CSIRO National Hydrogen Roadmap

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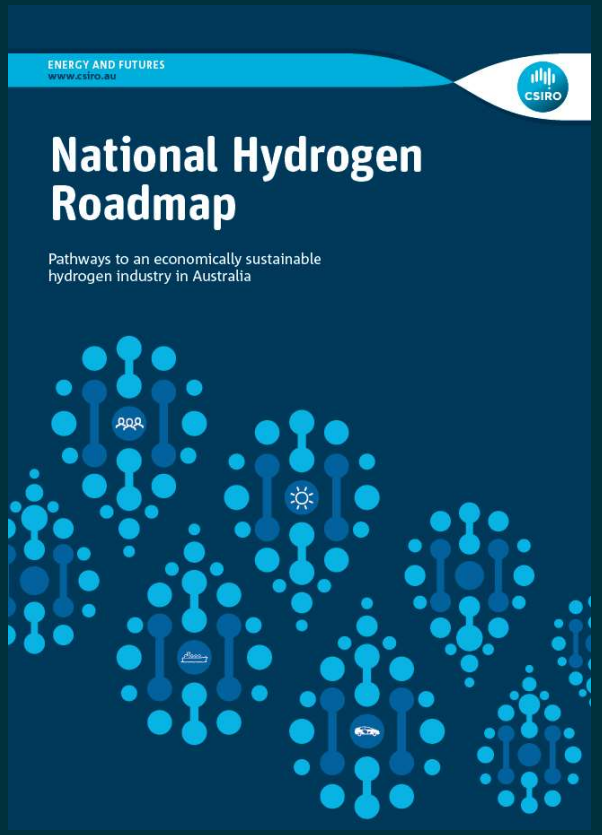
Roadmap Development Team

CSIRO Futures

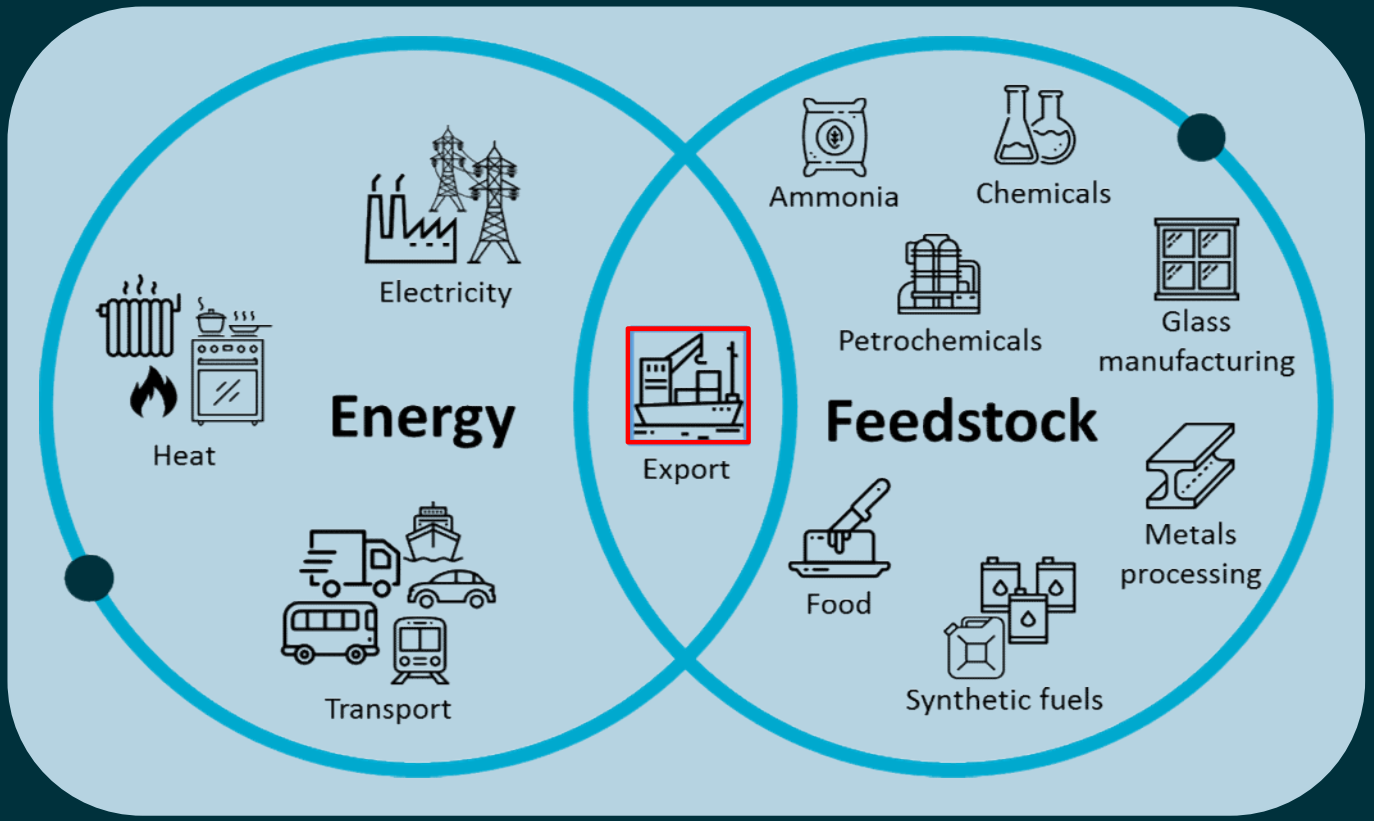
The strategic advisory arm of Australia’s national science agency. We leverage the deep expertise of CSIRO’s research professionals to help Australia's largest companies and government ‘translate science into strategy’.

CSIRO Energy

Delivering the R&D solutions that will enhance Australia’s economic competitiveness and regional energy security while enabling the transition to a lower emissions energy future.



Why Hydrogen in our Energy Systems?



Using Hydrogen can decarbonize diverse energy & industrial feedstock needs

We've been here before.....

Australian Government
Department of Industry Tourism and Resources

National Hydrogen Study

(2003)

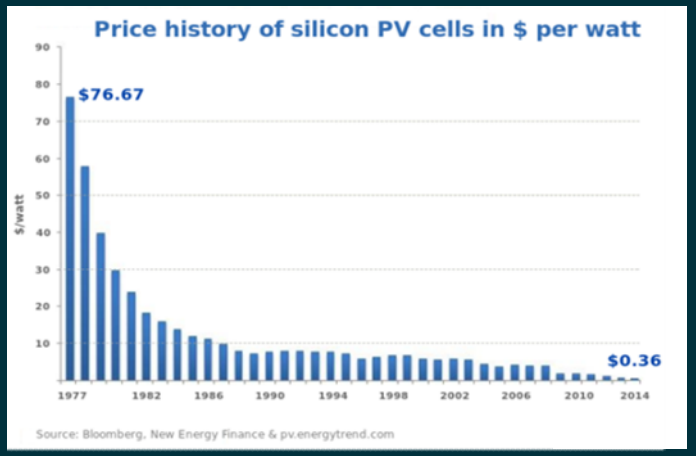
- 2003 –"Backing Australia's Resources and Energy" Federal Government national hydrogen initiative
- Issues Paper, Stakeholder Workshops (Melbourne & Perth)
- Recommendations: Hydrogen Vision Development, Opportunities for Australia (inc. renewable energy), roadmap development

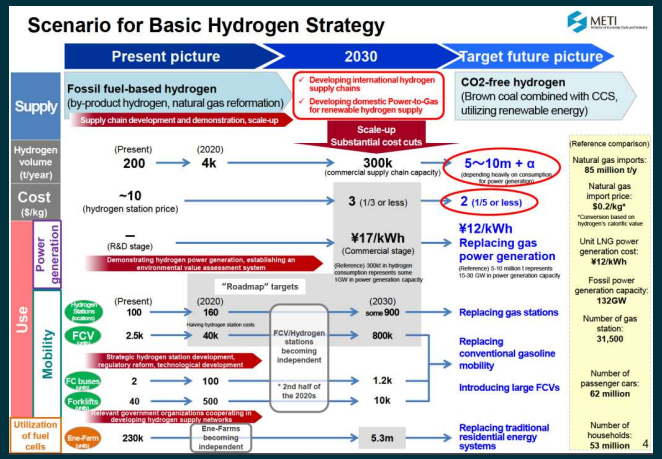
The National Hydrogen Study[2] put forward a vision for the future that

> *"would have Australia among the world leaders in hydrogen technology. Australian renewable energy/hydrogen hybrid power supply systems, developed to address local needs, could be exported all over the world. Our fossil fuel resources would continue to sustain major export industries, but in many instances coal exports would now be converted to hydrogen at their destination and flue gases would be sequestered. 'Hydrogen economy' power plants and related sequestration infrastructure could be founded on international technological R&D in which Australian input and collaboration played an important and influential role.*

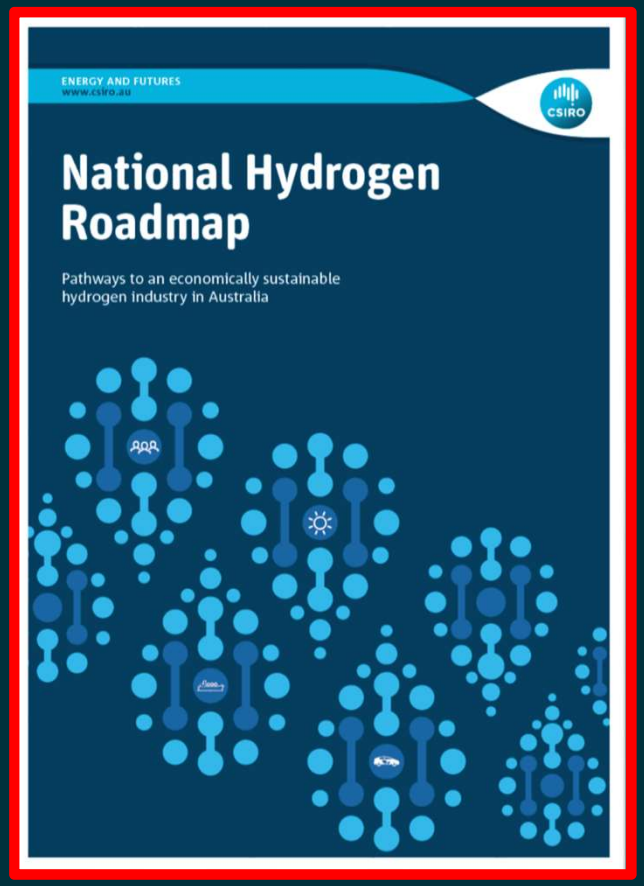
…..So Why Now?

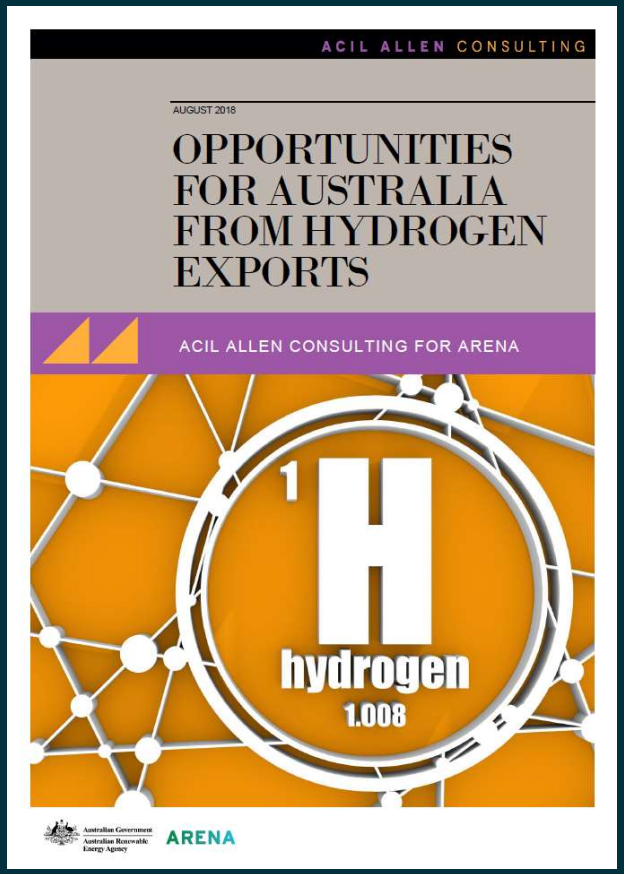
- Globally, the hydrogen industry is now underpinned by a series of mature technologies
- The costs of of renewable energy have fallen dramatically making hydrogen production from these resources cost competitive for energy applications
- Emerging overseas markets for low emissions energy (eg Japan)
- The hydrogen industry narrative has shifted from technology development to **market activation**





Communicating the Vision: August 2018

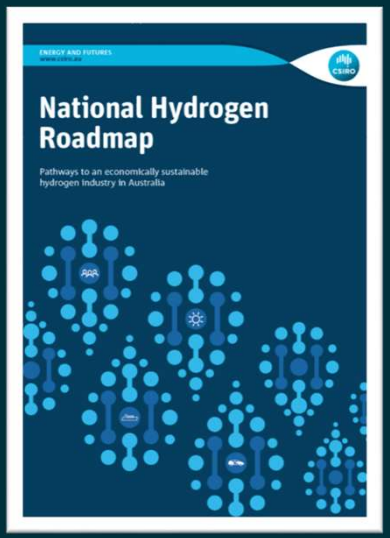




CSIRO National Hydrogen Roadmap

Primary objective: Assessment of Australian hydrogen opportunities to help inform and coordinate industry investment & government policy (released August 2018)

Secondary objective: Bring together the broad H2 stakeholder group (industry, government, research) to develop a clear view of the opportunity for Australia (released August 2018)



Electricity Generation & Storage
- Energy storage
- Grid support
- Remote Energy

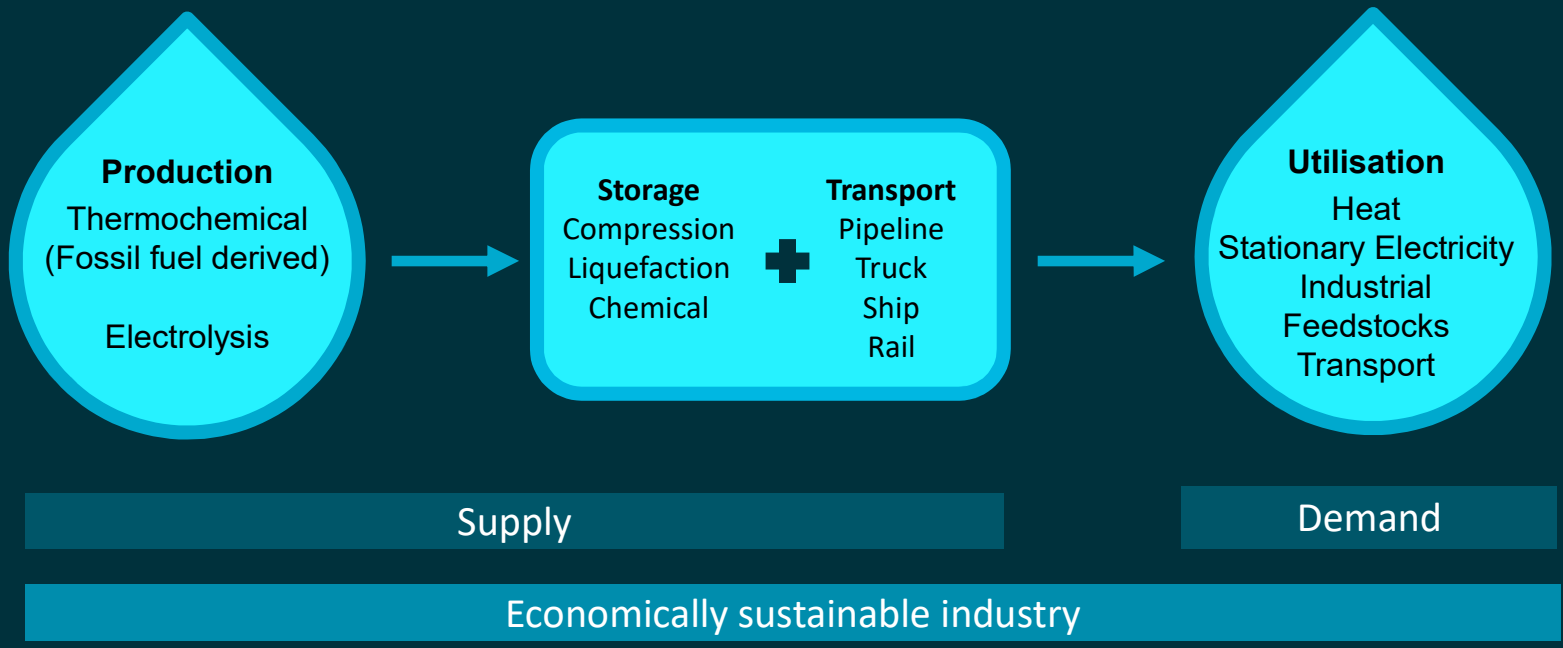
Direct Combustion
- Residential / Commercial
- Gas distribution network

Transport
- Passenger vehicles
- Heavy vehicles
- Shipping
- Rail

Export Commodity
- Hydrogen
- Ammonia
- Methanol
- Synth. Natural Gas

Industrial Feedstock
- Petrochemical
- Metallurgy
- Chemicals
- Synthetic fuels

Value Chain Approach



Understanding the Roadmap

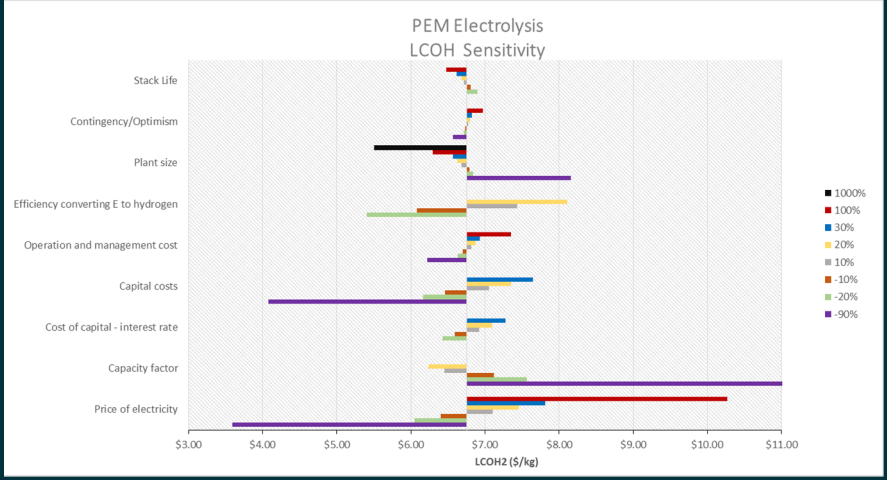
Methodology

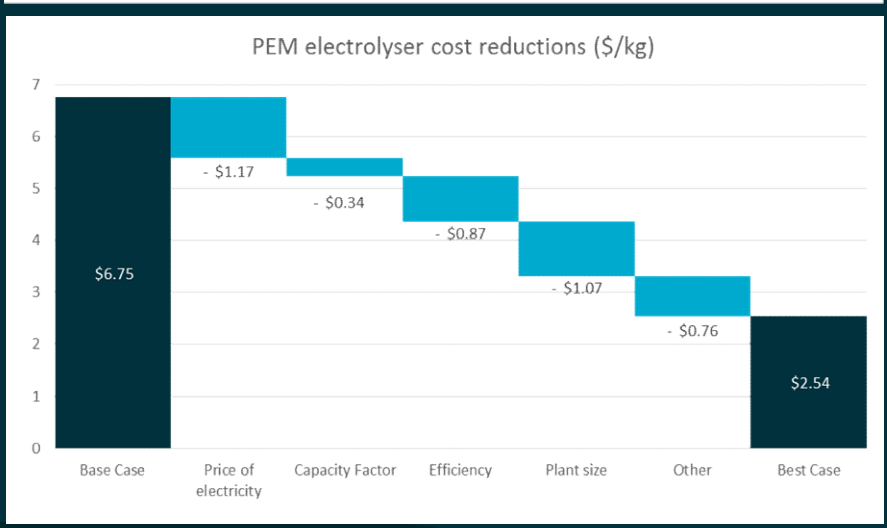
- Base case (2018) modelling of mature technologies

- Identification of material cost drivers

3. Identification of investment priorities
   - Commercial / Technical
   - Policy/regulatory
   - RD&D
   - Social licence

4. Modelling of best case achievable by 2030:
   - Cumulative impact of investment priorities

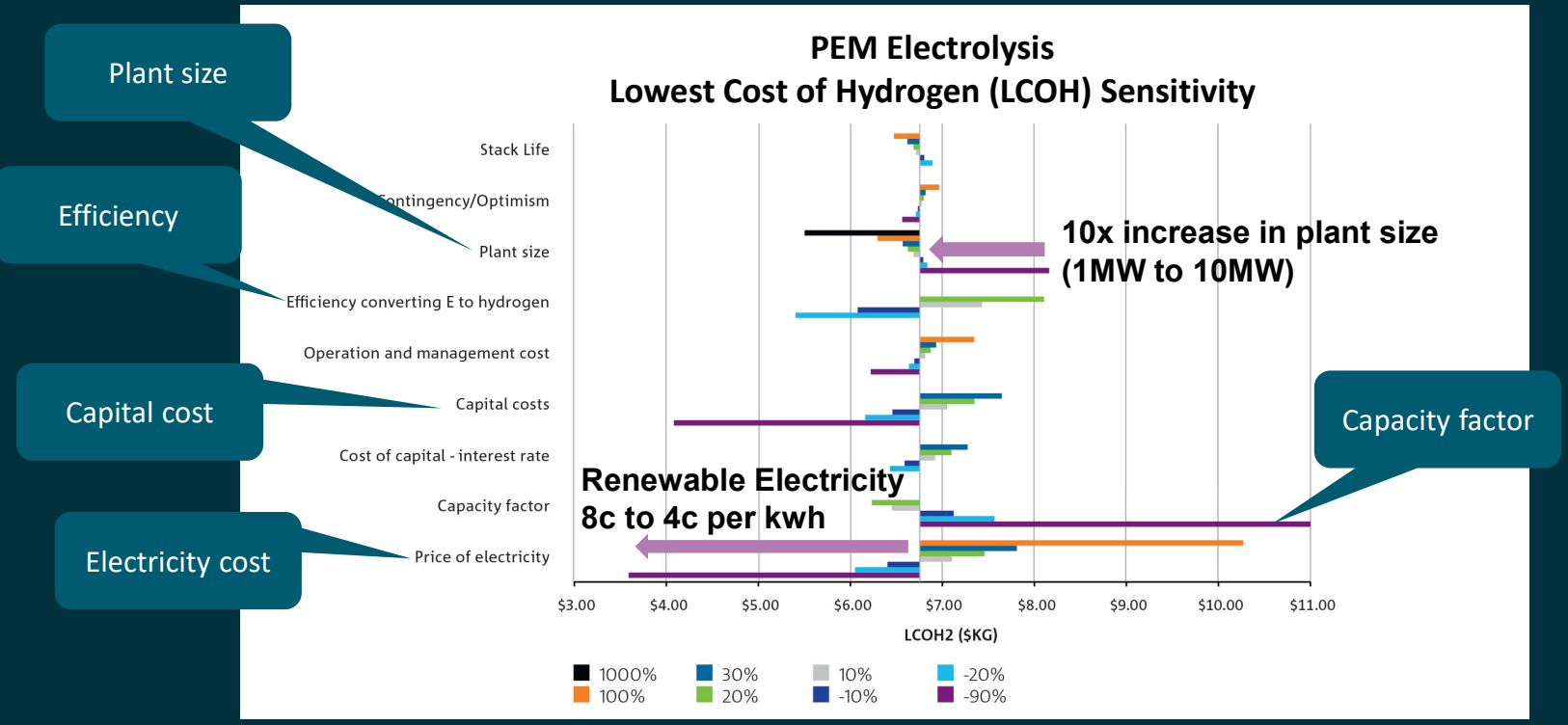




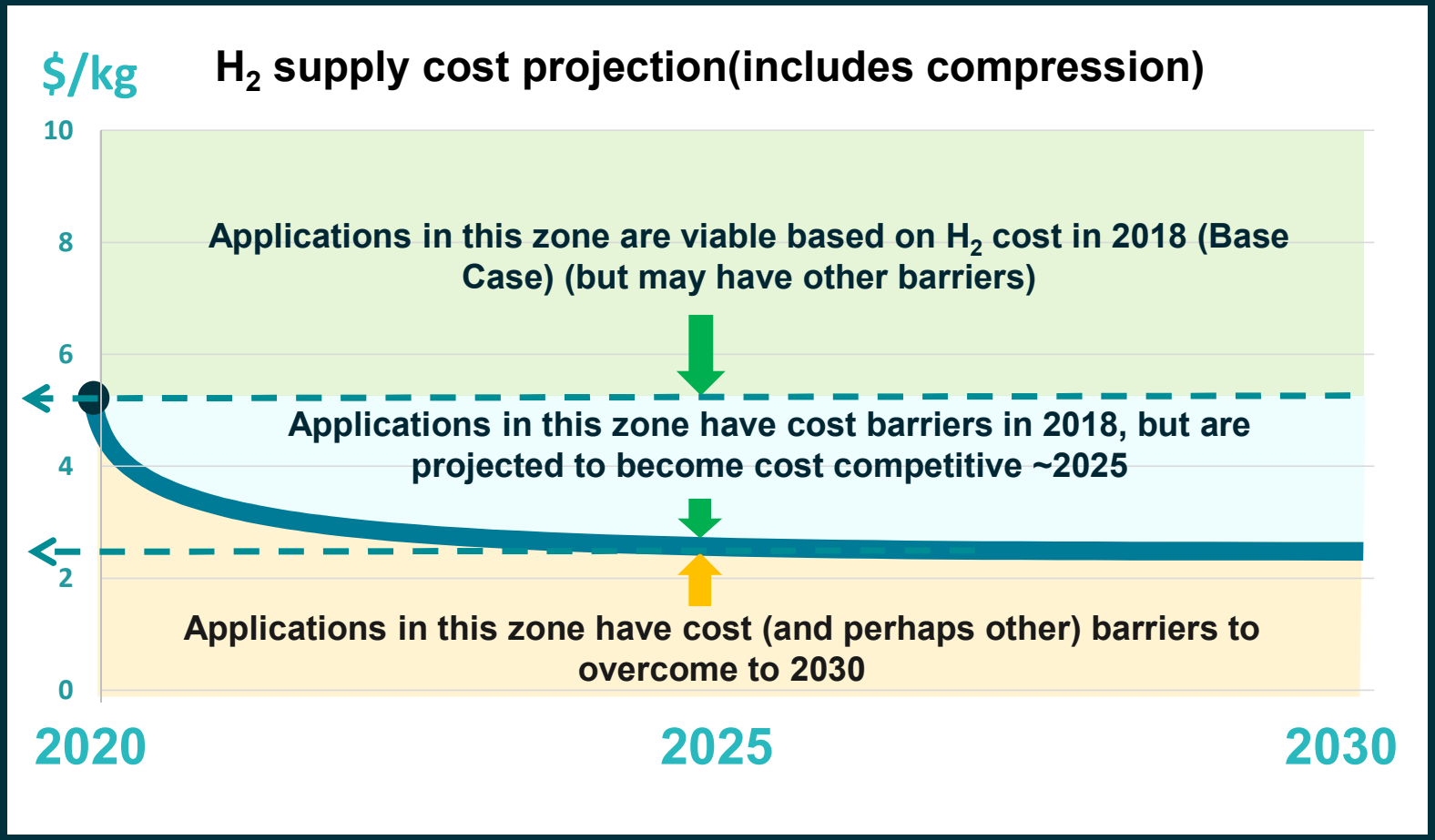
Base / Best Case Modelling

Example: Hydrogen Production Costs from Electrolysis

Tornado Charts: Sensitivities modelled using realistic changes with time, then used to derive 'best case' plot



Modelled H_2 Price Competitiveness Cost Curve



Market applications

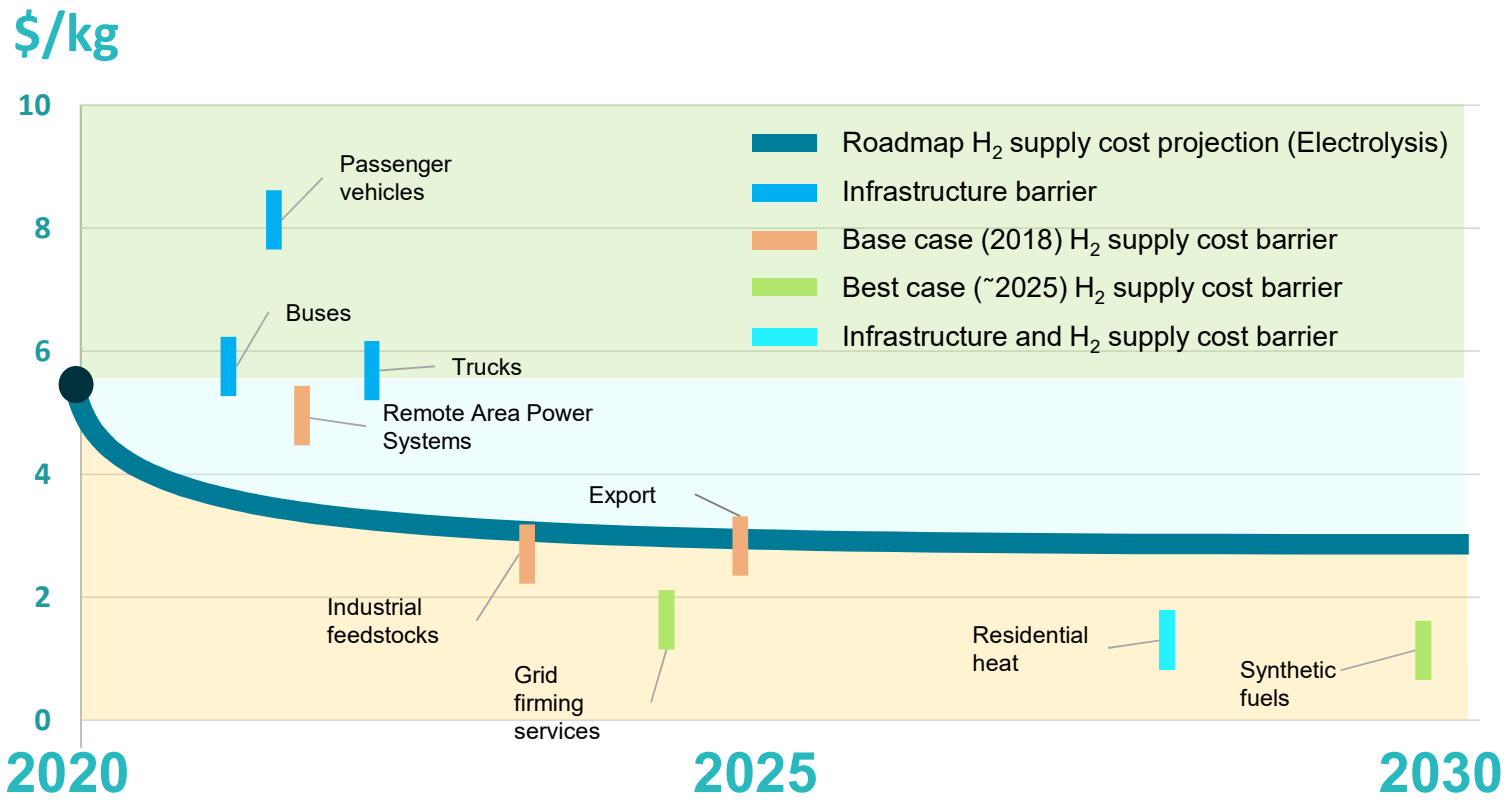
Target cost of hydrogen

- For a given application, the price point at which hydrogen could become competitive on a commercial basis with current technologies and feedstocks (e.g. natural gas in heating)

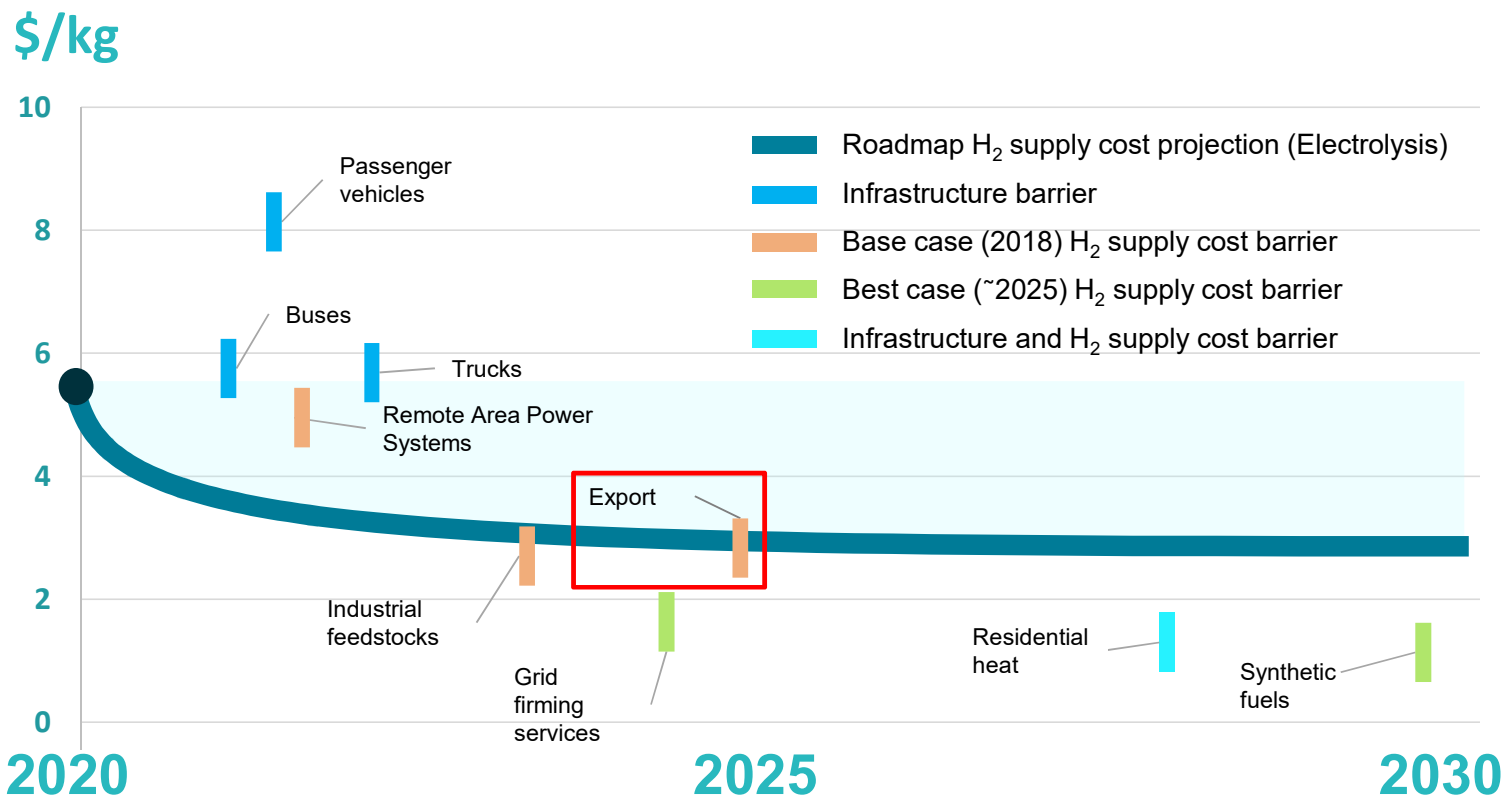
- Does not include the following factors, which could all improve competitiveness:
  - Localisation of relevant supply chains
  - Industrialisation & manufacture automation
  - Establishment of export industry
  - Environmental cost/carbon pricing risk
  - Energy supply risk

- The competitiveness cost curve is not the only driver – Target markets also influenced by stakeholder interest (i.e. H_2 is one of the few ways to decarbonise certain sectors), policy and existing infrastructure

Hydrogen Applications & The Cost Competitiveness Curve



The Export Opportunity



Hydrogen transportation Options

Compression, Liquefaction & Hydrogen Carriers

Energy Carrier	Hydrogen Density (kg/m^3)	Chemical Formula
Hydrogen Gas	0.08	
Compressed hydrogen (20MPa)	18	
Compressed hydrogen (70MPa)	42	
Liquefied Hydrogen (-253°C)	71	
Methane (LNG)*	108	CH_4

Increasing cost

- H_2 has a low volumetric density (kg/m^3) and hence energy density (MJ/m^3) is low in its uncompressed gaseous state
- Developments are underway to increase the volumetric density for cost effective transport
- Carrier technologies are available which improve density and therefore storage / transport economics
- Decisions are a trade off between H2 quantity, capex footprint, cost & energy required plus:

Other Carrier Considerations:

CO_2 neutral carbon sources required

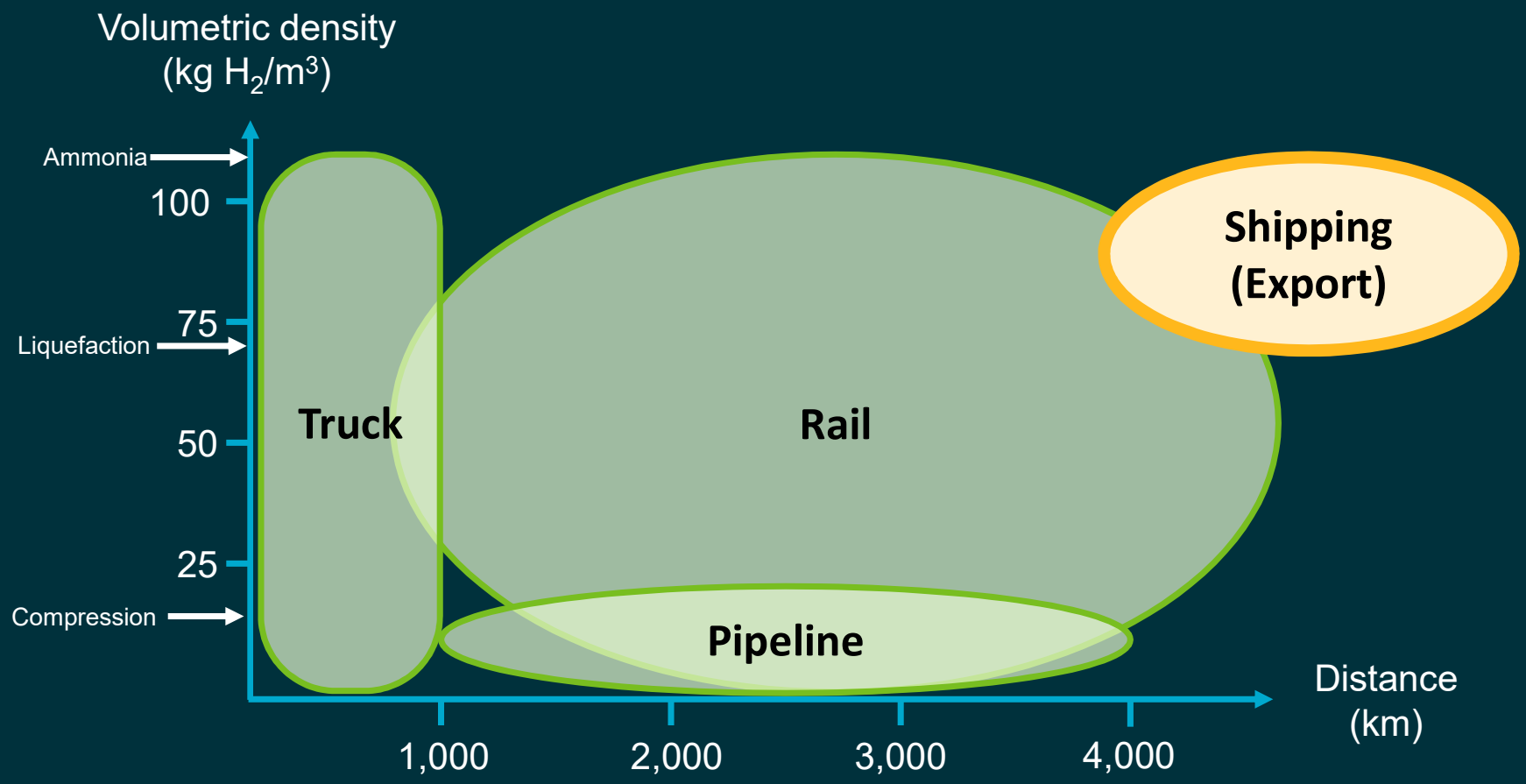
/ for other markets

etrochemical)

cerns

* Not considered in detail in CSIRO Roadmap

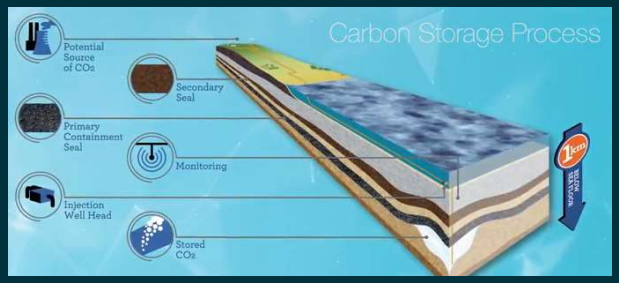
Hydrogen transportation options



Hydrogen Energy Supply Chain (HESC) project

Latrobe Valley
Victorian brown coal gasified to produce hydrogen

CarbonNet
CO_2 Storage Resource



Port of Hastings
Hydrogen is liquefied and loaded onto tankers to be shipped to Japan

Hydrogen Energy Supply Chain

Kawasaki Powering your potential · J-POWER · Iwatani · Marubeni · agl

Supported by: Australian Government Department of Industry, Innovation and Science · Victoria State Government · METI · NEDO

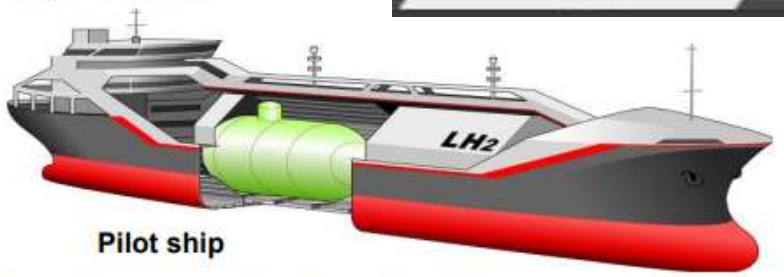
CSIRO

Large Scale Transport Options

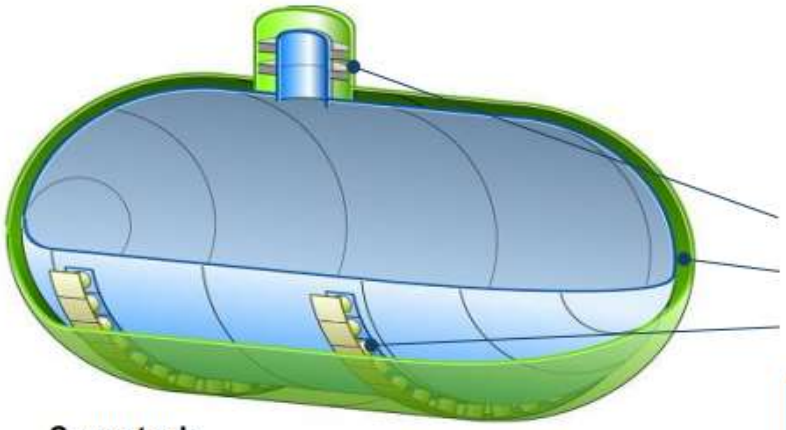
Liquefied Hydrogen Shipping

World's first liquefied hydrogen cargo ship: toward realization

Kawasaki
Powering your potential



Pilot ship



Cargo tank

Special dome structure for maintaining vacuum

Stainless steel vacuum thermal insulation double hull

High thermal insulation supporting structure

December 2013
Basic certification obtained from Nippon Kaiji Kyokai

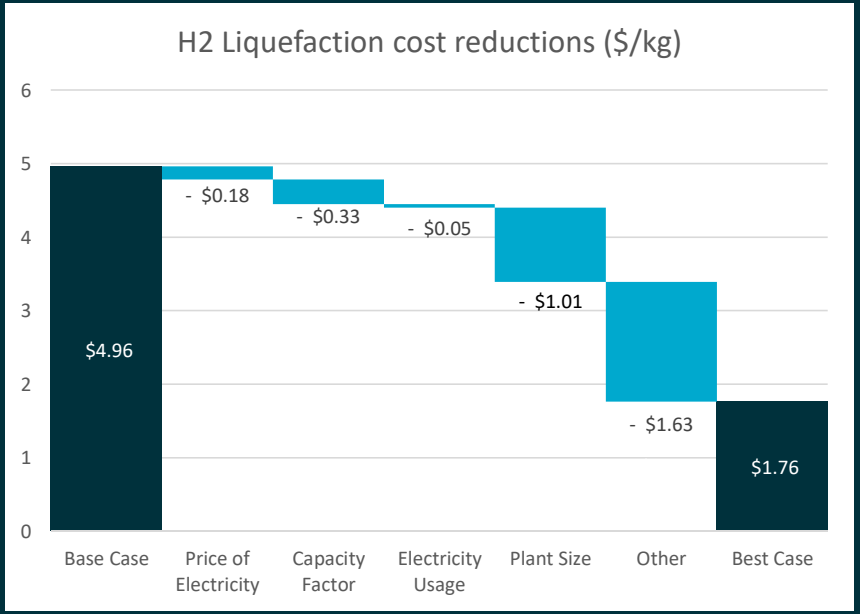
Guideline to complement IGC code is being proposed to IMO by both Japan and Australia

- Australia – Japan Interim Carriage Requirements agreed by IMO Maritime Safety Committee in November 2016

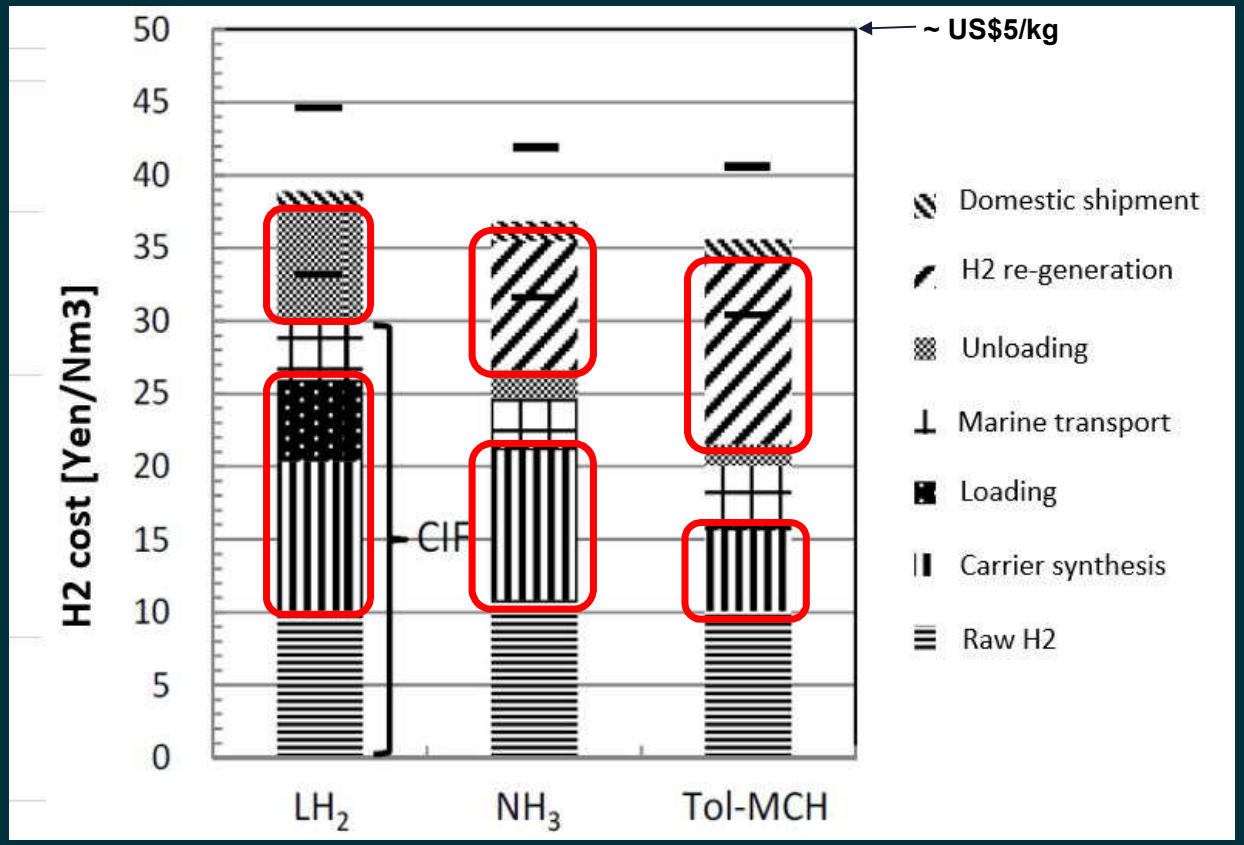
Liquefaction Pathway

Material Drivers of Cost

- Landed CIF cost AU$4.61/kg in 2025
- Expected liquefaction cost contribution by 2025 is AU$1.75/kg
- Further cost reductions expected as the export industry matures & technology improves:
  - Electricity pricing
  - Plant capacity
  - R&D measures designed to improve plant efficiency and maintain temperature



Export Supply Chain Costs



- Similar Costs for 3 pathways in 2030
- Liquefaction, storage & handling major costs for LH_2 pathway
- Carrier Synthesis and hydrogen regeneration significant costs for the Ammonia and MCH pathways

Mizuno, Y. et al. *Journal of Japan Society of Energy & Resources* Vol. 38(3) 11-17

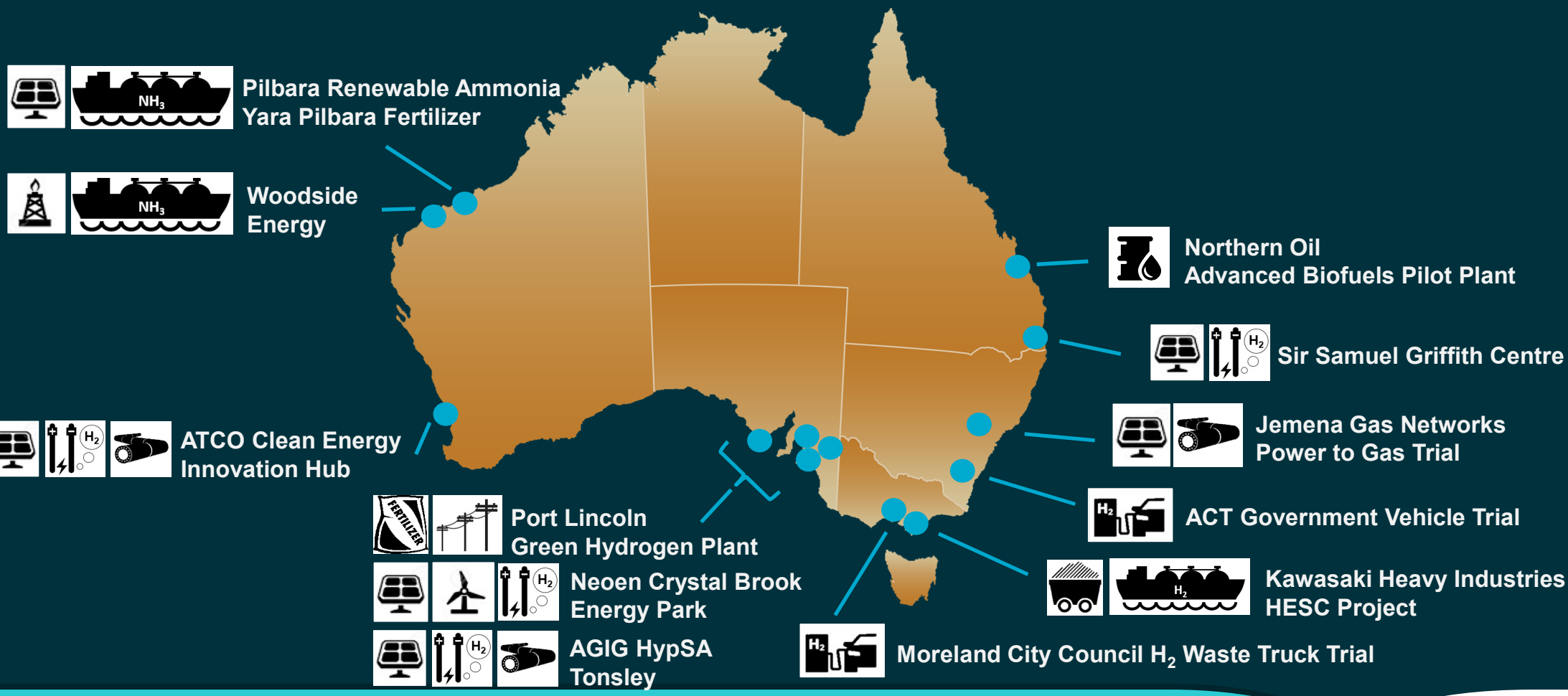
Summary of Actions

Hydrogen Export

TABLE 27. SUMMARY OF ACTIONS: HYDROGEN EXPORT

TIMEFRAME	COMMERCIAL	POLICY/REGULATORY	RD&D	SOCIAL
2018-2025	• Establish government to government agreements between countries to give industry confidence • Establish JVs (incl importing companies) to allow for vertical integration • Undertake land appraisal assessments for dedicated renewables and electrolysis • Establish long term take or pay agreements • Invest in local labour force • Negotiate favourable tariffs for hydrogen export (including in the existing FTAs) • Position production plants close to existing export terminals where possible	• As per production, storage and transport • Develop regulations permitting use of unutilised land for dedicated renewables • Engage bodies such as the International Maritime Organisation to ensure appropriate policy framework for shipping hydrogen	• As per production, storage and transport	• Continue education on potential for hydrogen as new low emissions export commodity

Demonstration Activities in Australia



CSIRO National Hydrogen Roadmap: Key Messages

- Hydrogen Technology is largely mature. **Market activation** is the key priority for developing an economically sustainable hydrogen industry in Australia
- Barriers to market activation stem from both a lack of infrastructure supporting markets and cost of hydrogen supply
- The opportunity for clean hydrogen to compete favourably on cost in many local applications is within reach and achievable by 2025.
- The development of an export industry represents a potential 'game changer' for hydrogen and the broader energy sector due to associated increases in scale.
- Development of an appropriate policy framework could create a local 'market pull' for hydrogen. Expect investment in value chain infrastructure to follow

Acknowledgements

National / International Stakeholder Input

Australian Gas Infrastructure Group (AGIG)
Air Liquide
Australian Pipeline and Gas Association (APGA)
Australian Petroleum Production and Exploration Association (APPEA)
ATCO
BHP
BOC Group
Bollard
California Fuel Cell Partnership
Caltex
CarbonNet
Caterpillar
Curtin University
Department of Defence: Science and Technology (DST)
E4Tech
Energy Australia
Energy Networks
Energy Pipelines CRC
Engie
EVO Energy
Fraunhofer Society
Fuel Cell and Hydrogen Energy Association
GE Power
Global CCS Institute
Griffith University
H2H Energy
Heraeus
Hydrogenics
Hydrogenious Technologies
Hyundai
International Partnership for Hydrogen and Fuel Cells in the Economy
ITM Power
Jemena
JPower
Linde
Ludwig-Bölkow-Systemtechnik
Monash University
Moreland Council
New Energy and Industrial Technology Development Organization (NEDO)
NOW: National Organisation Hydrogen and Fuel Cell Technology
Renewable Hydrogen Pty Ltd
Renewable Hydrogen Fuel Cell Collaborative
RMIT
Shell
Siemens
Southern Oil
Thyssenkrupp
Toyota
Transit Systems
U.S. Department of Energy
University of Hawaii
University of Melbourne
University of NSW
University of Queensland
Yara

Project Sponsors

CSIRO Project Team

Sam Bruce (Lead)
Max Temminghoff
Jenny Hayward
Elizabeth Schmidt
Chris Munnings
Doug Palfreyman

We deliver Australia's energy future

Working with industry across the energy value chain

Applying large-scale infrastructure to high-impact science

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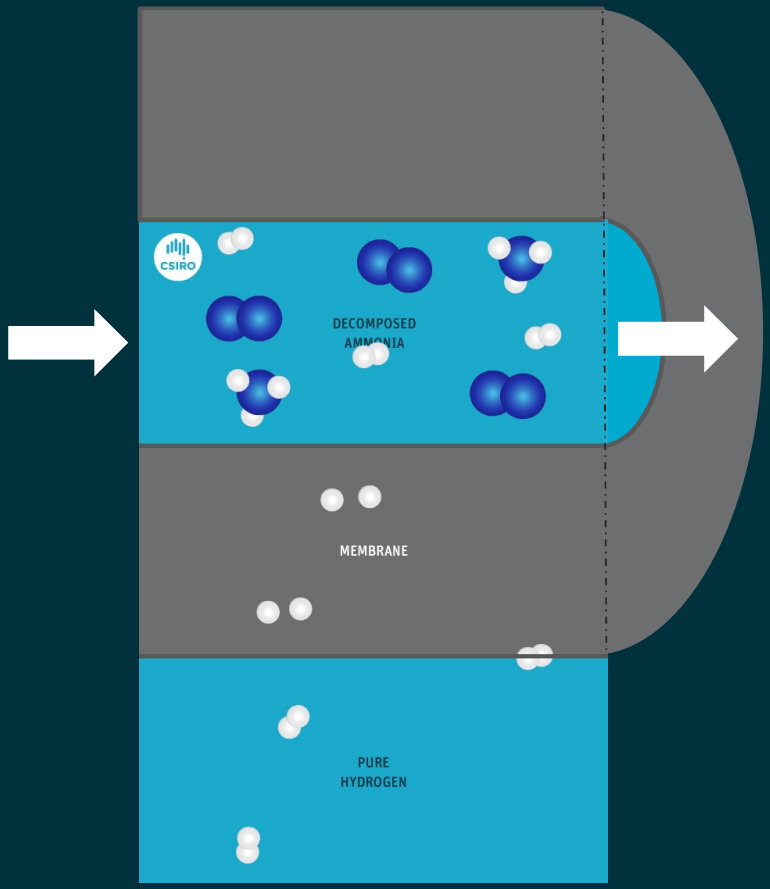
CSIRO Hydrogen Separation Membrane Technology



Vanadium-based membranes for H_2 purification