Research & Development Needs for Australia's H_2 Export Industry

WORKSHOP OUTCOMES REPORT

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Introduction and Objectives

Hydrogen has been identified as central to the decarbonisation of the energy and industrial sectors. The CSIRO has released a National Hydrogen Roadmap intended to help the development of a hydrogen industry. Significant efforts in research and development (R&D) are underway to promote hydrogen production, distribution and utilisation within Australia. Tremendous opportunities also exist to establish a hydrogen (H_2) export industry that builds upon our world-leading track record as global supplier of liquefied natural gas (LNG). However, many technical challenges exist regarding the most cost-effective methods of exporting H_2 from Australia to the large prospective markets in Japan, Korea, China and Europe. Overcoming these challenges efficiently will require Australia to develop systematic and coordinated R&D programs, informed by industry and the experience of other countries that builds upon existing strengths while minimising duplication. The design and use of research infrastructure that allows for industrial-scale validation of H_2 export technologies will be central to this program.

In 2018, the NERA Growth Centre co-funded with Chevron, Shell, Hyundai Heavy Industries (HHI) and UWA, the pre-FEED design of the LNG Futures Facility (www.lngfutures.edu.au). This is a 10 tonne-per-day LNG plant intended to serve as a national facility for industrial-scale research and technology validation for natural gas processing, liquefaction, storage and re-gasification. This proposed Facility could readily be augmented to include infrastructure for testing technologies that will accelerate the launch of a future H_2 export industry.

On 29 November 2018, the ARC Centre for LNG Futures (ACLNGF) hosted a workshop at the Australian Resources Research Centre in Kensington, Western Australia, which brought together global and local experts on H_2, natural gas and LNG to achieve the following objectives:

- Understand driving forces, current efforts and future plans for industrially-focussed H_2 research, both in Australia and internationally
- Learn about the LNG Futures Facility, its potential capabilities for industrial-scale testing at high-pressures and cryogenic temperatures, and the proposed R&D program
- Develop an industry-led R&D plan to accelerate the growth of H_2 exports from Australia that is complementary and avoids duplicating existing research initiatives.

The total attendance at the workshop was 64 participants representing industry organisations, government agencies, and research institutions in Western Australia, Victoria, New South Wales, Queensland, Korea, Germany and the United Kingdom. The workshop schedule is shown in Table 1, which includes the speakers and their presentation titles: copies of the slides from these presentations can be downloaded from www.lngfutures.edu.au/hydrogen-workshop-presentations/. At the conclusion of the presentations, a breakout session was held with participants asked to consider and nominate (1) the primary areas of R&D needed to help establish a H_2 export industry, and (2) the testing infrastructure that would be needed to conduct this industrial-scale R&D. Subsequently, the nominated R&D areas and infrastructure from each break-out group were summarised and presented to all the workshop participants by each group's facilitator. The summarised results from the breakout session are listed in Table 2 and Table 3. Commonalities between groups and the frequency with which R&D areas and infrastructure needs were proposed were used to develop a forward plan and, in particular, a conceptual framework for a new Cooperative Research Centre (CRC) proposal. The next steps towards establishing the R&D needed to support a world-leading Australian H_2 export industry, and the proposed CRC framework intended to help achieve this, are outlined in this report's concluding section and Appendix, respectively.

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

Time	Activity or Presentation Title	Speaker(s)	Organisation
8:30	Welcome & Workshop Objectives	Prof Eric May	UWA
8:45	The LNG Futures Facility	Prof Eric May	UWA
9:00	National Hydrogen Roadmap & CSIRO Hydrogen Research	Mr Sam Bruce & Dr Nick Burke	CSIRO
9:30	Future Fuels CRC - Overview	Dr Klaas van Alphen	CRC Future Fuels
10:00	Morning Tea		
10:15	R&D Needs for Hydrogen Utilization - German Perspective & Experience	Prof Roland Span	Ruhr University Bochum, Germany
10:45	Technology Gaps in Utility Scale Hydrogen Production	Ms Rachelle Doyle	Woodside
11:15	Renewable H_2 & H_2 Carriers as Clean Transport Fuels	Prof Dongke Zhang	UWA
11:45	Hydrogen Production Disruption	Dr Andrew Cornejo	Hazer
12:30	Lunch		
13:30	Low Carbon Technology for Marine Application	Dr Se-Young Oh	Hyundai Heavy Industries, Korea
14:00	Hydrogen Research at Curtin University	Prof Craig Buckley	Curtin University
14:30	UK Perspective and Experience	Prof J.P. Martin Trusler	Imperial College, London, UK
15:00	Presentation Summary and Breakout Session	Prof Eric May	UWA
15:30	Afternoon Tea		
16:00	Collation & prioritization	All	
16:15	Next steps	All	
16:30	Close & drinks		

Major Ideas from Presentations

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

- LNG Futures Facility could readily be extended to provide unique infrastructure for industrial scale R&D on liquid H_2 and/or high-pressure H_2 (70 MPa).
- A CRC is proposed to form a company that owns the LNG FF and is initially funded for 10 years (tiered membership, annual payments) to conduct high-priority industrial R&D programs.
- Although there is considerable scope for further R&D in H_2, the current technological maturity means the narrative is shifting to market activation and what is needed to make that happen.
- Barriers to market activation stem from both a lack of infrastructure supporting markets and/or the cost of hydrogen supply. This requires development of an appropriate policy framework which could create a 'market pull' for hydrogen.
- The driving force for a hydrogen economy is environmental benefit but the cost of H_2 also matters.
- There is need for techno-economic modelling of hydrogen export to identify most prospective routes, and also a need for R&D to establish and support demonstration projects.
- Existing R&D plans include Type-A testing to determine which domestic appliances can be accredited for operation on natural gas with 10% H_2 blends or more.
- Existing R&D plans include investigating the compatibility of steel pipes (including those with internal coating) and components in gas networks with hydrogen-based energy fluids.
- A strong transmission grid can reduce storage demands but it cannot replace storage.
- Hydrogen generation by hydrolysis can be used to ensure utilization of excess renewable power.
- Few problems are expected to result from the distributions with hydrogen levels up to 10% but higher concentrations may need networks with modified components.
- However, even at 10% issues arise in the areas of fiscal metering and custody transfer.
- If methods applied by natural-gas industry are to be applied in distributed gas-grids with increased hydrogen concentrations, uncertainties in fluid properties as low as those in the natural-gas industry have to be targeted. This requires highly accurate thermodynamic modelling based on high-quality experimental data measured at relevant conditions.
- H_2 economy initiatives have occurred at least 3 times in last 50 years. One difference now is renewable energy's status as a way of producing H_2, with appropriate carriers for export.
- Liquid fuels are broadly preferred and NH_3 has many advantages, including potential for direct combustion and the existence of long-standing industry practice for safe handling.
- The HAZER process is used to produce hydrogen and graphite from natural gas with virtually no CO_2 emissions with several advantages relative to other processes for producing hydrogen from fossil fuels.
- Graphite generated by the Hazer process is a high-grade product of value to battery markets.
- Significant consideration needs to be given to the efficiency and safety of liquid H_2 storage due to diffusion (3 times faster than hydrocarbon in air), low ignition energy, and high thermal conductivity. Technical issues with H_2 liquefaction include the need for new infrastructure, understanding H_2 boil off, and high cost.
- Hydrogen in metal hydrides can be used for heat storage to produce electricity, particularly in the context of concentrated solar thermal energy.
- Developing effective technologies for H_2 production coupled with CCS will enable a low carbon economy. This will also enable H_2 production from SMR with minimal carbon emissions.
- Temperature management is obviously a challenge for liquid hydrogen, there should be a scope to study other storage mechanisms.

Primary R&D Areas for H_2 Export

Table 2. Summary of core ideas on priority R&D areas to support a H_2 export industry that were developed during the break out session.

<table>
<tr><th>Production, Processing and Conversion</th><th>Liquefaction (cryogenic or carrier)</th><th>Storage and Transport</th><th>Re-gasification and Use</th></tr>
<tr>
<td>▪ PSA separation for CH_4/H_2 mixtures
▪ Low pressure TSA membrane technology for separation
▪ Direct electro-chemical synthesis of NH_3
▪ H_2 + NG separations: full life cycle analysis, separation efficiency, alternative technologies
▪ Alternative novel means of hydrogen production and separation technologies.
▪ Development of fundamental EOS and Standards and regulations regarding product purity
▪ Direct use of sea water electrolysis in hydrogen production
▪ Impurity and compatibility of H_2-based mixtures with process units
▪ H_2 from SMR coupled with CCS: Integration with existing gas infrastructure, mixture behavior, corrosion, sequestration systems, CO_2-H_2 stratification in geological systems.</td>
<td>▪ Increasing efficiency of hydrogen liquefaction process
▪ Reduce liquefaction process cost
▪ Low cost catalysts for improved ortho-para conversion, and ortho-para ratio measurement capability, to reduce boil off rate
▪ Need for studies of impurity freeze-out in H_2 production
▪ New liquefaction cycles: N_2/LNG synergy and/or helium cycles, mixed refrigerant development and cascade refrigeration optimization
▪ Compare round-trip energy efficiency of LH_2 vs NH_3 vs MeOH vs MCH.</td>
<td>▪ Standard and practices for H_2 fuel stations, and hydrogen safety and handling standards
▪ Solar thermal energy storage
▪ Evaluate H_2 liquid vs NH_3 vs MeOH vs LNG vs solid state storage (in various customer contexts)
▪ Use of NH_3/DME/MEOH in H_2-vehicles (to replace diesel)
▪ Potential for H_2 liquid storage: study important factors such as materials compatibility and boil-off
▪ Systems modelling and port handling facilities
▪ H_2 transported in NG grid in WA: capacity, on-line H_2 tools (sensors development) for grids and vehicles, advanced thermodynamic models for custody transfer and fiscal metering.</td>
<td>▪ Effective conversion of NH_3 which can be used in fuel cells, and displace coal fired power stations (turbines)
▪ Industrial integration of CO_2 utilization
▪ Co-location of energy systems and heat management
▪ Demonstration of hydrogen refueling stations and hydrogen-powered vehicles; build public understanding and acceptance.</td>
</tr>
<tr><th colspan="4">Economic, Social & Educational Priorities</th></tr>
<tr><td colspan="4">▪ Develop full life cycle sustainability analysis (techno-economic approach) evaluating alternatives H_2 generation/storage/transport and use, cost, energy efficient, energy cost of materials, fabrication and so on. Carbon used to develop hydrogen economy should be included in analysis.
▪ Develop outreach and public demonstration programs to secure social acceptance and adoption, plus local market uptake.
▪ Technical education programs to stimulate SMEs and larger companies to engage with and enter H_2 export industry; make Australia a H_2 knowledge exporter
▪ Economic analyses regarding how H_2 export and trade can accelerate energy transition without social disruption.</td></tr>
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Infrastructure Needs for Industrial-Scale H_2 R&D

Table 3. Summary of core ideas for infrastructure needed to support industry driven R&D programs for H_2 export industry that were developed during break out session.

Processing and Conversion	Liquefaction (cryogenic or carrier)	Storage and Transport	Re-gasification and Use
▪ Pilot scale (or larger) H_2 generation process, (e.g. Hazer, SMR, Coal Gasification, and eventually Renewable) ▪ HAZER process to produce H_2 from treated natural gas taken as slip stream from LNG FF ▪ Solar panels to power electrolysis-driven H_2 generation ▪ Separation testing facilities (PSA, TSA…) and membrane modules	▪ Benchmark liquefaction facility with offtake connections that allow new liquefaction technologies to be tested and validated relative to a known baseline. ▪ Ability to integrate H_2 liquefaction system with LNG refrigeration cycles to maximize thermal efficiency and lower capital cost ▪ Slip stream facilities to enable testing and benchmarking of catalytic or other processes for converting H_2 (or natural gas) into liquid carriers.	▪ Hydrogen loading facilities; heavy vehicles transport and H_2 highways to use ▪ Local demonstration site for public education and acceptance ▪ Slipstream facilities with take-off points to enable testing and validation of fiscal metering and custody transfer measurements for natural gas and H_2 blends.	▪ High pressure fueling station for code development ▪ NH_3-based turbines that can handle composition fluctuation ▪ Natural gas turbines and distribution grid handling facilities that can help establish allowable H_2 contents in mixtures.

Conclusions and Way Forward

The workshop's first objective regarding the driving forces and existing efforts for industrially-focussed H_2 research was clearly achieved through the presentations delivered. By covering a wide range of relevant topics, the presentations elucidated the motivation driving current and planned R&D initiatives in both an Australia 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.

One clear opportunity, which motivated the specification of the workshop's second objective, derives from the similarities between LNG export technology and the technology needed to establish a prospective hydrogen export industry. The importance of validating novel approaches at an industrially-relevant scale has driven the development of a detailed plan for the LNG Futures Facility, which will allow testing of new processes, sensors and digital models designed to operate across all stages of the LNG value chain. Through the workshop, key opportunities were identified to also support industrial-scale R&D for H_2 export by integrating a few simple extensions into the facility's design. These include the ability to convert a slip-stream of the natural gas into H_2 (and/or other H_2 carriers), the ability to plumb in and compare the efficiency of different H_2 liquefaction cycles (potentially integrated with the LNG refrigeration system), and the ability to utilise the product within a demonstration refuelling station for H_2 powered vehicles.

The workshop's third objective was addressed through the results produced during the breakout sessions summarised in Table 2 and Table 3 which were then used in the development of a preliminary R&D plan to accelerate the growth of H_2 exports from Australia. The current version of that plan is attached to this report as an appendix in which an outline for the *Future Energy Exports* Cooperative Research Centre is presented. A key feature of the plan is the strategic coupling of LNG and H_2 exports because the former is a major established industry in Australia with specific but well defined challenges, while the H_2 export industry is nascent but likely to leverage LNG-related know-how and infrastructure as it enters an accelerated growth phase. The plan is of course preliminary in nature with scope refinement and schedule definition essential prior to submission of a CRC proposal in 2019. Additionally, establishing the infrastructure necessary to conduct meaningful industrial-scale R&D in a manner compatible with CRC funding requirements is a key question to be addressed.

Several next steps will be undertaken as a result of this workshop. A second workshop focussing on the further development of the Future Energy Exports CRC proposal will be held early in 2019. As the plan is refined, briefing sessions for prospective industry members of such a CRC will be held and financial commitments sought in time for the June proposal deadline. With co-funding from NERA and industry partners, the LNG Futures Facility project will enter the Front End Engineering Design (FEED) phase with a scope that includes consideration of H_2 generation and storage facilities. These activities, together with the workshop outcomes, should also allow the preparation of a review paper covering the primary R&D areas for H_2 export, infrastructure needs for industrial-scale R&D in Australia, and potentially a review of current and emerging technologies across the entire value chain of hydrogen production. There is also need for a detailed case-study that includes a techno-economic analysis of hydrogen export from Australia, and how its implementation could be optimised. Such a case-study will necessarily be a collaborative, multi-disciplinary effort.

APPENDIX: Future Energy Exports CRC

Eric May – UWA, Craig Buckley – Curtin University, Gang Li – University of Melbourne

Australia is already a global leader in the export of liquefied natural gas (LNG), which is central to the global energy transition away from coal that is now underway. Hydrogen (H_2) has been identified as central to the decarbonisation of the energy and industrial sectors. By building upon our world-leading track record as global supplier of LNG, Australia is uniquely poised to take the lead in establishing a large-scale, international trade in hydrogen. If adequately supported, this nascent hydrogen trade could readily become a key pillar of Australia's future energy export industry alongside LNG.

However many technical challenges exist regarding the most cost-effective methods of exporting H_2 from Australia to the large prospective markets in Japan, Korea, China and Europe. The demonstration of new technologies and the adoption of innovation is also a significant problem within the LNG sector. Fundamental barriers to the adoption of research & development exist because of the incompatibility of two implicit principles central to all large-scale industries involved in the export of energy.

a) New technologies must be validated at industrially-relevant scales to mitigate risk adequately before operational deployment.
b) Interruptions to operations at existing production facilities are kept to a minimum.

Phase 1, which will be completed in 2018, consists of the pre-FEED design of a 10 tonne-per-day LNG plant that will serve as an open-access national facility for industrial-scale research and technology validation. The facility will enable research & development programs in natural gas processing, liquefaction, storage and re-gasification. An extensive research and development program that will utilise this unique infrastructure has also been defined, together with robust business and governance models. The LNG FF is readily extensible to include a hydrogen export train, including conversion, liquefaction and storage.

Simultaneously, Curtin's Fuels & Energy Technology Institute have led the development of new hydrogen storage technologies to support mobile, stationary, solar thermal and export applications. These and other relevant technologies were presented at a workshop on "H_2 Export R&D" held on November 29, 2018 to an audience of industry leaders and researchers from other research institutions including the University of Melbourne, CSIRO, Future Fuels CRC, and the University of Queensland. The workshop's outcomes included a prioritised list of research programs and the associated key infrastructure for testing technologies that will accelerate the launch of a future Australian H_2 export industry. Phase 2 of the LNG FF project will commence in 2019 with funding from the NERA consortium and will complete the Front End Engineering Design (FEED) necessary to take a Final Investment Decision by June. This will be coincident with the submission of the Future Energy Exports CRC proposal to the Department of Industry, Innovation and Science.

Research Themes

The key research themes & questions to be addressed by the Future Energy Exports CRC are:

1) LNG and Natural Gas Processing
2) H_2 Processing, Liquefaction and Utilisation
3) Storage, Transport and Regasification for H_2 and LNG.
4) Large scale Renewable Hydrogen

Digital technologies critical to research projects within all three themes will be integrated with these programs through the Industry 4.0 Testlab for Energy & Resources Digital Interoperability.

Theme 1: LNG and Natural Gas Processing. This theme will target projects that seek to improve the efficiency with which natural gas from a variety of sources is treated and/or liquefied to maximise value associated with Australia's gas reserves. Projects will be drawn from the following areas:

a) *Advanced Gas Separations*, including reduced foaming in acid gas removal, high-throughput dehydration, non-cryogenic helium recovery and N_2 rejection
b) *Cryogenic Fluids & Refrigerants*, including solids freeze-out prevention & remediation, refrigerant optimisation, efficient liquefaction technologies
c) *Data Analytics & Digital Twins*, including validation of online data monitoring and analysis software; improved predictive physical models scalable to large facilities.

Theme 2: H_2 Processing, Liquefaction & Utilisation. This theme will target projects that allow efficient generation and/or processing of blue or green hydrogen, as well as those that identify how best to get the H_2 from its source to its point of use. Projects will be drawn from the following areas:

a) *Processing & Conversion*, including the optimisation of large-scale H_2 production or conversion methods with low, neutral or negative carbon foot-prints, and the efficient separations processes required.
b) *Liquefaction and Liquid Carriers*, including identification of the most cost-effective ways of achieving energy densities necessary for intercontinental trade, including any application specific re-conversion costs.
c) *Hydrogen Utilisation*, including optimisation of hydrogen powered engines as well as the use of solid-state and porous media storage technologies in vehicles.

Theme 3: Storage, Transport and Re-gasification for H_2 and LNG. This theme will target projects that minimise hazards and/or energy loss in large-scale, long term storage and maximise energy or value recovery upon re-gasification. Projects will be drawn from areas such as:

a) *Optimised H_2 Storage for Transport*, including evaluation of context-specific hydrogen storage options for transport of various distances such as liquid H_2, NH_3, liquid organic carriers and in solid state storage materials.
b) *Boil-off and Rollover*, including the validation of boil-off and LNG rollover modelling, optimised ortho-para conversion in liquid H_2 and the reduction of re-liquefaction compressor duty.
c) *High-efficiency re-gasification*, including elimination of combustion-based vaporisers and Stirling cycle co-generation of electricity or additional green H_2.

Theme 4: Large Scale Renewable Hydrogen. This theme will concentrate specifically on using renewables to produce green hydrogen for export and the domestic market. Projects will be drawn from areas such as:

a) *Reduced Cost Renewable Hydrogen*, including technical and economic assessments of how renewable energy can be optimised for production on the large scales necessary for export
b) *Demonstration of Hydrogen Refuelling Stations (HRS)*, including the promotion of public acceptance for wide spread hydrogen use in cars, buses and trucks and the development of codes and standards for safe re-fuelling.

Techno-economic analyses of the options considered in each of the four themes would be conducted in parallel with technical research to provide a full lifecycle cost benefit analysis in each case.

Infrastructure and Research Organisations

The research programs will be executed using world-class laboratories and bench-scale facilities at the multiple national research organisations: UWA, Curtin, CSIRO (ARRC & Clayton), University of Melbourne, UNSW, Griffith University, UQ, University of Adelaide, ANU, UniSA, and/or others.

Industrial-scale infrastructure for technology demonstration will be available to the Future Energy Exports CRC through the LNG Futures Facility, which will be augmented to include a H_2 Export Train. The LNG Futures Facility consists of a small scale LNG plant (10 tonne per day), which has already been through a pre-FEED process and is well defined in terms of location, source and disposal of natural gas, unit operation definition, storage facilities, power supply and utilities. Various slip stream offtakes around different unit operations will facilitate the conduct of research projects from Themes 1 and 3.

The H_2 Export Train will be constituted by one slip stream of natural gas from a particular offtake (e.g. post acid gas and water removal) in the 10 tonne per day LNG plant. This slipstream could feed a Hazer process plant producing up to 100 kg per day of H_2 (and 300 kg per day of graphite). Alternatively (or in addition) a steam methane reforming (SMR) process could be used instead to generate the H_2 if preferred by industry users; in that case the SMR unit would ideally be coupled with a CO_2 capture process. As a final option, a coal gasification process may be used to generate the hydrogen; in this case separation and purification operations would then be required prior to liquefaction of the H_2. The hydrogen will then be available for various research activities (e.g. liquefaction & re-gasification, NH_3 conversion…). Ultimately the H_2 produced will be sold to the Perth market through the use of an appropriate buffering storage facility. That is H_2 generation would be periodic (e.g. 1 day per week) and/or turned down (e.g. 50 % throughput), and the storage capacity sufficient (e.g. 250 kg) to be commensurate with the demand of the Perth market (order 10 kg per day).

Subsequently (e.g. 3-5 years), following appropriate laboratory-scale demonstration, technologies for cost-effective large-scale generation of renewable hydrogen such as high efficiency solar-powered electrolysers will be installed and validated within the H_2 Export Train. The additional hydrogen generated would be used to supply a demonstration re-fuelling station for cars, buses and trucks.

Business and Governance Models

The Future Energy Exports CRC would be a not-for-profit company, limited by guarantee with a company board of around 9, including an independent chair and about four independent directors. The other directors would be representative of the foundation members. The CRC Company would own the infrastructure assets and be run by a CEO, COO, Research Coordinator, Administration and Engagement Officers. An Industry Research Panel (IRP) representing members would design and prioritise the elements of a collective research program.

Industry membership would occur at two levels: Tier 1 at $300k per year and Tier 2 at $150k per year. This would principally impact the IRP decisions with Tier 2 companies having 1 vote and Tier 1 companies 2 votes. Once launched, new industry members would be admitted through IRP vote. Usage ratios of the major infrastructure within the LNG FF & H_2 Export Train would be adjusted annually by the CRC Board. Below is a proposed initial distribution of operating time with costings:

Entity	Time Fraction	Charge Rate	IP
CRC Member Company Research	> 25 %	Nil	Member company
CRC Collective Program	> 25 %	Nil	CRC company
Small-Medium Enterprises	≤ 25 %	Cost price	Shared with CRC
Private 3rd Parties	≤ 25 %	Cost + 50 %	If shared with CRC
		Cost + 100 %	If not shared with CRC

IP generated through the Collective Research Program would be owned by the CRC Company, which would also provide seed funding for commercialisation (e.g. to PCT stage). All CRC members would receive either low cost or royalty-free licenses to IP generated by the CRC. Further commercialisation of CRC IP would be offered to members first. The CRC would be licensed to use Member and 3rd party IP as required.