging stations is approximately 1:4 (https://www.zap-map.com). It is unclear if this ratio would be maintained within Australia but it is likely that the number of slow chargers would be significantly larger than that of fast chargers. The lower cost of these charging stations (typically around $1000 AUD) would lead to additional costs for slow charging being relatively modest (around 5-10% of the fast charging cost). There has been no detailed modelling of the number of refuelling stations that would be required to support a fleet of fuel cell electric vehicles (FCEVs) within Australia, however, it is likely that the number of refuelling stations would be approximately equivalent to the current petrol refuelling infrastructure leading to around 6400 stations being required, with an approximate cost of around $2-10 million per station. This would equate to $13-64 billion AUD to replace the entire refuelling infrastructure within Australia with a hydrogen alternative. Hydrogen refuelling infrastructure is as a very early stage of deployment and there is potential for a significant reduction in the cost of hydrogen refuelling infrastructure. This could lead to further reductions in the cost of a refuelling network within Australia (Bruce *et al*., 2018). FCEV and BEV's are technologies that are highly complementary to each other and it is likely that neither technology would fully replace the other.

Role of transport and stationary energy in meeting emissions reduction targets

CSIRO's Low Emissions Technology Roadmap (Campey *et al*., 2017) considered four different pathways to achieve Australia's emission reduction targets as agreed to in the Paris Climate Change Agreement:

1. Energy productivity plus – ambitious energy productivity improvements in buildings, industry and transport to reduce demand for energy
2. Variable renewable energy – business-as-usual (BAU) energy productivity with high levels of uptake of variable renewables for electricity generation
3. Dispatchable power – BAU energy productivity, hydrogen for transport and export, a 45% limit on variable renewables for electricity generation and a range of other low emissions technologies for electricity generation
4. Unconstrained – ambitious energy productivity improvements, hydrogen for transport and export and all low emissions technologies allowed for electricity generation.

In each pathway, the electricity sector makes a greater contribution to emissions reduction than the transport sector (see **Figure 18** taken from the report below). By comparing the projected 2030 emissions with those of each pathway, it can be seen that emissions from the electricity sector are projected to reduce by ~50% and those of transport to reduce by at most 25%.

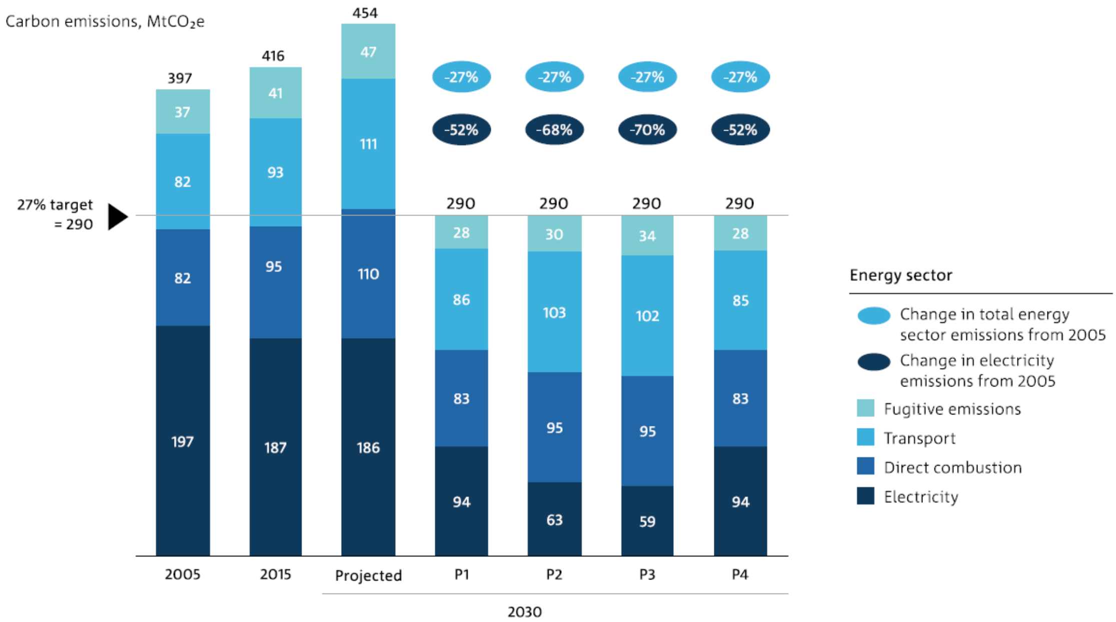


Figure 18. 2030 abatement achieved by each pathway[46]

The projected emissions from each pathway by 2050 are shown in **Figure 20** (taken directly from the report). The electricity sector again makes the greatest contribution to emissions reduction, by at most 95% compared to the projected 2030 emissions while transport reduces emissions by at most 57%.

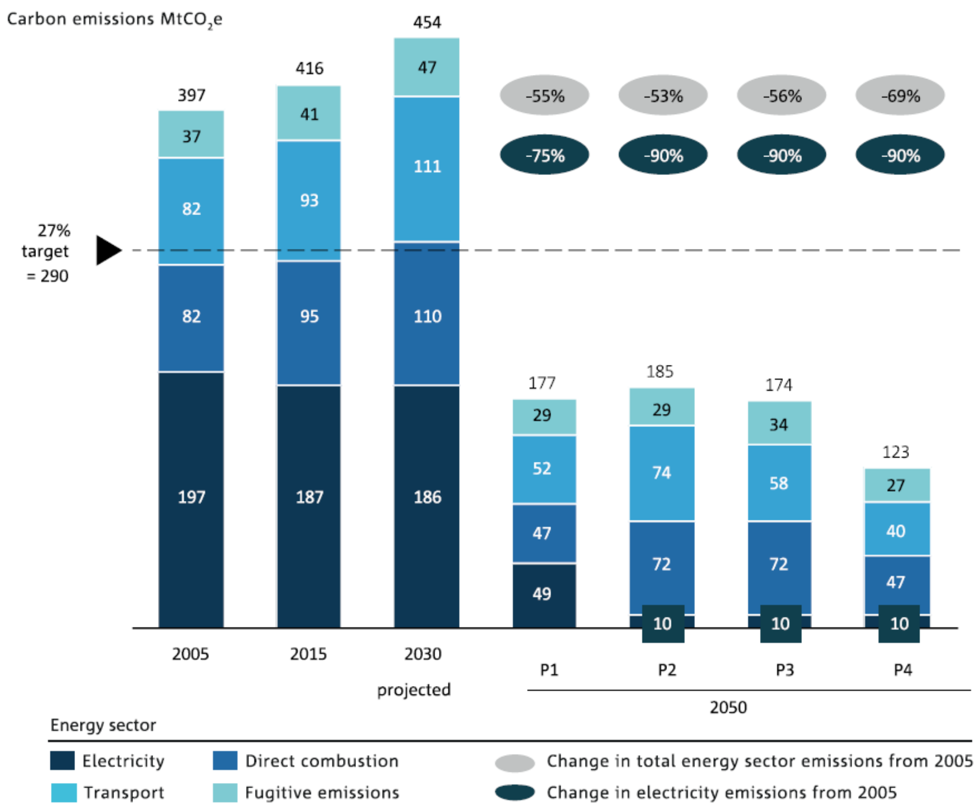


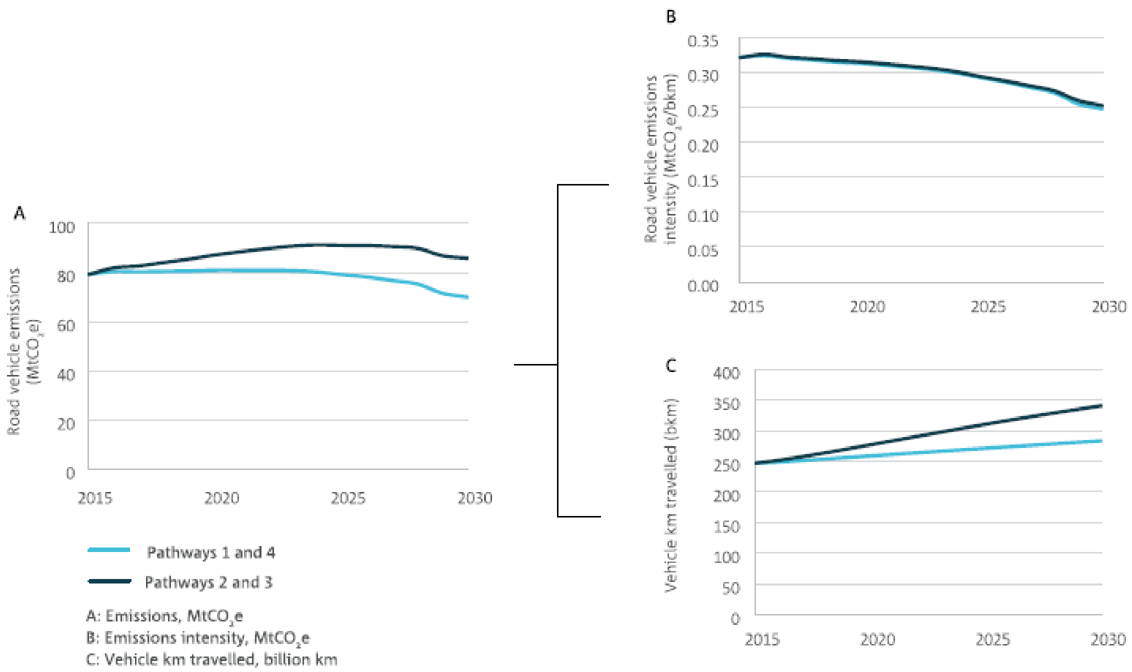
Figure 20. 2050 abatement achieved by each pathway

In 2015 the road transport sector was responsible for 85% of emissions. Most of the potential abatement in this sector in 2030 is likely to stem from vehicle efficiency improvements, which can offset projected growth in transport demand. Vehicle efficiency improvements include fuel switching (biofuels, compressed natural gas and LNG in freight), uptake of electric vehicles and fuel cell electric vehicles and improvements to fuel economy in internal combustion engines. However, switching to EVs and FCEVs is not expected to have a big impact by 2030 on reducing transport emissions but this is anticipated to increase by 2050.

Reductions in demand for road transport also reduces emissions; technologies expected to achieve this are mode shifting to public transport, use of bicycles and improved urban design. Improved logistics and routing, mode shifting and innovative business models could result in demand reduction in freight.

In terms of air transport, biofuels and aircraft improvements to aerodynamics for example can help to reduce emissions.

A comparison of the different pathways' modelled road transport projections out to the year 2030 is in shown in **Figure 16** (taken directly from the report). The emissions intensity is assumed to be the same in all pathways but demand for road transport is lower under Pathways 1 and 4, which reduces emissions.



Pathways 1 and 4
Pathways 2 and 3

A: Emissions, MtCO$_2$e
B: Emissions intensity, MtCO$_2$e
C: Vehicle km travelled, billion km

Figure 16. Road transport modelling results

Concluding Remarks

CSIRO has a number of ongoing projects that are looking at the potential benefits of transition to low emissions and renewable fuels for transport applications. This includes work relevant to Fuel Cell Electric Vehicles (FCEV) and battery Electric Vehicles (EV). Both technologies are synergistic making it possible that both forms of drivetrain will co-exist within the Australian transport fleet in the future. Large scale adoption of these technologies will potentially provide a number of benefits to Australia including decarbonisation of the transport fleet, reduced air pollution, reduced costs of motoring via increased efficiency, greater fuel security and a reduction in the cost of imported fuels.

In order to realise these benefits CSIRO has active projects in life cycle analysis, air quality monitoring and the development of new technology concepts for charging and refuelling infrastructure.

CSIRO is also developing technologies to support accelerated development of hydrogen production, storage, transport (including export) and utilisation for fuel cell electric vehicle systems. This could facilitate a new export energy industry for Australia based on low emission and renewable hydrogen energy systems.

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