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CSIRO Submission 18/647

Inquiry into automated mass transport

House of Representatives Standing Committee on Infrastructure, Transport and Cities

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Introduction

CSIRO welcomes the opportunity to contribute to the Standing Committee on Infrastructure, Transport and Cities' inquiry into automated mass transport. CSIRO offers comments regarding the Committee's stated areas of interest in mass transit systems and autonomous vehicles below and the main body of the submission relates to the Committees interest in "the role of new energy sources, such as hydrogen power, in land-based mass transit".

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. 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.

Our comments relate to the following aspects of the hydrogen value chain:

- Hydrogen energy systems;
- Hydrogen production;
- Hydrogen carriers;
- Carbon capture and storage (CCS).

This information has been extracted from a separate CSIRO submission provided to the 'Senate Select Committee on Electric Vehicles' inquiry into the use and manufacture of electric vehicles.

Relevant research conducted by CSIRO in mass transit systems and automated vehicles includes:

- **Transport Network Strategic Investment Tool (TraNSIT)** – CSIRO's TraNSIT tool analyses transport and logistics options for freight to identify potential cost savings. TraNSIT works by analysing every possible combination of transport routes and modes (road and rail) and determining those that optimise vehicle movements between enterprises in the freight supply chain, particularly agriculture, forestry, fuels and mining. CSIRO recently applied TraNSIT to inform the Federal Government's $100 million Northern Australia Beef Roads Programme, $3.5 billion Roads of Strategic Importance and maximise transport cost savings from infrastructure investments. Along with costs, TraNSIT also provides other transport measures such as greenhouse gas emissions, vehicle t-km etc. (www.csiro.au\TraNSIT)
- CSIRO's Data61 has a range of projects and capabilities relevant to this inquiry. Some examples of work underway (not comprehensive) include:
- **Traffic Congestion Management** – Data61 has partnered with Transport for NSW (TfNSW) to help improve the efficiency and effectiveness of transport systems (https://www.transport.nsw.gov.au/newsroom-and-events/media-releases/premiers-innovation-initiative-big-data-to-help-manage). This work includes analysing automated end-to-end, multi-modal journey planning for operators and passengers. Data61 and TfNSW have jointly developed a prototype artificial intelligence (AI) engine for congestion management. This tool is the first of its kind in Australia and is being integrated with TfNSW's Intelligent Congestion Management Program for mass transit network management. Using this tool, it is possible to model the impact of network changes or disruptions and then issue automatic journey planning information for transport operators and travellers. (https://www.its-australia.com.au/events/its-australia-awards/)
- **On-demand public transport** - Data61 and partners including TfNSW, AECOM, Keolis Downer, Via and GoGet have collaborated to operate on-demand, point-to-point passenger transport in

Sydney's northern beaches and Macquarie Park, which currently includes automation of bookings, routing and driver assignment. (https://www.transport.nsw.gov.au/data-and-research/nsw-future-mobility-prospectus/nsw-future-mobility-case-studies/procurement-as-3)

- **Autonomous vehicle networks** – Data61 has been heavily involved in a test bed deployment of connected vehicles and traffic signals in partnership with TfNSW. Providing technology leadership and project management, Data61 has helped deliver Australia's first semi-permanent test bed, known as CITI. CITI provides a significant and unique research platform for TfNSW and Data61 to investigate a number of fundamental problems for connected vehicles. (https://research.csiro.au/ng/research/network-measurement-modelling/avn/)

- **Transport Logistics** – Data61 has expertise in developing solutions to transport logistic problems, for example: Data61 has designed a hub-and-shuttle service which costs no more than current services and simulations have shown the system is capable of improving the convenience of off-peak services (https://research.csiro.au/data61/logistics-supply-chains-and-transportation/); and additionally Data61 has assisted a leading Australian Fast Moving Consumer Goods company to improve delivery driver routes (https://research.csiro.au/optimisation/research/last-mile-logistics/).

CSIRO would be pleased to provide further information to the Committee regarding any of the research topics listed above and in the following pages.

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 we are well positioned to be an exporter of hydrogen and to make significant domestic use of hydrogen in transport and power generation and, potentially, 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 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 through the use 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 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 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 develop an impactful hydrogen export industry, supply chains must be developed to produce hydrogen 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 oxides, particulate emissions and photochemical smog precursors.

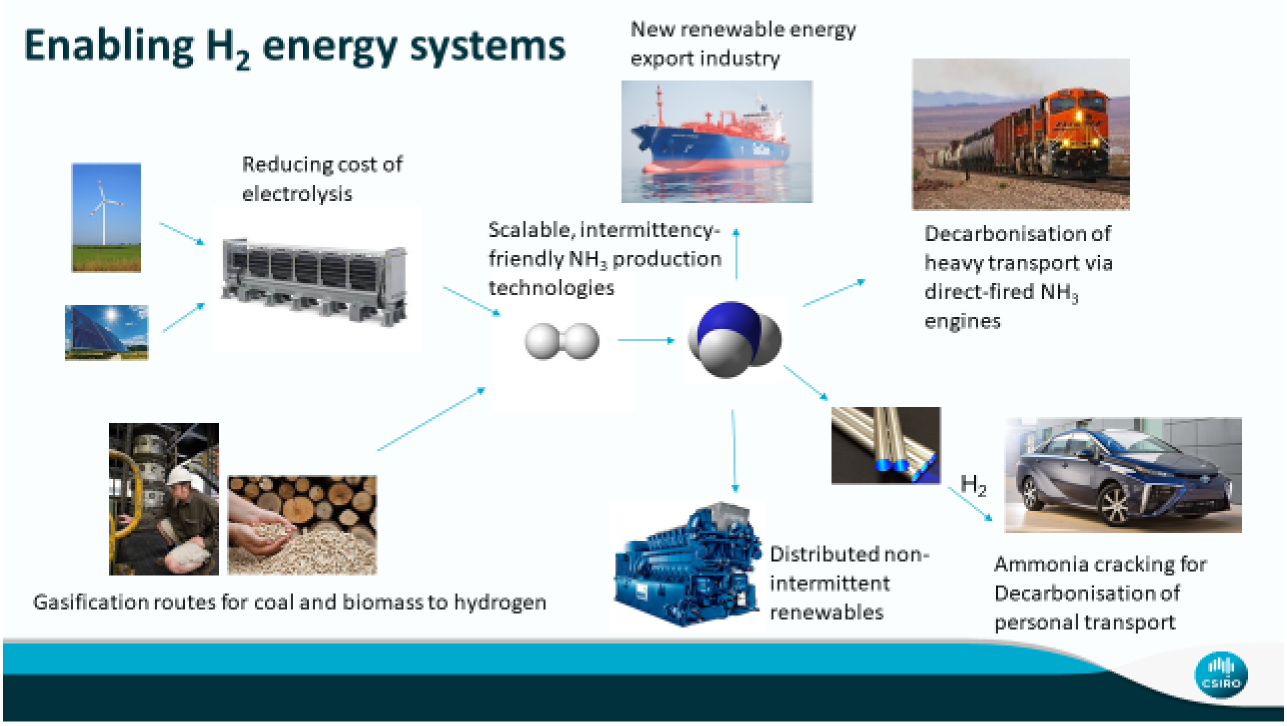
Development of hydrogen energy systems to support fuel cell electric vehicles and associated value chains will be supported and enabled by focussed R&D. Current activities being undertaken by CSIRO and its partners to increase the efficiency of hydrogen production, storage, transport and utilisation. 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.



Enabling H_2 energy systems

New renewable energy export industry

Reducing cost of electrolysis

Scalable, intermittency-friendly NH_3 production technologies

Decarbonisation of heavy transport via direct-fired NH_3 engines

H_2

Gasification routes for coal and biomass to hydrogen

Distributed non-intermittent renewables

Ammonia cracking for Decarbonisation of personal transport

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 fuel based energy routes, but will shift towards more renewable routes as renewable electricity is harnessed to drive electrolysis processes and other renewable energy sources, such as biomass and waste streams are, processed 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 maximize gravimetric density (i.e., the weight % 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 is the lightest gas, and 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 200bar, is very low, however, at just 20 kg/m^3.

Liquid hydrogen is the transport medium being explored by Kawasaki Heavy Industries in their HESC 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 and application, 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% 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.

Where ammonia suffers in comparison to liquid hydrogen, is in the relative paucity of technologies which enable it to be used directly as a fuel, or converted back to hydrogen for proton exchange membrane (PEM) fuel cells such as those used in commercial fuel cell electric vehicles. Research programs in Japan, USA and in Australia (including CSIRO) are developing direct-ammonia combustion technologies for large-scale power generation or transport applications. There are advanced programs developing direct-ammonia fuel cells for high-efficiency stationary power generation and large scale internal combustion engine technologies capable of being fueled directly with ammonia. 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 are being developed, 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 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. 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) to achieve 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 direct CO_2 emissions. Two types of technologies are currently 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. Each kg of hydrogen produced from water electyrolysis 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 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, 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 conventionally 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, 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, integration with CCS is necessary. These hydrogen production processes (e.g. gasification of coal) can typically present the carbon dioxide as a concentrated form which can significantly bring down the costs of capture. 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 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 CO_2 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 in these applications are associated with combustion based processes where CO_2 is captured from a dilute flue gas and these are not transferrable directly 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 and costs of capture of CO2 are consequently lower than from dilute, combustion-based systems. There are fewer cost estimates available for the cost of transport and storage of CO_2 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).

Social license to operate: 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.

Concluding Remarks

CSIRO has a range of research capabilities and projects relevant to mass transit systems and automated vehicles.

Deployment of hydrogen systems and infrastructure is gaining considerable momentum globally. CSIRO and other research and industry groups are exploring and developing new technologies across the hydrogen 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.

CSIRO would be pleased to discuss any aspects of this submission with the Committee including our work in autonomous vehicles and mass transit systems.

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