Hydrogen Liquefaction & Storage Workshop

Workshop Outcomes Report

DRAFT

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Introduction and Objectives

The transport and storage of hydrogen in the liquid state has been identified as key energy vector option for Australia's prospective hydrogen export industry. The liquefaction process and storage of liquid hydrogen needs to be efficient and safe for this option to be viable from an economic and ecological point of view. However, current technologies that enable this option are limited by many challenges including cost, energy consumption, materials design and boil-off gas, making the identification and development of more advanced liquefaction processes crucial.

Hydrogen liquefaction is an energy intensive process that requires a significant number of stages to reach the temperature at which hydrogen gas becomes liquid (around 20 K at atmospheric pressure). The first step of the process involves pre-compression of the hydrogen feed gas. Hydrogen is then cooled using a closed loop cryogenic refrigeration cycle down to temperatures between (20 and 30) K. This cycle requires a continuous or batch catalytic conversion of ortho to para hydrogen. The final step in the process is adiabatic expansion, which either takes the form of Joule-Thompson expansion or turbine expansion depending on the process design. Hydrogen is then stored in the form of liquid in a storage tank or shipped.

On 26 and 27 September 2019, the ARC Centre for LNG Futures (ACLNGF) hosted a workshop at the University of Western Australia, which brought together global and local experts on H_2, cryogenics, natural gas and LNG to achieve the following objectives:

- Address and share the latest research and technologies available for hydrogen liquefaction and storage.
- Understand driving forces, current efforts and future plans for industrially-focused liquid H_2 research, both in Australia and internationally.
- Learn about the proposed Future Energy Exports CRC, its potential capabilities for industrial-scale testing at high-pressures and cryogenic temperatures, and the proposed R&D program for a hydrogen export industry.
- Develop an industry-led R&D plan to accelerate the growth of liquid hydrogen exports from Australia that is complementary and avoids duplicating existing initiatives.

A total of 67 participants attended the workshop, representing industry organisations, government agencies, and research institutions in Western Australia, Victoria, New South Wales, Japan, the United States, Germany and the United Kingdom. The workshop schedule is shown in **Table 1** and **Table 2**, and includes a list of the speakers and their presentation titles: copies of the slides from these presentations can be downloaded from www.lngfutures.edu.au/.

On each day, at the conclusion of the presentations, two workshop sessions were held with participants asked to identify key challenges in the following areas: (**1**) liquefaction, (**2**) thermodynamics, (**3**) storage and transport, and (**4**) policy, standards, regulation and social license. Each group then identified the key technologies or ideas required to overcome this challenge and the infrastructure and research needed to support this work. Quick wins and future partners were then discussed. Subsequently, the ideas from each workshop group were summarised and presented to all the workshop participants by each group's facilitator. A summary of the results from the breakout session is listed in **Table 3.**

Table 1: Day 1. Agenda and presentations delivered at the workshop. The slides are available from www.lngfutures.edu.au/

08:30am - 09:00am	**Registration Open**
09:00am - 9:15am	Eric May (The University of Western Australia) Opening and Introduction
09:15am - 9:45am	Amy Tait (Manager, Energy Futures Team- Department of Primary Industries and Regional Development) Hydrogen Economy in Australia: National and State Strategy
09:45am -10:15am	Saif Al Ghafri & Stephanie Munro (The University of Western Australia) Technical Challenges in Hydrogen Liquefaction: Overview
10:15am - 10:30am	Morning Tea
10:30am - 11:15am	Bill Notardonato (NASA, Kennedy Space Centre Exploration Research and Technology Programs) NASA's Experience with Large Scale LH_2 Operations
11:15am - 12:00pm	Jacob Leachman (Washington State University, HYPER Lab) Understanding the Thermophysical Properties of Cryogenic Hydrogen
12:00am - 13:00pm	Lunch
13:00pm - 13:20pm	Michael Johns (The University of Western Australia) Detection of Para-H_2 using Mobile NMR
13:20pm - 13:55pm	Martin Trusler (Imperial College London) Thermodynamic Principles in Hydrogen Liquefaction Processes
13:55pm - 14:30pm	Rajnish Kumar (Indian Institute of Technology) Hydrogen Hydrates for the Storage and Release of Molecular Hydrogen
14:30pm - 15:15pm	Roland Span (Ruhr Universitat Bochum) Process Simulation - The Need for Accurate Thermodynamic Property Models
15:15pm - 15:30pm	Afternoon Tea
15:30pm - 16:30pm	Day One Technical Workshop
16:30pm – 17:00pm	Day One Wrap Up

Table 2: Day 2. Agenda and presentations delivered at the workshop. The slides are available from www.lngfutures.edu.au/

08:30am - 09:00am	**Registration Open**
09:00am - 09:15am	Eric May (The University of Western Australia) Day One Review and Day Two Overview
09:15am - 10:00am	Thomas Funke (Technische Universität Dresden) Development of Large-Scale Hydrogen Liquefaction
10:00am - 10:45am	Umberto Cardella (Linde Aktiengesellschaft) Large-Scale Liquid Hydrogen Production and Supply
10:45am - 11:00am	Morning Tea
11:00am - 11:30am	Donatella Cirrone (Ulster University) Liquid Hydrogen Safety- PRESLHY project (video conferencing)
11:30am - 12:00pm	Shoji Kamiya (Kawasaki Heavy Industries) Development of the Large Scale Liquid Hydrogen Value Chain
12:00pm - 13:00pm	Lunch
13:00pm - 13:30pm	Garth Pearce (UNSW) Design of a Linerless Carbon Fibre Composite Pressure Vessel for Cryogenic Fuel Tank Applications
13:30pm - 14:00pm	Peter Kasprazk (Innovative Australia, CEO) Australian Hydrogen Highway - Creating a Blueprint for Zero Emission Transport
14:00pm - 14:30pm	Ross Elliott (StarCore Nuclear, Director Business Development – Australia) Some Energy Profiles for Hydrogen as a Transport Fuel
14:30pm - 15:00pm	Eric May and Saif Al Ghafri (The University of Western Australia) Exporting Hydrogen Energy from Australia to the World: Drivers & Technical Challenges
15:00pm - 15:15pm	Afternoon Tea
15:15pm - 16:15pm	Panel Discussion/Day Two Technical Workshop
16:15pm - 17:00pm	Symposium Wrap Up and Next Steps

Major Ideas from Presentations

The following bullet points capture select, key ideas discussed in the presentations and the workshop sessions.

Australia and H_2

- There is considerable potential for hydrogen within the Western Australian Economy, both as a domestic fuel and as an export product. Western Australia is suitable for the development of a hydrogen industry because of: its renewable energy resources, strong trading partnerships, established LNG industry, established port infrastructure, land mass, and its capabilities and skills.
- The key challenges for hydrogen development in Australia and globally include cost/scale, technology, social license and commercialisation.
- The Western Australian government has recently released the Western Australian Renewable Hydrogen Strategy and has recently opened submissions to the WA Renewable Hydrogen Fund ($10m)
- Some of the key hydrogen projects in Western Australia include: the Yara & ENGIE Renewable Hydrogen/Ammonia project, the ATCO Clean Energy Innovation Hub, and the Hazer Group and MinRes Pilot Plant.
- If Australia were to produce hydrogen equivalent to our 2018 LNG exports (70 MT), we would need to produce 30 MT of equivalent liquid hydrogen. This would require 1,980 TWh of energy, or 8 times the electricity produced in Australia in 2018.
- The CSIRO has predicted a base liquefaction cost of approximately $2.57-$3.14 AUD/kg H_2 (not including the cost of hydrogen) for a 50 TPD plant operating with an energy consumption of 9.05 kWh/kg H_2. The cumulative impact of plant size increase (to 210 TPD), favourable electricity pricing and R&D improvements reducing energy consumption to 7.88 kWh/kg is projected to decrease the cost of liquefaction to $1.59-$1.94 AUD/kg H_2. This price decrease would make liquid hydrogen competitive with other technologies like ammonia (base case $1.39-$1.68 AUD/kg including recovery of hydrogen).

Liquefaction

- Current global liquid hydrogen capacity is approximately 350 TPD with over 20 hydrogen liquefaction plants worldwide. The specific energy consumption of these plants ranges between 10 and 15 kWh/kg H_2, dependent on the liquefaction cycle type and the technology used.
- Conceptual liquefaction plants that have been proposed in literature which reduced the specific energy consumption of hydrogen liquefiers to between 4-10 kWh/kg H_2. These values are significantly closer to the minimum exergy for liquefaction of 3.9 kWh/kg H_2.
- The largest known hydrogen liquefaction plant is the Air Products Plant in Los Angeles with a capacity of 70 TPD. This capacity is achieved with two hydrogen liquefiers of 35 TPD each.
- There are currently two Australian projects that feature liquid hydrogen as part of their value chain: the Hydrogen Energy Supply Chain (HESC) Project led by Kawasaki Heavy Industries, J-Power, Iwatani Corporation, Marubeni Corporation, Shell and AGL; and the proposed Collie Synfuels Project. The HESC demonstration project is due to be completed by 2020.
- NMR provides an option for quantification of the amount of parahydrogen in hydrogen. Both direct and indirect detection are available but need to be developed and demonstrated at relevant temperatures.
- Challenges of the overall liquefaction process were identified. These include (1) improving the exergy efficiency and reducing process cost (OPEX); (2) overcoming safety challenges in material

design and boil-off gas; (3) the lack of safety standards and regulation around hydrogen-based processes; and (4) the lack of thermodynamic models that are used in process design and simulation.

- Reciprocating piston-compressors and rotary screw compressors were identified has having reached their limits in terms of flow-rate and efficiency in current liquefaction operations. This was identified as presenting a problem when looking to scale-up hydrogen liquefaction capacity. To overcome this it was proposed that turbocompressors be used on the working-fluid side of the liquefaction process.
- Current liquefaction processes use pure fluids (hydrogen or helium) as the working refrigerant fluid – this was identified as presenting a problem in compression because helium and hydrogen both have low molecular weights and therefore require a significant number of turbocompressors to achieve the desired pressure. In light of this, further work should be performed into understanding the behaviour of mixed refrigerants with higher molecular weights than pure fluids.
- The method of expansion plays an important role in the overall exergy efficiency of the plant. Current liquefiers use Joule-Thompson expansion (which results in considerable losses), or turbines to recover mechanical work from the system. Turbines, although more efficient, are more complex machinery and attract a higher capital expenditure. Future research should be undertaken into the design of large oil-free turbines.
- The dimensions of existing coldboxes, which are used to store cryogenic equipment, were identified as a limiting factor in scale-up of existing plants. As liquefaction equipment becomes larger, so do the required dimensions of the coldbox. This was identified as presenting a problem because coldboxes are required to be transported from the point of construction to site. It was proposed that further research should be done into potential fabrication on site, or the viability of hosting the cryogenic equipment in multiple smaller coldboxes.
- The most commonly used catalyst in hydrogen liquefaction is iron (III) oxide. This para-magnetic catalyst is used to induce the conversion of normal-hydrogen to para-hydrogen more rapidly during liquefaction. The state-of-the-art technology to enable continuous conversion is to pack cryogenic heat exchangers with this catalyst. As a result, considerable pressure drop is experienced across the heat exchanger. To overcome this issue it is proposed that new types of catalysts for para-ortho conversion are investigated and different designs of catalytic heat exchangers are studied – for example coating the inside of heat exchangers.
- It was identified that the 'bigger-is-better' view may not be appropriate for future large-scale hydrogen liquefaction plants. Future work should be conducted into the optimal design for large-scale liquefiers – i.e. one large 1000 TPD liquefier, or 10 x 100 TPD liquefiers.

Thermodynamics

- Due to the complexity of hydrogen (as a result of its quantum nature at low temperatures), there is still a need to improve current thermodynamic models, in particular at conditions relevant to liquid hydrogen. This includes full ortho-para mixture models, transport properties for cryogenic hydrogen, models for mixed refrigerants and for the properties of solid hydrogen.
- Thermodynamic fundamentals place essential constraints on the design of processes such as gas liquefaction; exergy and exergy-based efficiency metrics show how close a real process is to ideal reversible operation. However, the trade-off between thermodynamic efficiency and engineering cost should be always considered.
- Models that currently exist for hydrogen are roughly one order of magnitude less accurate than for other fluids. In light of this, there is a need to utilise existing experimental facilities to improve the quality and quantity of data available for cryogenic hydrogen such as density, heat capacity, viscosity and interfacial tension (IFT). From this data, improved models may be developed.

- The more detailed process simulations are, the more relevant accurate property models become. The ability to accurately describe arbitrary mixtures of ortho- and parahydrogen is critical for large scale hydrogen liquefaction process design.

Transport and Storage

- There are a number of similarities in how NASA uses LH_2 and how Australia plans to produce & export the fluid. Notably, Australia can take a number of lessons from the NASA experience in storing liquid hydrogen over long periods of time.
- Over the entire NASA space shuttle program, around 12% of hydrogen was lost due to normal evaporation (Boil Off Gas, BOG) alone.
- NASA proposed a series of new technologies for liquid hydrogen storage tanks to reduce boil-off. These include glass bubble bulk fill insulation in lieu of perlite, and an integrated refrigeration and storage heat exchanger to remove heat leak directly from the tank. The potential for densifying liquid hydrogen was also investigated for the purpose of increasing storage capacity.
- Special requirements for LH_2 carrier safety include: (1) thermal insulation to prevent heat leaks (2) vacuum insulation systems for cargo containment (3) design and arrangement of process piping, pressure vessels and equipment considering thermal defection (4) pressure relief for cargo tanks which will experience boil-off (5) vent systems for cargo containment (6) continuous and accurate measurement of temperature, gas concentration, as well as gas detection and fire detection (7) qualitative and quantitative risk assessments
- Kawasaki Heavy Industries in collaboration with TEN, JAXA, JARI and the University of Tokyo have conducted experiments into: diffusion behaviour of liquefied hydrogen and LNG, ignition points of LH_2 in low temperature, vacuum system deterioration, level sensors/level switches for LH_2, heat leaks through LH_2 tank supporting structures, pressure relief valves for LH_2 tanks, evaluation of LH_2 tank materials, fire extinguisher composition and basis of extinguishing methods for LH_2, loading arm tests and rapid depressurisation tests for LH_2 tanks.
- LH_2 propellant and storage tanks experience cryogenic temperatures, high structural loads and sometimes high pressures. There is a need to investigate the potential for composite materials and tank designs able to withstand these conditions. UNSW in partnership with Lockheed Martin and OmniTanker is currently investigating the design of a linerless carbon fibre composite pressure vessel for cryogenic fuel tank applications.
- Safe road and rail transport of hydrogen can be achieved with existing technology; however this is not at a scale comparable to the existing petroleum fuel distribution network, nor is it commercially viable (for most applications). Significant challenges still exist regarding the structural and thermal properties of tanks and their permeability.
- The transport and storage costs of hydrogen will play a significant role in its competitiveness as a fuel. Innovation is required to substantially bring down the cost of hydrogen haulage, particularly given the small margins associated with this industry.
- PRESLHY is currently conducting experimental work in hydrogen release and mixing, ignition and combustion with a view to providing enhanced recommendations for safe design and operations of liquid hydrogen technologies. Key findings of their experimental work is available here: https://preslhy.eu
- Clathrate hydrates represent a novel option for the storage of 1.5 wt% to 4.0 wt%. molecular hydrogen at ambient conditions. Hydrates are crystalline cage-like inclusion compounds that form through the combination of water and suitably sized “guest” molecules. H_2 could be stored as a binary hydrate of tetrahydrofuran (THF) and H_2 at close to ambient pressure and temperature. Further requirements for research include: kinetics of hydrate growth, ortho/para hydrogen ratios in the hydrates, and spin conversion between ortho- and para- states inside hydrate cages

Table 3. Summary of core ideas on priority R&D areas and infrastructure required to support a Liquid H_2 export industry that were developed during the workshop session.

Area	Liquefaction	Thermodynamics	Storage & Transport	Policy, regulation & social license
Challenge	• Upscaling to >1,000 TPD • Predicting properties of refrigerant mixtures • Cold box will need scaling up/multiples used • Turbine sizes need to be improved • Increasing efficiency of hydrogen liquefaction process • Reduce liquefaction process cost • Impurity freeze-out and high demand for ultra-high purity hydrogen • Ortho-para conversion and reliable equations of state for conversion • Pressure drop through catalyst bed • High price and limited availability of catalysts	• Prediction of cryogenic hydrogen properties including mixtures impurities. • Full ortho-para mixture models and measurements • Transport properties for cryogenic hydrogen (viscosity, thermal conductivity, IFT) • Models for mixtures of helium, neon and hydrogen • Properties for H_2 and H_2-rich mixtures in the presence of solid phases.	• Transporting liquid hydrogen over large distances (e.g. Australia to Japan) • Scaling up tanks to large scale e.g. composite tanks and vacuum jackets • Reduce chill down losses • Need for further materials research • Lack of understanding around kinetics of solidification • Slow kinetics of hydrates • Maritime regulation and Boil-off Gas (BOG) safety • Leak detection – standards and codes • Thermal insulation and boil-off minimisation • High fidelity modelling of transfer processes • Hydrogen safety – educating society • Convert from spherical to conformal or cylindrical tanks	• Paving the way to adoption • Social license to operate • Maritime regulations – are these mature enough? E.g. Fuel and carriage, port regulations, port readiness • Safety and public concerns • Lack of community ownership and figurehead • Standards – ensure international alignment • Lack of coordinated national approach
Idea/technology	• Use of turbo compressors and electrochemical 'expander' and magnetic refrigeration • Modular vs large scale liquefaction plants • Ortho-para ratio measurement capability and handheld device to measure para content of product • New liquefaction cycles: N_2/LNG synergy and/or helium cycles, mixed refrigerant development and cascade refrigeration optimization • Ability to integrate H2 liquefaction systems with LNG refrigeration cycles to maximize thermal efficiency and lower capital cost • New types of catalysts; Catalytic coating and Vortex tube catalytic system	• Accurate thermodynamic models for hydrogen liquefaction process design and simulation	• Pure: cryogenic liquid, slush, compressed gas • Physical: hydrates • Chemical: metal hydrides, ammonia and others • Evaluate H2 liquid vs NH3 vs MeOH vs LNG vs solid state storage (in various customer contexts) • Heat intercept with boil-off gas • Leak free umbilicals and disconnects with thermal insulation + standards • Vacuum panels, surface coatings, tank wall channels, 3D printed tanks and insulation	• Get investment into concept by public through marketing • Leverage leadership from KHI project at a global level and leverage at a local industry level • Develop full life cycle sustainability analysis (techno-economic approach) evaluating hydrogen liquefaction and storage • Technical education programs to stimulate SMEs and larger companies to engage with and enter H2 export industry; make Australia a H2 knowledge exporter

			• Leak detection • Meta-stable storage state	• Economic analyses regarding how H2 export and trade can accelerate energy transition without social disruption.
Infrastructure and Research Required	• Low temperature cryogenic apparatus for thermophysical properties measurements • Pilot liquefaction plant and slip stream facilities to enable testing and benchmarking of catalytic or other processes for converting H_2 (or natural gas) into liquid carriers. • O-P test cryostat design/upgrade of existing facility • Characterisation of catalyst at variable temperatures • Standard approach to measurement P-H_2 and packed bed catalyst models	• Experimental facilities need to be improved • Possible adaption of existing thermodynamic technologies • Improved functionality of modelling systems	• Leverage NASA work in zero-boil-off technology • Last mile distribution • Kinetics of solidification and hydrates • BOG studies and prediction models • Slipstream facilities with takeoff points to enable testing and validation of fiscal metering and custody transfer measurements for natural gas and H_2 blends • LH_2 heat transfer and meta-stable storage (not equilibrium).	• Ensure local body developing standards • Government to identify 'figurehead' projects • Develop leadership position on standards
Quick wins/ programs	Case study on modular arrangements (10 x 100 TPD) for liquefaction Isothermal p-H_2 measurement at 77 K		Zero Boil Off technology minimize new development, maximize learnings	Demonstration project in iconic location or celebrity "Hydrogen Champion" with large public profile.
Partners and collaboration	Industry and Academic such as UWA, WSU (J. Leachman) TUD (T. Funke) and Linde (Umberto)	UWA-Imperial-WSU-RUB	• KAIST (CPVT) • NASA/MetaVista (ZDO and Slush)	Work with Victorian Government and Japan on standard development

Conclusions and Way Forward

- By covering a wide range of relevant topics, the presentations elucidated the motivation driving current and planned R&D initiatives in both an Australian and an international context. Areas where significant activity was imminent, underway or well advanced were clearly identified and informed the subsequent breakout sessions. The presentations also helped identify key issues and opportunities relevant to H_2 export from Australia across near term and longer time frames.
- The workshop outlined key enabling technologies that could be used to address the challenges that exist in scaling-up hydrogen liquefaction capacity. These include using turbocompressors on the working-fluid side of the liquefaction process; developing greater understanding of the behaviour of hydrogen and mixed refrigerants; designs of large oil-free turbines; alternative cold box configurations and construction methods; and the development of new types of catalysts for para-ortho conversion and heat exchanger designs with better pressure drop characteristics.
- The transport of liquid hydrogen over long-distances brings with it a number of challenges. Boil-off minimisation through thermal insulation was identified as a key area where future research efforts should be focused. The workshop identified that work should be undertaken into vacuum panels, surface coatings (to capture and hold bubbles as insulation), internal insulation, 3D printed tanks and insulation, and into meta-stable storage states.
- Several next steps will be undertaken as a result of this workshop. This include the preparation of a review paper covering the primary R&D areas for liquid H_2 export, infrastructure needs for industrial-scale R&D in Australia, and potentially a review of current and emerging technologies across hydrogen liquefaction and liquid hydrogen storage. There is also need for a detailed case-study that includes a techno-economic analysis of hydrogen exports from Australia, and how its implementation could be optimised. Such a case-study will necessarily be a collaborative, multi-disciplinary effort.
- In Summary, three key ideas were established in this workshop:

  (**1**) Australia is well placed as a 'testing-ground' for future hydrogen liquefaction technologies due to the experience that exists in cryogenic research with LNG, and the wide variety of hydrogen projects that have emerged around Australia.

  (**2**): Significant opportunities exist for the reduction of energy consumption of hydrogen liquefiers below 10 kWh/kg by integrating state-of-the-art technologies. Demand will be a key enabler in driving this transition; however scale-up beyond 50 TPD will be a challenge and significant future research to this end is needed.

  (**3**) Hydrogen is not a 'well known fluid'. Moving forward, significant research must be undertaken to improve the quality of data that exists for hydrogen, particularly at cryogenic temperatures and high pressures. This research also extends to understanding the safety of hydrogen processes and its interaction with container and other materials.

Supporters

Institute for Advanced Studies

The Institute of Advanced Studies brings researchers from all over the world to The University of Western Australia, with the aim of further enhancing UWA's global research profile. Throughout the year the Institute hosts visits from distinguished scholars, public intellectuals and artists. These visits form part of their annual program of public lectures, masterclasses, symposia and workshops.

Australian Centre for LNG Futures

Launched in 2016 the Australian Centre for LNG Futures (ACLNGF) is an Australian Research Council (ARC) Industrial Transformation Training Centre (ITTC) based at The University of Western Australia (UWA). The LNG focused research has a strong industry focus and aims to increase growth, productivity and capabilities in this key Australian industry. Through innovation and investment through partnership the Centre builds on UWA's track record of LNG industry aligned research. The Training Centre further fosters links with industry and promotes innovation and technology transfer. Key roles of the Training Centre include fostering stronger collaboration between researchers and industry and to train industry-ready PhD students.

Fluid Science and Resources Division

The Fluid Science and Resources research group at The University of Western Australia conducts applied research aimed at advancing knowledge, maximising the value of resources produced, and minimising the environmental impact of their production.

Future Energy Exports (FEnEx) CRC

The Future Energy Exports Cooperative Research Centre (FEnEx CRC) will execute cutting-edge, industry-led research, education and training to help sustain Australia's position as a leading LNG exporter, and enable it to become the leading global Hydrogen exporter.

Herbert Akroyd Stuart Lecture Series

Akroyd Stuart invented the hot bulb engine, or heavy oil engine – the fore-runner of the diesel engine. In 1885, a fortuitous accident involving spilt paraffin oil led to an idea to pursue the possibility of using this oil for an engine, which unlike petrol would be difficult to be vaporised as its volatility is not sufficient. Akroyd-Stuart's hot bulb engines were produced from 1892 until the late 1920s and were the first internal combustion engine to use a pressurised fuel injection system.