PIANC

The World Association for Waterborne Transport Infrastructure

Welcome to Hydrogen Workshop

Challenges and Opportunities for Hydrogen in the Port Industry

Sam Mazaheri

18th April 2024, EA Auditorium, Brisbane,

Acknowledgement of Country

- PIANC ANZ acknowledges the traditional custodians of the country throughout Australia including the land on which we gather and meet today, and recongnises their continuing connection to land, water and community.
- We pay our respect to them and their cultures, and to elders past, present and emerging.

- **Turrbal and Yuggera peoples**

PIANC

The World Association for Waterborne Transport Infrastructure

PIANC, The World Association for Waterborne Transport Infrastructure (formerly known as Permanent International Association of Navigational Congress) IS

A worldwide network of professionals and leading partners, providing expert advice in the design, development and maintenance of ports, waterways and coastal areas.


Maritime Navigation Commission


Inland Navigation Commission


Environmental Commission


Recreational Navigation Commission

SINCE 1885!

Remains
the leading international
source of
waterborne transport-
related information
in the 21st century

Workshop Objectives

- To uncover key subjects needed to be considered by port and maritime sector to transfer their existing infrastructure and facilities towards better and more efficient way of handling hydrogen in future
- To address the key challenges and opportunities presented by hydrogen integration
- To discuss insights and solution to propel our industry towards sustainable and prosperous future

Program

Challenges and Opportunities for Hydrogen in the Port Industry

Thursday 18 April	
1230-13:00 Arrival / Registration and coffee	
13:00–13:15	**Welcome & workshop introduction and objectives** Sam Mazaheri, Chair, PIANC ANZ Northern Chapter
Facilitated session (Andrew Catto): Hydrogen Market and Project Overview	
1315-13:40	**Global perspective on Hydrogen markets (Online)** Pooja Jain, Senior VP, WSP USA
1340-1405	**Queensland Government policy and directions** Alana Barlow, Deputy Director General, Hydrogen and Future Fuels
1405 –1430	**Large-scale Hydrogen plans** Craig Haymes, CEO, Gladstone Ports Corporation Limited
1430-1455	**HyNQ Project Overview** Claire Speedy, Energy Estate
14:55-15:20 Afternoon Tea	
Facilitated session (Michael Coull): Port Perspective	
1520-1545	**Development of existing port infrastructure to handle green ammonia – the synergies and challenges** Richard Woollard / Mike Sudmalis, Aurecon
1545-1615	**Future fuels: Challenges and opportunities for ports** Jeffrey Gomes, Hatch
1615-1640	**Storage and transportation facilities** Dr. Prakash Aryal, WSP Aus
Panel Session (Sam Mazaheri)	
1640–1705	**Panel Session: Discussion and learnings**
1700-1800	**Networking, drinks, and finger foods**

Panel Session

- Questions

PIANC APAC 2024

3RD PIANC ASIA PACIFIC CONFERENCE

27-30 AUGUST 2024

SYDNEY, AUSTRALIA

www.piancapac.com

Connecting Asia Pacific ports in a changing world

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Thank You

PIANC

The World Association for Waterborne Transport Infrastructure

Global Perspectives on Hydrogen Markets

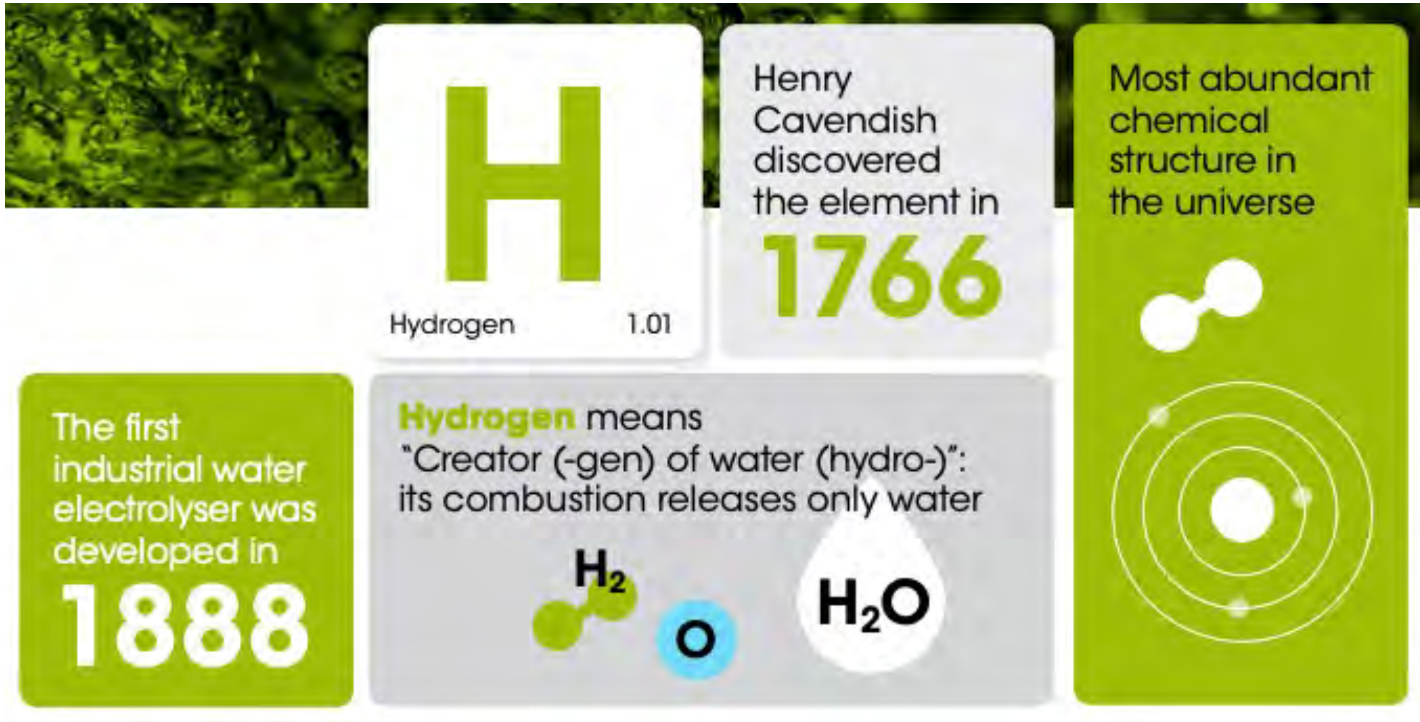
PIANC Australia and New Zealand | April 18, 2024

Pooja Jain

SVP Strategic Innovations | WSP

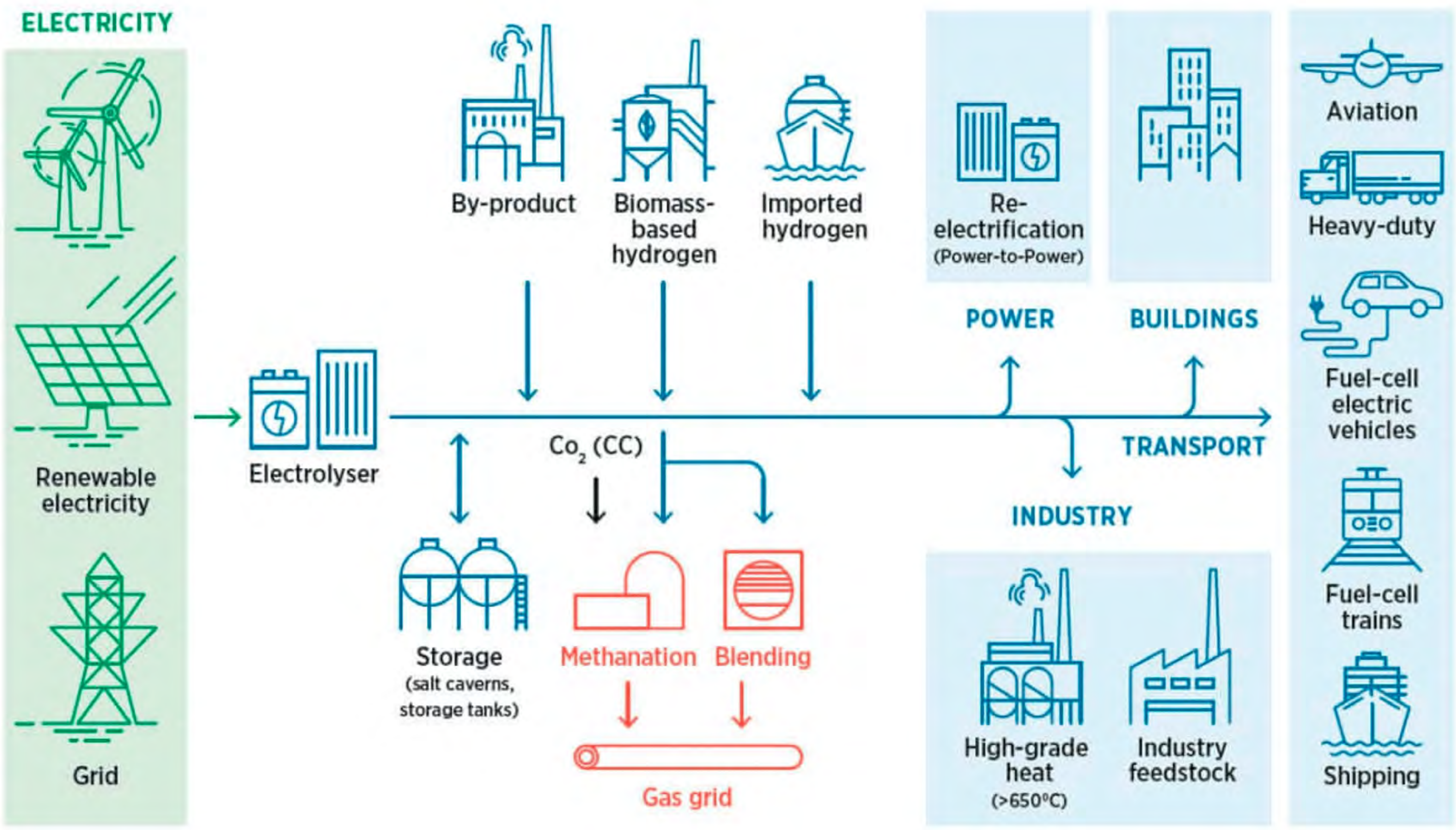
AGENDA

- Introduction
- Future Outlook
- Regional perspectives & Ports
- Conclusion



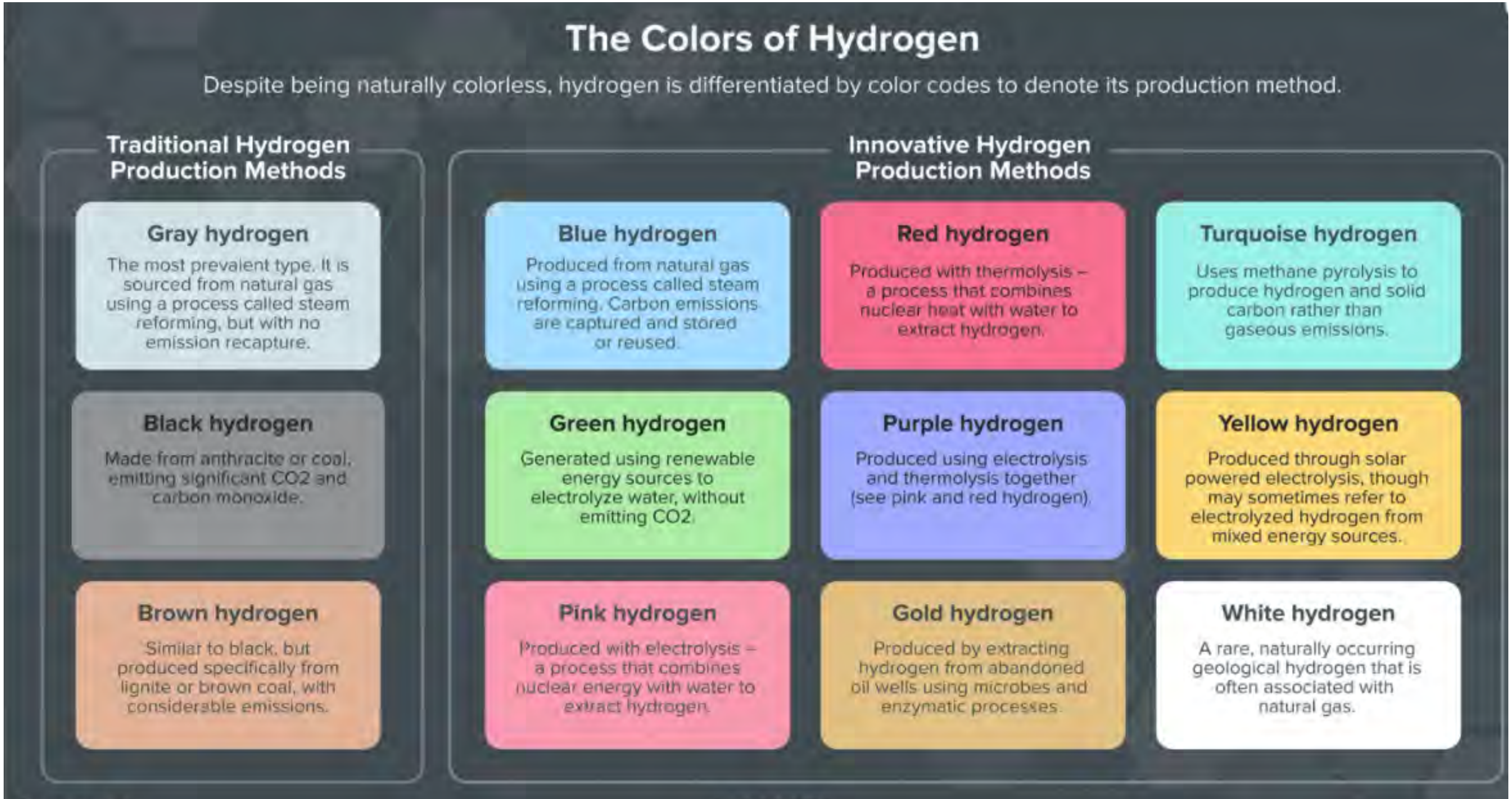
Introduction

Hydrogen

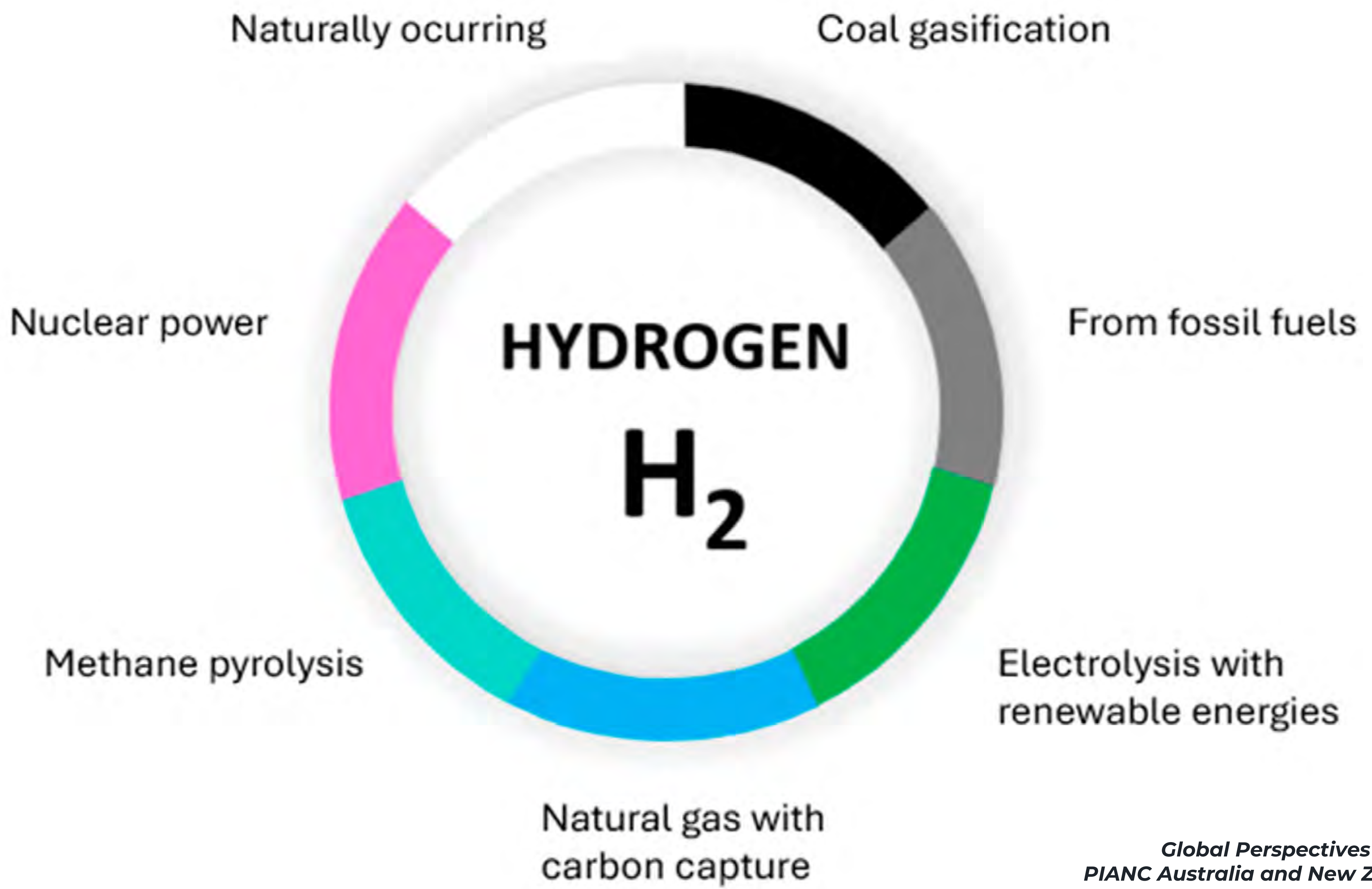

ELECTRICITY
Renewable electricity
Grid
Electrolyser
By-product
Biomass-based hydrogen
Imported hydrogen
Storage
(salt caverns, storage tanks)
Co2 (CC)
Methanation
Blending
Gas grid
Re-electrification
(Power-to-Power)
POWER
BUILDINGS
TRANSPORT
INDUSTRY
High-grade heat
(>650°C)
Industry feedstock
Aviation
Heavy-duty
Fuel-cell electric vehicles
Fuel-cell trains
Shipping

Hydrogen

COLORS OF HYDROGEN



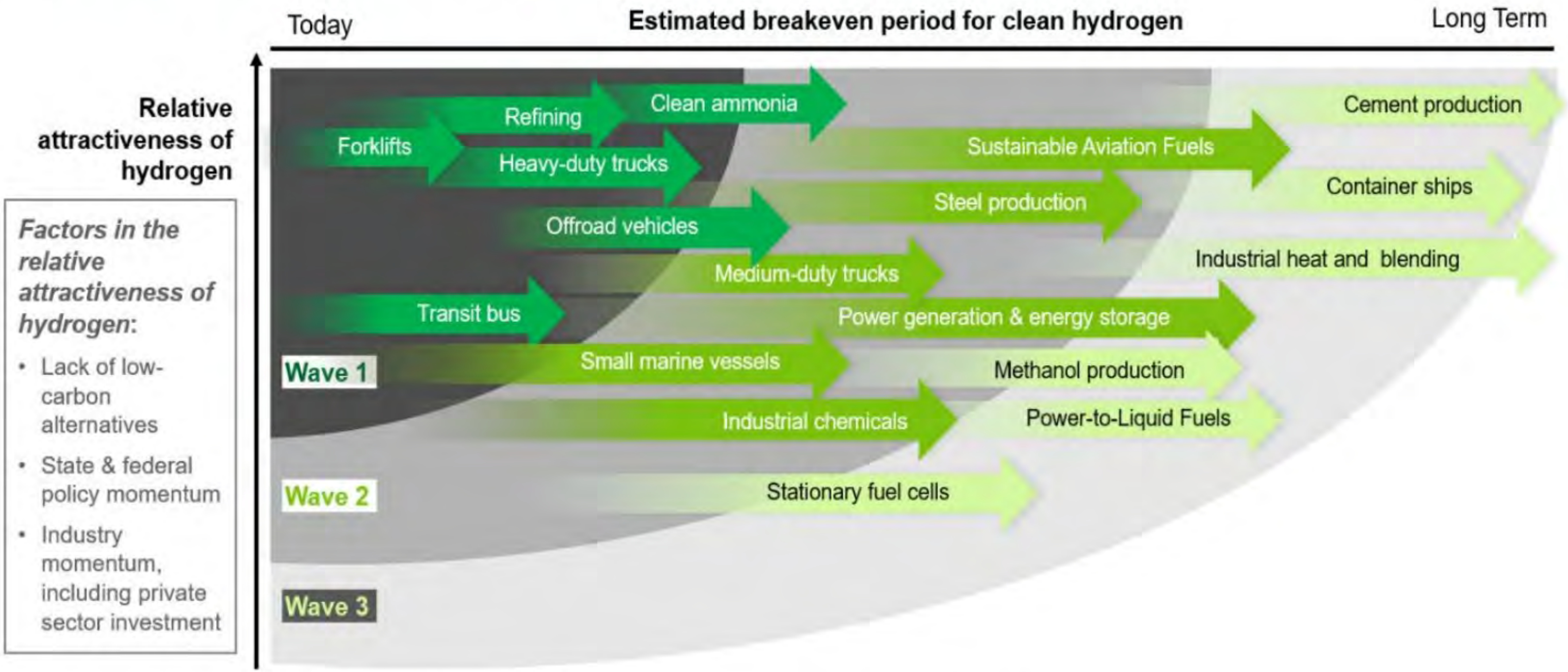
Hydrogen



Naturally ocurring
Coal gasification
Nuclear power
HYDROGEN
H_2
From fossil fuels
Methane pyrolysis
Electrolysis with renewable energies
Natural gas with carbon capture

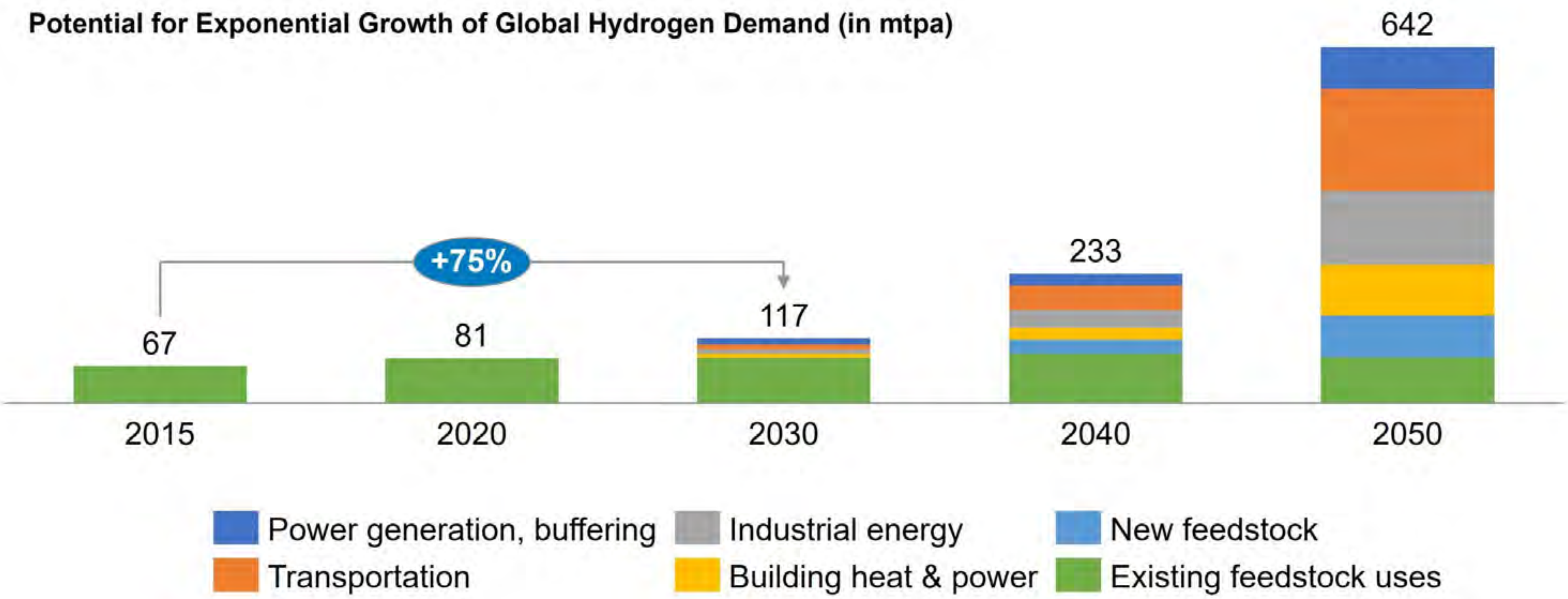
Hydrogen

APPLICATIONS OF HYDROGEN



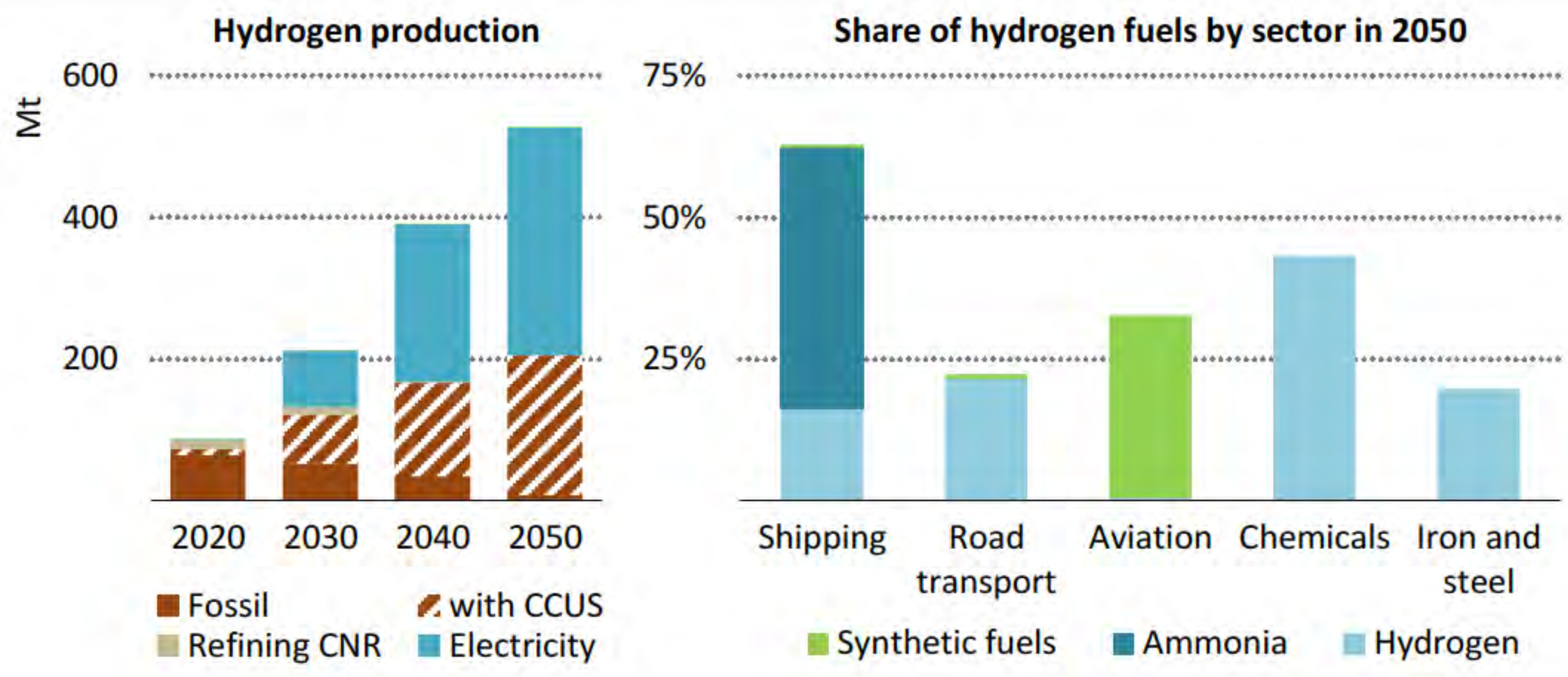
Future Outlook

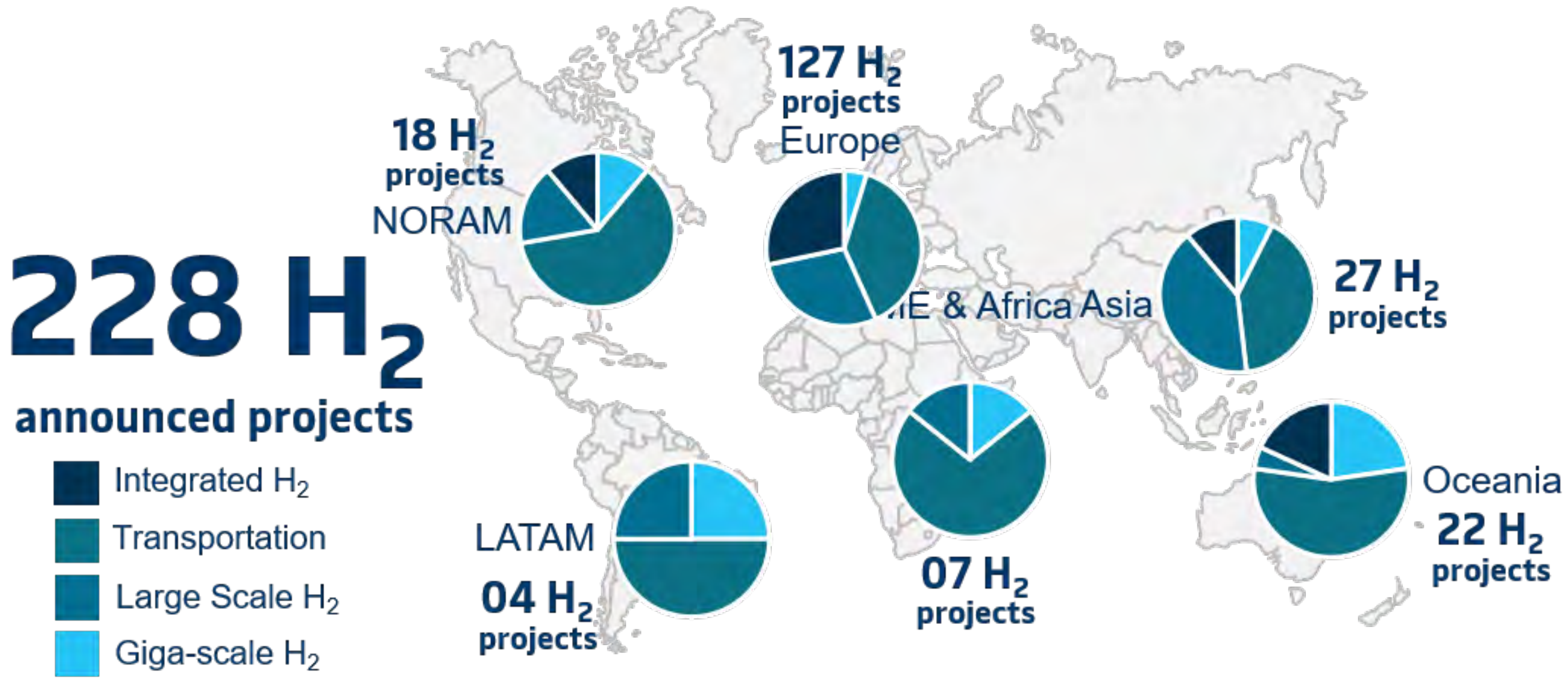
HYDROGEN DEMAND OUTLOOK



Source: Hydrogen Council

HYDROGEN SUPPLY OUTLOOK





17 Projects

Giga-scale production: Renewable H_2 projects >1GW and low-carbon H_2 projects >200 kt p.a.

90 Projects

Large scale projects: Industrial usage like refinery, ammonia, power, methanol, steel & industry feedstock

53 Projects

Transport projects: Trains, ships, trucks, cars & other hydrogen-based mobility applications

45 Projects

Integrated H_2: integrated H_2 economy, cross-industry and projects with different types of end-uses

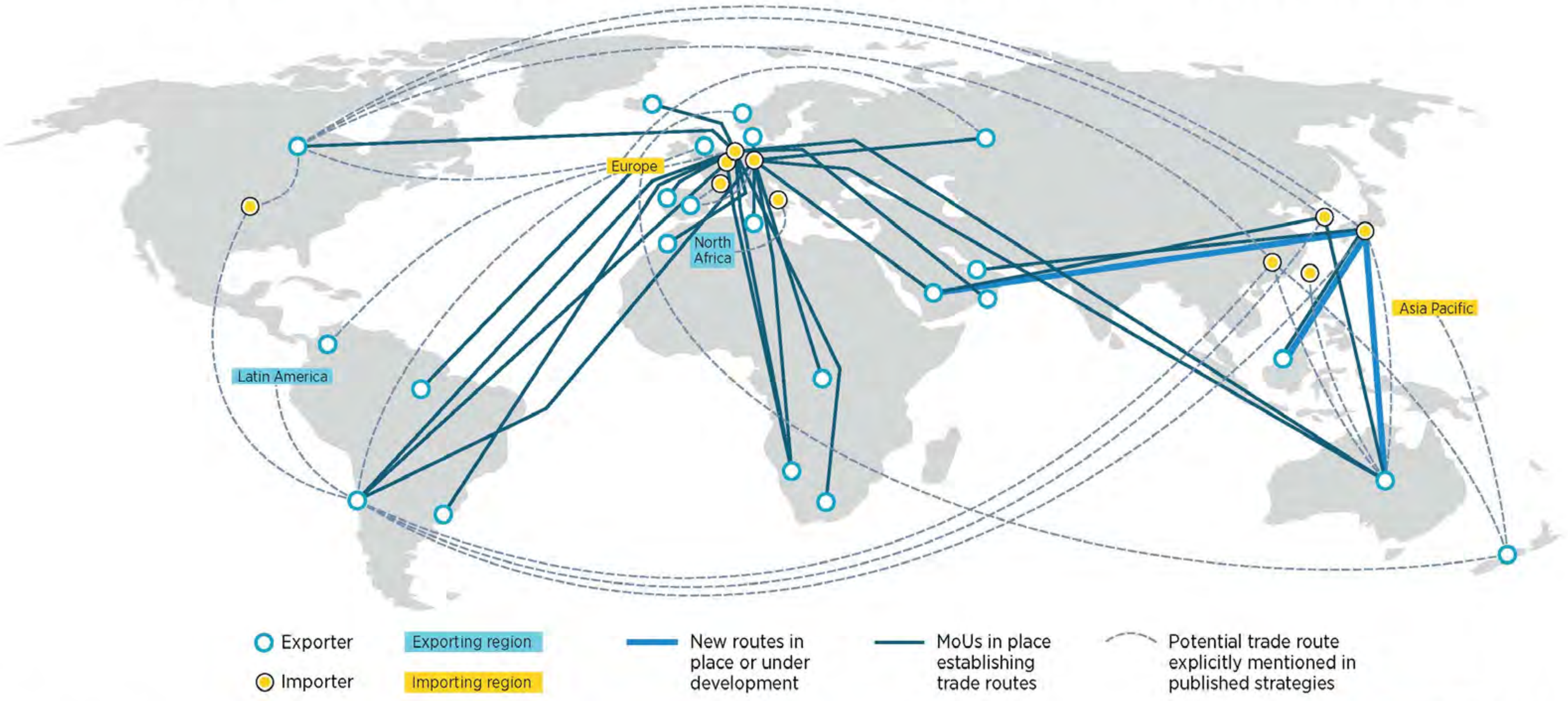
23 Projects

Infrastructure projects: H2 distribution, transportation, conversion and storage projects distributed across globe with major share in Europe only.

Source: Eninrac research, McKinsey Insights & Channel Checks

Regional Perspectives & Ports

An expanding network of hydrogen trade routes, plans and agreements



Source: IRENA (2022) *Geopolitics on Hydrogen* at **www.irena.org**

IRENA
International Renewable Energy Agency

PORTS ENGAGED IN HYDROGEN PROJECTS

- Port of Rotterdam
- Port of Los Angeles
- Port of Kobe

...and many more

PORTS PLAY A VITAL ROLE!

- Production and supply of hydrogen
- Hydrogen distribution infrastructure
- Hydrogen consumption and transport to end-users

Conclusion

Questions

Contact Information:

Pooja Jain

Pooja.jain1@wsp.com

SVP Strategic Innovations | WSP

Image: Artist Impression of Stanwell's Future Energy Innovation Training Hub (FEITH)

Queensland Government Policy and Direction

Alana Barlow

Deputy Director-General, Hydrogen and Future Fuels division

Department of Energy and Climate

Queensland Government

Acknowledgement of Country

I would like to acknowledge the Traditional Owners of the land on which this event is taking place and Elders and pay my respects to Elders both past and present.

I also recognise those whose ongoing effort to protect and promote Aboriginal and Torres Strait Islander cultures will leave a lasting legacy for future Elders and leaders.

Queensland's 2035 Clean Economy Pathway

Queensland's emissions reduction targets

30%
below 2005 levels by 2030

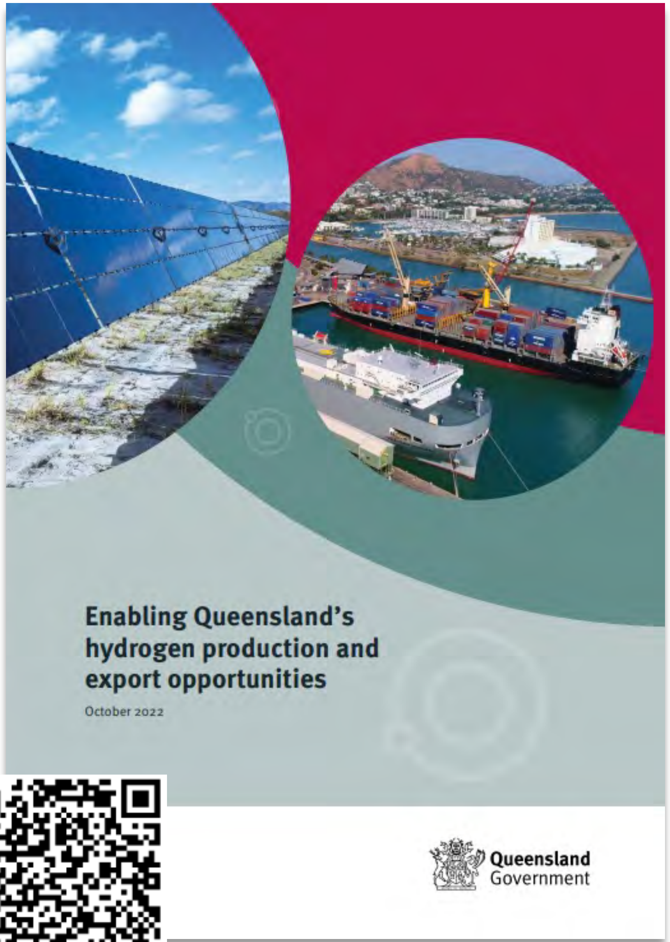
75%
below 2005 levels by 2035

Net zero
by 2050

Why do we need to decarbonise Queensland's economy?

- ✓ Climate action is a jobs opportunity for all Queenslanders
- ✓ Decarbonisation generates investment throughout the economy
- ✓ Creating the jobs of the future economy
- ✓ Diversification and community resilience
- ✓ Protecting the environment.

The *Enabling Queensland's hydrogen production and export opportunities* report:



- ✓ **Demonstrates Queensland's unique opportunity** to create an internationally significant renewable hydrogen export industry.
- ✓ **Identifies and evaluates each of Queensland's key export regions** including existing infrastructure and its potential role in local supply chains.
- ✓ **Gives strategic insight for proponents** into Queensland's hydrogen production potential as they plan, develop and secure capital, partners and off-take for their projects.
- ✓ **Provides industry and government partners a platform for future planning** and provides a reference to guide industry to grow sustainably, while balancing economic, social, environmental and cultural values.

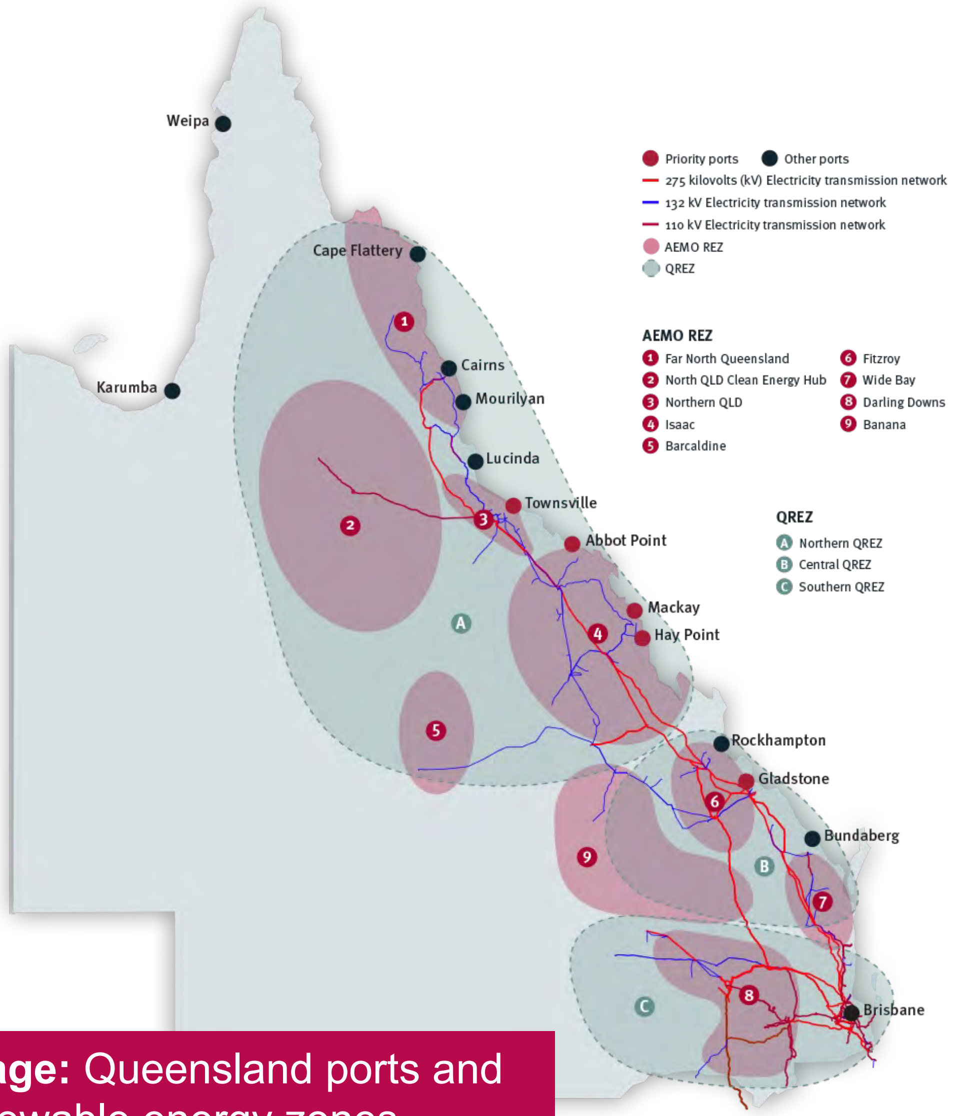
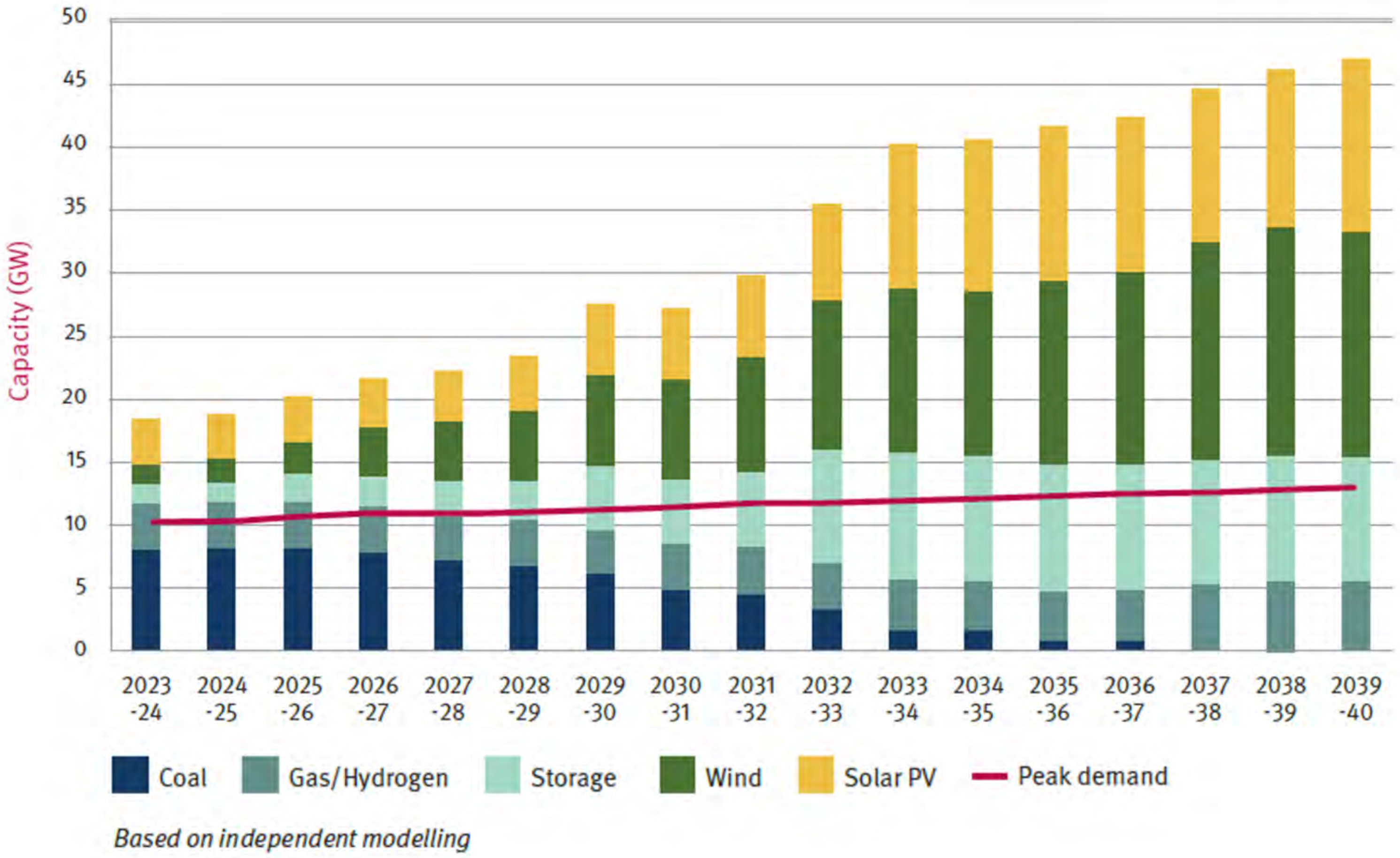


Image: Queensland ports and renewable energy zones

Hydrogen in Queensland just makes sense!

- ✓ Significant wind and solar resources.
- ✓ Large transmission network and established industrial hubs in Northern Queensland.
- ✓ 14 ports, 5 priority ports - majority public owned.
- ✓ Experience and an energy exporter and capability in export of bulk commodities out of multiple ports.
- ✓ Publicly owned generators, ports and transmission network.
- ✓ Plenty of land including State Development Areas (SDAs) and Infrastructure Corridors.
- ✓ Large regional population and highly skilled workforce

Changing generation mix



Queensland's generation mix will transform over time to include more wind, solar and storage to ensure we always have enough energy to meet Queensland's energy demand including at peak times.

Queensland is on track to be a Hydrogen powerhouse

CS Energy Brigalow Peaking Power Plant

- ✓ 400MW hydrogen-ready gas peaker with fast-start capability
- ✓ 35% green hydrogen blend from day one
- ✓ Targeting commercial operations mid-2026
- ✓ Complements Kogan Creek Renewable Hydrogen project

Central Queensland Hydrogen Project (CQ-H2)

- ✓ 3000MW Project at Aldoga
- ✓ Significant Japanese and Singaporean Partners
- ✓ Currently undertaking FEED
- ✓ $15m funding QREHJF
- ✓ Shortlisted for Hydrogen Headstart

Rio Tinto & Sumitomo Yarwun Hydrogen Calcination Pilot Demonstration Program

- ✓ Construction starting 2024 on a hydrogen plant at Yarwun Alumina Refinery
- ✓ Lower carbon emissions from the alumina refining process
- ✓ 2.5MW on-site electrolyser to supply 6,000 tonnes of hydrogen to the refinery per year

Sustainable Fuels are another element in the plan to decarbonise

ENERGY CONSUMPTION

NOW

50%

PETROLEUM FUELS

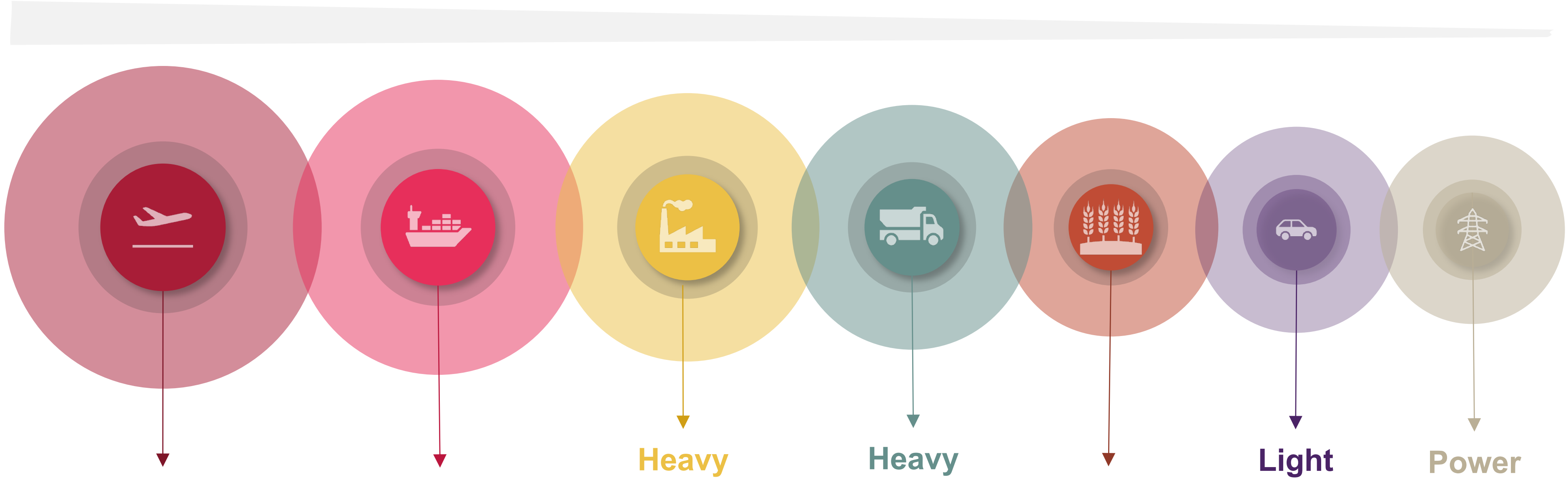
FUTURE

100% MIX

RENEWABLE ENERGY, HYDROGEN, SUSTAINABLE LIQUID FUELS

FUTURE SECTOR RELIANCE ON LIQUID FUELS

MORE LIKELY — LESS LIKELY



Aviation
Jet fuel replacement and blending

Marine
Ship fuel diesel replacement

Heavy industry
Diesel replacement for mining and construction

Heavy transport
Diesel replacement for heavy vehicles, rail

Agriculture
Diesel replacement for farming equipment

Light transport
Petrol replacement

Power generation
Diesel power generation replacement

Creating a clear pathway

Community engagement

$5 Million to expand community awareness on hydrogen and build social licence

Policy and legislation

Initial Bill passed with broader reforms being considered and consulted on

Project planning

$15 Million in technical studies to support strategic project planning in our hydrogen hubs

Revising the strategy

Refreshing the Queensland Hydrogen Industry for actions beyond 2024

Industry investment

- Project facilitation
- $35 Million Hydrogen Industry Development Fund
- $4.5 Billion Queensland Renewable Energy and Hydrogen Jobs Fund

Thank you

Alana Barlow
Deputy Director-General, Hydrogen and Future Fuels
Department of Energy and Climate
www.epw.qld.gov.au/about/initiatives/hydrogen

Queensland Government

Gladstone Ports Corporation

Growth, prosperity, community.

GPC's Hydrogen Future

PIANC "Challenges & Opportunities for Hydrogen in the Port Industry"

Brisbane, 18 April 2024

Acknowledgement of **Traditional Owners**

GPC acknowledges the First Nation peoples **Bailai**, **Gurang**, **Gooreng Gooreng**, **Taribelang Bunda**, **Darumbal**, **Kabi Kabi** and **Butchulla** whose original land we all share, live, work and play on.

GPC acknowledges and pay our respect to all Elders of past, who have made the many sacrifices, contributions and paved the way for us all to be here today.

GPC acknowledges our present and emerging Leaders who will continue the fight for a better and united Australia for all our generations of **today**, **tomorrow** and in the **future**.

GPC also extends this respect to other Aboriginal, Torres Strait Islander and Australian South Sea Islander Elders and peoples within our operating footprint.

Koongo, Bailai word meaning place of water. Original artwork by Patricia Coleman, Bailai.

OUR FOOTPRINT

GPC is a Government Owned Corporation responsible for managing 4 port precincts in Central Queensland:

- **Port of Gladstone**
- **Port of Bundaberg**
- **Port of Rockhampton** (Port Alma)
- **Port of Maryborough**

110 YEARS 1914 - 2024

A world leading multi-commodity ports' corporation

>1,900
Vessels per year

120MT/Year
Trade

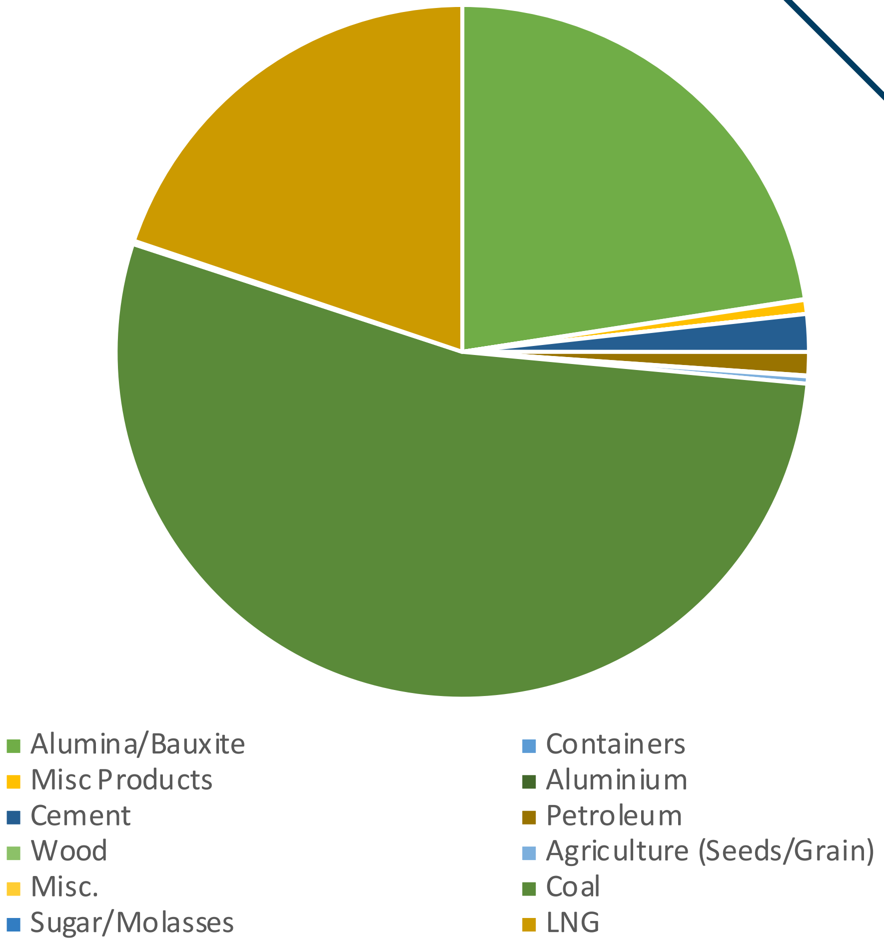
34+
Commodities

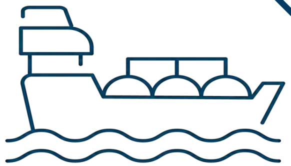
26
Wharf Centres

Gladstone Ports Corporation

GPC – Who are we?

GPC has a long history of facilitating the transportation, export and import of multiple products in support of meeting the energy needs of Queensland, Australia and the world.





20%

Metallurgical Coal

TICOR QUARRY

STEVEDORING SERVICES

>65ha PARKLANDS

25%

World LNG Trade

4^{TH} LARGEST COAL TERMINAL

5-GOLD ANCHOR MARINA

>95% HAZARDOUS GOODS - ALMA

Gladstone Ports Corporation

Leading Environmental, Social and Governance (ESG)

ESG

Environmental
- Climate Change
- Carbon Emissions
- Biodiversity and Land Use
- Habitat Protection

Social
- Indigenous Affairs
- Community Relations
- Culture & Employee Engagement
- Sustainable Growth Management

Governance
- Safety and Health & Wellbeing
- Business Ethics
- Governance
- Board Diversity

Decarbonise GPC Operations

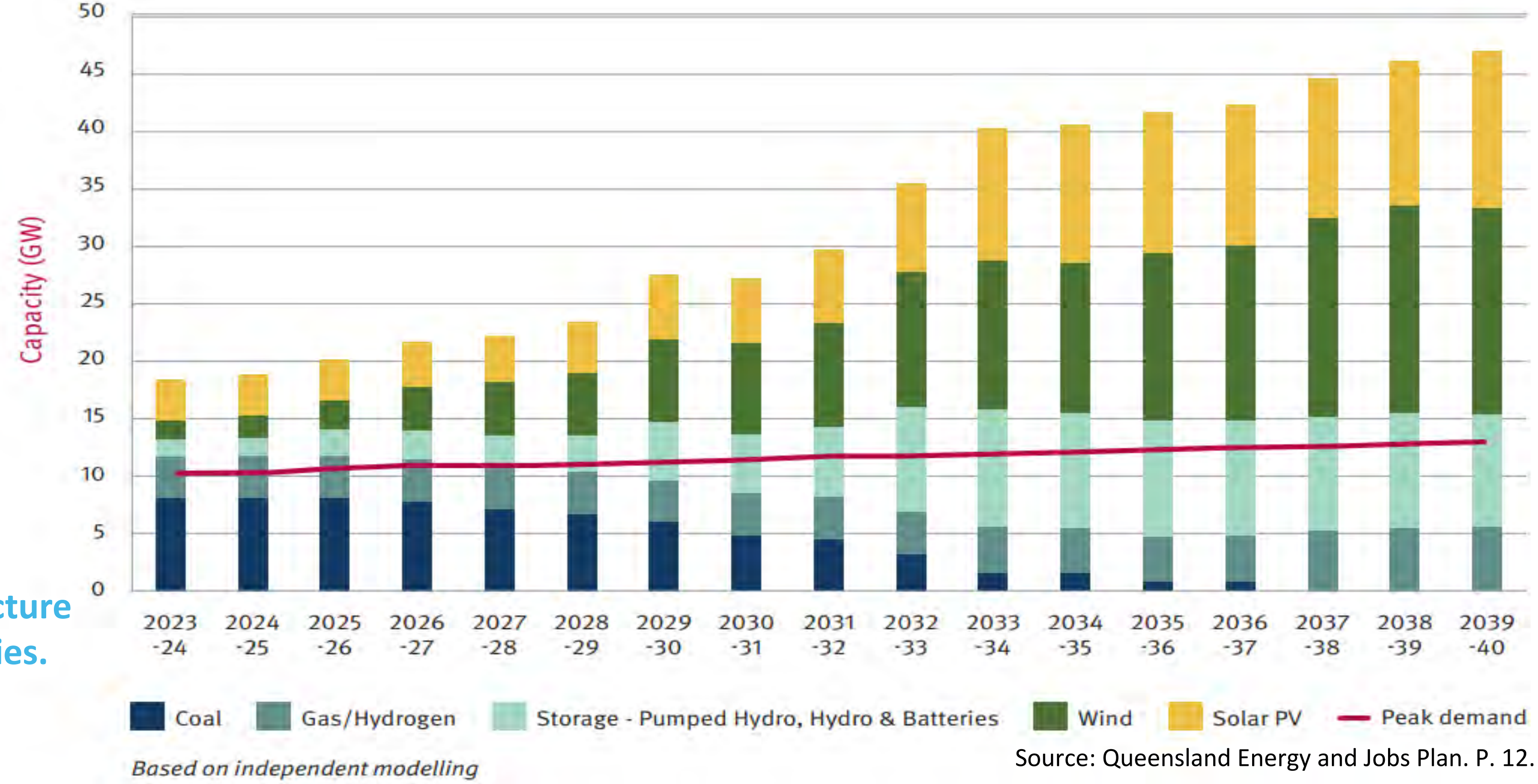
Reduce GHG emissions by **30%** by **2030.**

Reduce GHG emissions by **75%** by **2035.**

Facilitating the Renewable Energy Transformation

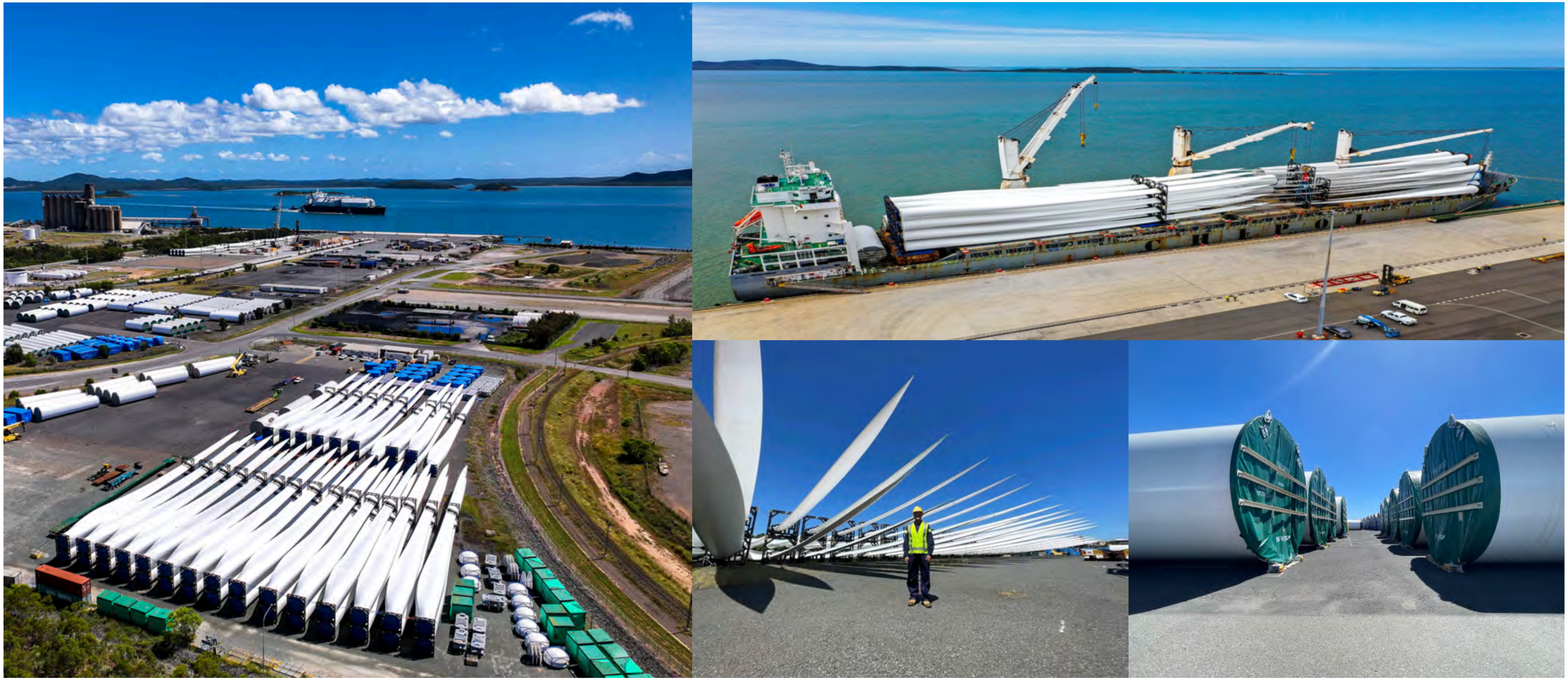
GPC is a key enabler to facilitate development, common user infrastructure and export/import trade opportunities.

Queensland Energy and Jobs Plan capacity mix (GW)

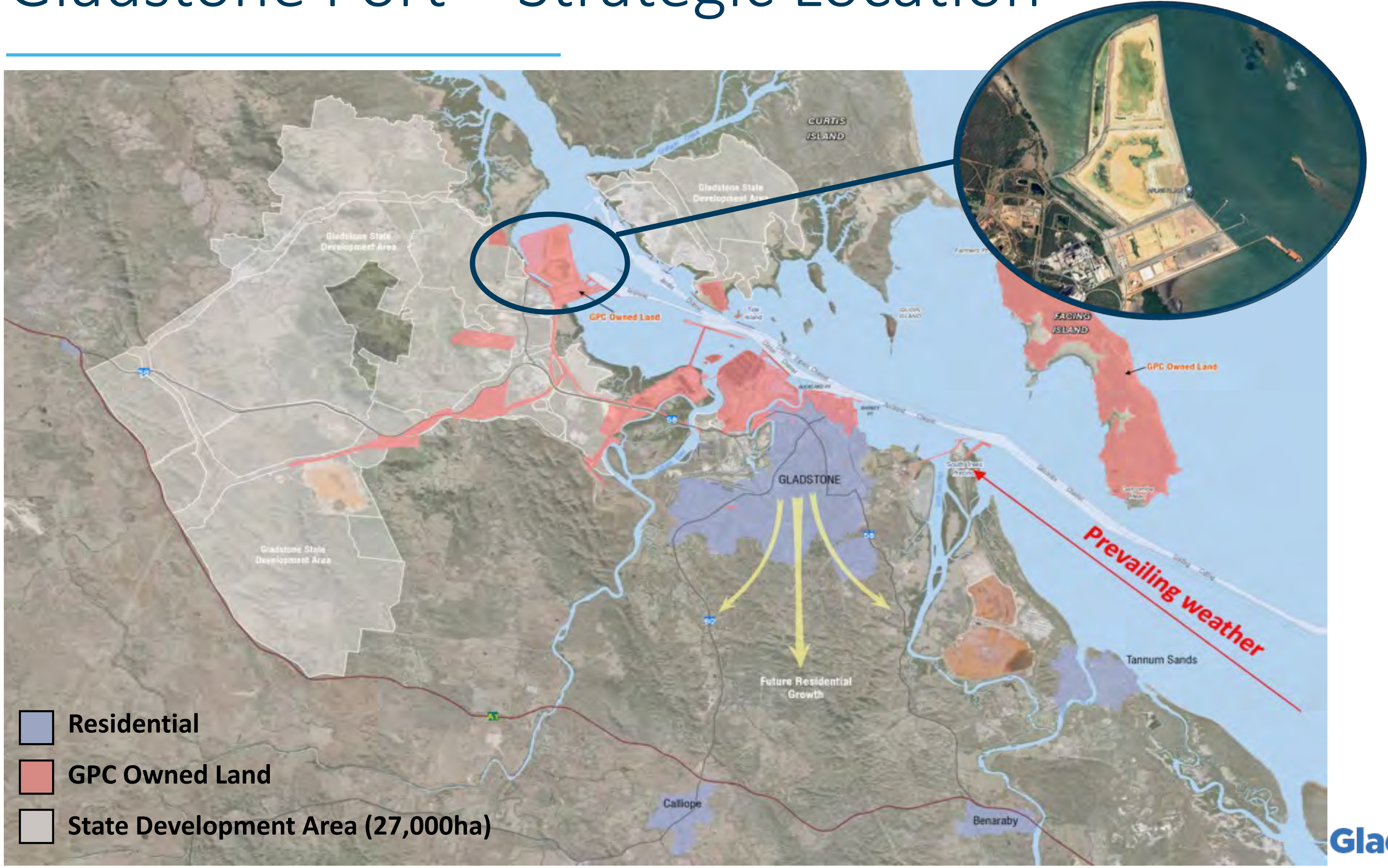


Source: Queensland Energy and Jobs Plan. P. 12.

Currently in progress: Clark Creek Wind Farm



Gladstone Port – Strategic Location



Deepwater Harbour

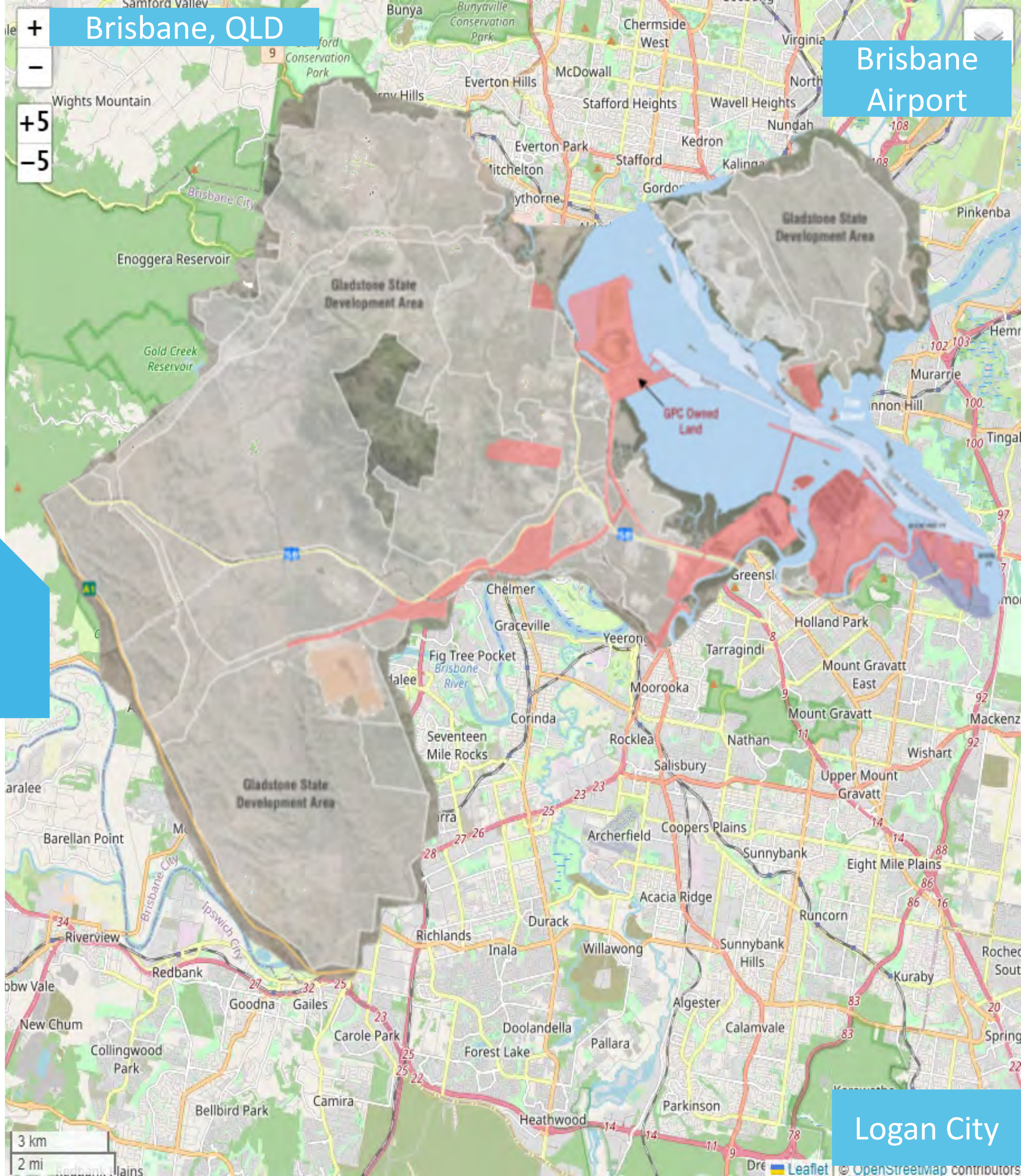
Industrial Hub

Substantial Land

Gladstone Ports Corporation

Size Comparison

A world leading multi-commodity ports corporation



Precinct Planning

Precinct Land Plan
- Maximise volumes
- Compatible land use
- Sustainable footprint

License to Operate
- WHS
- MHF
- ESG

Supporting Infrastructure
- Power
- Water
- Waste streams

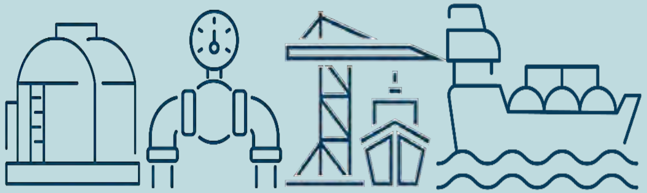
Common User Infrastructure
- Wharf Centers
- Storage (e.g. HN3)
- Pipelines

Technical & Commercial

Facility Layout
Process Safety
Land use & lease

Bulk Liquids Storage	Liquid Hydrogen
Ammonia	Future Reclamation
OSOM	Infrastructure Corridor
Water Management	Future industrial & Services

CUI Advantages



- Requires ~ third of land
- 50% less tanks.
- Construction CO2 emissions reduced > 50%.
- Capital costs 60%

Gladstone Ports Corporation

Gladstone Ports Corporation

Growth, prosperity, community.

More than a port

A world leading multi-commodity ports' corporation

HyNQ
North Queensland Clean Energy Project

April 24

HyNQ respects the rich history of the First Nations People connection with Country throughout Australia.

Across our proposed project site there are four First Nations parties - the Juru, the Gia People , the Kyburra Munda Yalga Aboriginal Corporation RNTBC and the Birriah people - we acknowledge them as the Traditional Custodians of the area in which the Project would be located. We recognise and respect their continuing connection to land, sky, sea and waterways. We thank them for protecting this land and its ecosystems since time immemorial and pay our respects to their Elders past, present and emerging.

About Energy Estate

Energy Estate was stablished in early 2018 to accelerate the transformation of the energy sector and the decarbonisation of industry, and to be a vehicle to deliver global scale decarbonisation. 6 years later, with a deeply experienced and multi-disciplined team, we have established a portfolio of over 30GW of renewable energy, storage and green hydrogen projects with a strategically diversified range of technologies and industry partners. We have a portfolio of renewbale energy and e-fuels projects in Australia, NZ, US and Europe with teams in Sydney, Melbourne, Brisbane, Hong Kong and London.

Energy Estate was one of the first renewable energy developers to put communities and regional economic development at the centre of our development principles. We are at the forefront of the development of the green hydrogen economy, with a dedicated Director of Hydrogen and a portfolio of developments including developing HyNQ, a large-scale green ammonia facility in northern Queensland and H2N, one of the world's first dedicated green hydrogen pipelines in the Hunter Valley, NSW. Our project partners include IHI and Idemitsu for the HyNQ Project and Eurus Energy for the H2N Project.

Our team has a track record developing large scale bioenergy projects including bioethanol and biodiesel projects in multiple markets globally. We work closely with leading technology providers and believe strongly in partnerships to drive forward our platform of projects.

energy estate

HyNQ Project Partners

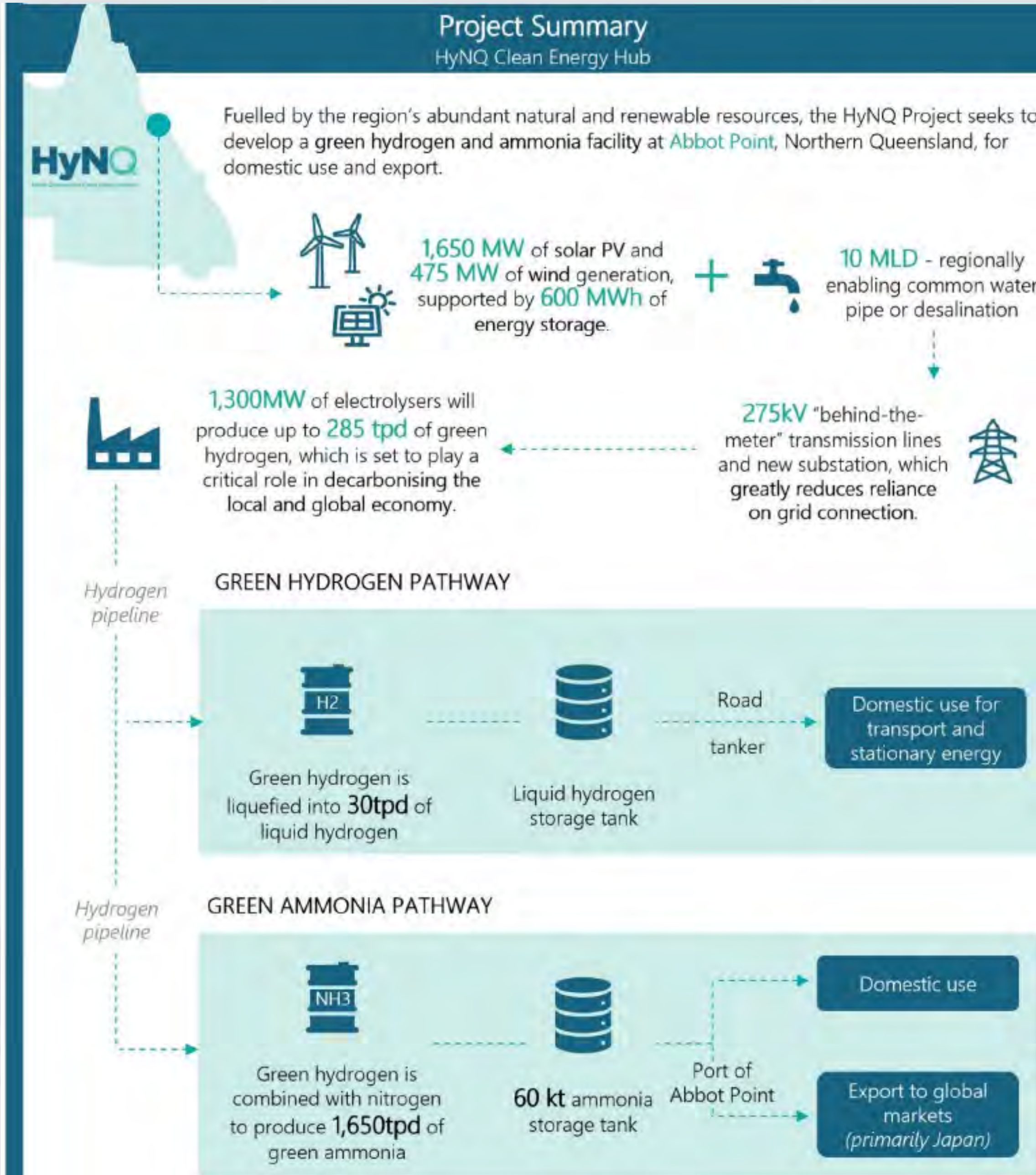
A consortium of domestic and global energy players, led by Energy Estate, has come together to accelerate the development of HyNQ.

The consortium includes Idemitsu Australia, a subsidiary of global energy supplier Idemitsu Kosan Co Ltd, Queensland Government owned energy company CS Energy and IHI Engineering Australia. The partners have funded the $6M AUD HyNQ Pre-FEED study, including 1.5M AUD from the Queensland Government through CS Energy.

Abbot Point Aerial View

HyNQ Overview

HyNQ
North Queensland Clean Energy Project

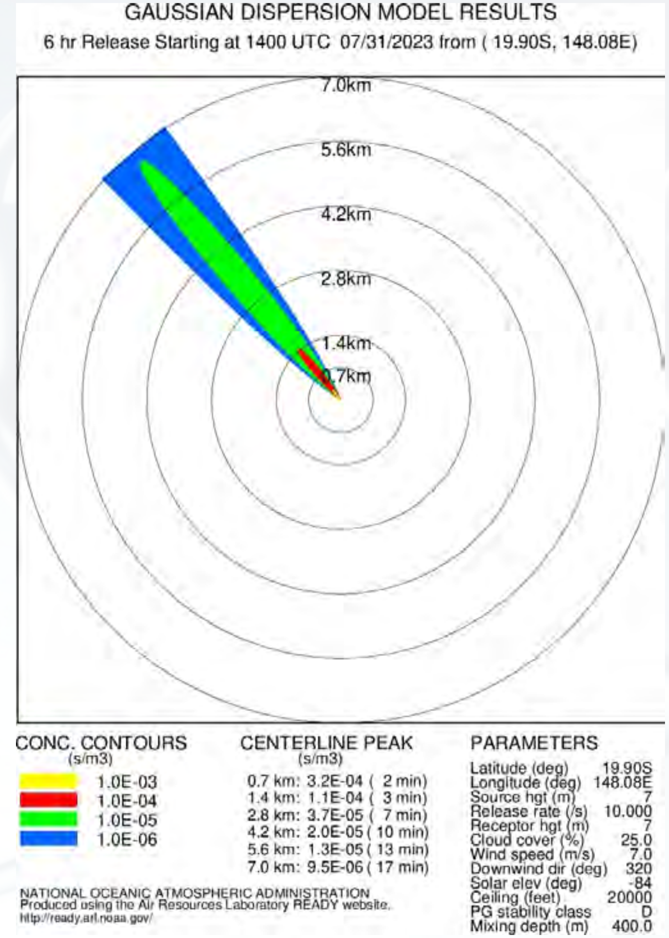

Project Summary
HyNQ Clean Energy Hub
HyNQ
Fuelled by the region's abundant natural and renewable resources, the HyNQ Project seeks to develop a green hydrogen and ammonia facility at Abbot Point, Northern Queensland, for domestic use and export.
1,650 MW of solar PV and 475 MW of wind generation, supported by 600 MWh of energy storage.
10 MLD - regionally enabling common water pipe or desalination
1,300MW of electrolysers will produce up to 285 tpd of green hydrogen, which is set to play a critical role in decarbonising the local and global economy.
275kV "behind-the-meter" transmission lines and new substation, which greatly reduces reliance on grid connection.
Hydrogen pipeline
GREEN HYDROGEN PATHWAY
H2
Green hydrogen is liquefied into 30tpd of liquid hydrogen
Liquid hydrogen storage tank
Road tanker
Domestic use for transport and stationary energy
Hydrogen pipeline
GREEN AMMONIA PATHWAY
NH3
Green hydrogen is combined with nitrogen to produce 1,650tpd of green ammonia
60 kt ammonia storage tank
Port of Abbot Point
Domestic use
Export to global markets (primarily Japan)

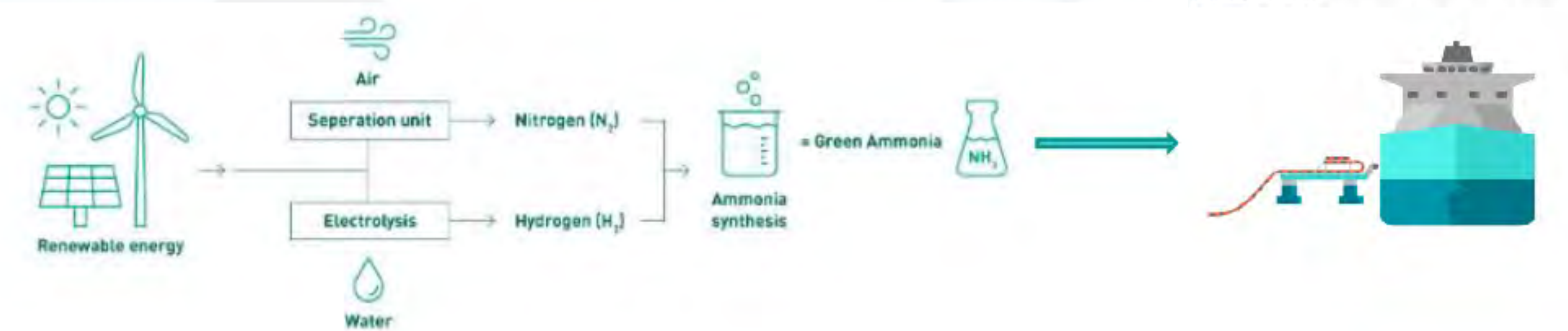
HyNQ Landscape View

HyNQ or North Queensland Clean Energy Project is an integrated renewable energy generation, hydrogen production and green ammonia project. To be built at Abbot Point Port in Queensland for domestic supply and export of green hydrogen and ammonia, utilising behind the meter renewables and leveraging common infrastructure.

HyNQ Pre-FEED Shipping Studies

- Trade-off between certainty, cost and timing
- Preference for using existing infrastructure
- Econnect Floating Ammonia Export Study
- Maximising compatibility with offtakers, design for VLGC vessels
- Two storage tanks each of 30,000 tons of liquid ammonia stored at 1 atmospheric pressure. Equivalent to 88,106 m^3 at -33^{0}C.
- Between 8 and 20 operations per year depending on size of vessels
- Minimum operations dependent on storage sizing
- Preliminary Hazard Analysis to assess facility is consistent with State Code 21 planning criteria

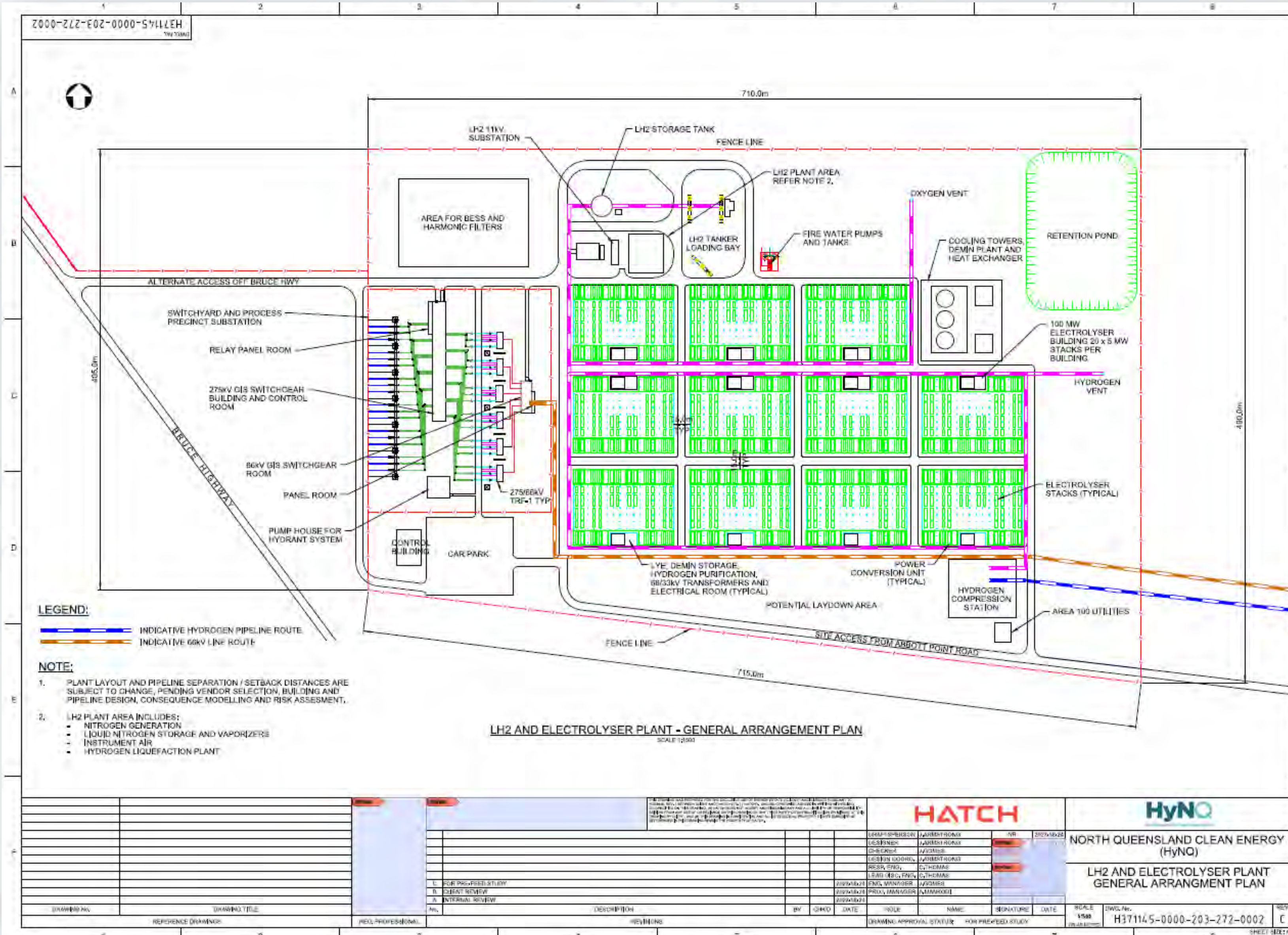




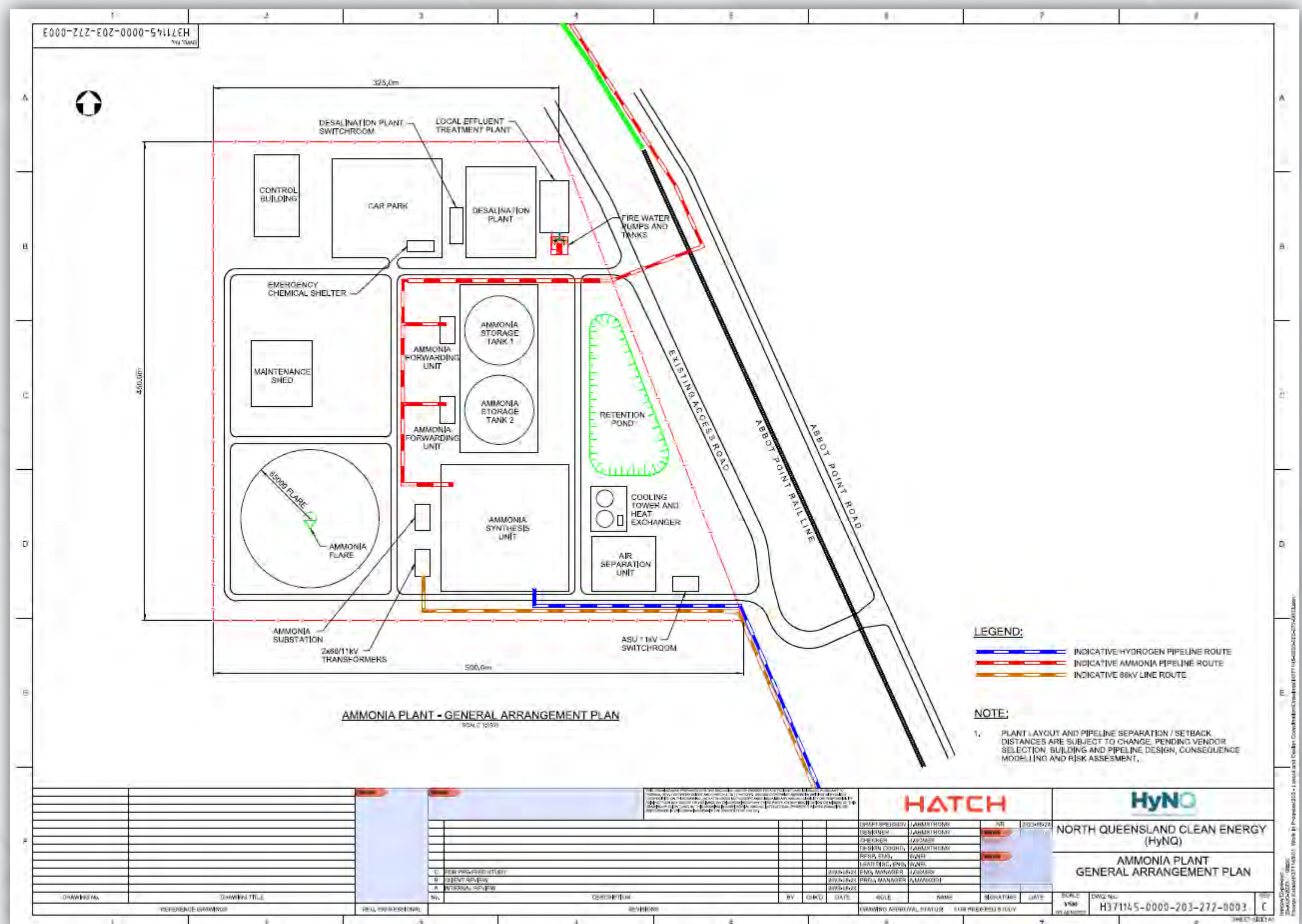
HyNQ
North Queensland Clean Energy Project

HyNQ Process Precinct Layout View

HyNQ Electrolyser Layout View

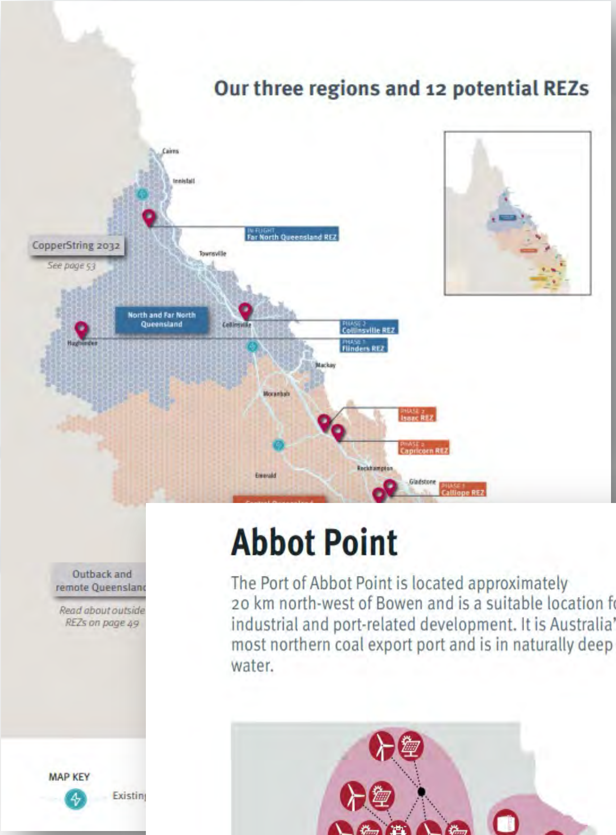


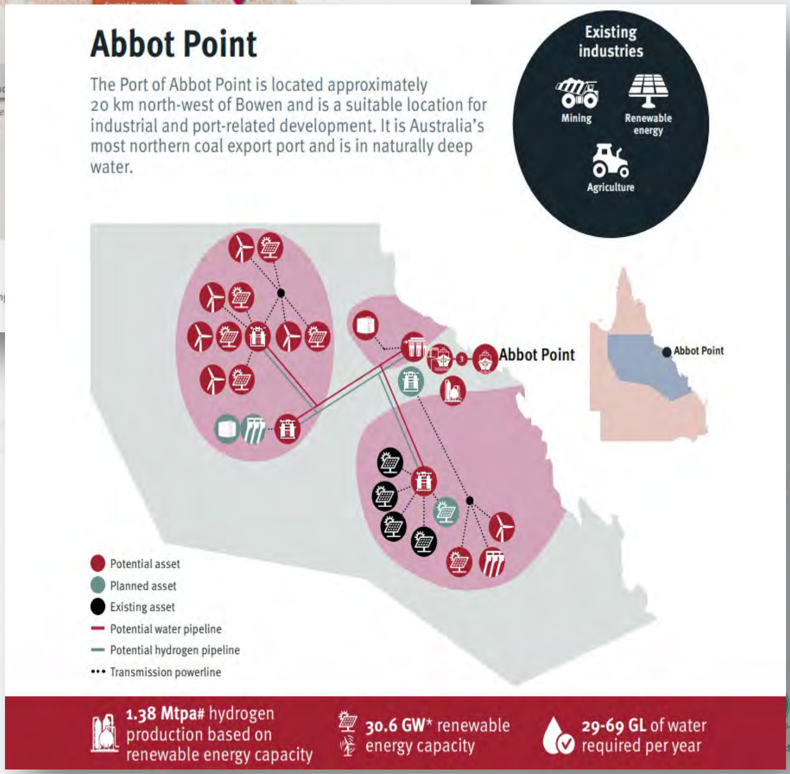
HyNQ Ammonia Layout View



Queensland Government Commitment

- Queensland Government 8.5M AUD Abbot Point Activation Initiative
    - Recent allocation of land to HyNQ project
- Queensland Government commitment to supporting renewable energy and hydrogen production through policies
    - 2023 Queensland Renewable Energy Zone Roadmap
    - Queensland SuperGrid Infrastructure Blueprint
    - Queensland Energy and Jobs Plan
    - Enabling Queensland's hydrogen production and export opportunities report
    - Port master planning – Priority Port of Abbot Point





HyNQ Collaboration Approach

We believe in
- Early partnering
- Better by co-design

Letter of Collaboration with Unions
Letter of Collaboration with The Hydrogen Utility (H2-Hub Gladstone)
Deep thinking on Common Infrastructure opportunity
Baringa report on access pricing for common infrastructure

10th November 2023

Letter of Collaboration – Energy Estate HyNQ Pty Ltd and the United Workers Union, Electrical Trades Union, and the CFMMEU (Maritime Union of Australia and Construction Divisions)

Introduction

We refer to our recent discussions in respect of the HyNQ Clean Energy Project, a green hydrogen energy hub to be located at Abbot Point in North Queensland (the "Project").

The HyNQ Clean Energy Project is to be developed by Energy Estate, CS Energy, Idemitsu and IHI. Energy Estate HyNQ Pty Ltd is acting as lead operator for the unincorporated joint venture.

The Project could see significant investment into (i) behind them meter solar and wind renewable energy infrastructure, (ii) hydrogen and ammonia facilities at the Port Precinct, and (iii) shared infrastructure, such as pipelines (including water), storage facilities and transportation systems.

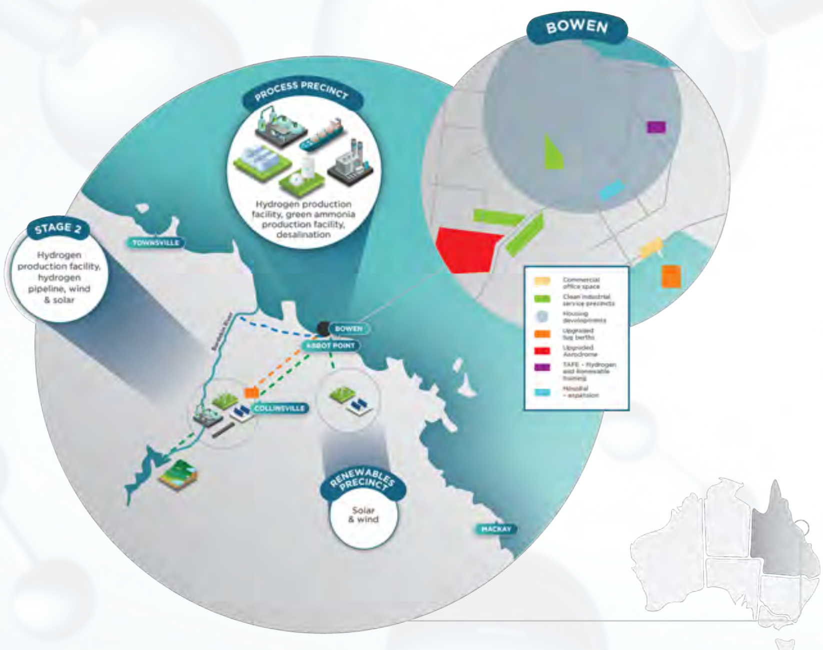
Hydrogen, being a key component of a wide range of products, from sustainable aviation fuel, fertilizers, to green plastics creates an immense opportunity for Queensland to capitalise both domestically and internationally from the development of the Project.

The Project will create a significant number of jobs over the construction and operations timeframes, including equipment manufacture, construction and installation trades and service providers.

The Project offers substantial opportunities for the development of existing industrial ports and infrastructure of North Queensland for a renewable energy future.

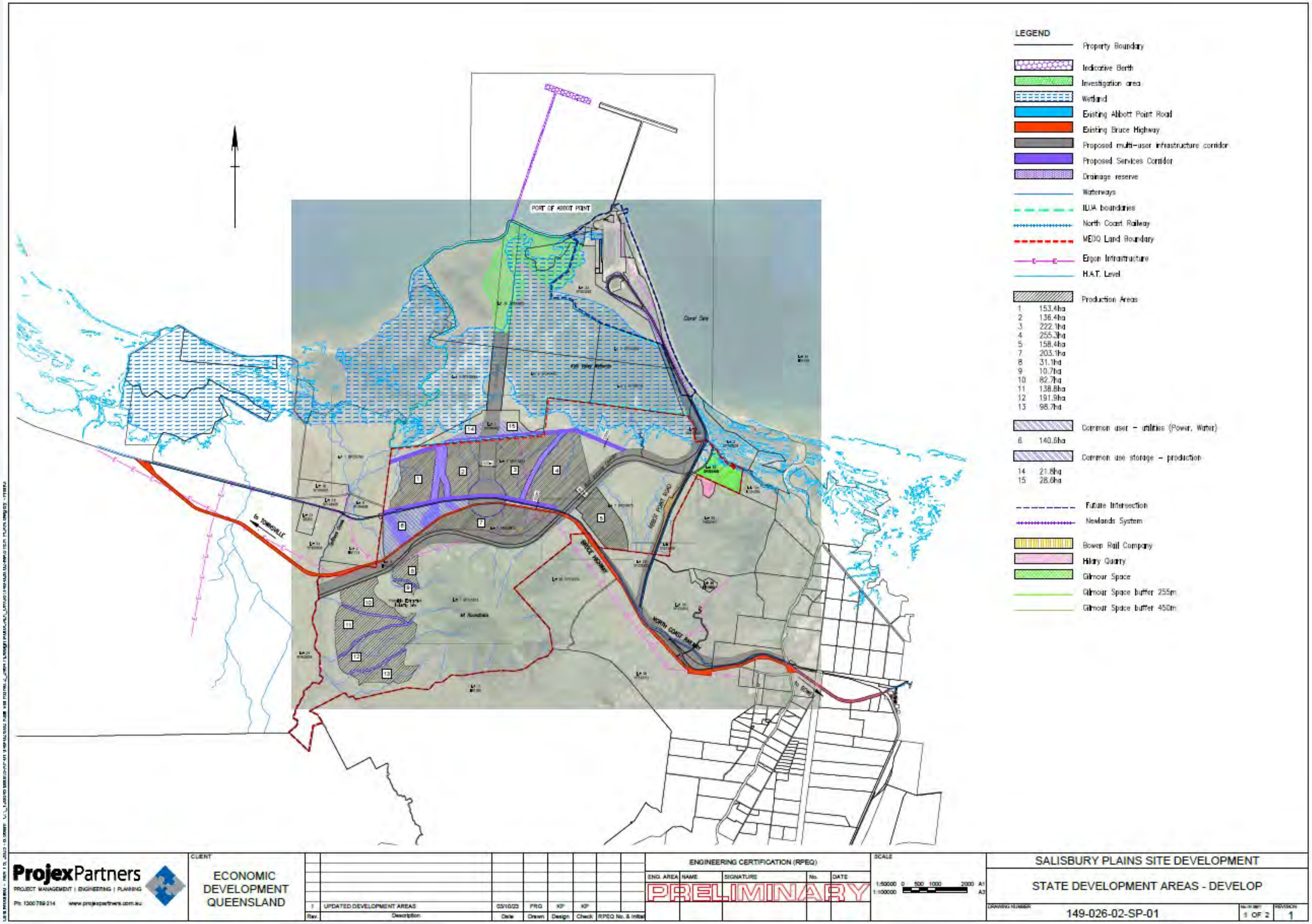
UWU, ETU, CFMMEU (MUA and Construction Divisions)

- The United Workers Union (UWU) represents over 150,000 members across over 45 different industries, including workers in manufacturing, refining and distribution of chemicals, minerals, and bulk liquids.



HyNQ
North Queensland Clean Energy Project

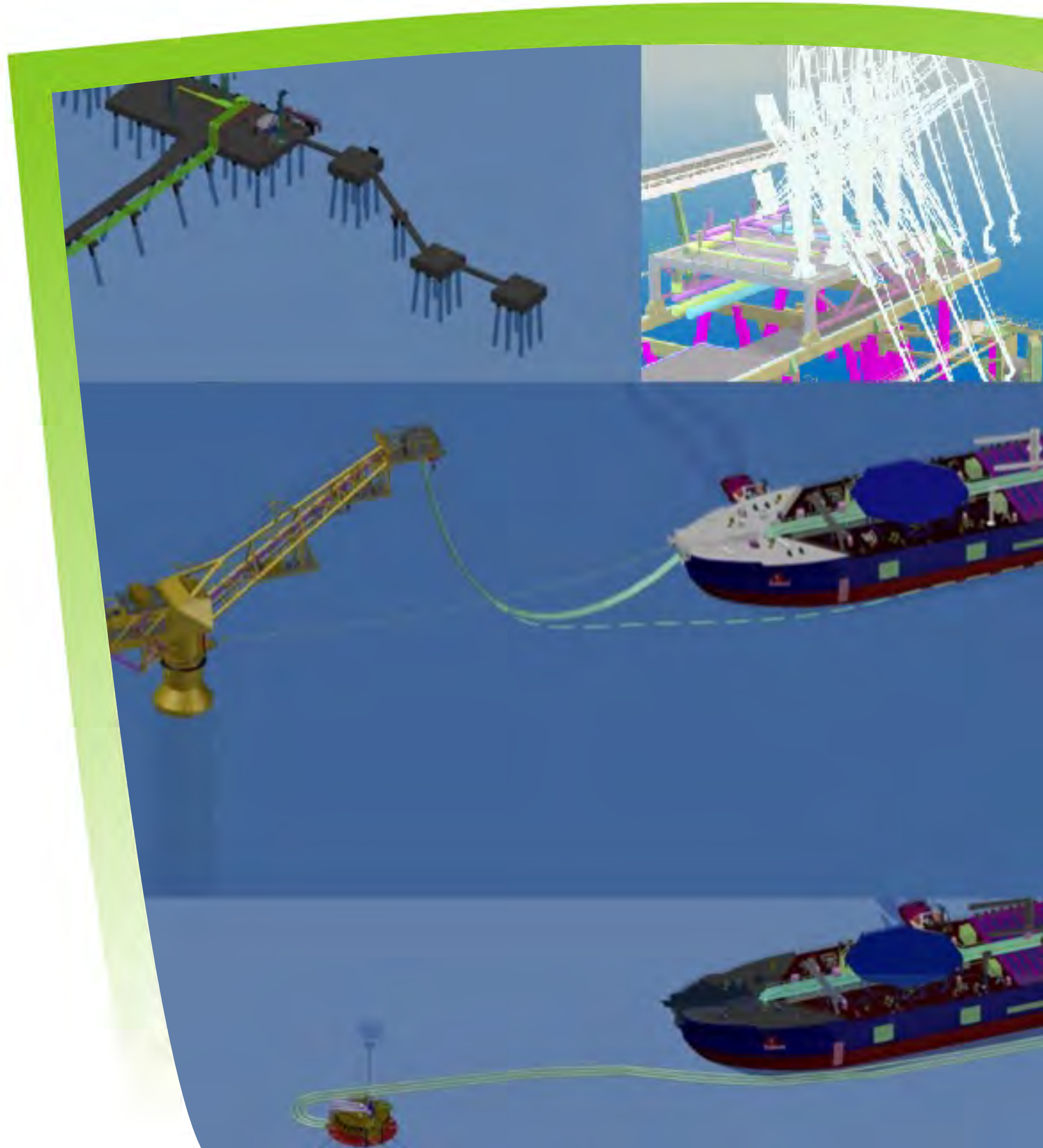
Draft Masterplan for Abbot Point SDA




HyNQ
North Queensland Clean Energy Project

Challenges & opportunities for hydrogen in the port industry

Development of existing port infrastructure to handle green ammonia – the synergies and challenges



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Bringing ideas to life

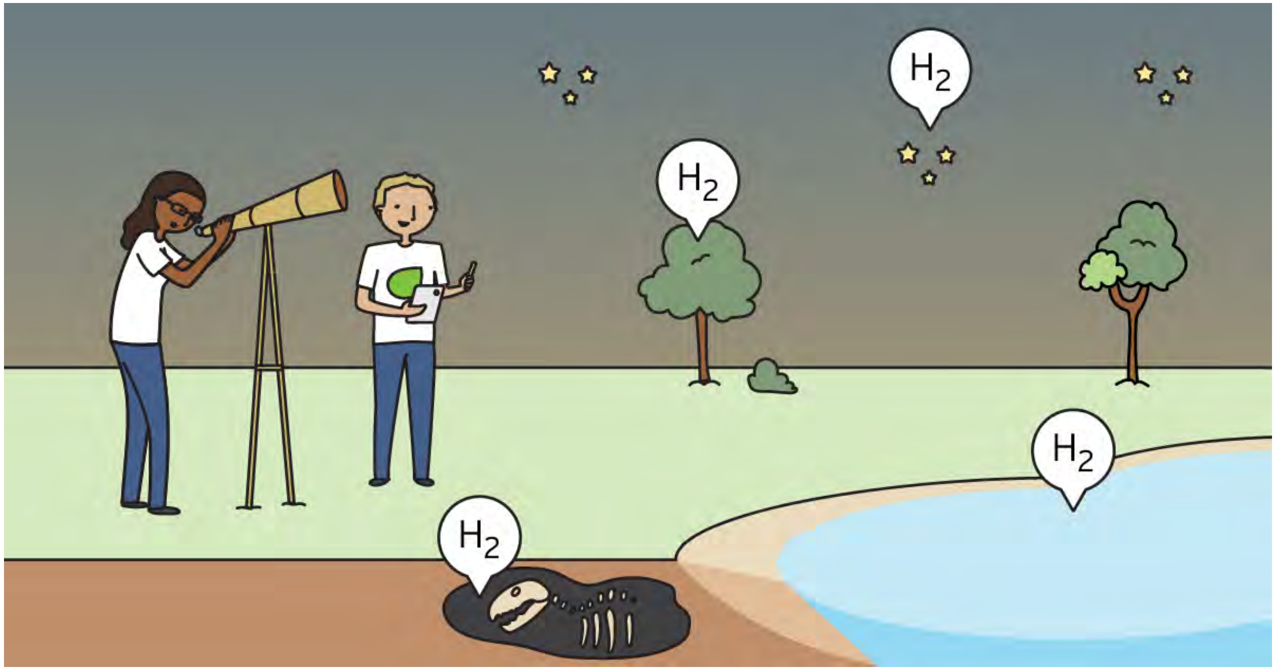
Challenges and Opportunities for Hydrogen in the Port Industry

Thursday 18 April	
1230-13:00 Arrival / Registration and coffee	
13:00–13:15	**Welcome & workshop introduction and objectives** Sam Mazaheri, Chair, PIANC ANZ Northern Chapter
Facilitated session (Andrew Catto): Hydrogen Market and Project Overview	
1315-13:40	**Global perspective on Hydrogen markets (Online)** Pooja Jain, Senior VP, WSP USA
1340-1405	**Queensland Government policy and directions** Alana Barlow, Deputy Director General, Hydrogen and Future Fuels
1405 –1430	**Large-scale Hydrogen plans** Craig Haymes, CEO, Gladstone Ports Corporation Limited
1430-1455	**HyNQ Project Overview** Claire Speedy, Energy Estate
14:55-15:20 Afternoon Tea	
Facilitated session (Michael Coull): Port Perspective	
1520-1545	**Development of existing port infrastructure to handle green ammonia – the synergies and challenges** Richard Woollard / Mike Sudmalis, Aurecon
1545-1615	**Future fuels: Challenges and opportunities for ports** Jeffrey Gomes, Hatch
1615-1640	**Storage and transportation facilities** Dr. Prakash Aryal, WSP Aus
1640–1705	**Panel Session: Discussion and learnings**
1700-1800	**Networking, drinks, and finger foods**

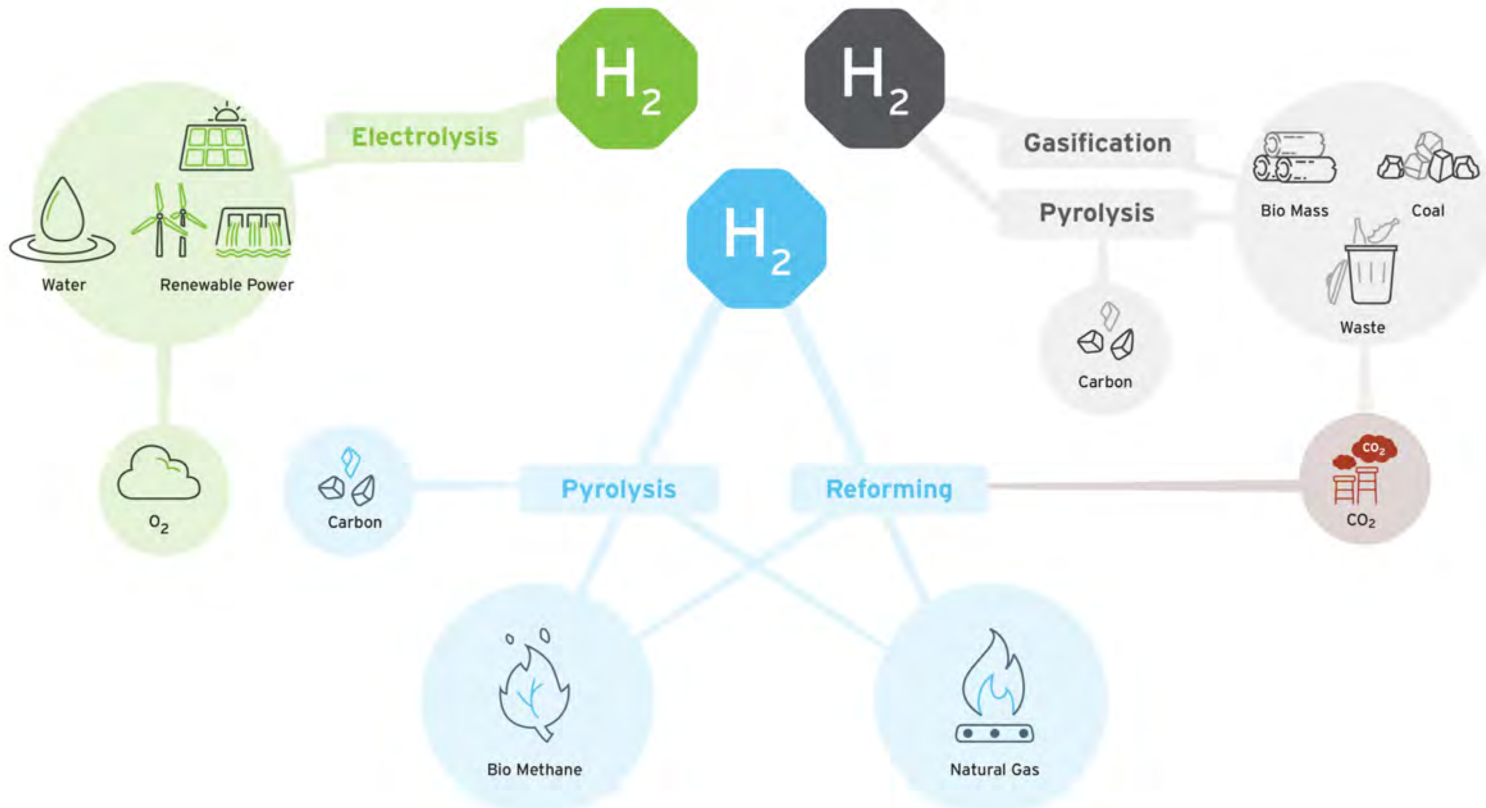
Context – Hydrogen: What it is… and what it isn't

- It is an energy carrier – it isn't an energy source
- It is abundant on earth – it isn't readily available
- It provides a 'clean' release of energy – doesn't mean the source is clean
- It could be the solution to many decarbonisation challenges – doesn't mean it should be the answer to them all
- There are however plenty of cases where it is the best / only answer

- MCH vs LH_2 vs NH_3 as H_2 carriers



Context – Hydrogen: How can it be made?

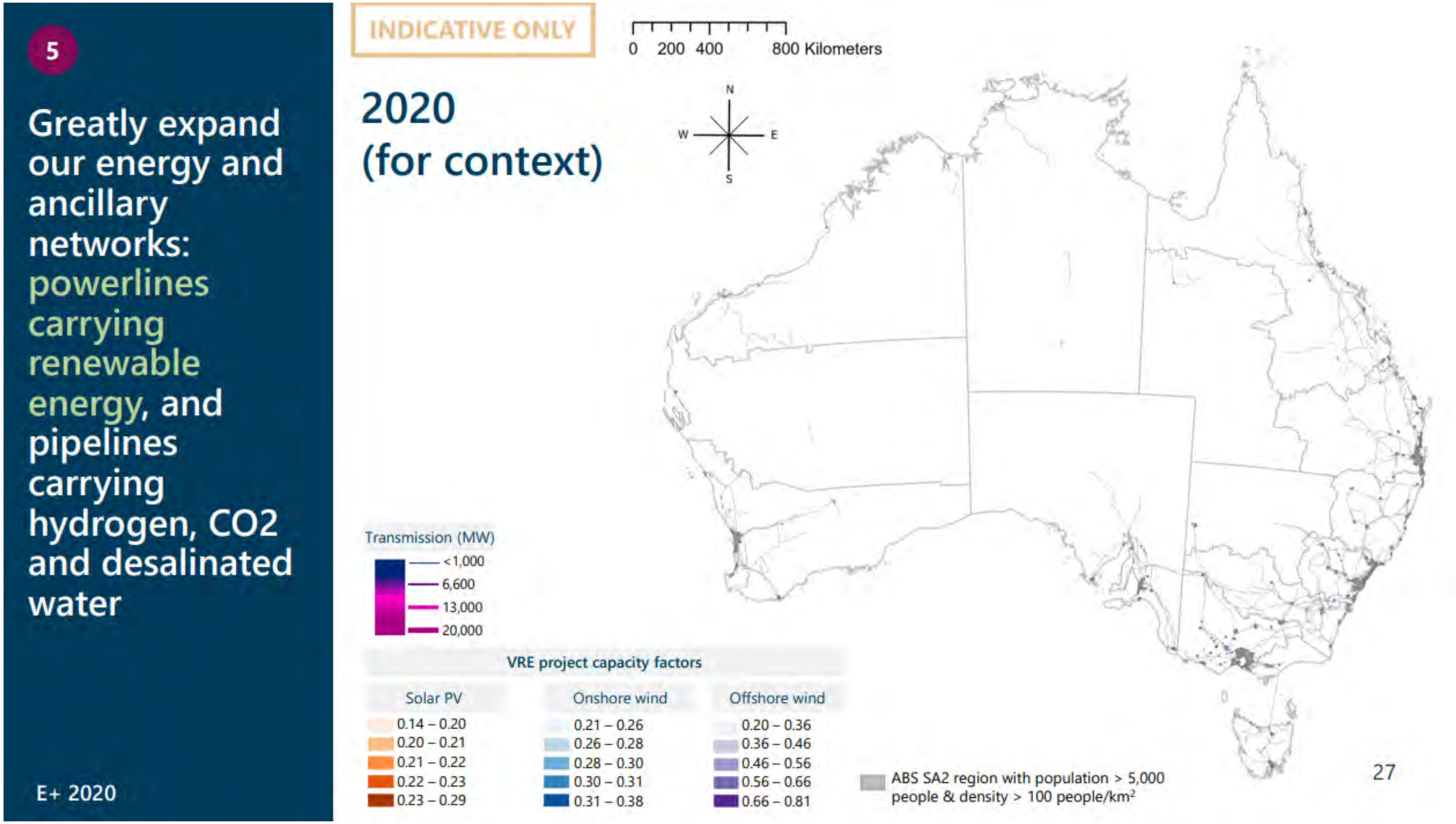


- Blue Hydrogen includes carbon capture and storage/utilisation
- Resurgence inspired by decarbonisation initiatives

Net Zero Australia – Export Option

Net Zero Australia – Export Option

Net Zero Australia – Export Option



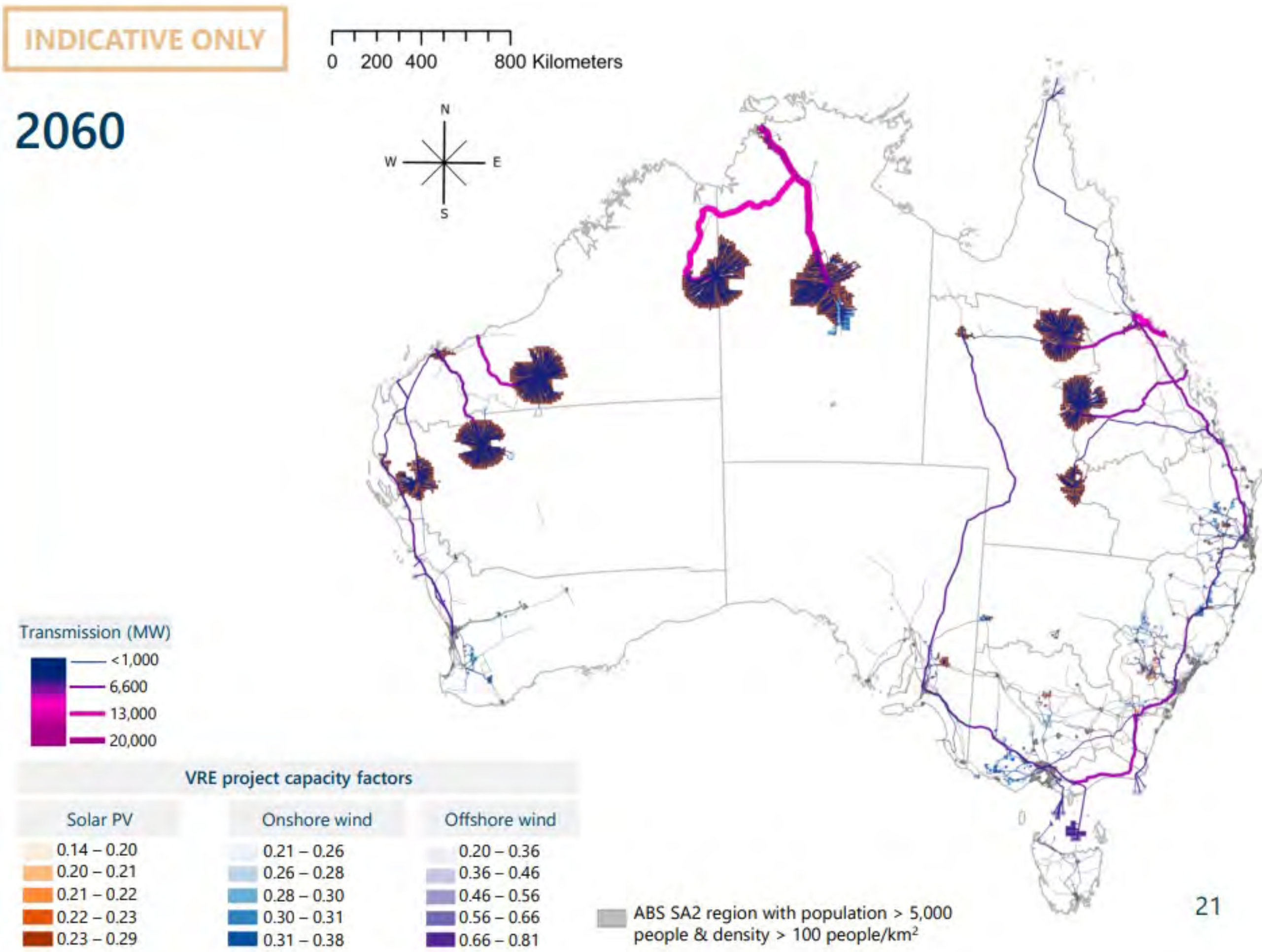
- Current Network circa 40GW

Net Zero Australia – Export Option

1

Grow renewables as our main domestic and export energy source, to 40 times current National Electricity Market capacity – for direct use and clean fuel production

E+ 2060



- Expansion from 40GW to ~ 1200-1500 GW
- China to have 1200 GW installed by 2025

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Net Zero Australia – Export Option

2. WHAT WOULD IT TAKE TO ACHIEVE NET ZERO

Attract and invest $7-9 trillion of capital to 2060 from international and domestic sources

6

Cumulative supply-side capital committed by year (2020 AUD trillions)

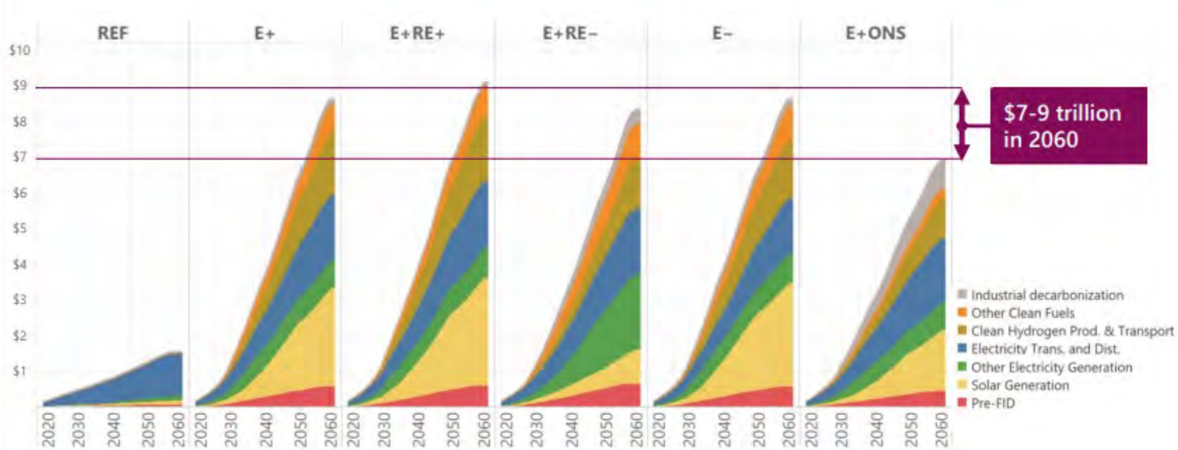


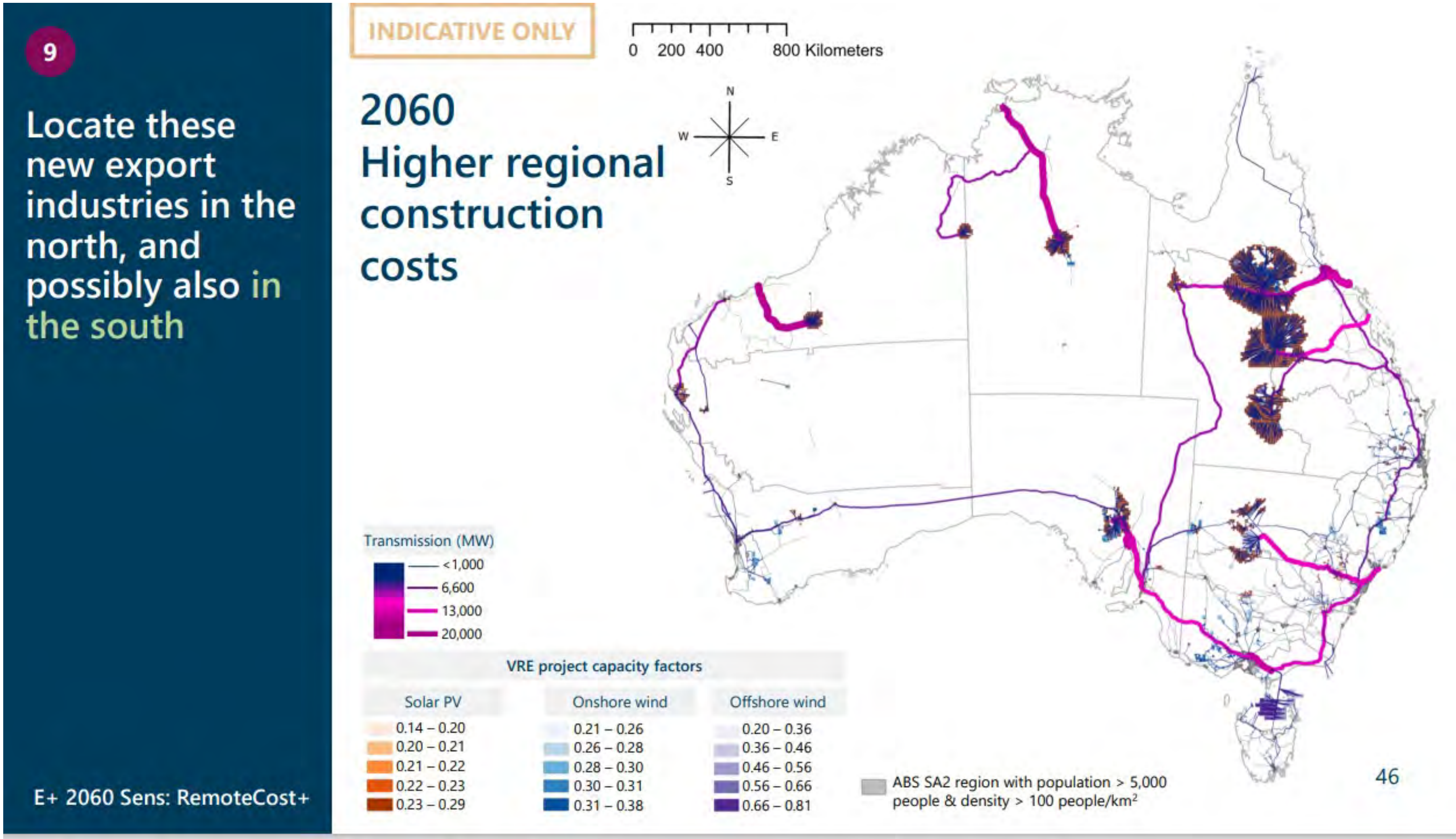
CHART 1 OF 3

Investment is much higher in the net zero transition than continuing to use fossil fuels. However:

- Decarbonisation will **reduce our reliance on gas and oil imports**.
- The Reference case **assumes that fossil fuel costs remain consistently low**, which is deeply uncertain and has not been modelled.
- **Conventional technologies that use fossil fuels** will become less available.
- The **costs of inaction** would be substantial

36

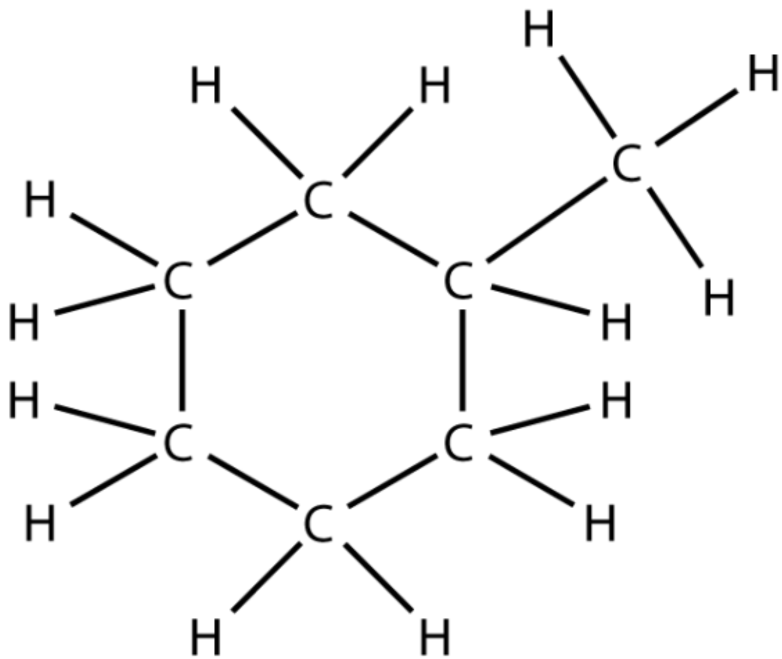
Net Zero Australia – Export Option

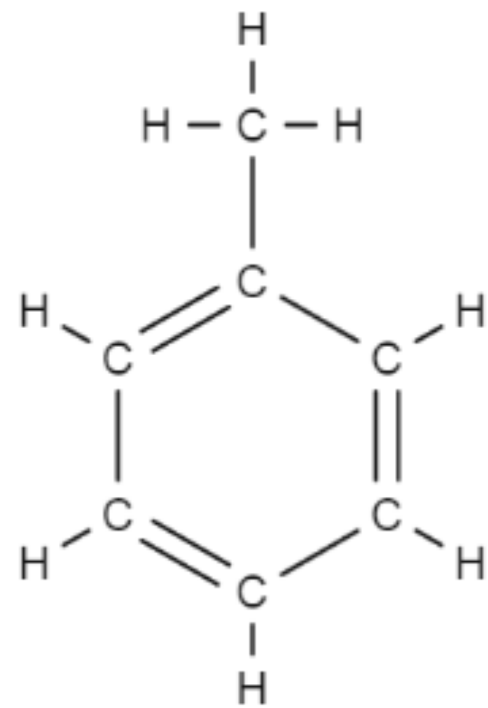


- Result of 30% WA/NT & 15% Qld construction cost premium in "remote" areas (circa 1.2-1.5 TW case)
- Ecology and land use constraints considered

Context – Hydrogen carriers (MCH vs LH_2 vs NH_3)

- Methylcyclohexane / toluene





Context – Hydrogen carriers (MCH vs LH_2 vs NH_3)

Product	End use Case	Starting with 100 tonnes, tonnes consumed or lost during			
		Production	Losses During Transportation	Utilisation	Remaining
$L\text{-}H_2$	Combustion	42%	3%	25%	30%
$L\text{-}H_2$	Fuel Cell	42%	3%	22%	33%
MCH	Dehydrogenation, Combustion	5%	0%	66%	29%
MCH	Dehydrogenation, Fuel Cell	5%	0%	70%	25%
NH_3	Combustion	42%	1%	23%	34%
NH_3	Fuel Cell	42%	1%	19%	38%
NH_3	Dehydrogenation, Fuel Cell	42%	1%	23%	34%

*Coarse Numbers

- Adapted from "Energy Procedia" February 2019, Volume 158 pages 4086-4091: Comparison of liquid hydrogen, methylcyclohexane and ammonia on energy efficiency and economy – Aziz, Oda & Kashiwagi

Context – Hydrogen carriers (MCH vs LH_2 vs NH_3)

LH_2:	-253 degC
LNG:	-162 degC
NH_3:	-33degC
LOHC:	Ambient

Context – Hydrogen carriers (MCH vs LH_2 vs NH_3)

Hydrogen Liquefaction

- Largest liquefaction plant ~60tpd (NASA)
- Technology being optimised for large (export) scale

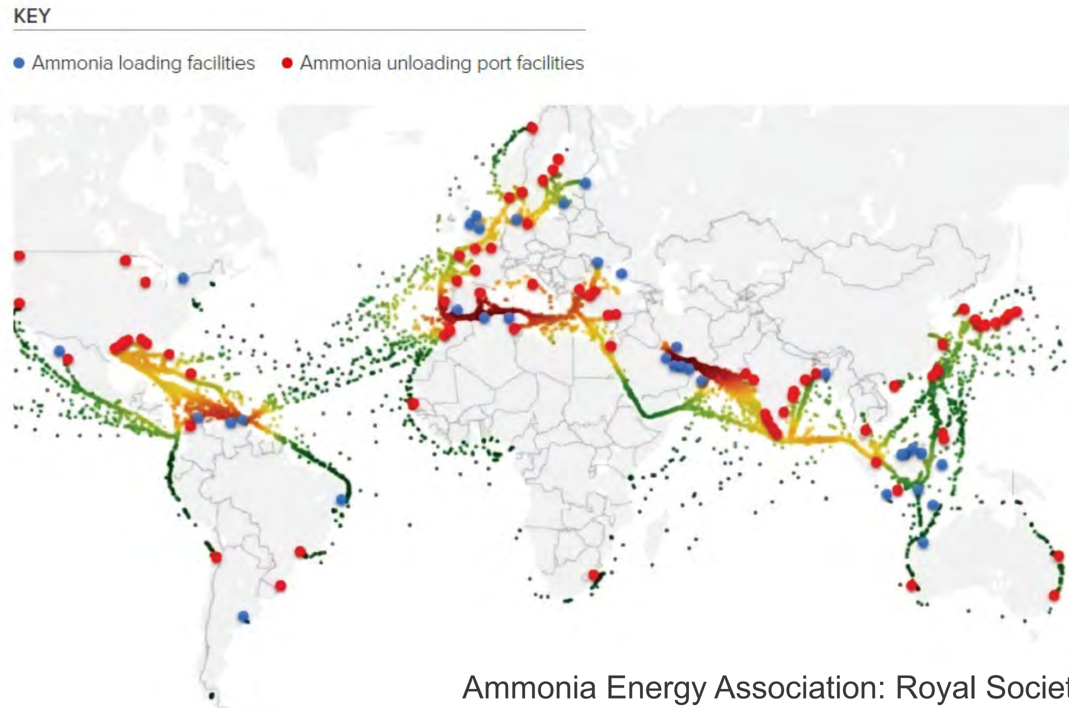
The Incheon Liquefied Hydrogen Plant is a remarkable engineering feat that boasts the capacity to produce 90 tons of liquefied hydrogen per day, equivalent to 30,000 tons per year. The liquefied hydrogen is obtained through a process of purifying gaseous hydrogen to a high purity and cooling it to an incredibly low temperature of minus 253 degrees Celsius, resulting in a liquid state. The plant is currently at an impressive progress rate of approximately 99%, and its commercial operations are scheduled to begin in the fourth quarter of this year after a successful test run.

Site	operated by	Capacity	built
Painsville, OH / USA	Air Products	3 tpd	1957 *
West Palm Beach, FL / USA	Air Products	3.2 tpd	1957 *
	Air Products	27 tpd	1959 *
Long Beach, CA / USA	Air Products	30 tpd	1958
Mississippi (Test Fac.)	Air Products	> 36 tpd	1960 *
Ontario, CA / US	Praxair	20 tpd	1962 *
Sacramento, CA / USA	Union Carbide, Linde Div.	(54) 60 tpd	1966 *
	Air Products	6 tpd	1986
New Orleans, LA / USA	Air Products	34 tpd	1977 (1963)
	Air Products	34 tpd	1978
Niagra Falls, NY / USA	Praxair	18 (40?) tpd	1981
Pace, FL / USA	Air Products	30 tpd	1994 *
McIntosh, AL / USA	Praxair	24 (29?) tpd	1995
East Chicago, IN / USA	Praxair	30 tpd	1997
Sarnia, Ontario / Canada	Air Products	30 tpd	1982
Montreal, Canada	Air Liquide Canada Inc.	10 tpd	1986
Bécancour, Quebec /Can.	Air Liquide	12 tpd	1988
Magog, Quebec /Canada	(BOC) Linde	15 tpd	1989
Kourou, Franz. Guayana	Air Liquide	5 tpd	1990
Lille (Wazier), France	Air Liquide	10.5 tpd	1985
Rozenburg, Netherlands	Air Products	5 tpd	1986
Ingolstadt, GER	Linde	4.4 tpd	1992 *
Leuna (close to Leipzig, GER)	Linde	5 tpd	2008
	Linde	5 tpd	2021
Dresden	TUD	10 l/h	2004

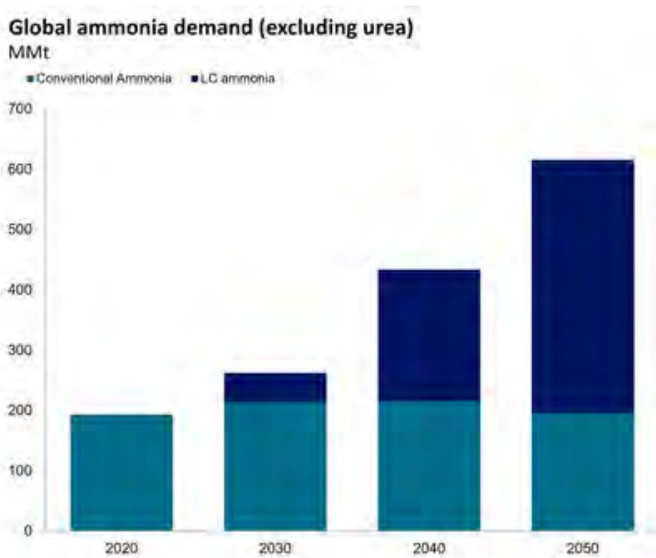
Site	operated by	capacity	built
Amagashi, Japan	Iwatani	1.2 tpd	1978 *
Tashiro, Japan	Mitsubishi Heavy Industr.	0.6 tpd	1984 *
Ooita, Japan	Pacific Hydrogen Co, Jpn.	1.4 tpd	1986
Tane-Ga-Shima, Japan	Jpn Liquid Hydrogen	1.4 tpd	1986
Minamitane, Japan	Jpn Liquid Hydrogen	2.2 tpd	1987
Kimitsu, Japan	Nippon Steel Corp. (Air Products?)	0.2 (0.3?) tpd	2004
Sakai, Japan	Iwatani Gas	1.1 tpd	2006
Osaka, Japan	Iwatani (Hydro Edge)	11.3 tpd	2006
Chiba (Tokio), Japan	Iwatani (built by Linde)	10 (5?) tpd	2008
Yamaguchi, West-Japan	Iwatani (built by Linde)	5 tpd	2008
KHI Akashi, Japan	Kawasaki Heavy Industries → own development!	(5 tpd prototyp)	2015
Indien	Asiatic Oxygen	1.2 tpd	k.A.
Mahendragiri, Indien	ISRO	0.3 tpd	1992
Beijing, China	CALT	0.6 tpd	1995

Context – Hydrogen carriers (MCH vs LH_2 vs NH_3)

- Ammonia is currently primarily consumed as a feedstock for fertiliser, explosives and to a much lesser extent refrigeration
- Global market is currently about 180 million tonnes per year



Ammonia Energy Association: Royal Society Publishes Green Ammonia Policy Briefing

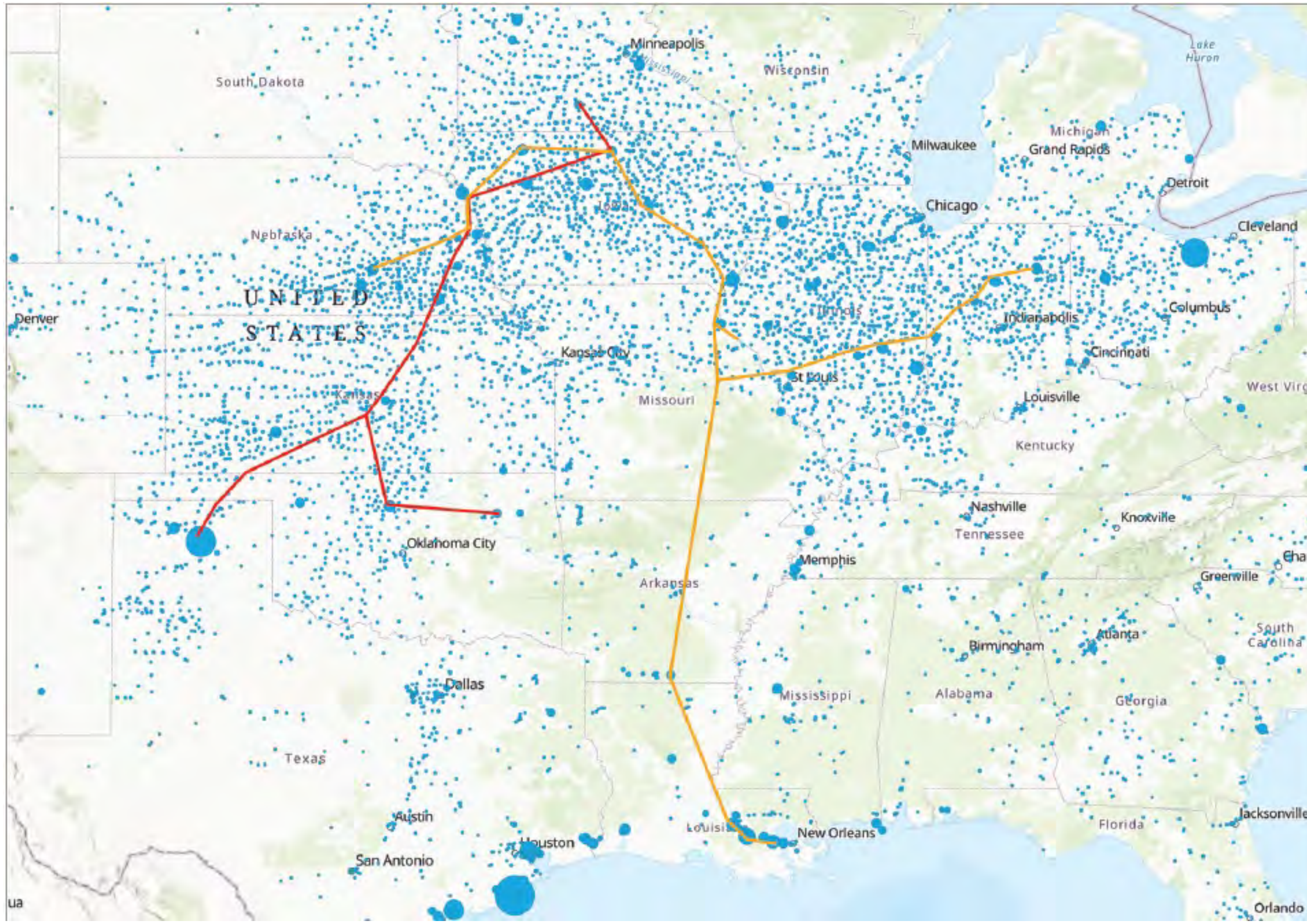


S & P Global Commodity insights, June 2023

Context – Hydrogen carriers (MCH vs LH_2 vs NH_3)

Liquid pipelines (at pressure circa 2000kpag)

Blue dots are liquid storage tanks



Ammonia Energy Association: Royal Society Publishes Green Ammonia Policy Briefing

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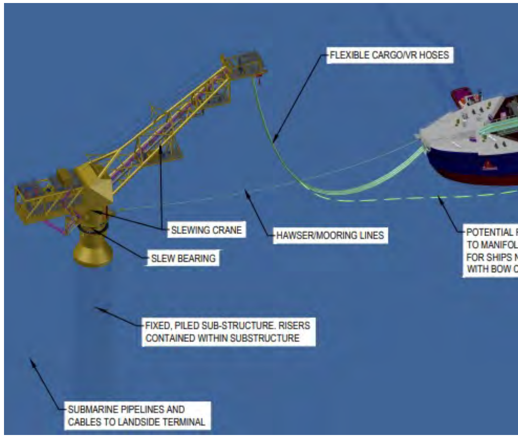
Context – Hydrogen carriers (MCH vs LH_2 vs NH_3)

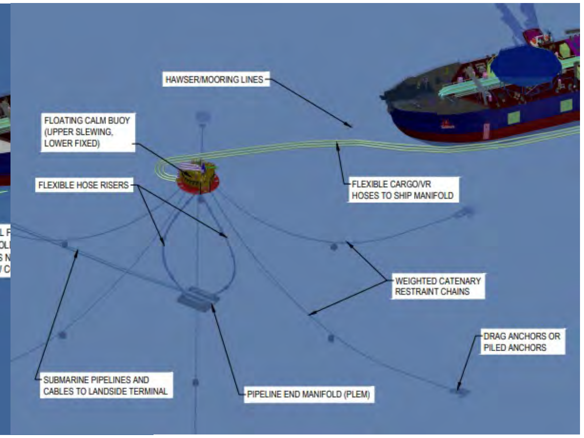
Ammonia currently preferred due to:

- Better energy efficiency at user side than LOHCs
- Mature technology at scale as opposed to Liquid Hydrogen
- Existing market for green ammonia (decarbonise fertiliser industry)

IPL Gibson Island - Brisbane

Context - Options for greenfield NH3 export

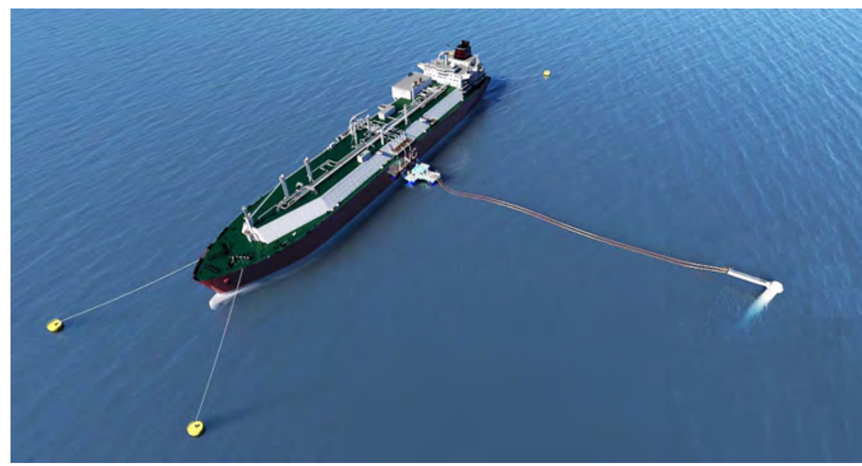




SPM – Tower | SPM – CALM buoy

Island berth (subsea pipelines)

FPSO



MBM + Floating platform

Challenges – Adapting for NH_3

- Existing ports can be typically categorized by the amount of effort to convert:
  - Currently handle NH3
  - Currently handle other bulk liquids
  - Currently handle bulk solids
- Challenges split into:
  - Technical
    - What is the right ship size to consider?
    - Can infrastructure be modified safely and efficiently?
    - Is environment / mooring arrangement suitable operationally?
  - Safety
    - What are the requirements for handling it adjacent to other products at existing infrastructure?
    - QRAs

Shipping Options – Energy Export

Product	Number of ships to export 800PJ
LNG	~250
LH_2	~3,000+ (~800?)
NH_3	~900

Note:
Coal = 34 – 43 MJ/L
LNG = 22.2 MJ/L
LH_2 = 8.5 MJ/L
NH_3 = 12.7 MJ/L

LNG Q-Flex: ~300m x 46m | ~200,000m^3 ≈ 4PJ

NH_3 VLAC: ~230m x 38m | ~90,000m^3 ≈ 1.3PJ

LH_2 Suiso Frontier: ~116m | ~1,250m^3 ≈ 0.01PJ
(concept design for up to 150,000m^3 ≈ 1PJ)

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LPG carrier fleet information

Shipping Options – Energy Export

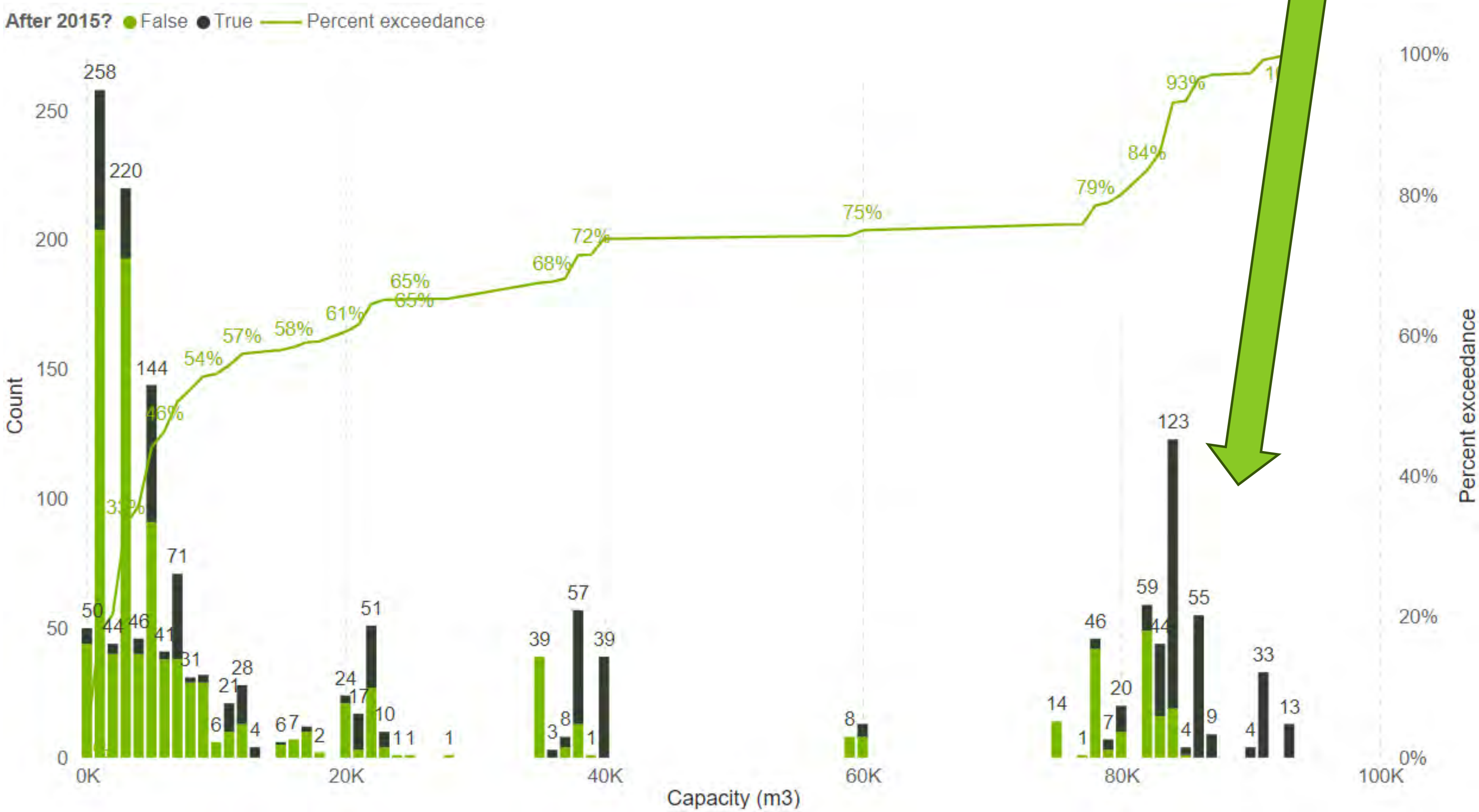
Dorian LPG joins VLAC bandwagon with debut order

VESSELS

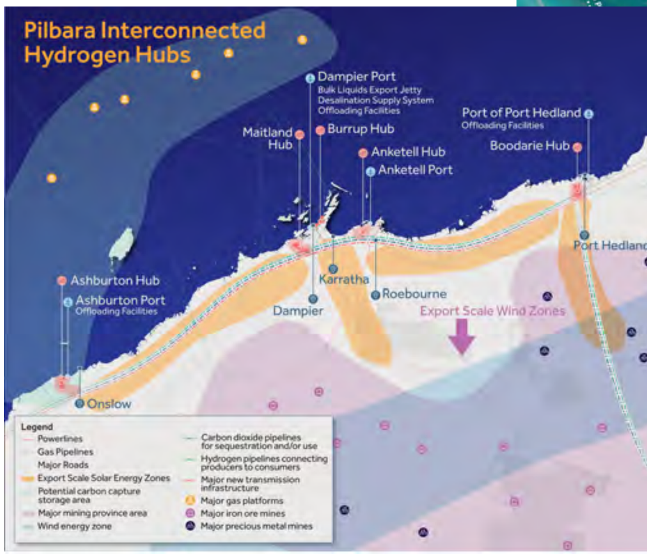
February 1, 2024, by Jasmina Ovcina Mandra

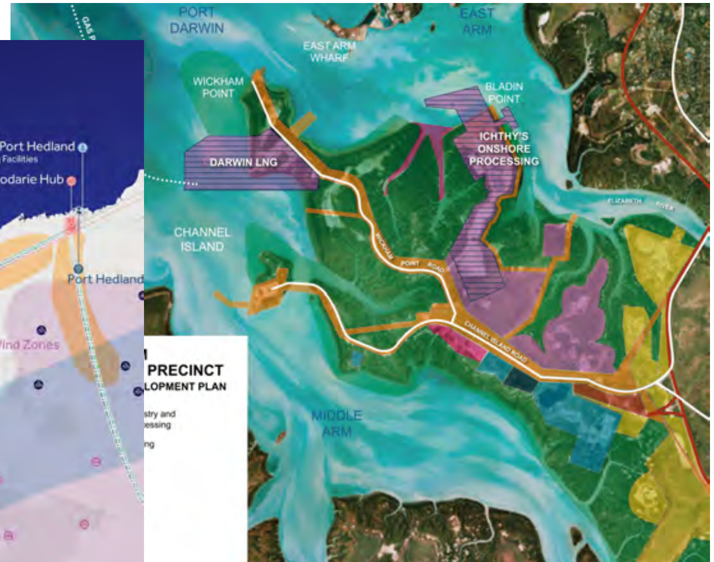
U.S.-headquartered LPG shipping company Dorian LPG has placed an order for the construction of a Very Large Gas Carrier (VLGC) /ammonia carrier.

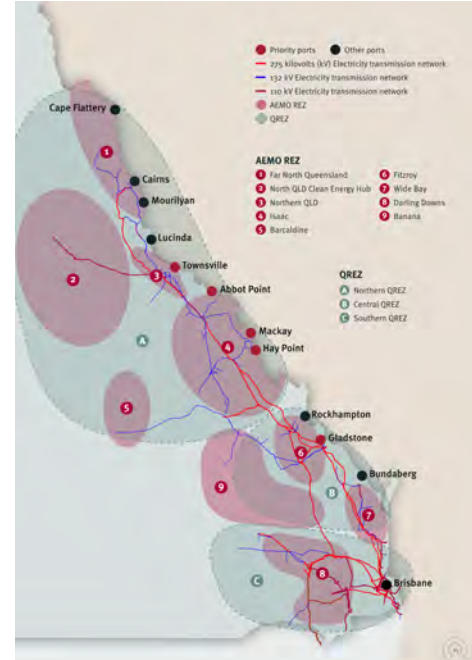
NH_3 VLAC: ~230m x 38m | ~90,000m^3 ≈ 1.3PJ

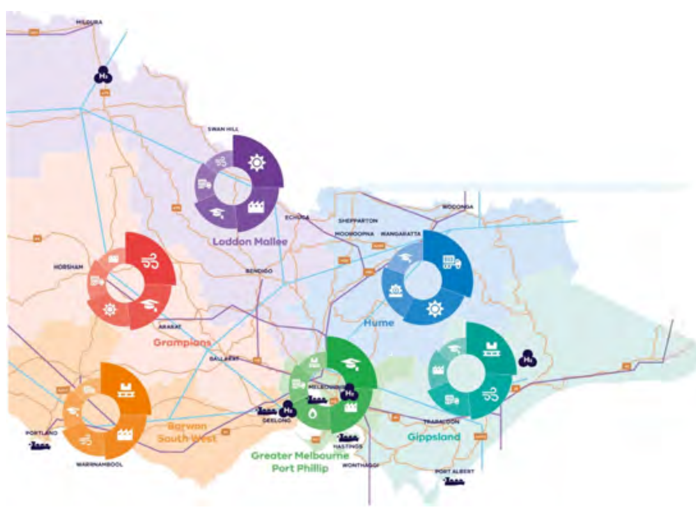


Context – Existing port infrastructure









Existing port infrastructure – Shared use examples

Trolley-mounted MLAs for diesel import at the Port of Mackay’s Berth 3

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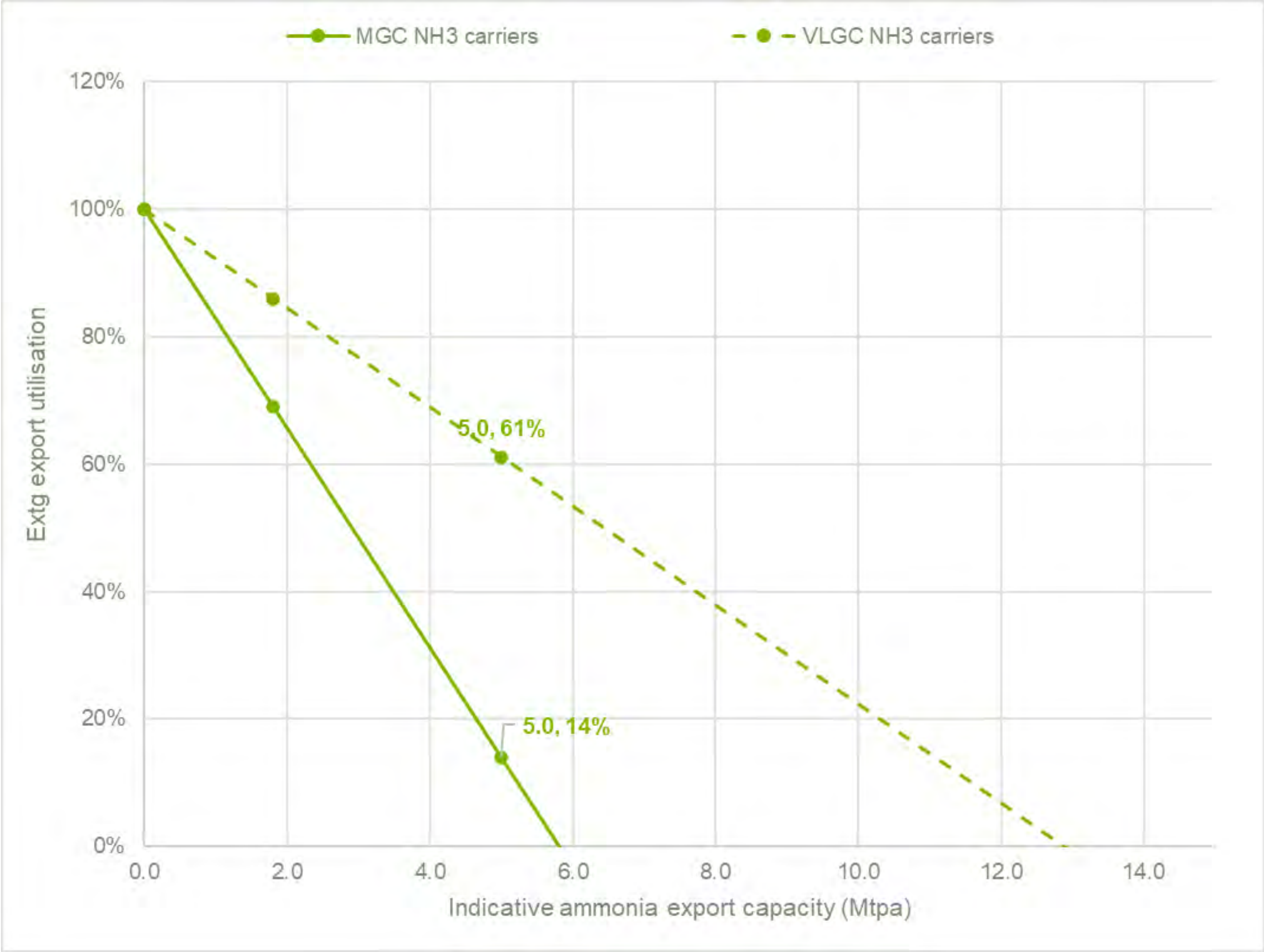
Existing port infrastructure – Shared use examples

MLAs for loading LPG incorporated within Trigon coal export facilities at Prince Rupert, Canada

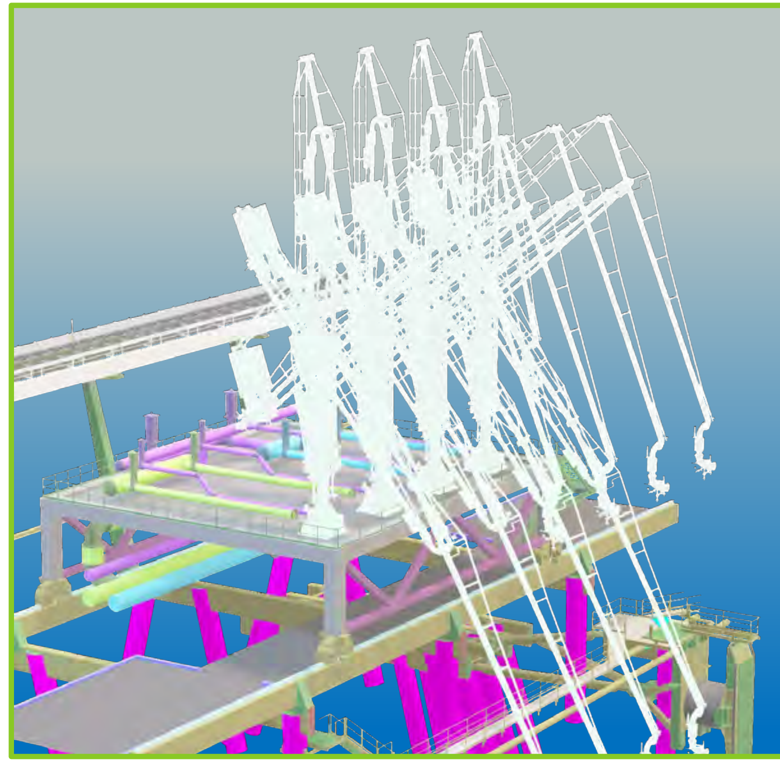
Opportunity – Berth time required vs available



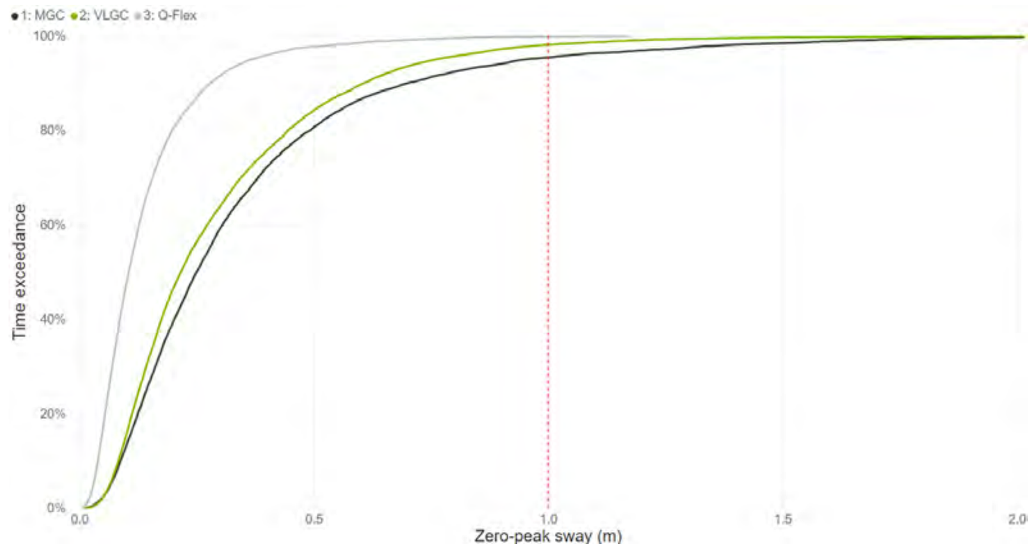
Simplified assessments possible from public information – with some confirmation by DES modelling

Challenges – Technical – marine infrastructure

- Spatial challenges for pipeline routes
  - require suitable access for maintenance / inspection
  - space for expansion loops on longer structures
  - Consider safety – prevailing wind
- Challenges at wharf
  - Existing long travelling machine envelope and safe storm park
  - Maintain ability to maintain / access
  - Interfaces with existing equipment – safety upgrades to instrumentation may be needed
  - High level MLAs and tidal ranges – relatively large MLAs
- Mobile MLA platform can be considered / developed
- Commercial challenges also exist



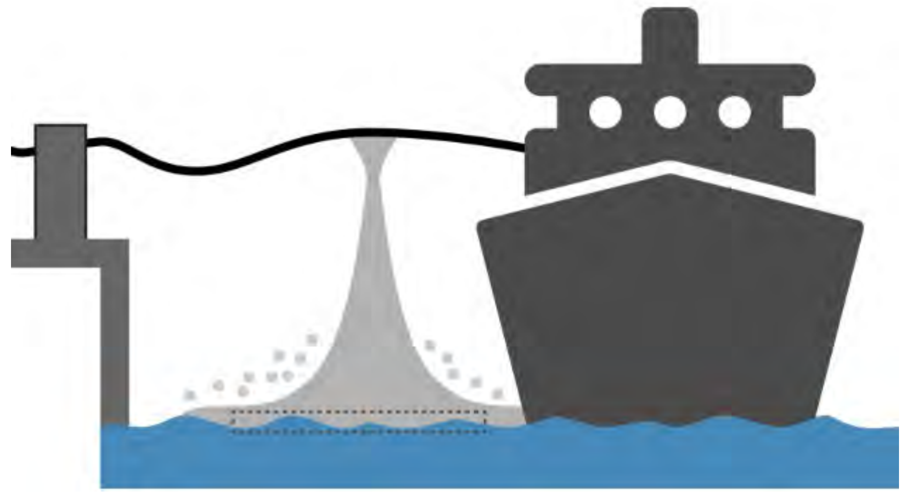
Challenges – Technical – marine infrastructure



- Use of continuous quay type mooring arrangement in somewhat exposed locations vs typical 'gull wind' liquids berth – Dynamic Mooring Analyses
- Early preliminary DMA
- Uncertainty – PIANC WG212 allowable motions: great reference, but seems potentially conservative compared to MLA manufacturers stated capabilities. Needs testing with regulators?
- Consideration of suction type mooring – limited benefit in more exposed locations

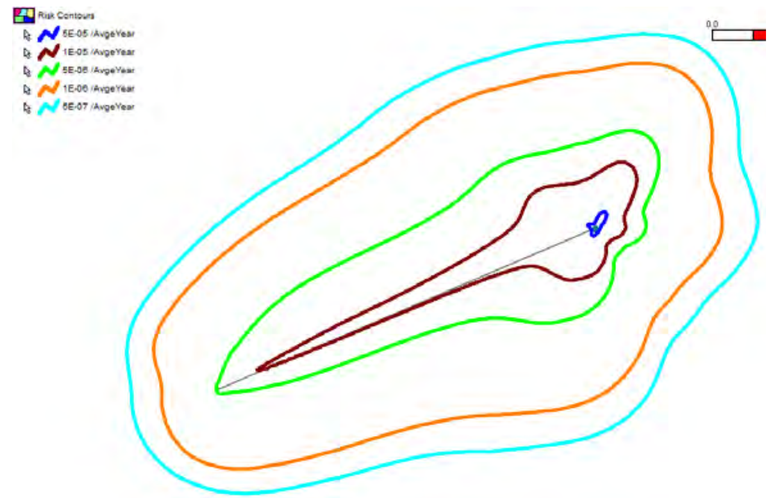
Challenges – Safety

Dakar, Senegal – 1992
129 reported fatalities



- Fire / explosive risk is low relative to other commonly handled bulk liquids (LNG and other fuels)
- Potential consequence-only toxic gas vapour cloud radius could extend to 14km
- Risk based approach (NSW HIPAP No. 4) likely required for most locations
- Early preliminary Quantitative Risk Assessments (QRAs) important

Challenges – Safety



- The details matter, in QRAs
  - Loading at VLAC capacity rates → Loading at MGC capacity rates (same throughput) can result in up to 50% lesser individual fatality risk contour radius
  - Export throughput increase 4x → Up to 10x individual fatality risk contour radius
- So, close inter-relationship between engineering and economic decisions and process safety (size of ship affects pipeline affects tank size, etc.) – value in close inter-discipline relationships

Some final thoughts

- Feasibility of re-purposing existing infrastructure depends on site specifics – but in cases we have reviewed it appears feasible → significant Capex and sustainability benefits
- New industry → Uncertainty to be addressed in ship sizes, allowable manifold motions, regulator approaches to tug requirements, and safe colocation / operation, etc.
- As much or perhaps more than previous port major projects, close inter-discipline understandings likely valuable
- Earlier consideration of more complex analyses than more established industries - DMA and QRA

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Bringing ideas to life

linkedin.com/company/Aurecon

youtube.com/user/AureconGroup

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instagram.com/Aurecon

aurecongroup.com/podcast

Bringing ideas to life

Future Fuels – Opportunities for Ports

Jeff Gomes

PIANC Hydrogen Workshop – 18 Apr 2024

HATCH

Employee-owned

partners who think like owners

Projects in
150 countries

6 decades of experience

US$50 billion
in projects

10,000+ professionals worldwide


Private ownership
Engineering as our core service offering
Research and technology development expertise
Unique, differentiated products and services
Comprehensive service across our clients' lifecycle needs
Sustainable development solutions approach
HATCH

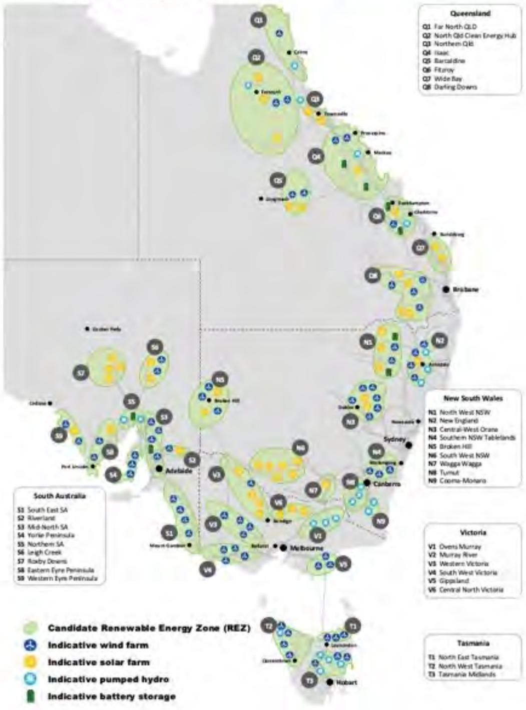
HATCH

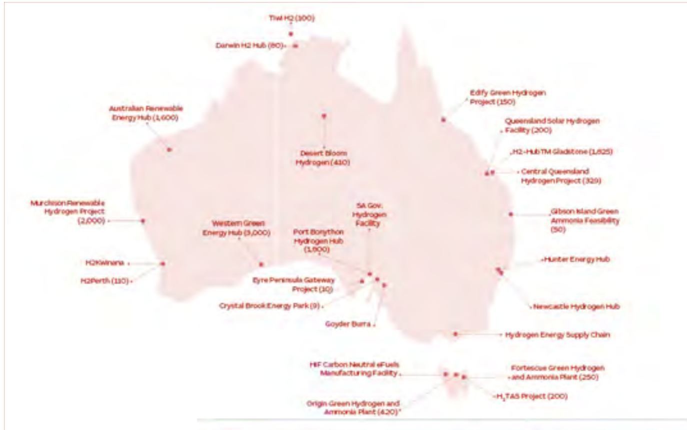
Our Business

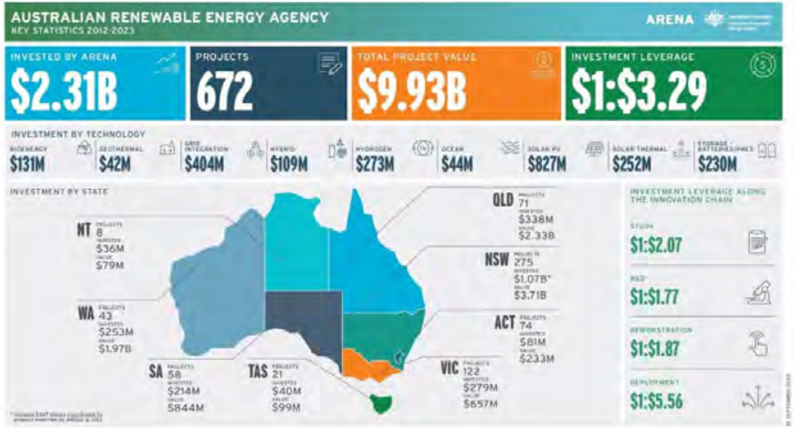
HATCH

Australia energy projects pipeline

Figure 13 Identified candidate Renewable Energy Zones (REZs) for assessment in developing the optimal development path in the NEM







Source: Clean Energy Council, Hatch analysis

HATCH

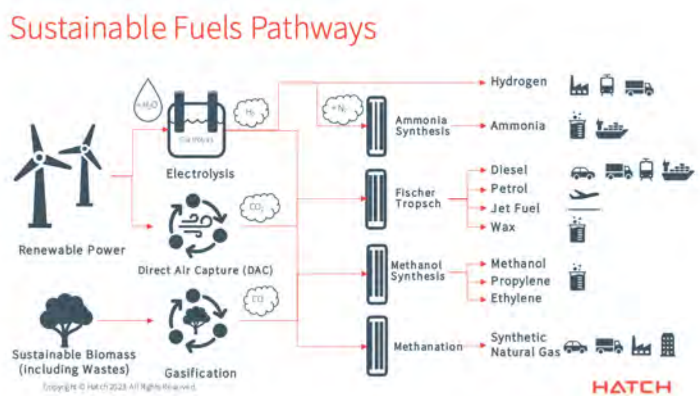

What are
future fuels?

What are future fuels?

Fuels produced from a renewable source – the flow scheme used to produce these fuels result in lower carbon emissions

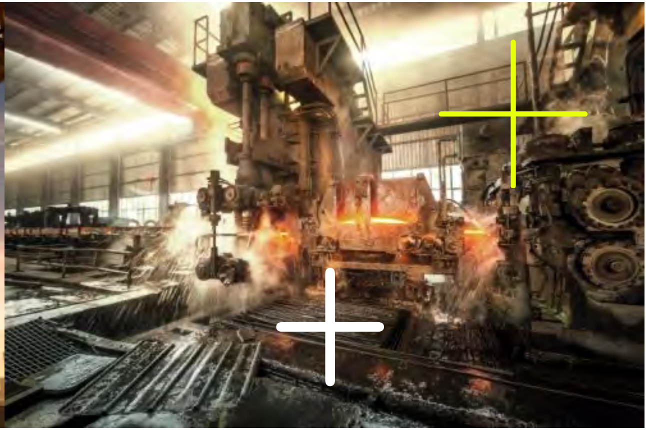
Future fuels include

- Hydrogen - compressed/liquefied
- Ammonia
- Methanol
- SAF
- Biofuels



Boegoebaai Green Hydrogen Project



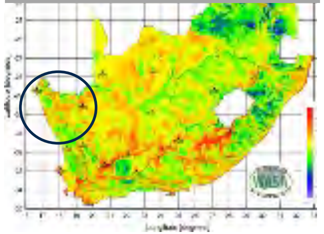


HATCH

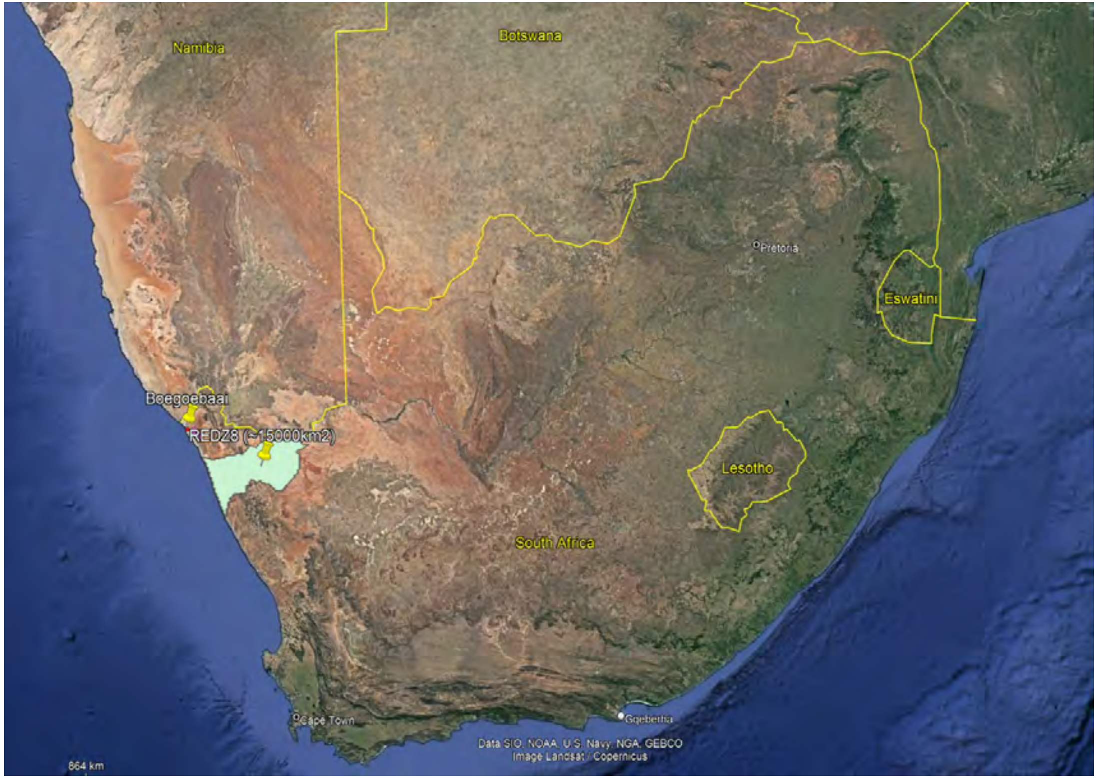
Project Overview and Background

Solar Map

Wind Map



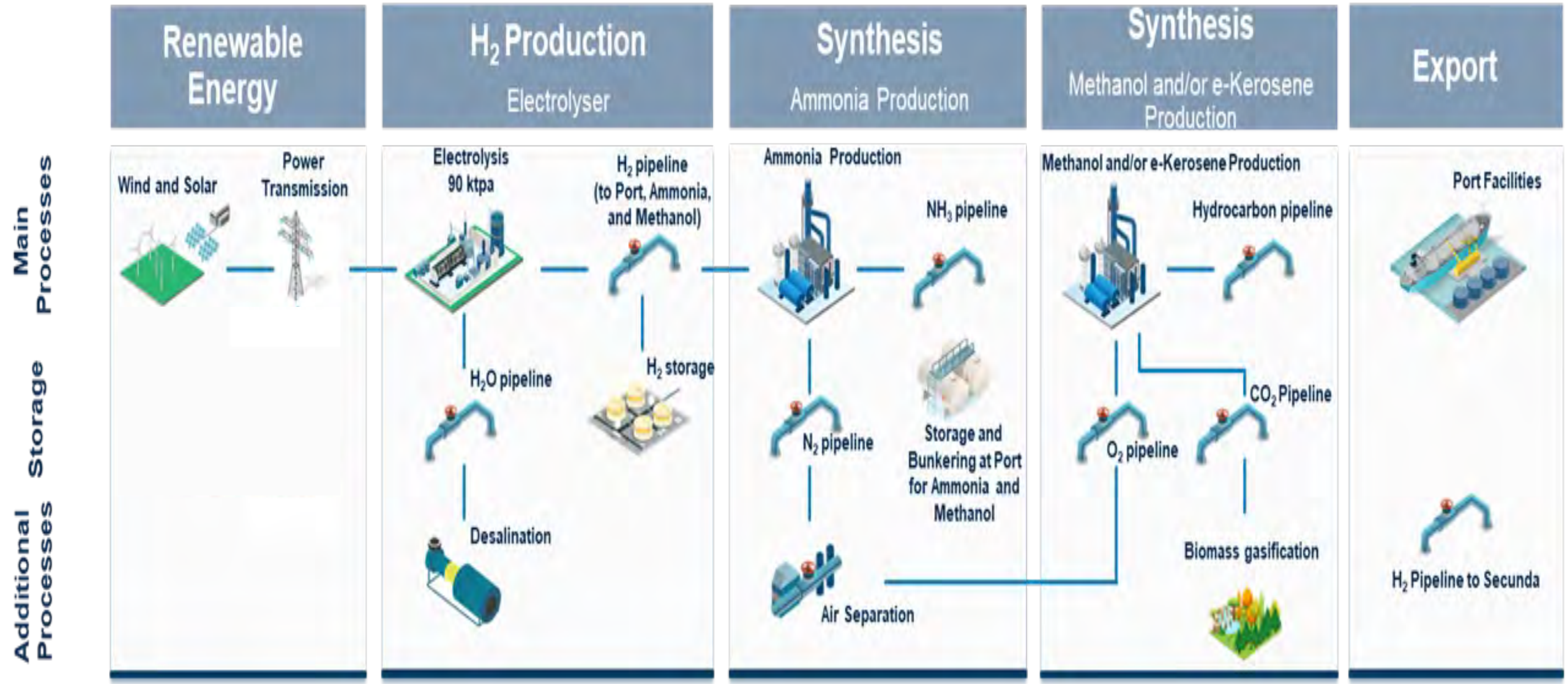
Population Density



sasol

HATCH

The Green Hydrogen Process



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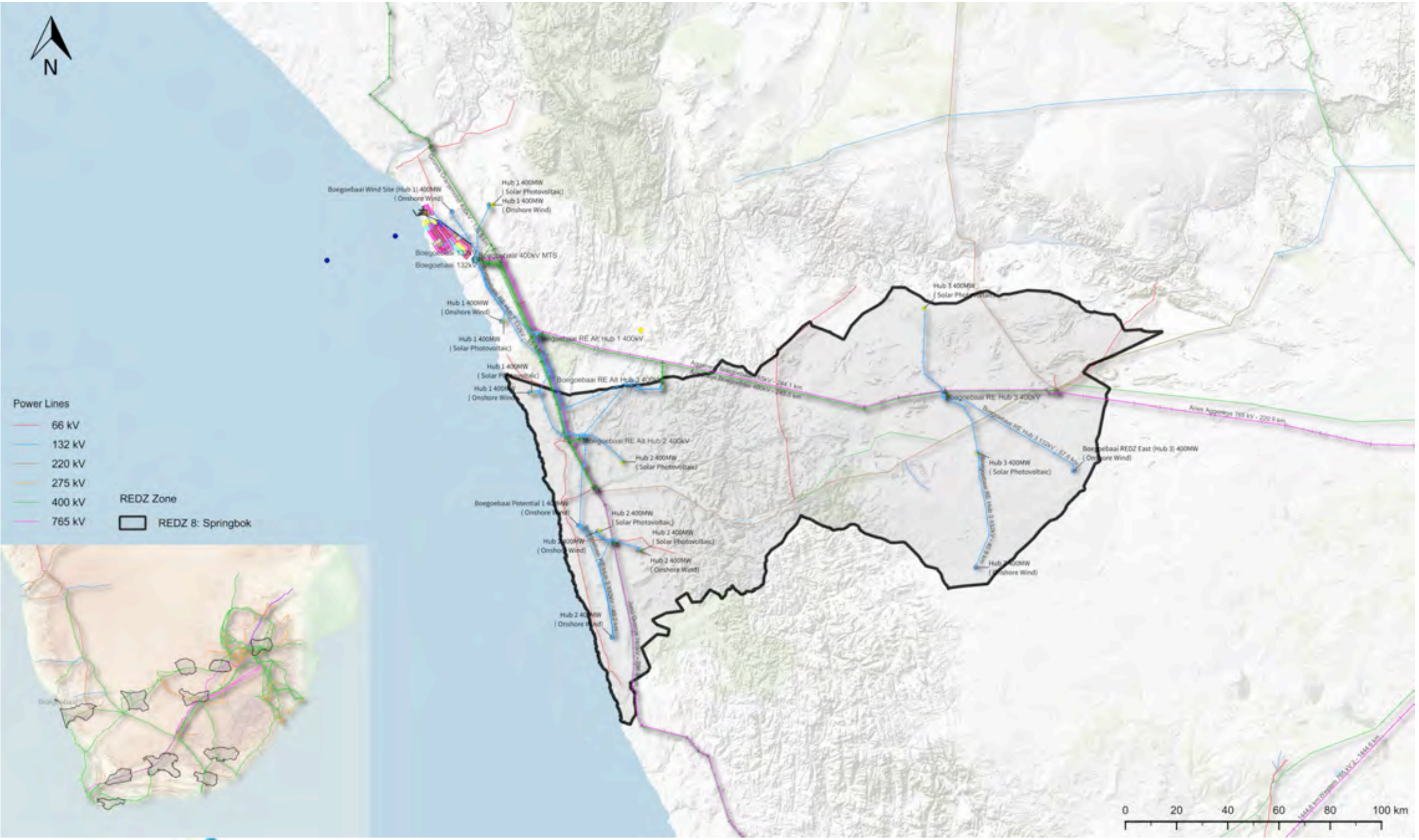
HATCH

The Boegoebaai Project Site



~5 GW electrolyser

>12 GW RE

~580 ktpa green H_2

H2, NH3, MeOH, SAF*

North Queensland Clean Energy Project

- Hydrogen Plant capable of producing 18,200 kg/hr of green hydrogen from 1100 MW of electrolysers
- 275 kV Substation connected to 1.8 GW of renewable renewable generation (wind and solar)
- Hydrogen Liquefaction Plant of 30 tpd capacity to supply liquid hydrogen for domestic offtake
- 11 km pipeline for the storage and transfer of hydrogen
- A 1600 tpd Ammonia Synthesis Plant
- Ammonia storage and cryogenic pipeline to transfer ammonia to the export terminal
- A 10 MLD desalination Plant
- All balance of plant systems including seawater evaporative cooling towers to manage heat loads, flares and site utilities.

HATCH

Challenges

- Fuels are different
- Demand/timing is different
- Vessels are different
- Safety/MHF
- Workforce skillset

Opportunities

- Enabler for decarbonisation and energy transition
- Common user infrastructure
- Ecosystem/circular economy
- Dual fuels
- Skills

HATCH

Hydrogen Storage and Transportation Facilities

Workshop on :
Challenges and Opportunities for Hydrogen in the Port

Prakash Aryal
WSP

Contents to Cover

- Supply Chain pathways
- Hydrogen Compression
- Storage options
- Transportation options
- A Case Study
- Risks and Challenges

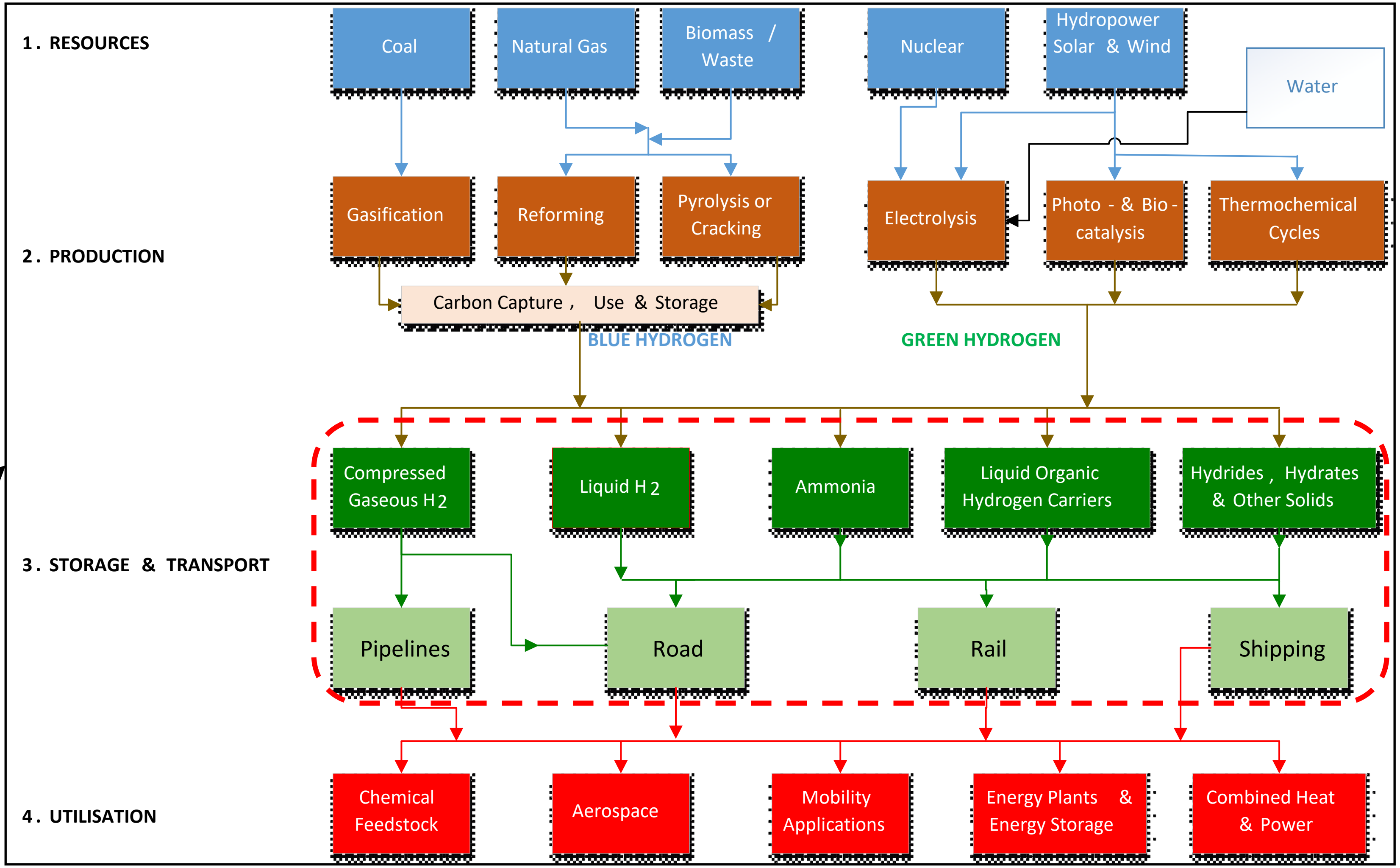
Supply Chain

Hydrogen Supply Chain Pathways

Four Primary Stages:

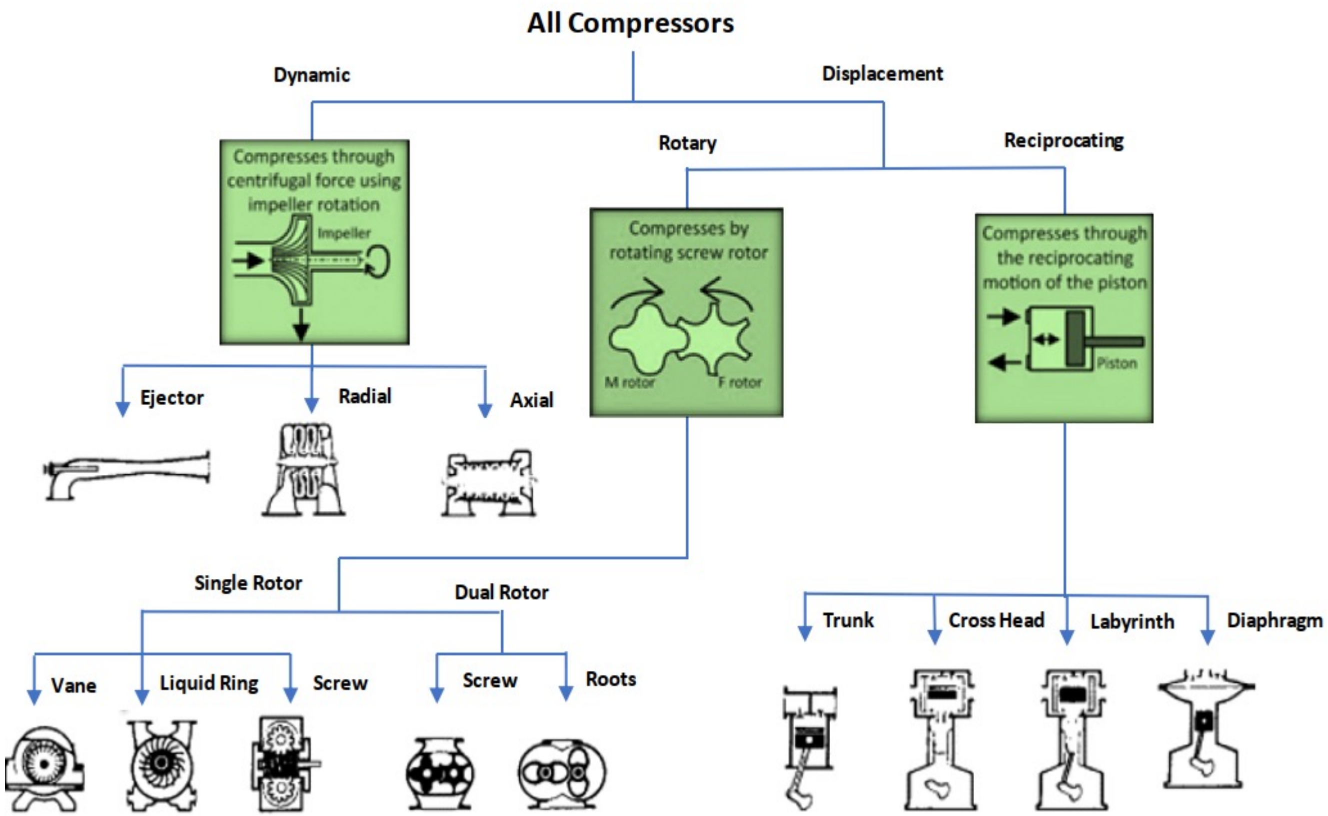
- Resources,
- Production
- Storage & Transport,
- Utilisation

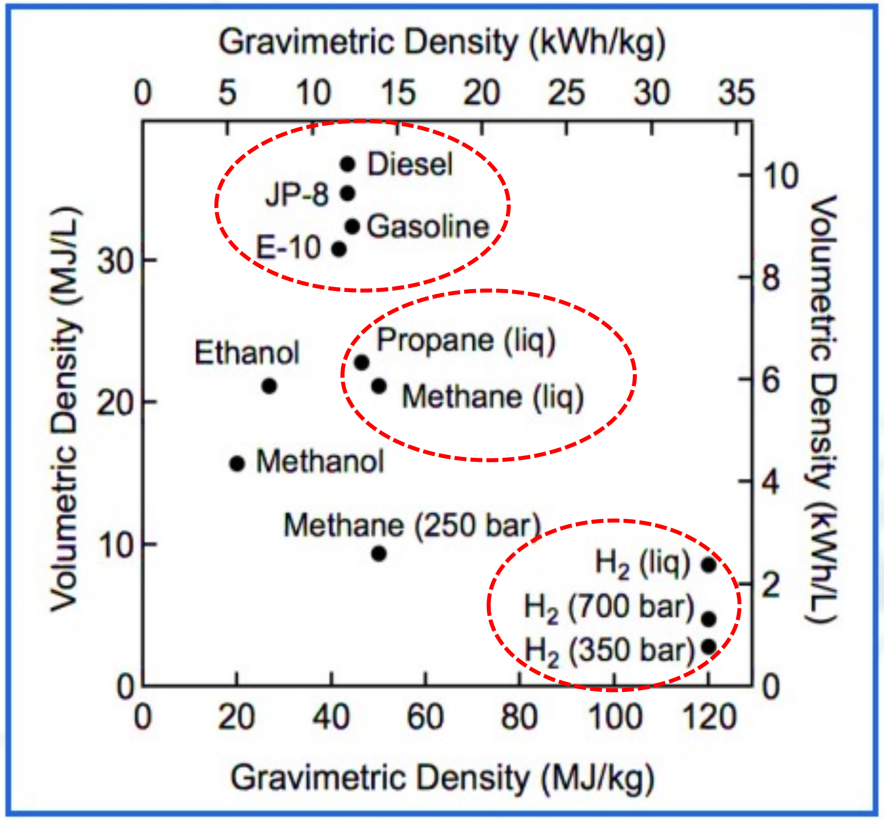
Several pathways



Selection depends on cost, technical merit, end point use, carbon footprint, safety etc.

Gaseous Hydrogen Compression

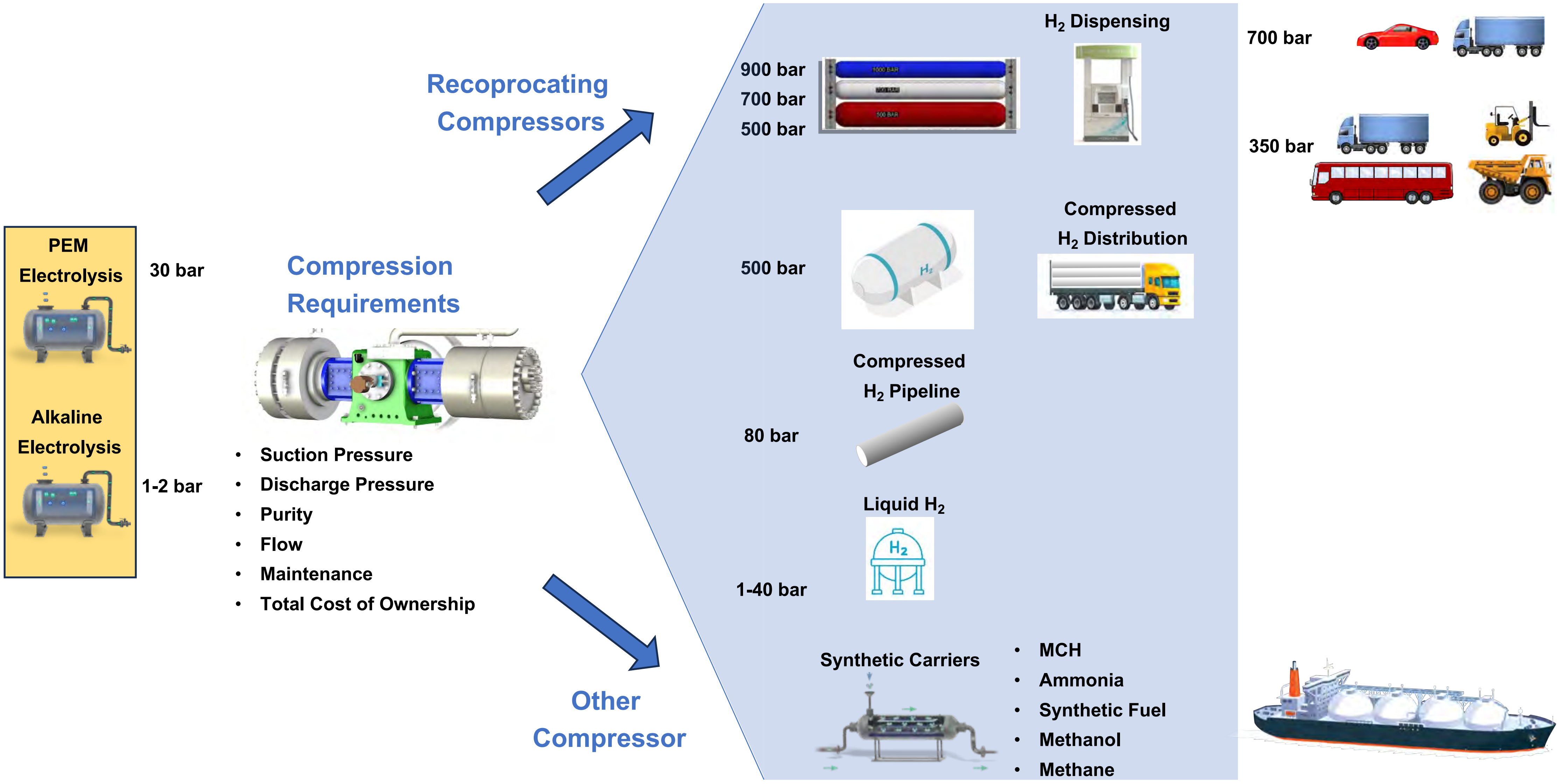




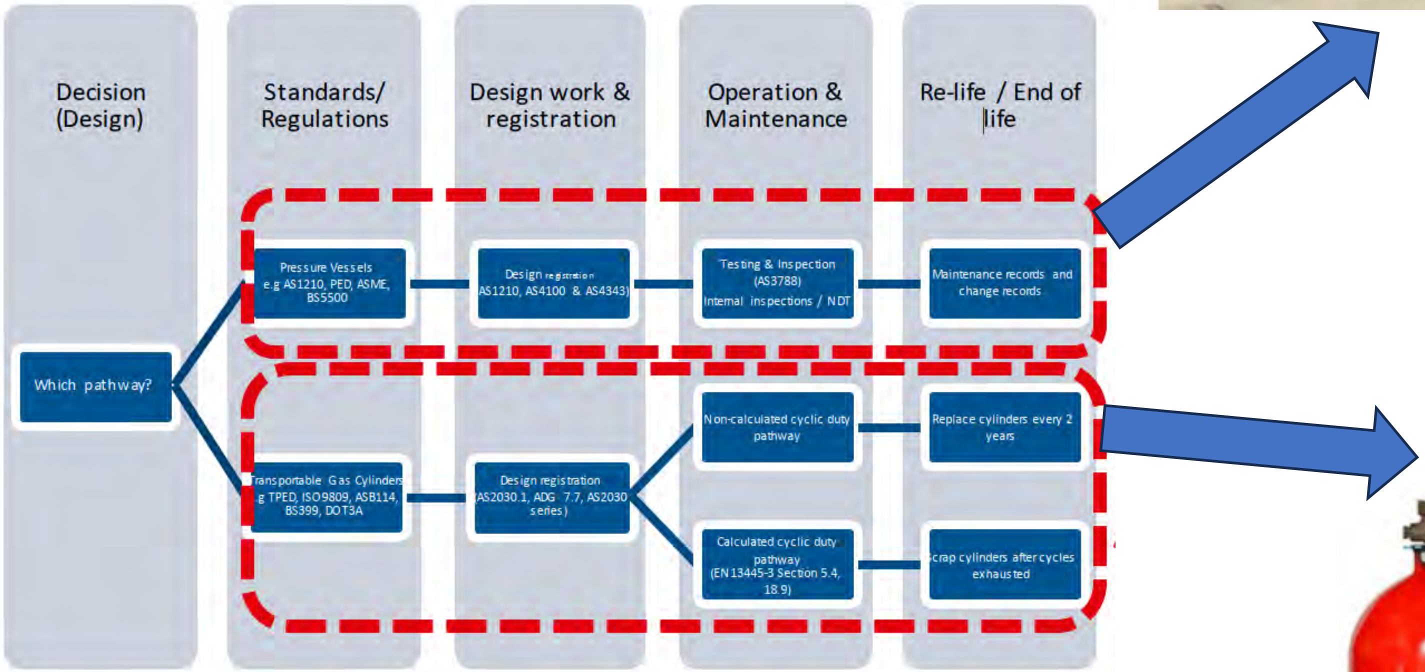
- Reciprocating compressor – High pressure ratio, but removal of heat may be an issue
- Centrifugal compressor, pressure ratio 1:1.1 per stage for Hydrogen compared to > 1:20 for heavy gases

- We may require 4 gasoline tankers or 2.5 LNG carriage vessel to carry equivalent energy via even LH2

Compression for Hydrogen



Types of gaseous Hydrogen storage – Cylinders



Static Storage

Transportable

Types of gaseous storage – Cylinders

Feature	Type I	Type II	Type III	Type IV
Working pressure MAX (bar) – STATIC	550	1000	1000	1000
Working pressure MAX (bar) – TRANSPORTABLE	300	300	700	700
Weight	Heavy	Moderately heavy	Light	Very light
Temperature range (°C)	-40 to +65	-40 to +65	-40 to +65	-40 to +65
Fill/discharge rate	Non specific	Non specific	Determined by design / prototype testing	Determined by design / prototype testing
UV resistance	High (painted)	Limited	Limited	Limited
Cycles permitted (typical)	12,000+	Determined by design	Determined by design	Determined by design
Operating life (typical)	Non-limited	Limited life	Limited life	Limited life
Periodic Inspection	AS 2337, ISO 18119, etc..	AS 2337.3, ISO 11623, etc..	Determined by design	Determined by design
Cost (Life time)	$	$$	$$$	$$$$

Types of gaseous storage – Bulk

Key design considerations – Bulk

- User Design Specification (AS1210) typically working with a vessel fabricator;
  - a) Hydrogen purity
  - b) Pressure(s)
  - c) Temperature(s)
  - d) Fluid behaviour (HE!)
  - e) Special thermodynamic properties
  - f) Flow rates (in and out)
  - g) Pressure cycles (can be tricky)
- Safety/separation distances
- Explosive gas atmosphere, leak/fire detection, fire protection
- Environmental hazards (site specific)

30 bar, 43kg
18,000L

300 bar, 4,400 kg total
10,000L each

450 bar, 30kg each
1,000L each

137 bar, 7.7kg
750L

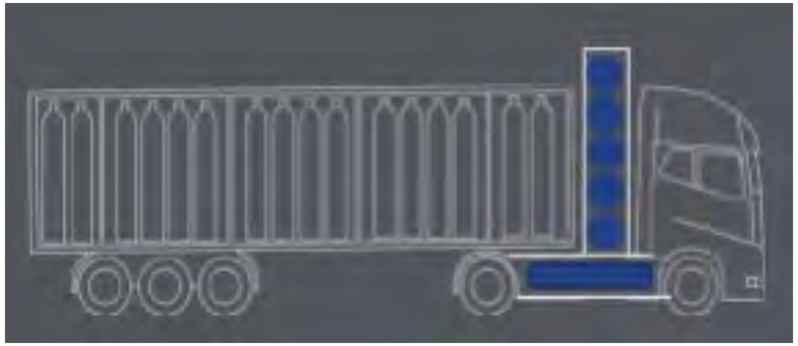
Hydrogen Transport: Gaseous hydrogen

Tube Trailers

- Pressure regulation and safety systems
- Loading and unloading equipment
- Monitoring and control systems
- High-pressure cylinders or tubes 200-700 bar
    - Type 1 rated at 200 Bar low payloads of about 160kg
    - The next generation up to 220 bar with payloads up to 370kg
    - The latest trailer Type 4 cylinders or tubes, payloads close to 1 tonne at pressures of 300 bar, and over 1.5 tonnes when filled at 700 bar.

Tankers

- MEGC (Multi-element gas containers)
- Alternative to Tube Trailers.
- Modern styles utilizing Type III/IV cylinders
- for significantly reduced weight.



- Compressed hydrogen MEGCs have up to 400 cylinders and Tube trailers typically have 8 to 10 tubes.

H_2 Transport via Pipeline

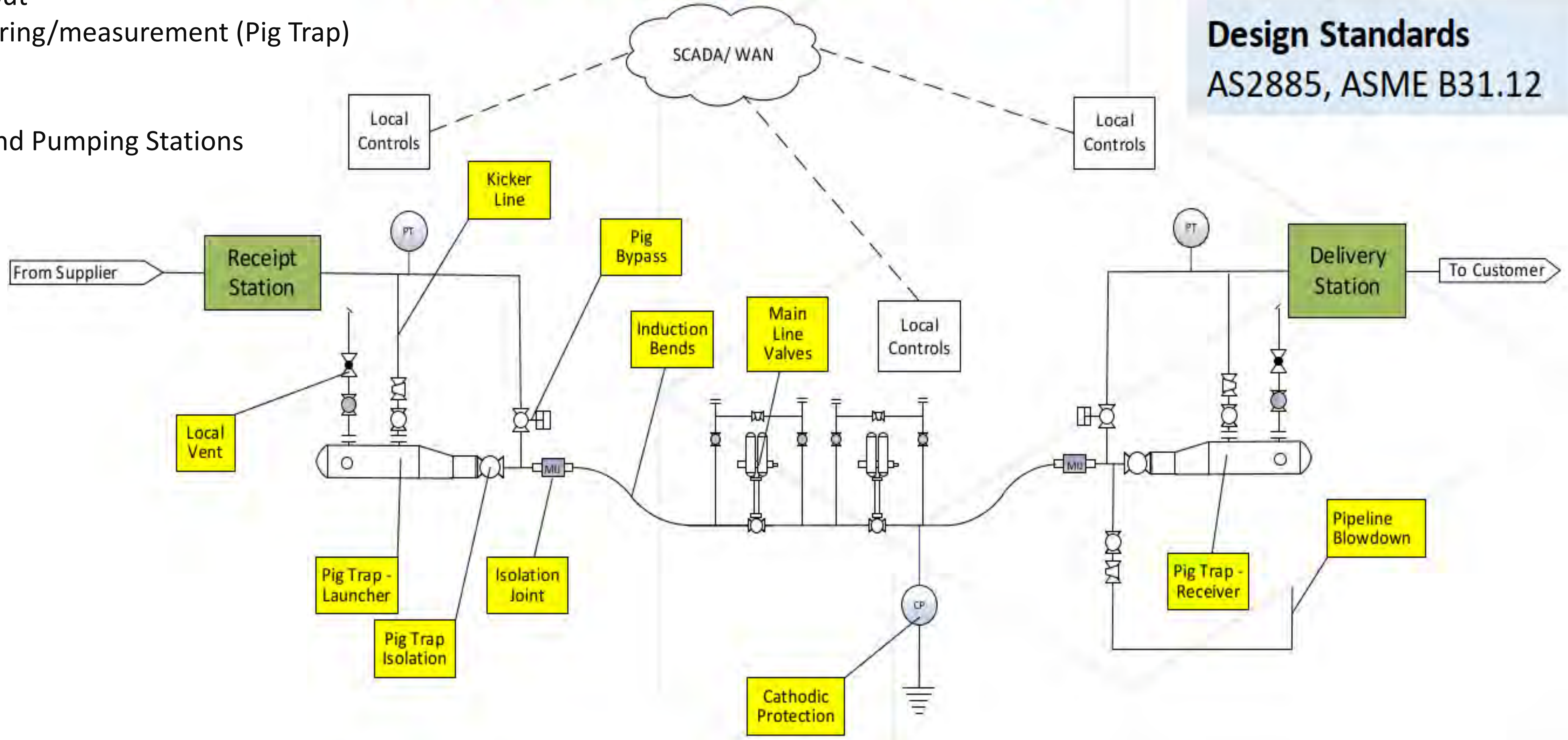
Factors to consider in pipeline design

- Hydrogen Purity
- Pipeline Material
- Pipeline Diameter and Wall Thickness
- Operating Pressure, Temperature & Flow
- Pipeline Routing and Layout
- Safety Features & Monitoring/measurement (Pig Trap)
- Cathodic Protection
- Material Compatibility
- Hydrogen Compression and Pumping Stations
- Regulatory Compliance

Simplistic Pipeline Design

Design Standards

AS2885, ASME B31.12



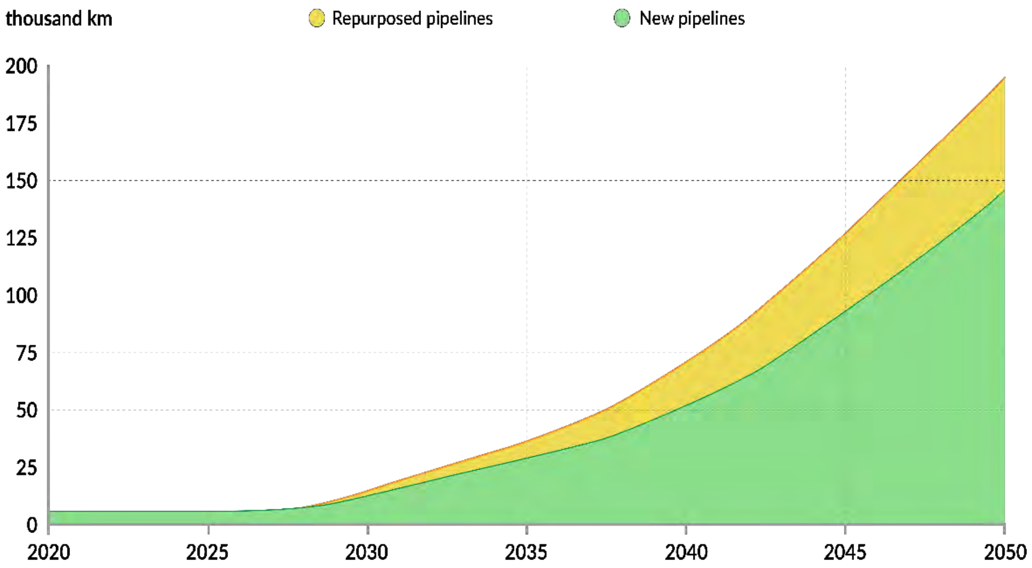
H_2 transport via Pipeline

Minimum depth of cover

- For natural gas pipelines, the minimum depth of cover is 750 mm; however, for hydrogen pipeline, the recommended depth of cover as per ASME B31.12 shall be:
  - Normal excavation: DOC ≥ 900 mm
  - Rock excavation: DOC ≥ 600 mm
  - Agricultural areas: DOC ≥ 1200 mm

- The final DOC will be based on the results of the risk assessment.

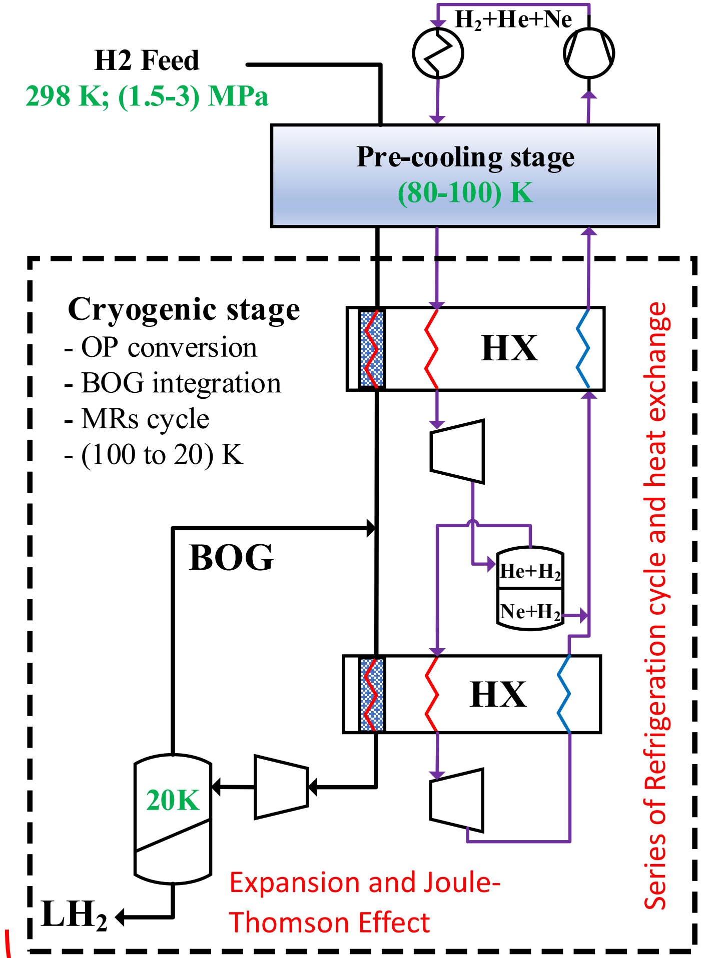
- Further, a minimum clearance of 450 mm between all buried hydrogen pipelines and any other underground structure must be maintained.



IEA 2022

Liquid Hydrogen

Hydrogen Liquefaction Processes

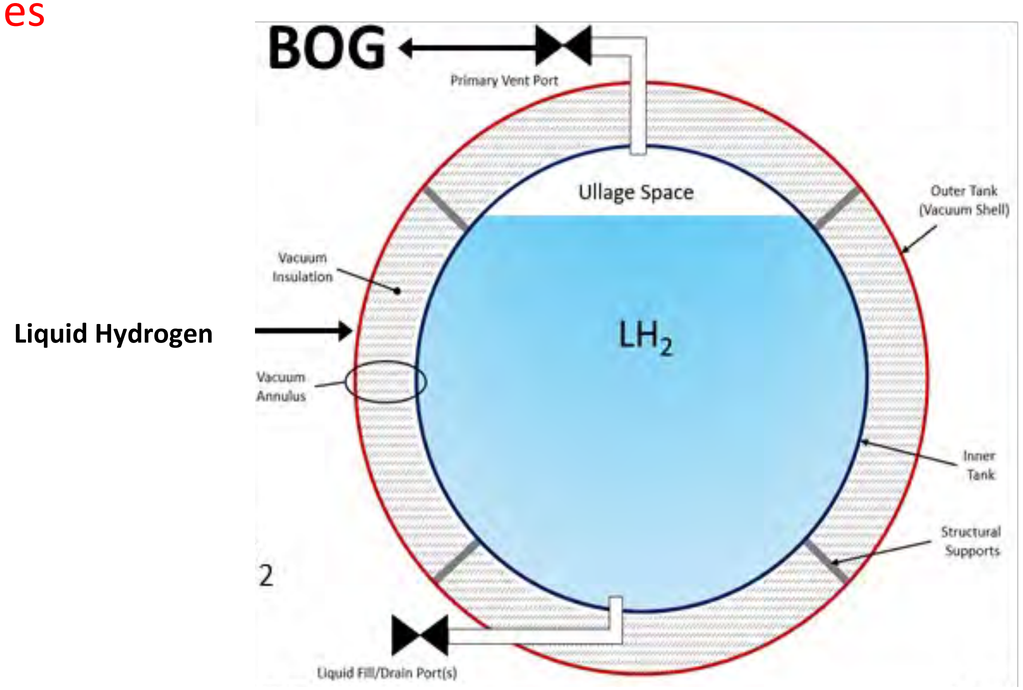


mixed refrigerant technologies

Impact on SEC/design and operation:

- MRs composition and thermophysical properties
- Compressors/expander types/efficiencies
- MRs cycle layout and BOG handling
- Neon potential freeze-out at cryogenic temperatures

Plausible target:
SEC: (6–8) kWh/kg_{H2}
SLC: (1–2) US$/$kg_{H2}$



H_2 Feed → Compression 2 – 8 MPa → Pre-Cooling 80 K → Cryogenic Cooling to < 30 K → Liquid H2 Product → Liquid H2 Storage → Liquid H2 Transport

- BOG: For example on a 9,000-kilometer shipping route – up to 40 percent might be lost due to boil-off and fuel usage for propulsion

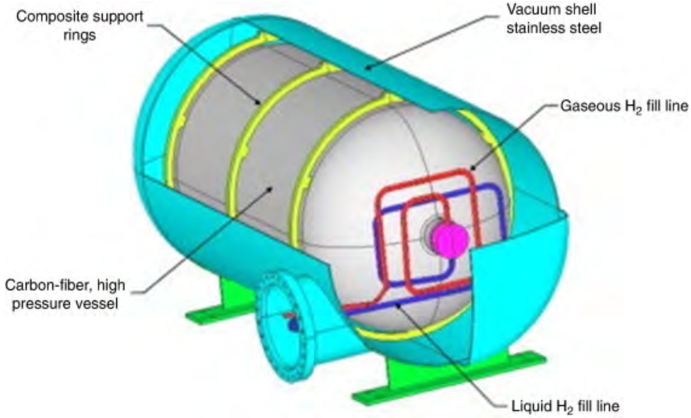
Hydrogen Transport: Liquid hydrogen

- Temperatures around -253⁰C, Pressures up to 11 bar liquid
- Hydrogen is distributed in cryogenic pressure vessels and pipes
- Inner vessel wrapped in multi-layer insulation
- Supported within an outer jacket with a vacuum established
- Cold temperature and potential for HE: Austenitic Stainless Steels are permitted
- The trailer section where pipes pass through the outer jacket are always made from Austenitic Stainless Steel.
- The rest of the outer jacket is made from either Carbon Steel or Austenitic Stainless Steel.

https://ntrs.nasa.gov/api/citations/20220004276/downloads/Cold%20Facts_LH2%20Sphere%20Update.pdf

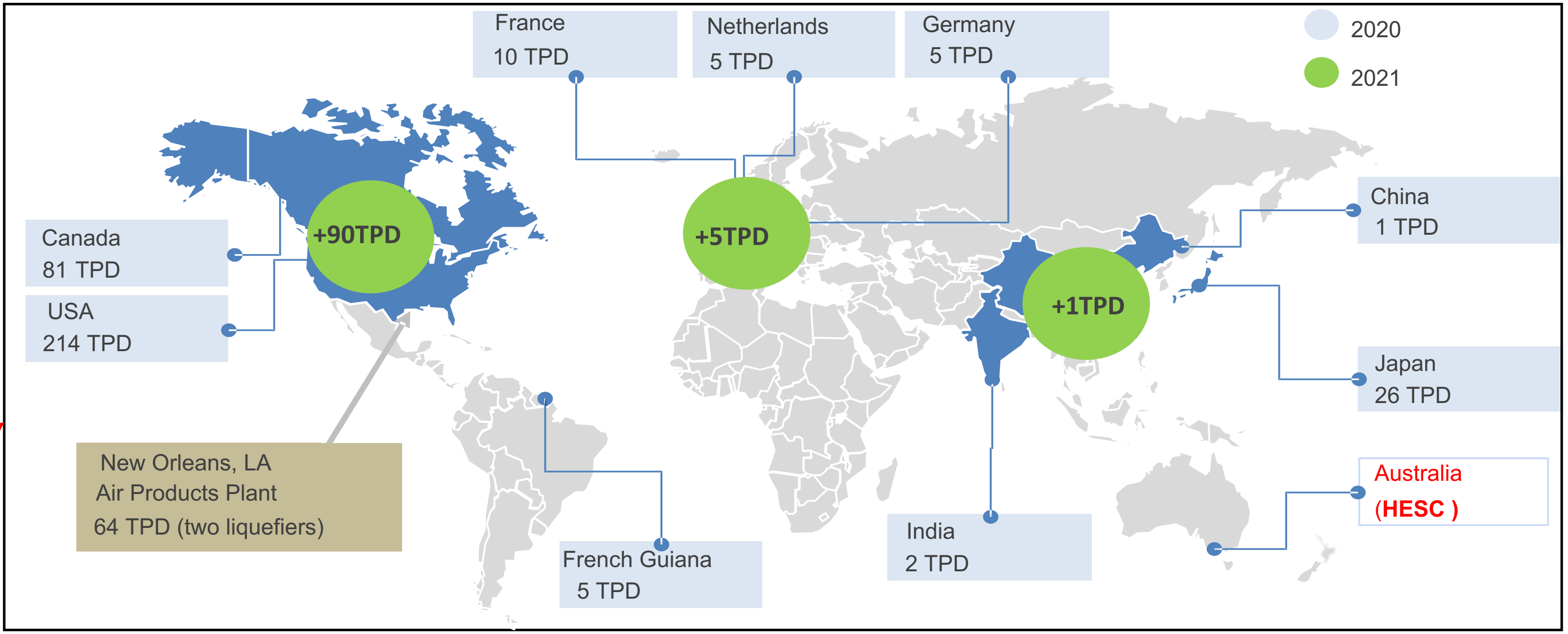
LH2 ISO Container, EIGA DOC 247/24

Liquid hydrogen Trailer, EIGA DOC 247/24



Liquid Hydrogen Transport: Ship

- Due to transport efficiencies, gaseous hydrogen is usually only transported on relatively short sea routes.
- Hydrogen is transported on the longer sea routes in either liquid or chemical form.
- High purity, high volumetric density, end-use versatility, and ease of gasification
- Global capacity in 2020 > 350 TPD; with >96 TPD in 2021
- Globally, there are very few deep-sea bulk ships for liquid hydrogen. However, it is likely to increase rapidly as the global hydrogen economy grows.

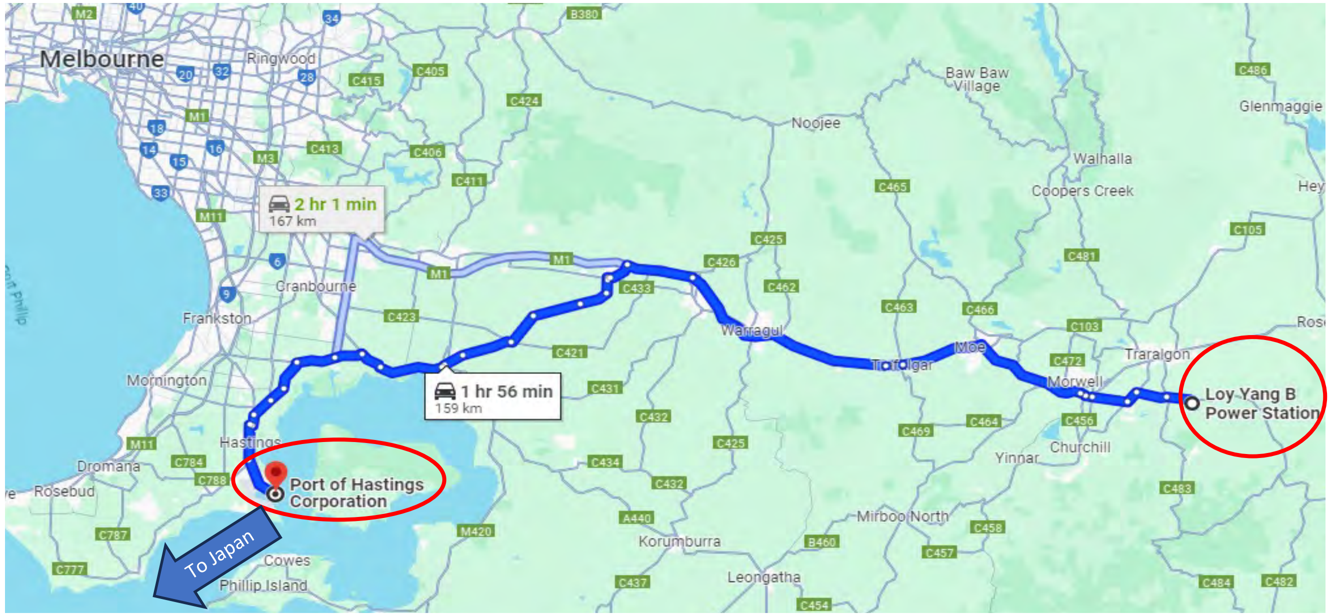


Case Study

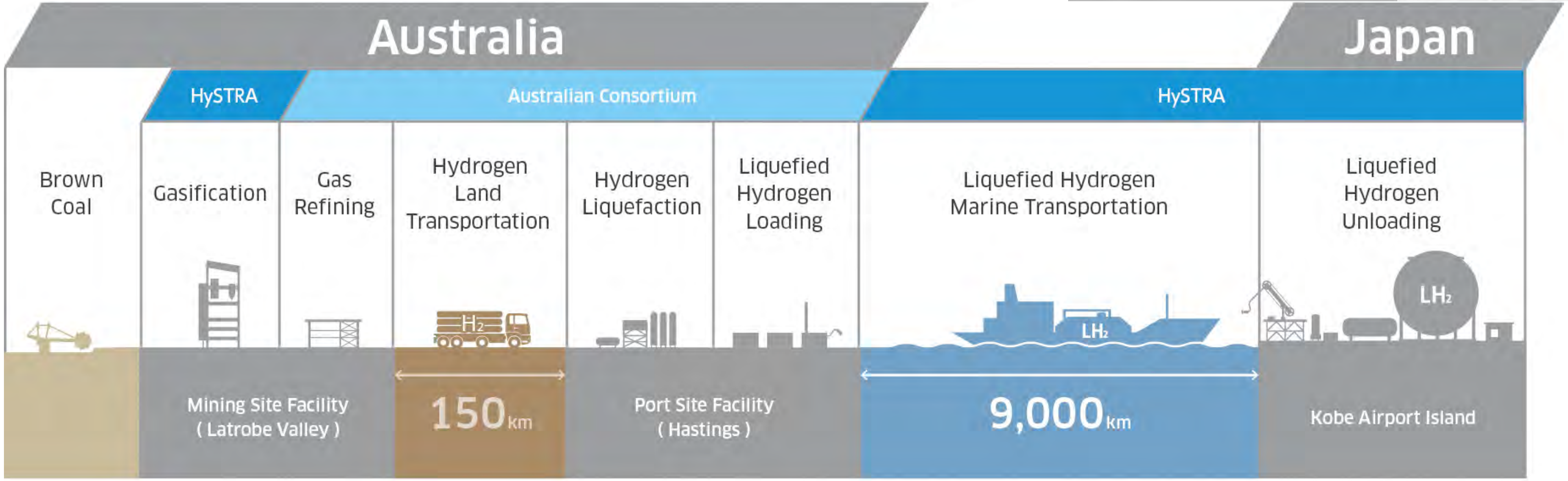
A case of HYST (VIC Hydrogen to Japan): The Suiso Frontier

LH2 loading operation at BSL jetty

- Transported the gaseous hydrogen generated in Latrobe Valley (coal + biomass) to the Port of Hastings via a high-pressure (20MPa) gaseous hydrogen tube trailer (320kg H2 max capacity);
- Liquefied the hydrogen via cooling and expansion and transfer into a hydrogen container; this process reduced the volume of H2 to 1/800.
- Stored LH2 in a truck-mounted container and loaded the hydrogen into a LH2 marine carrier.
    - 20 January 2022, LH2 carrier vessel arrived at Hastings. From 21 to 28 January 2022, LH2 loading operation had been carried out and successfully completed
    - 1,831kg of LH2 was loaded onto the LH2 carrier ship, the Suiso Frontier
    - Departed Hastings on 28 January and arrived at Kobe terminal in Japan on 25 February 2022.
- Successfully demonstrated, and the process was particularly informative regarding the technology required in this part of the Project.



Specifications	
Length overall	116.0 m
Length between perpendiculars	109.0 m
Molded breadth	19.0 m
Molded depth	10.6 m
Molded draft	4.5 m
Gross tonnage	Approx. 8,000 t
Tank cargo capacity	Approx. 1,250 m^3
Propulsion system	Diesel electric propulsion
Sea speed	Approx. 13.0 kn
Capacity	25 persons
Classification	Nippon Kaiji Kyokai (ClassNK)
Country of registration	Japan
Ship owner	CO_2-free Hydrogen Energy Supply-chain Technology Research Association (HySTRA)



World's First Liquefied H_2 Carrier SUISO FRONTIER

Chemical Hydrogen Compounds

- Chemical hydrogen compounds (hydrogen carriers)

- Several compounds are being researched, the most common currently in use are:

- Liquid Ammonia (NH_3 -33ºC)
  - Distributes a greater mass of hydrogen per unit volume than liquefied hydrogen
  - The future concept is bulk carriage of ammonia by sea, with cracking into hydrogen (and nitrogen) performed at the import terminal.
  - The onward transport of this hydrogen is by road or pipeline, which minimises the hazard associated with transporting toxic ammonia.

- Methanol (CH_3OH): It has the advantage that liquid is distributed at ambient temperatures and pressure by road, rail, sea and pipelines.
  - This also distributes a greater mass of hydrogen per unit volume than liquefied hydrogen and utilises existing infrastructure.

- Liquid Organic Hydrogen Carriers (LOHC): organic compounds that can absorb and release hydrogen through chemical reactions.

- Metal Hydride (MHx): usually in powder form that requires cooling and heating under pressure to load and release hydrogen. Technology is being developed for scale deployment of substances such as Lithium Borohydride ($LiBH_4$), which has a higher energy density per litre than conventional hydrocarbon fuels such as gasoline, $LiBH_4$ is being used to developed on-board vehicle storage packaging for FCEV.

Safety First: Materials selection & Hydrogen embrittlement

- Why is materials selection important when designing Hydrogen Storage & handling systems w.r.t. T & P?

1. Tightness: Smallest molecule in the world, seals and fitting tolerances are critical to ensure process tightness.
2. Detonation & deflagration potential: At elevated pressures, the likelihood of detonation or deflagration in vent lines must be considered.
3. Surface finish: H2 compatibility with austenitic stainless steels is markedly influenced by surface finish. Oxides at metals and alloy surfaces will influence the degree of embrittlement.
4. Hydrogen embrittlement (HE): Incidents occurred in the 1970's that tragically lead to fatalities. The HE effect was not known at this point.

H embrittlement involves different mechanisms

- HELP – H enhanced localised plasticity
- HEDE – H enhanced decohesion
- HAC – H assisted cracking
- HESIV - H enhanced strain induced vacancy
- HID – H induced decohesion

Materials selection & Hydrogen embrittlement

Environmental HE	Plastic deformation of metals and alloys in a gaseous hydrogen environment. The deformations lead to increased surface cracks, loss in ductility and decreases in fracture stress. Cracks start at the surface.
Internal HE	Caused by the absorption of hydrogen. Small amounts of hydrogen may cause premature failures in some metals, which may be with little or no warning. Cracks start internally.
Hydrogen Reaction Embrittlement	Caused by the absorbed hydrogen chemically combining with one or more of the constituents of the metal to form a brittle hydride. Reactions occur more readily at elevated temperatures. Hydrogen can even form methane with the carbon in steels.

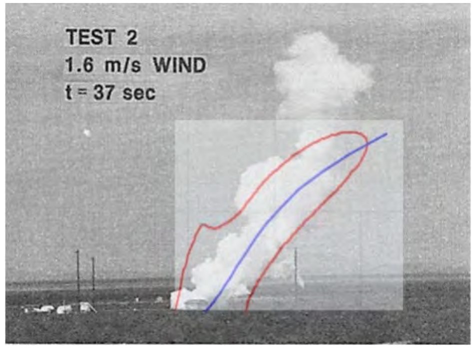
The above can occur in combination!

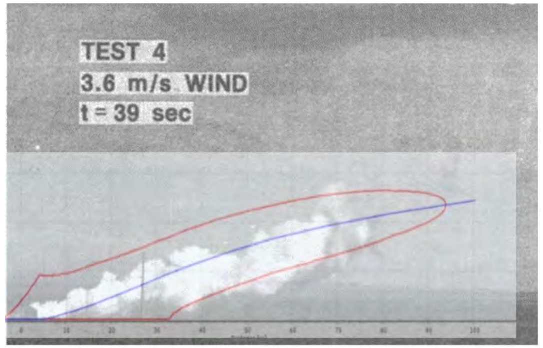
Source: Sourcebook for Hydrogen applications

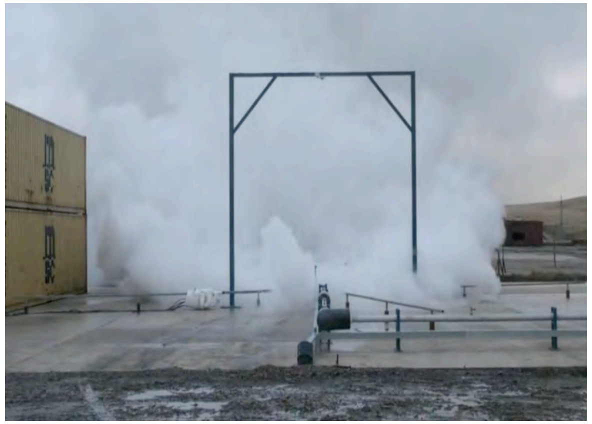
Examples of hydrogen (internal) embrittlement failure in 1970s

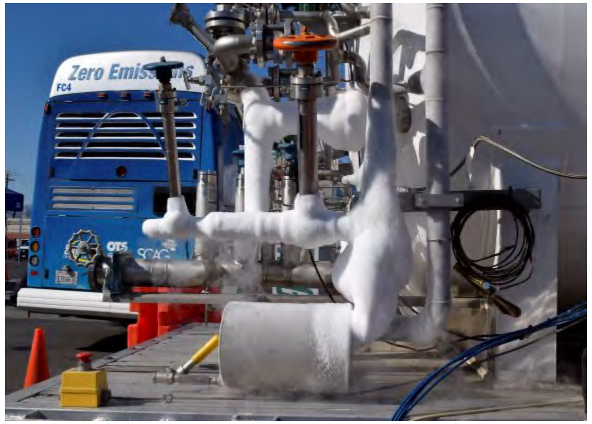
LH_2 :Things to consider

- H_2 exists as a liquid at 20K (-253 °C)
- Potential for frostbite and cryogenic burns
- Volume ratio of liquid to gas 1:848
- May cause problems due to solid “ice” formation
- Air can condense on the outside surface of uninsulated LH2 piping.
- LH2 exposed to air at ambient pressure will continually draw in air due to a process called cryo-pumping.
  - LH2 must be stored, transported, and evaporated under pressure (10-12 bar?).
- Continuous LH2 evaporation increases the pressure in a closed containment;
  - May result in pressure failure, if not properly vented.
- Experiments show that liquid accumulation doesn’t occur;
  - Released liquid boils-off quickly, releasing large amount of gas.
- Potential for oxygen enrichment → Detonation?
- Dispersion behaviour: dense or buoyant?









Thank You !

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