Renewable Hydrogen for the Pacific

Lecture 2: Hydrogen Storage, Transportation and Utilisation

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Agenda

- Ways of storing pure hydrogen and issues
- Transporting hydrogen in pure form and Power to X Pathways
- What is Power to X
- Green Ammonia Economy
- Green Synthetic Fuels

Storage and Transport of Pure Hydrogen

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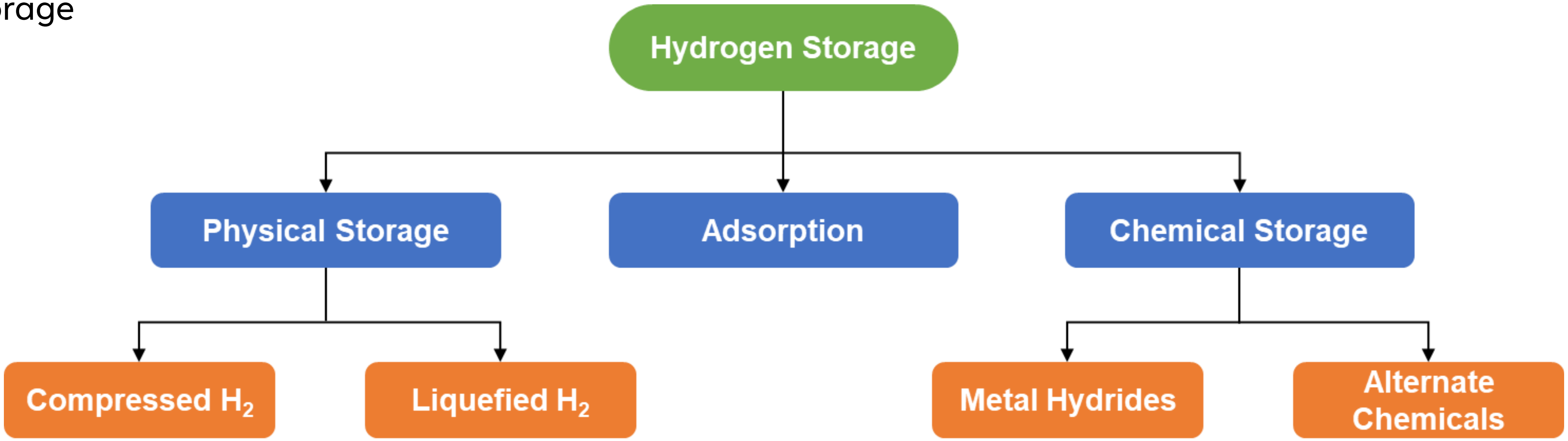
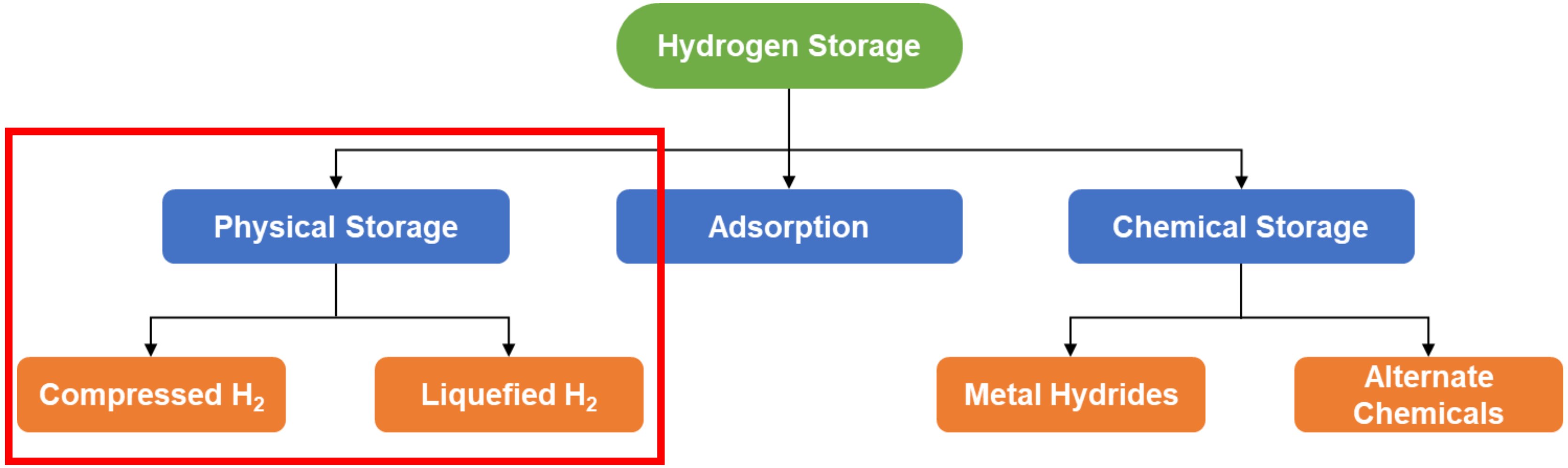
Storage of Hydrogen

- Once produced, hydrogen must be safely stored
- Hydrogen can be stored in many forms:
  - Physical storage
  - Adsorption
  - Chemical storage



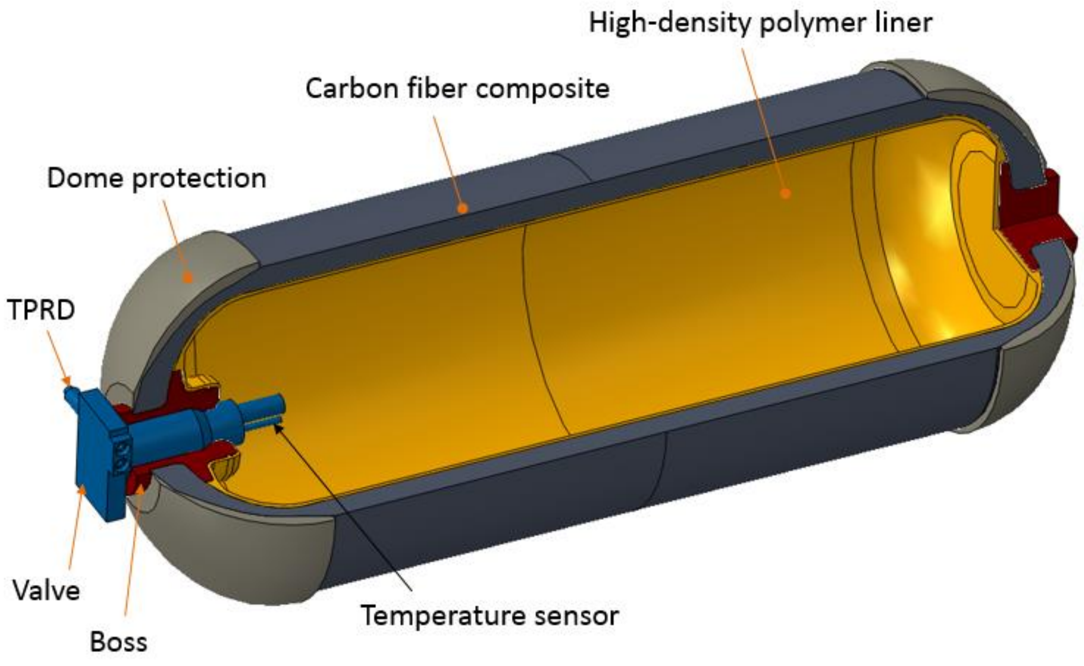
Physical Storage of Hydrogen

- The storage of pure hydrogen
  - In compressed (gas) form
  - In liquefied form



Storage of Compressed Hydrogen

- Under ambient conditions, 1 kg of hydrogen gas occupies a volume of 11 m^3
- It must therefore be compressed for effective storage and transport
- Compressed hydrogen is generally stored in cylindrical pressure vessels
- Pressures are between 3 to 35 MPa

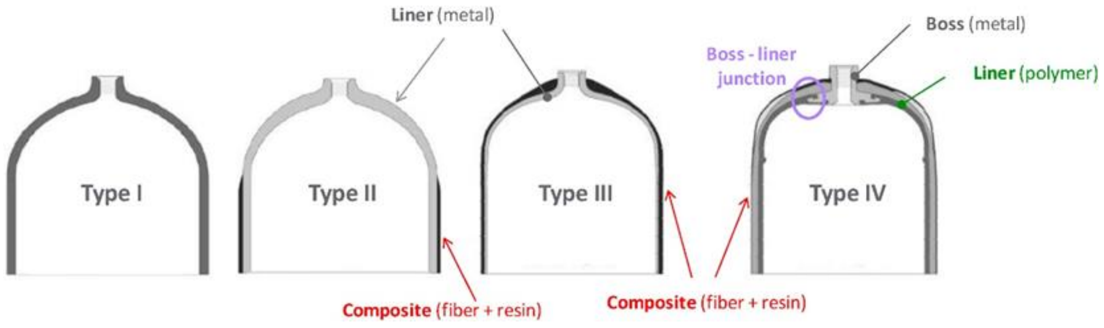


TPRD = Thermally Activated Pressure Relief Device

Credit: Process Modeling Group, Nuclear Engineering Division. Argonne National Laboratory (ANL)

Storage of Compressed Hydrogen

- Type I:
  - Composed of metal
  - Cheap but low maximum pressures
- Type II:
  - Metallic liner with a composite fiber and resin overwrap
  - Improved mechanical strength but high cost
- Type III:
  - Carbon fiber composite pressure vessel with a metal liner
  - Improved mechanical strength but high cost
- Type IV:
  - Carbon fiber composite pressure vessel with a polymer liner
  - Reduced risk of hydrogen embrittlement at a higher cost

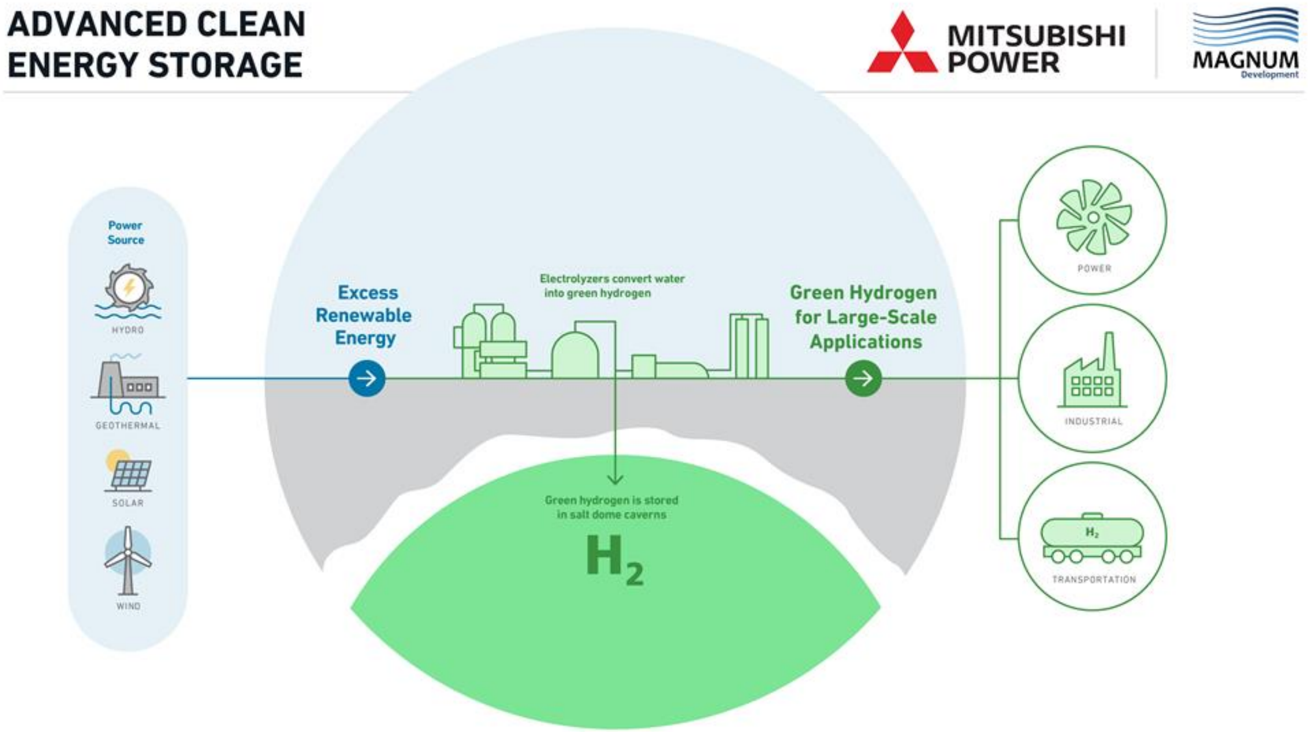


Compressed Hydrogen Advantages and Disadvantages

Advantages	Disadvantages
• Most mature hydrogen storage technology • High mobility and flexibility • Lower pressure than liquefied hydrogen, requires less compression and hence reduced operating costs • Stored as pure hydrogen, therefore no requirement for separation by end user	• Requires large volume and significant investment costs • Vessels must be thick and strong to maintain structural integrity and avoid leakage • Not considered viable for large-scale operations • High flammability of gaseous hydrogen

Large Scale Compressed Hydrogen

- Feasibility of storing large quantities of gaseous H_2 in underground caverns is being investigated
- Water is pumped into salt caverns to dissolve and extract the salt
- Hydrogen is then pumped into the empty cavern for long-term, large-scale storage



Underground Compressed Hydrogen Advantages and Disadvantages

Advantages	Disadvantages
• Low construction costs • Low leakage rates • Fast injection and withdrawal rates • Minimal risks of hydrogen contamination • Stored as pure hydrogen, therefore no requirement for separation by end user • Large-scale storage can provide a buffer for intermittent renewable energy	• Difficulty in finding caverns with the required geological prerequisites: site-specific • Lower mobility and flexibility compared to above-ground storage • High flammability of gaseous hydrogen

Storage of Liquefied Hydrogen

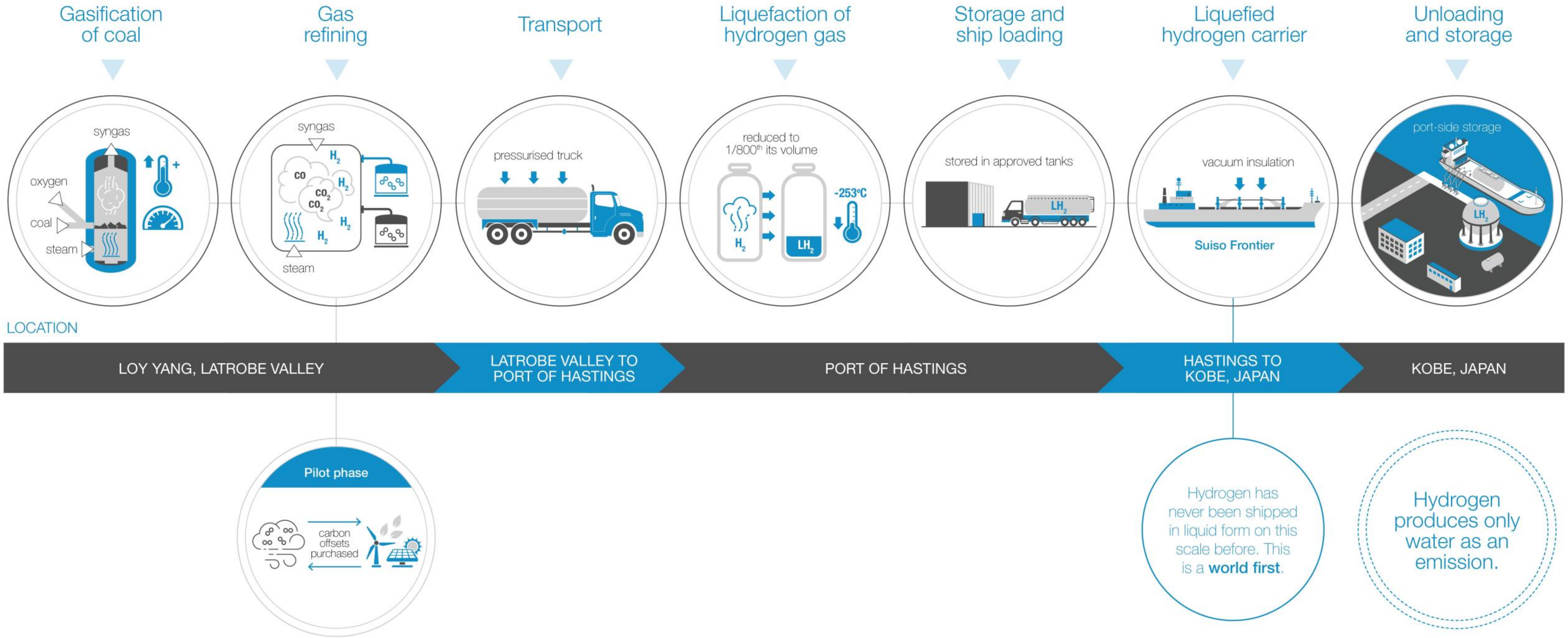
- The density of hydrogen can be further increased through liquefaction
  - Liquid nitrogen pre-cooling achieves a temperature of -193°C
  - Claude or Brayton cycle further cools to -253°C
- Liquid hydrogen storage vessels are most commonly double-walled with a high vacuum applied between the wall
- The vacuum minimizes heat transfer via conduction and convection

Liquefied Hydrogen Advantages and Disadvantages

Advantages	Disadvantages
• Mature hydrogen storage technology • Much higher hydrogen densities than compressed hydrogen, reducing transport capital and operational expenditure • Pure hydrogen, therefore no requirement for separation by end user	• Energy-intensive liquefaction process (greater than a third of the energy value of producing the hydrogen) • Expensive storage vessels • Hydrogen is prone to evaporation or “boil-off” over time • High flammability of liquefied hydrogen

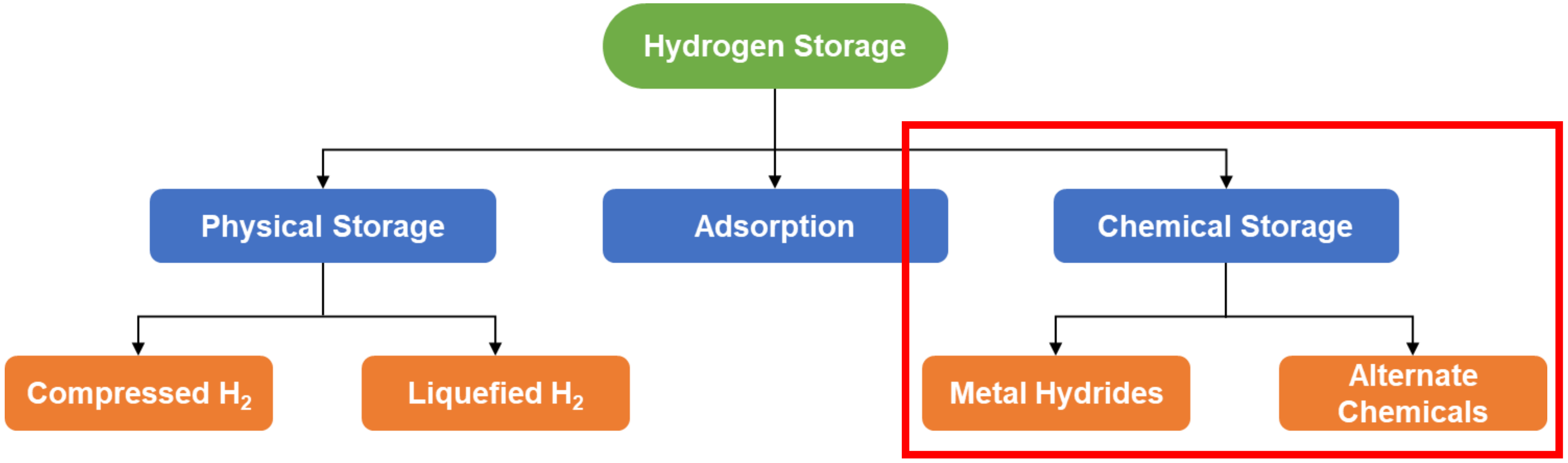
Pilot Project Supply Chain

HESC



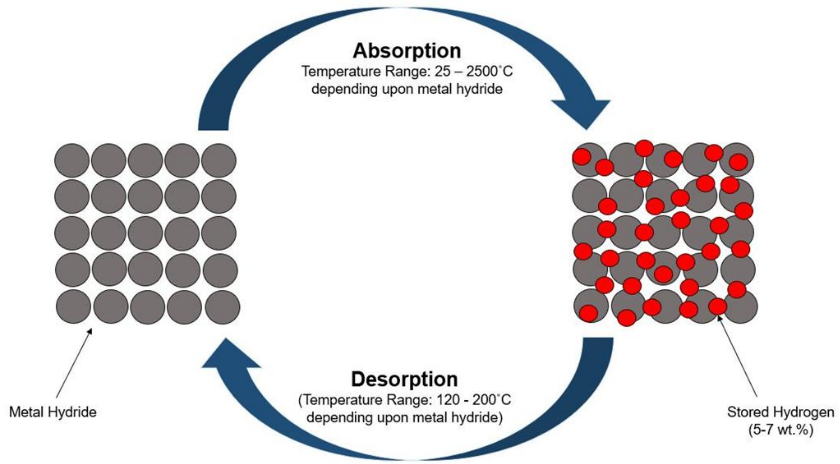
Chemical Storage of Hydrogen

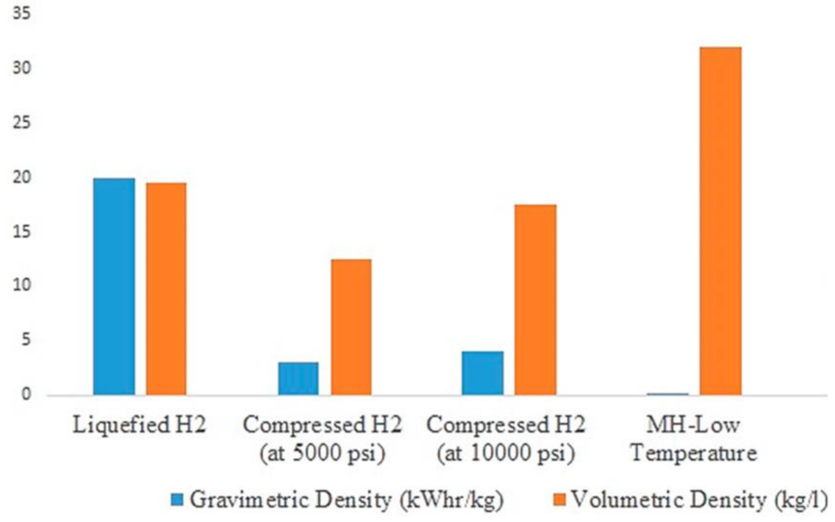
- Hydrogen can be chemically stored, allowing conditions more favourable than physical storage:
  - Storage as metal hydrides
  - Conversion to alternate chemicals (Power to X)



Metal Hydrides

- Hydrogen is bonded in hydrides with the addition of energy
- Several types of hydrides include:
  - Intermetallic hydrides (FeTi-based alloys, $LaNi_5$)
  - Metal hydrides (e.g. MgH_2, AlH_3)
  - Complex hydrides (e.g. $NaAlH_4$, $LiBH_4$)
- Hydrogen is released by either heating or reaction with water
- Solid storage of hydrogen exhibits a high volume density and mitigates many issues associated with compressed and liquefied hydrogen



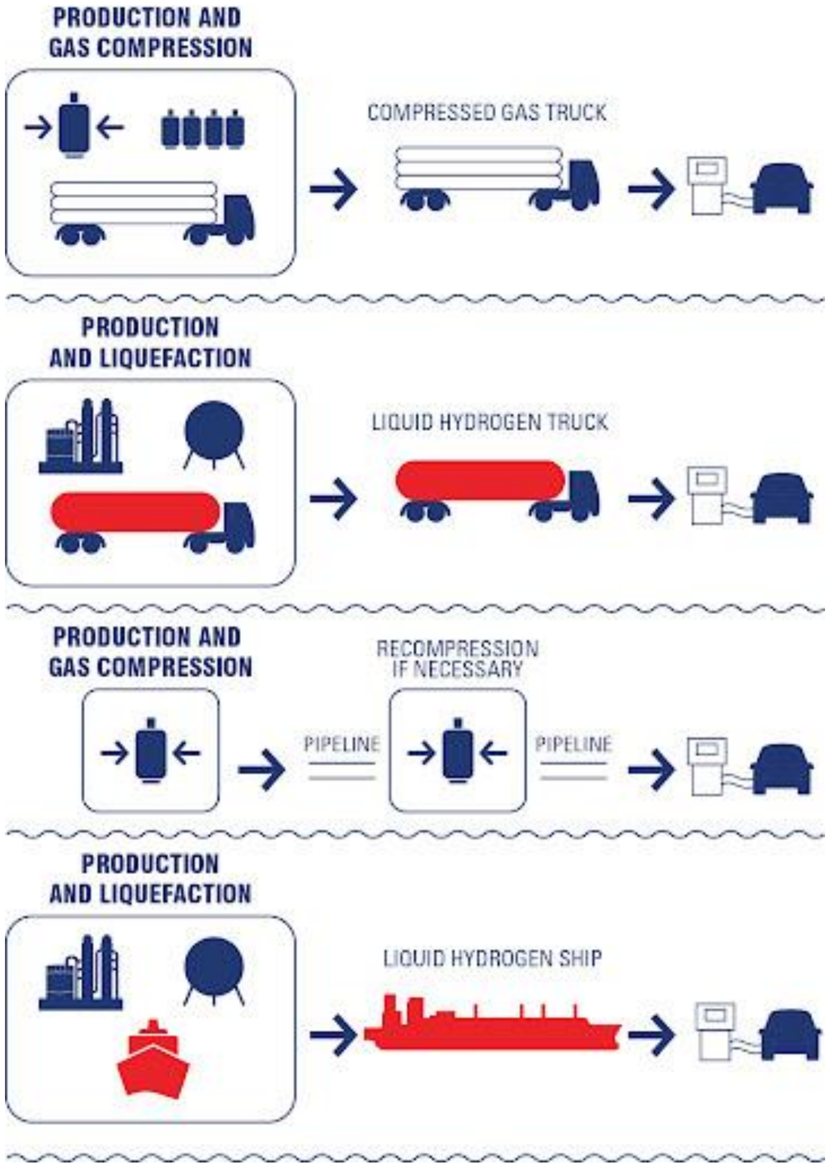


Metal Hydrides Advantages and Disadvantages

Advantages	Disadvantages
• Strong bonding allows high-density storage at ambient conditions • Mitigates issues (such as flammability) of compressed and liquefied hydrogen • Reversible cycle and reusability of metals for storage	• Low maturity • More energy is required to release chemically bonded hydrogen compared to physically bonded hydrogen • Will require significant mass of metals for large-scale use • Exposure to moist air can cause violent reaction with metal hydrides

Transportation of Hydrogen

- Once produced, hydrogen must be transported for use, including export
- Common methods for the transportation of pure hydrogen include:
  - Road
  - Rail
  - Ship
  - Pipeline



Road

- Transport of compressed and liquefied hydrogen in pressure vessels can be undertaken on roads by trucks using tube trailers
- A single truck is capable of transporting up to 1000 kg of compressed hydrogen or up to 5000 kg of liquefied hydrogen a distance of up to 1000 km
- The cost of transport is approximately 2.5 $ tH_2km^{-1} for compressed hydrogen and 1.0 $ tH_2km^{-1} for liquefied hydrogen

$ tH_2km^{-1} is the cost of transporting one tonne of hydrogen over one kilometer

Rail

- Transport of compressed and liquefied hydrogen in pressure vessels may also be undertaken by rail
- Rail transport would allow for a greater quantity of compressed hydrogen transport over longer distances, reducing operational expense
- The cost of transport is approximately 0.5 \$ tH_2km^{-1} for compressed hydrogen and 0.3 \$ tH_2km^{-1} for liquefied hydrogen

Pipeline

- Hydrogen may be transported over short and medium distances using steel pipelines
- Pure hydrogen can cause embrittlement in steel pipes over long distances, however other piping materials such as fiber reinforced plastic (FBR) and HDPE have been proposed
- Costs of piping compressed hydrogen are expected to be around 0.2 to 0.4 \$ tH_2km^{-1}
- Pipelines may also be used for hydrogen carriers such as methane

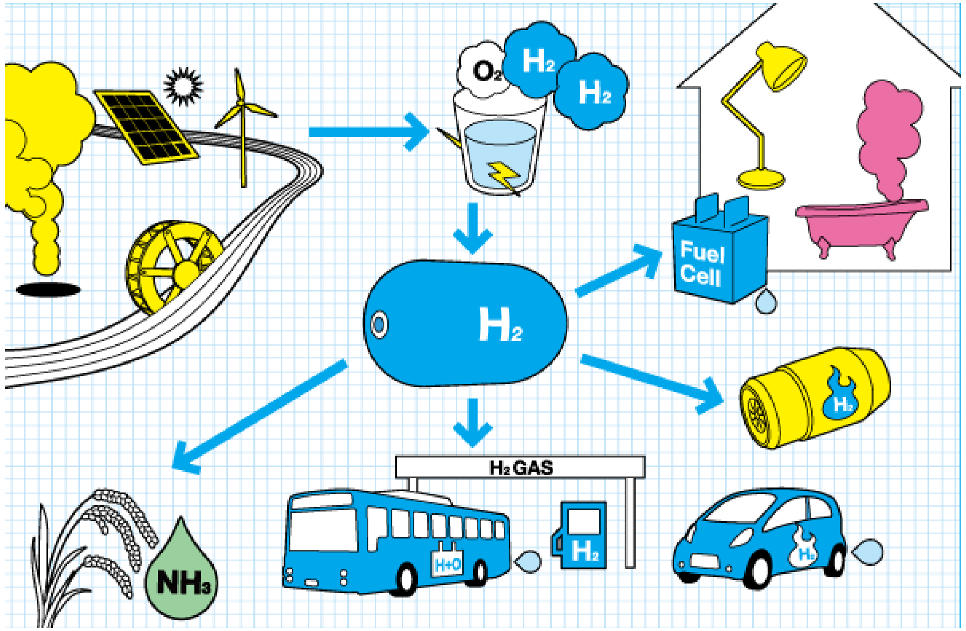
Ship

- Road, rail, and pipelines may be used to transport hydrogen to export hubs, where it can be shipped overseas
- Kawasaki Heavy Industry has developed a ship that will carry up to 1,250 cubic meters of liquid hydrogen
- Liquefied hydrogen may only be suitable for short to medium length voyages due to energy losses associated with boil-off
- Cost estimates range between 0.02 to 0.6 $\$ \; tH_2km^{-1}$, with the inclusion of loading and unloading facilities adding significant cost

Use of Pure Hydrogen

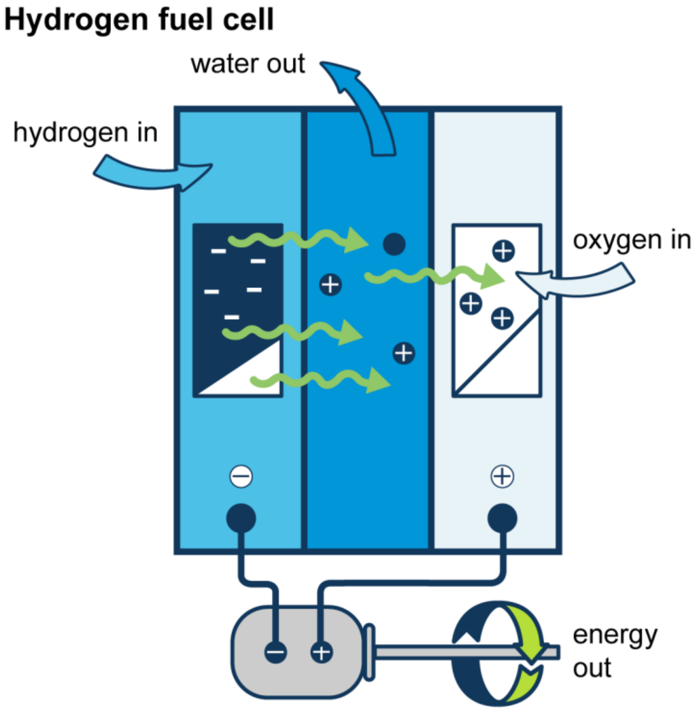
Hydrogen as an Energy Source

- The primary use of pure hydrogen is as an energy source
- Advantages of hydrogen as an energy source:
  - Potentially unlimited supply
  - High energy density
  - Clean-burning
  - Storage of intermittent renewable electricity
- How can pure hydrogen be used for energy?
  - Burned in gas form
  - Converted to electricity in fuel cells



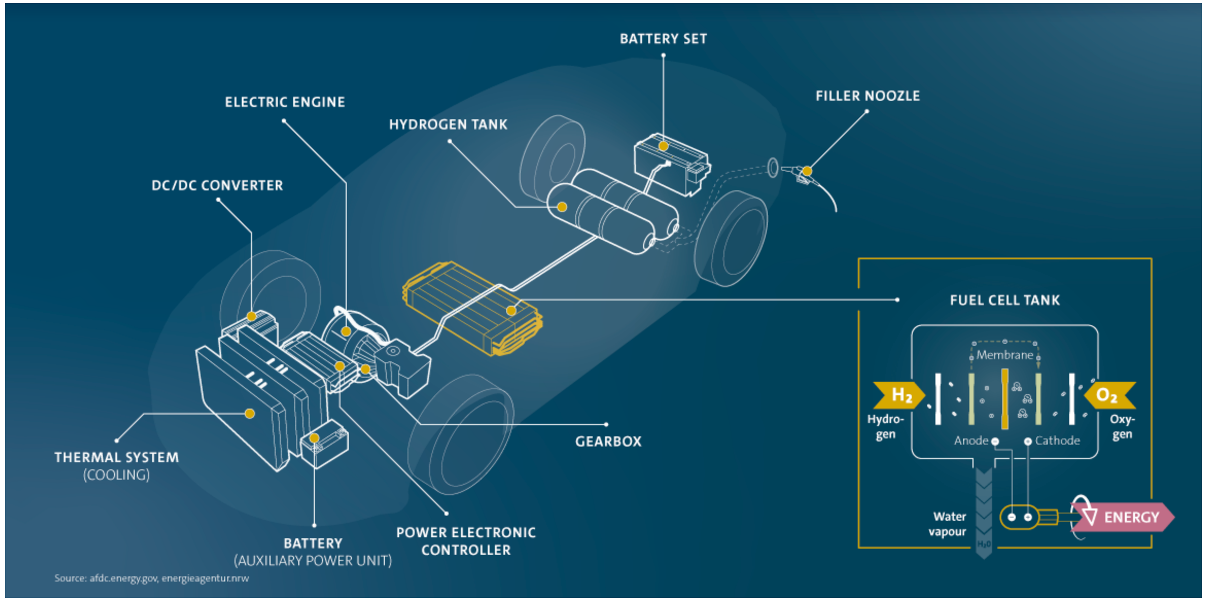
Fuel Cells

- Fuel cells were first used commercially by NASA as part of Project Gemini in the 1960s
- Fuel cells work like a battery
  - Chemical energy is converted into electrical energy
  - Charged hydrogen ions travel across a membrane to generate current, recombining with oxygen to produce water
- Efficiencies:
  - Fuel cells: Around 60%
  - Batteries: Around 95%
  - Internal combustion engines: Around 25%



Powering Vehicles

- Fuel cells are seeing application for powering vehicles such as cars, buses, and forklifts
- Advantages include the high energy density of compressed hydrogen, low refueling times and zero-carbon emissions
- If metal hydrides were used as hydrogen storage in vehicles, they could be instantly replaced when empty



H_2 Powered Boats in Fiji

- Fiji aims to begin replacing its current Government shipping fleet with hybrid and green hydrogen solutions.
- During Fiji's Presidency of COP23, it launched the 'Oceans Pathway', with the expectation to place oceans where it belongs – at the heart of climate action.
- In Fijis's Low Emissions Development Strategy 2018-2050, the potential for methanol, ammonia, and hydrogen as the most likely alternative fuels for maritime transport is discussed.

FIJI NEWS | NATION | NEWS

PM: Fiji To Replace Govt Vessels With Hybrid, Green Hydrogen Solutions

During Fiji's Presidency of COP23, it launched the 'Oceans Pathway', with the expectation to place oceans where it belongs – at the heart of climate action.

By **Rosi Doviverata**

05 Nov 2021 15:30

References:
https://fijisun.com.fj/2021/11/05/pm-fiji-to-replace-govt-vessels-with-hybrid-green-hydrogen-solutions/
https://unfccc.int/sites/default/files/resource/Fiji_Low%20Emission%20Development%20%20Strategy%202018%20-%202050.pdf

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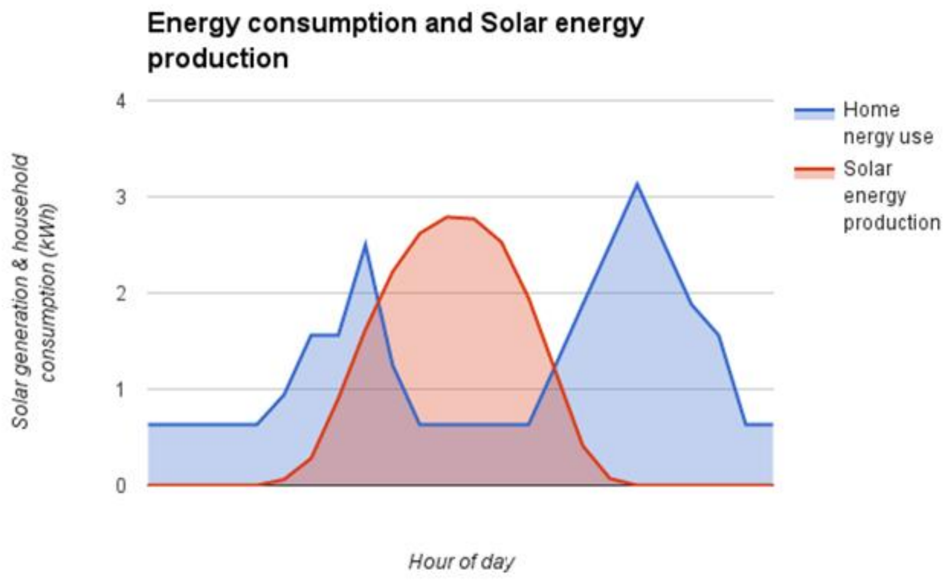
Hyundai Nexo

- Hyundai has developed the first commercial hydrogen fuel cell electric vehicle (FCEV)
- Driving range of over 600 km with one tank
- Refueling time of 3-5 minutes
- Currently costs approximately $100,000, but costs will drop as technology and infrastructure improves, and as competitors enter the market

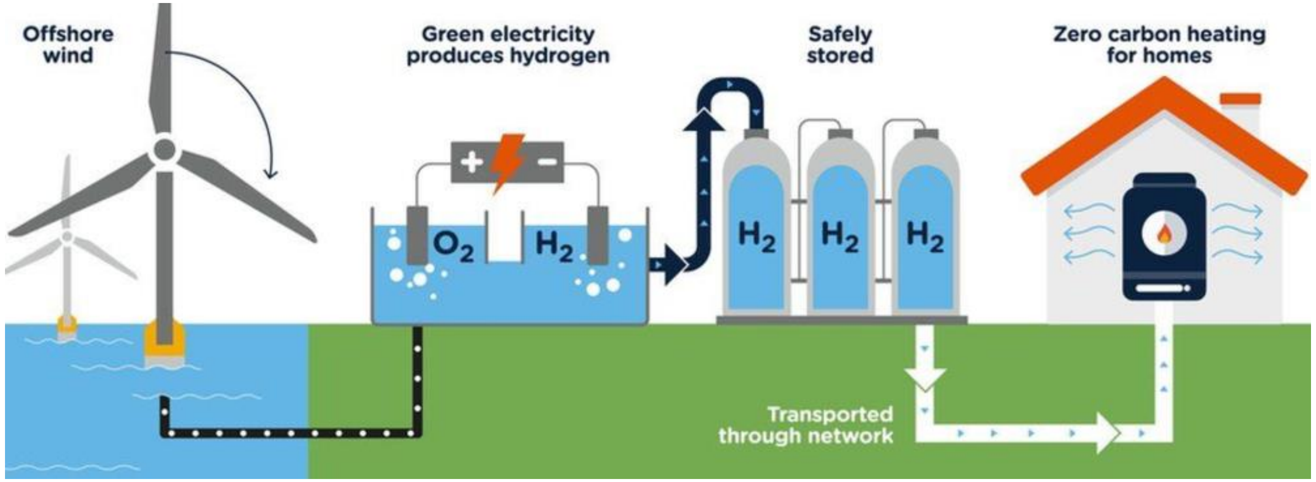
Smoothing of Intermittent Renewable Electricity

- Renewable electricity (e.g. wind and solar) is not consistently delivered
- If the electricity grid was powered by renewable electricity, peak demand would occur when supply is the lowest (at night time)
- Renewable energy can be "stored" in a chemical form (by using the energy to produce hydrogen) and can then be used to generate electricity when required
- This is known as "smoothing"



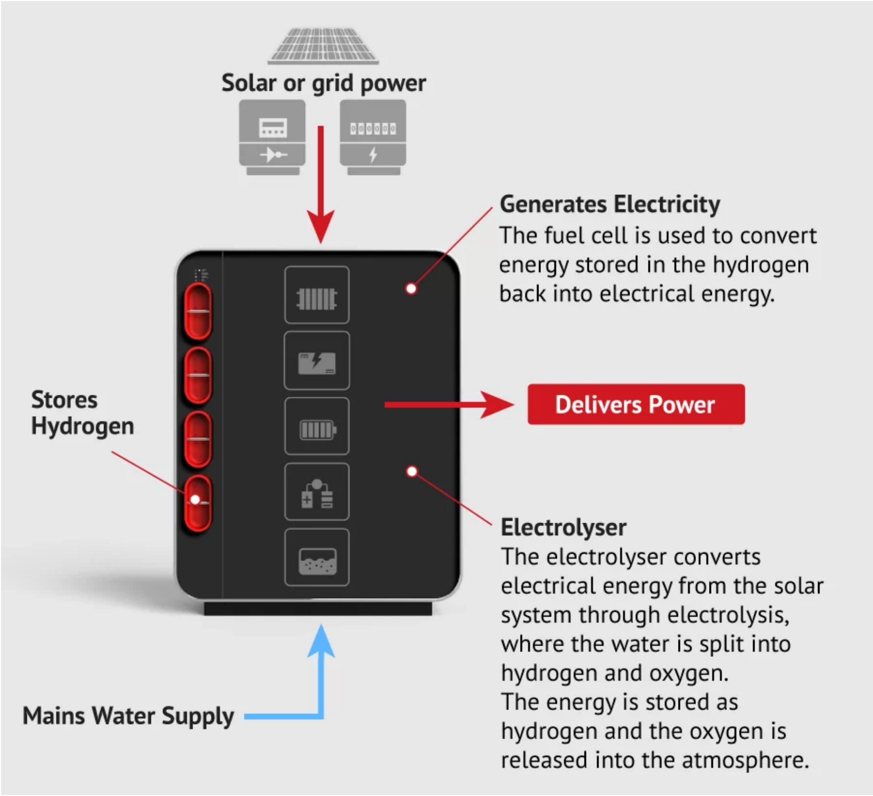
Hydrogen in Home: Heating

- Hydrogen may be employed to heat homes in the same manner that natural gas is used
- Hydrogen can be blended with natural gas and supplied to home using current piping infrastructure
- The Hyp SA project, run by Australian Gas Infrastructure Group (AGIG), plans to blend about 5% green hydrogen into its gas distribution network in Adelaide



Hydrogen in Home: Electricity

- Hydrogen fuel cells may also be used for supplying electricity in homes
- The LAVO Green Energy Storage System, developed in partnership with UNSW, uses patented metal hydrides to store hydrogen
- The system is able to hold 40 kilowatt-hours of power – enough to supply an average household for more than two days, and cost $34,750



Metals Processing

- About 7-9% of the world's CO_2 emissions arise from the manufacturing of steel
- Hydrogen can be used as a reducing agent in steel production, to extract or "reduce" the iron ore to metal
- Hydrogen can also be used as an energy source to replace fossil fuels to heat the furnaces to high temperatures required
  - Electricity cannot provide such heat requirement

Glass Manufacturing

- Hydrogen has several applications in glass manufacturing:
- Atmosphere Control
  - Prevent formation of glass defects via oxidation reactions
- Melting and Softening
  - Supplement or replace air-fuel combustion applications to increase heat transfer
- Heat Treating
  - Supplement or replace air-fuel combustion applications for annealing, tempering, strengthening and toughening
- Cutting and Polishing
  - Supplement or replace air-fuel combustion applications to increase heat transfer

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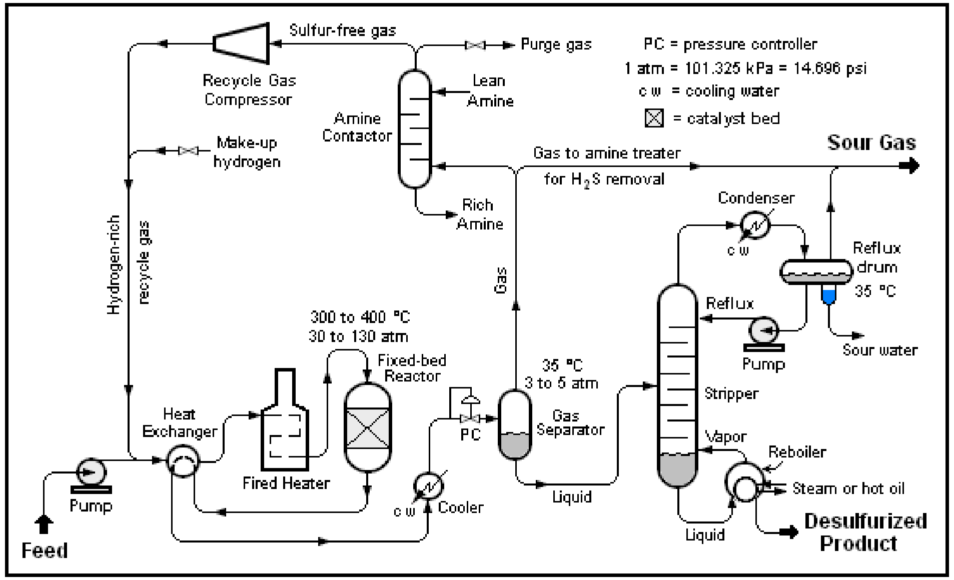
Hydrocracking and Desulfurisation

- Desulfurisation is the process of using hydrogen gas to reduce the sulfur content in hydrocarbons such as petroleum or kerosene, reducing the emission of sulfur oxides
- Hydrocracking is the process of converting heavy fuel oil components into naphtha, kerosene, jet fuel, diesel oil or lubricating oils
- Stringent emissions regulations and use of heavier hydrocarbon feedstocks is causing high hydrogen demand for this application



$$\underset{\text{Ethanethiol}}{C_2H_5SH} + \underset{\text{Hydrogen}}{H_2} \longrightarrow \underset{\text{Ethane}}{C_2H_6} + \underset{\text{Hydrogen sulfide}}{H_2S}$$

Power to X: Hydrogen Transport and Utilisation

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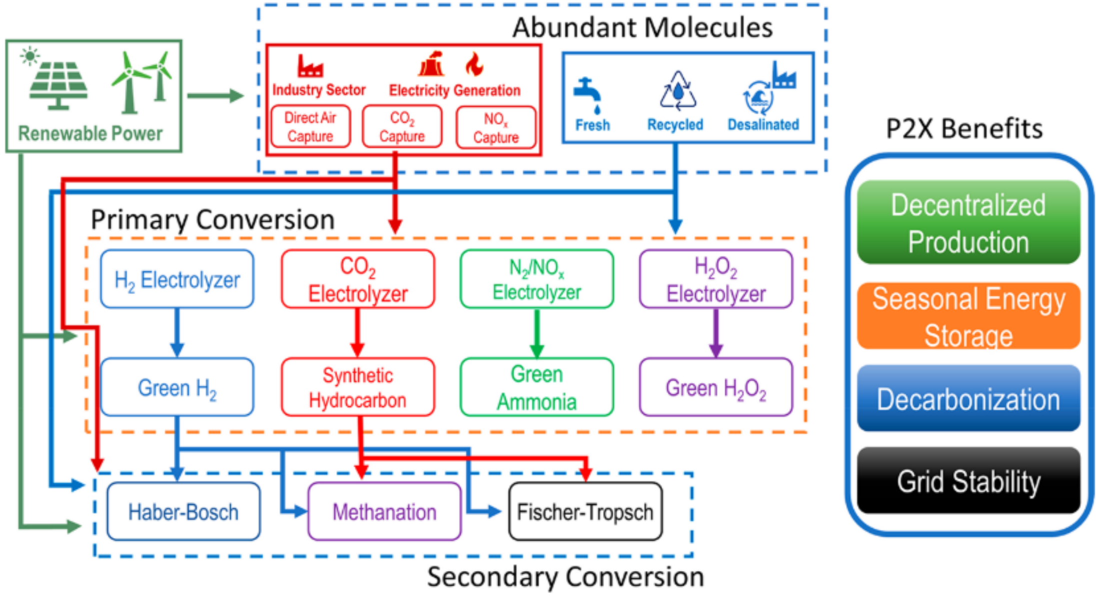
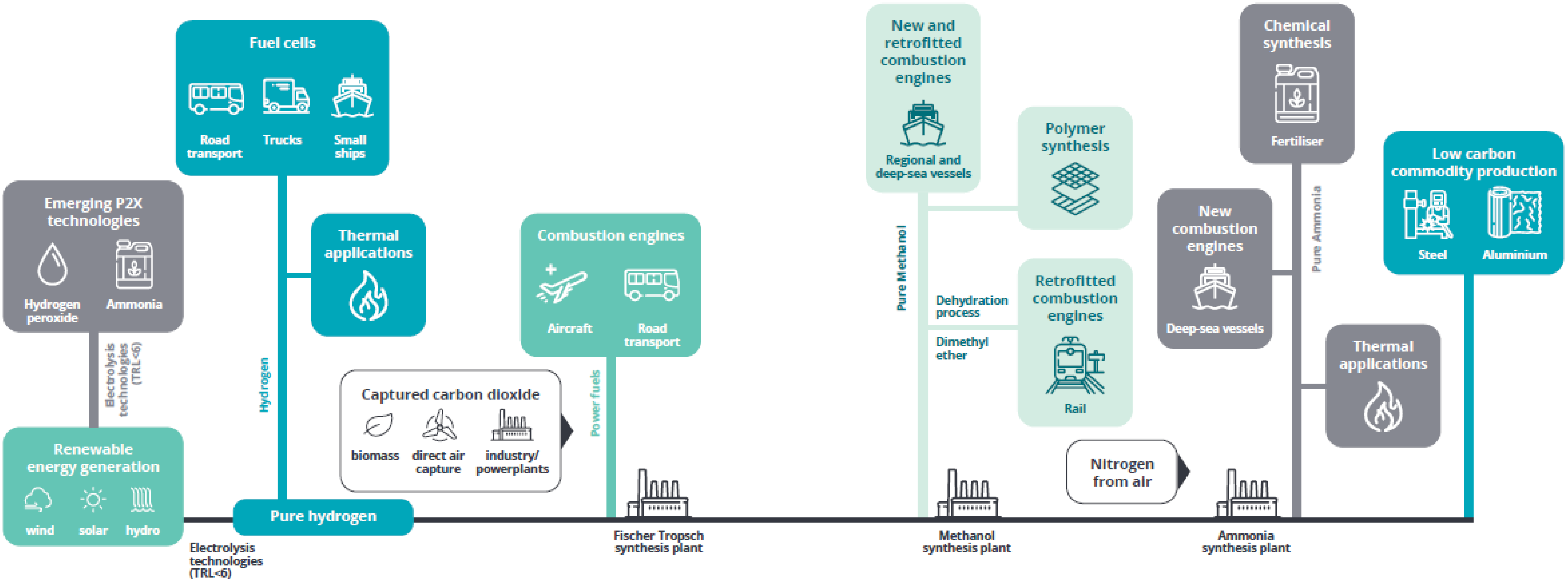
Renewable Power-to-X

- This concept of "storing" excess renewable energy as chemicals is referred to as "renewable power-to-X"
- X can be a wide range of chemicals:
  - Hydrogen
  - Synthesis gas
  - Methane
  - Ammonia
- Electrolysis is powered by renewable energy to produce these chemicals from feedstock such as water or CO_2
- The use of these chemicals is discussed later this lecture



Hydrogen: The Decarbonisation Catalyst



PtL Pathways

PowerFuel Comparison				
Each of the powerfuels evaluated offer pathways for decarbonising existing and emerging applications. However, there are parameters that must be considered when developing the value chain for these powerfuels, including decarbonisation benefits, safety and storage conditions, which are summarised in the table below:				
	NH_3 **Ammonia**	**CH_3OH** **Methanol**	**SNG** **Synthetic Natural Gas**	**SAF** **Sustainable Aviation Fuel**
Production, Storage & Transport Technology Readiness Level	TRL 9	TRL 8	TRL 9	Production via PtL[c,d]: TRL 7 – 8 Storage & Transport: TRL 9
Powerfuel Storage Conditions	Pressurised: Ambient temperature and 16-18 bar Low-Temperature Liquid: minus 33°C and 1.1-1.2. bar	Ambient conditions as liquid	Pressurised:200-250 bar at ambient temperature Liquified: -162°C	Ambient conditions as liquid. Can use conventional jet fuel storage infrastructure
Volumetric Energy Density (MJ/L)[a,b]	12.7	16.0	20.6	33.2
Gravimetric Energy Density (MJ/kg)[a,b]	18.6	20.0	53.6	44.2
Decarbonisation Benefit (kg CO_2-e/kg fuel)[e,f]	0	0.25	0.18	0.33-0.52 for bio-based production. Lower values for PtL production
Safety	Flammable with toxic fumes and dangerous for the environment if released	Flammable, toxic and dangerous for the environment if released	Highly flammable and will explode at gas-to-air ratio between 5% and 15%	Aviation
End-Use Sectors	Agriculture, Mining, Power Generation, Maritime, Chemical Feedstock	Power Generation, Mining, Maritime, Chemical Feedstock	Power Generation, Residential Appliances	Aviation

References:
a.- H2 Tools.Link
b.- IATA. Link
c.- Johnson Matthey. Link
d.- Collis, J., Duch, K. & Schomäcker, R. Techno-economic assessment of jet fuel production using the Fischer-Tropsch process from steel mill gas. Front. Energy Res. 10, (2022). DOI: 10.3389/fenrg.2022.1049229
e - ICAO. Link
f.- Sean M. Jarvis, Sheila Samsatli, Renewable and Sustainable Energy Reviews Link

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Shipping PtL

Global shipping of PtL can take advantage of current infrastructure

Figure 23: LNG Shipping Density Map for 2019[172]

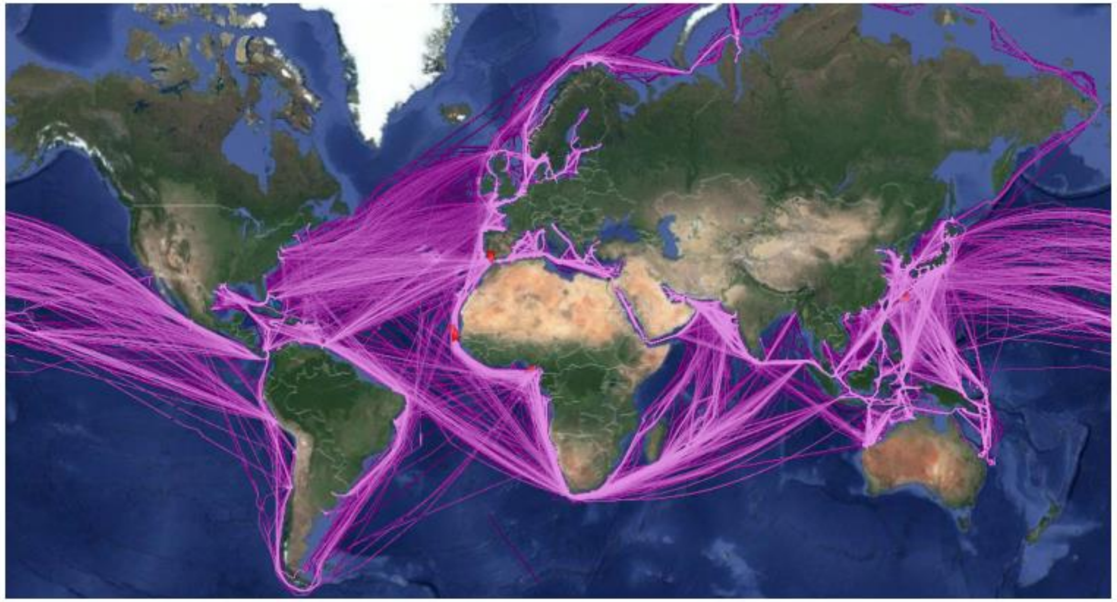
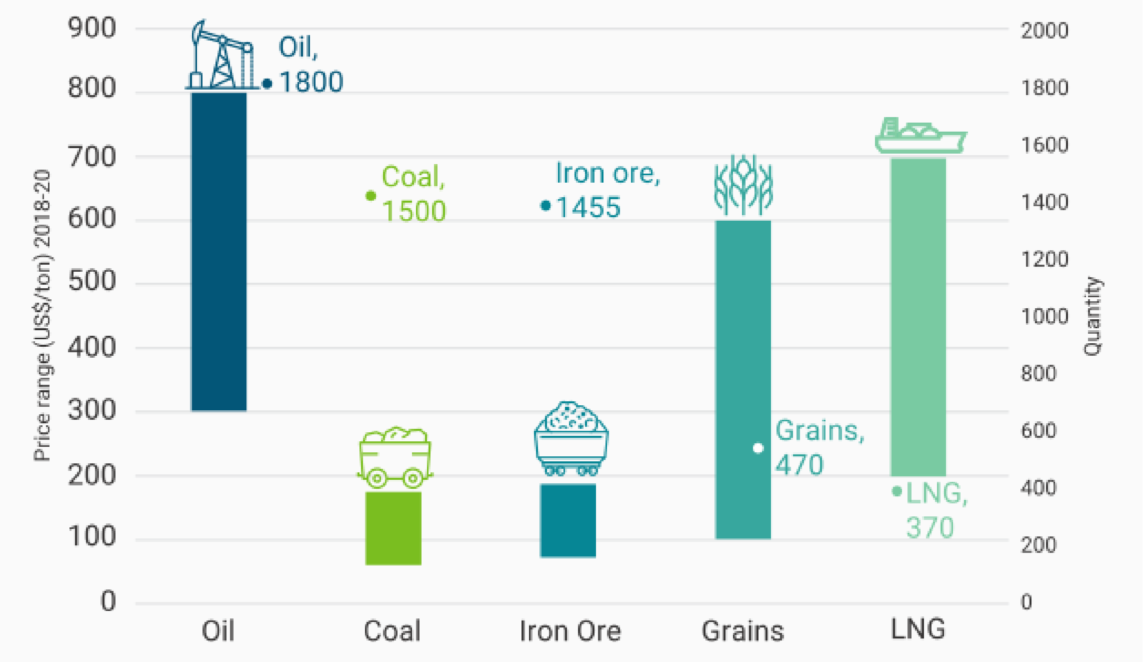


Figure 5: Shipped tonnage and average price ranges for some key traded commodities.
Note that the price indications are spot price ranges over 2018-2020 and shipped tonnages from 2019. For hydrogen trade, prices of around US$1.50 – 2.50/kg would translate to ~US$1,500-2,500/ton, representing a relatively high value commodity while traded volumes in various 2050 scenarios would likely be well below the shipped tonnage of some existing commodities.



Power to Ammonia (1/5)

The Concept

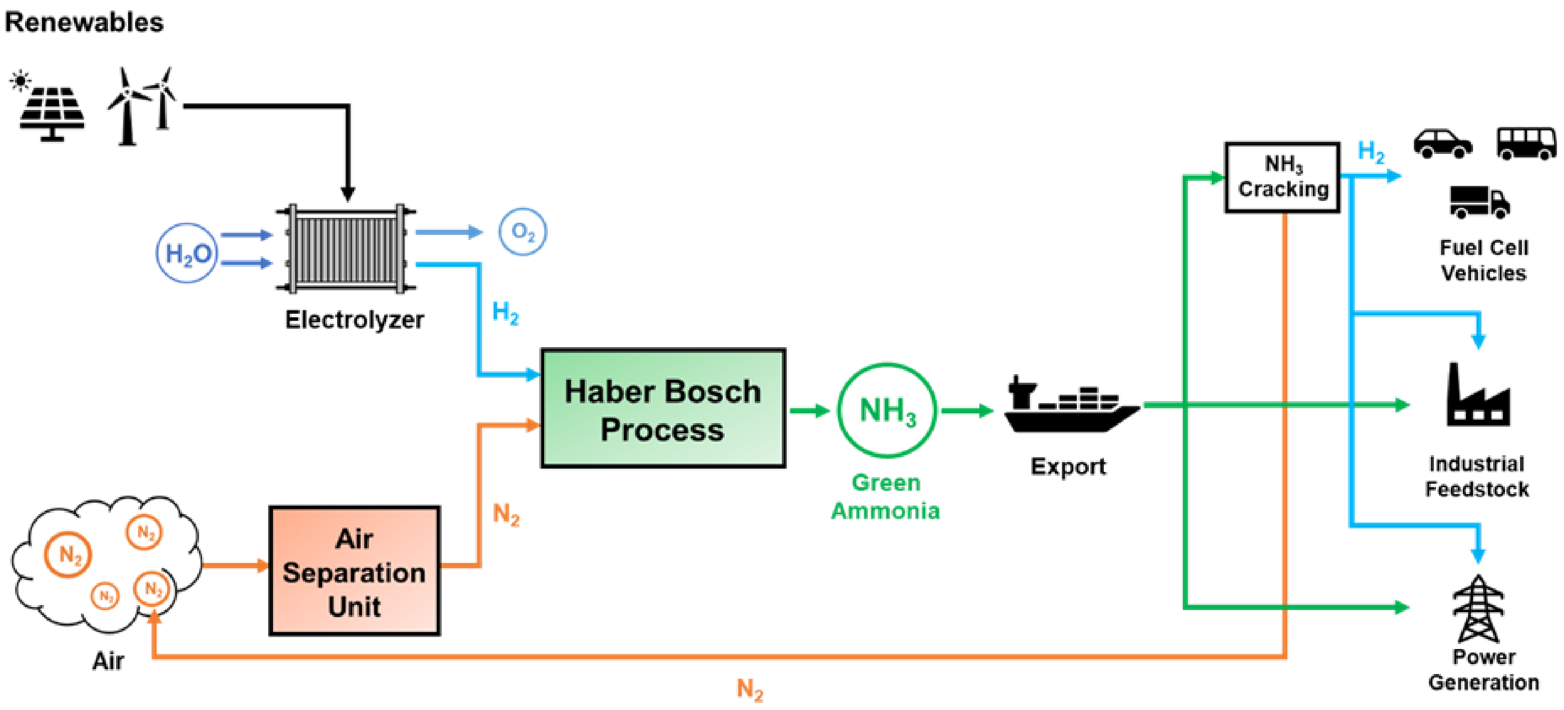


Figure: A Green Ammonia Export Chain

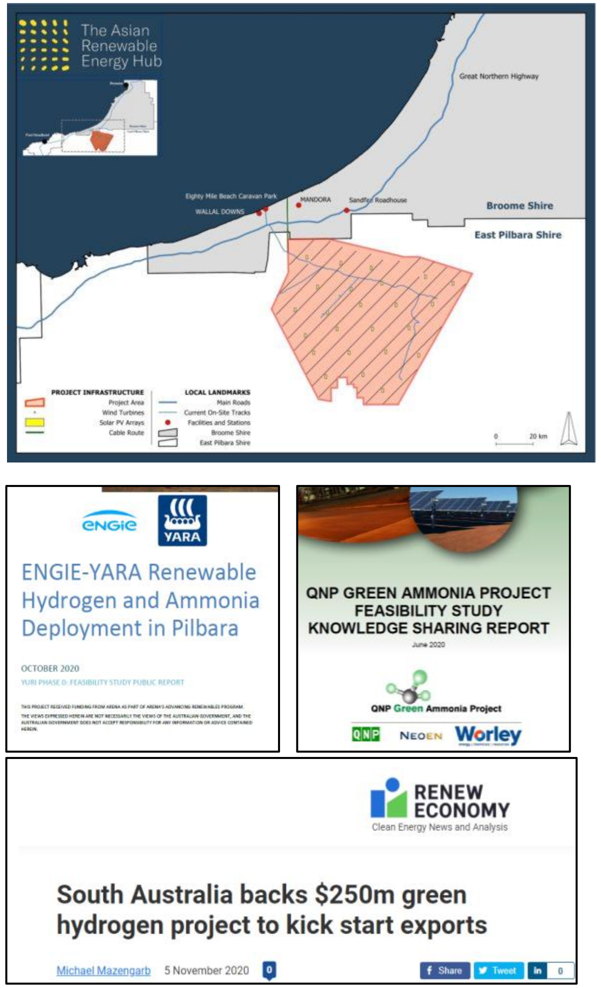


Figure: Several high-profile Green Ammonia Generation Projects are already being proposed across Australia.

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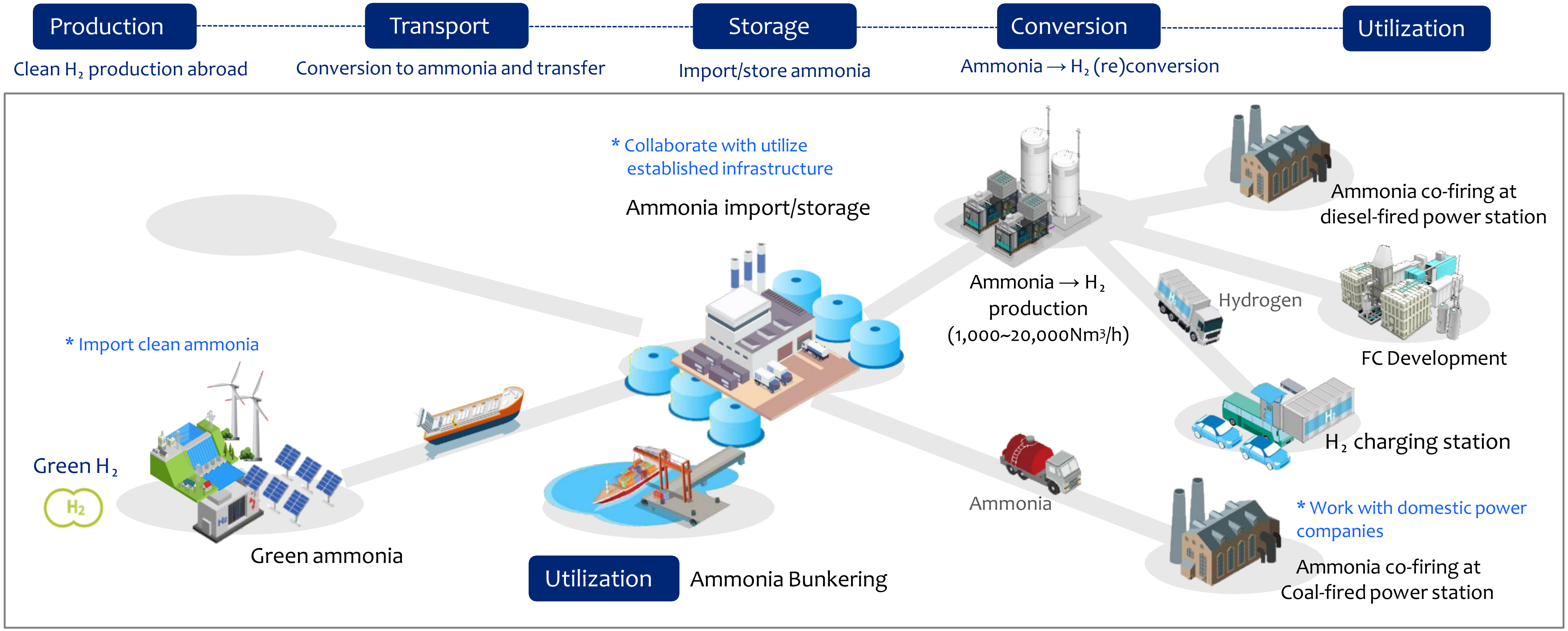
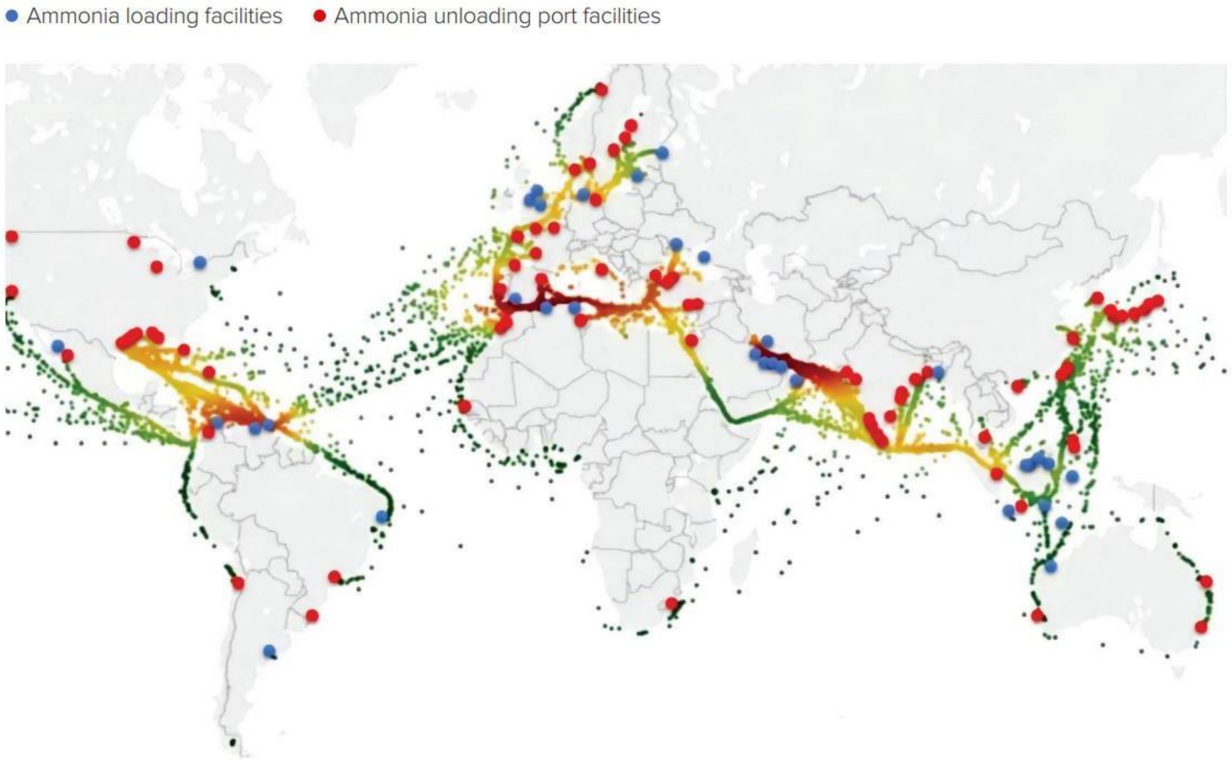
Power to Ammonia (2/5)

Ammonia Economy

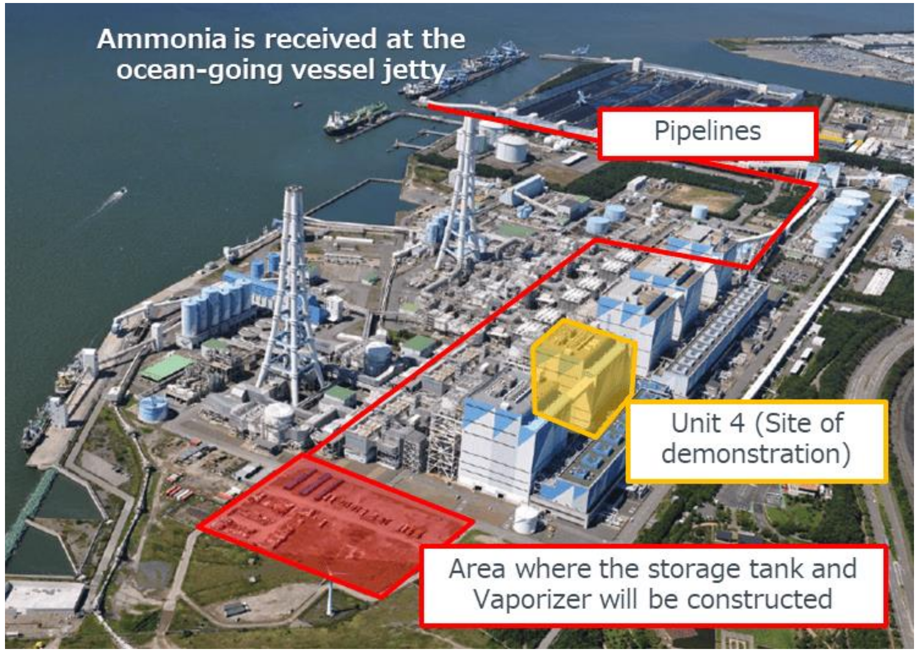


Power to Ammonia (3/5)

Ammonia Infrastructure and Projects

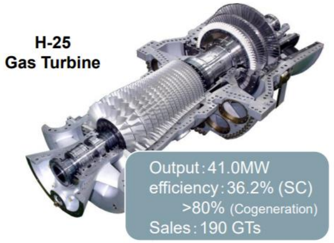


Source: The Royal Society, 2020; IEA, 2020



Mitsubishi Power is now expanding the line-up of carbon free combustion system, not only hydrogen combustion but also ammonia direct combustion.

- ☞ start development of ammonia direct combustor
- ☞ plan to verify the system in 2024
- ☞ start commercial operation from 2025



Development Schedule

yr	2021	2022	2023	2024	2025
Combustor Development					
System Design					
Verification					
Commercial operation					

Power to Ammonia (4/5)

Economic Considerations

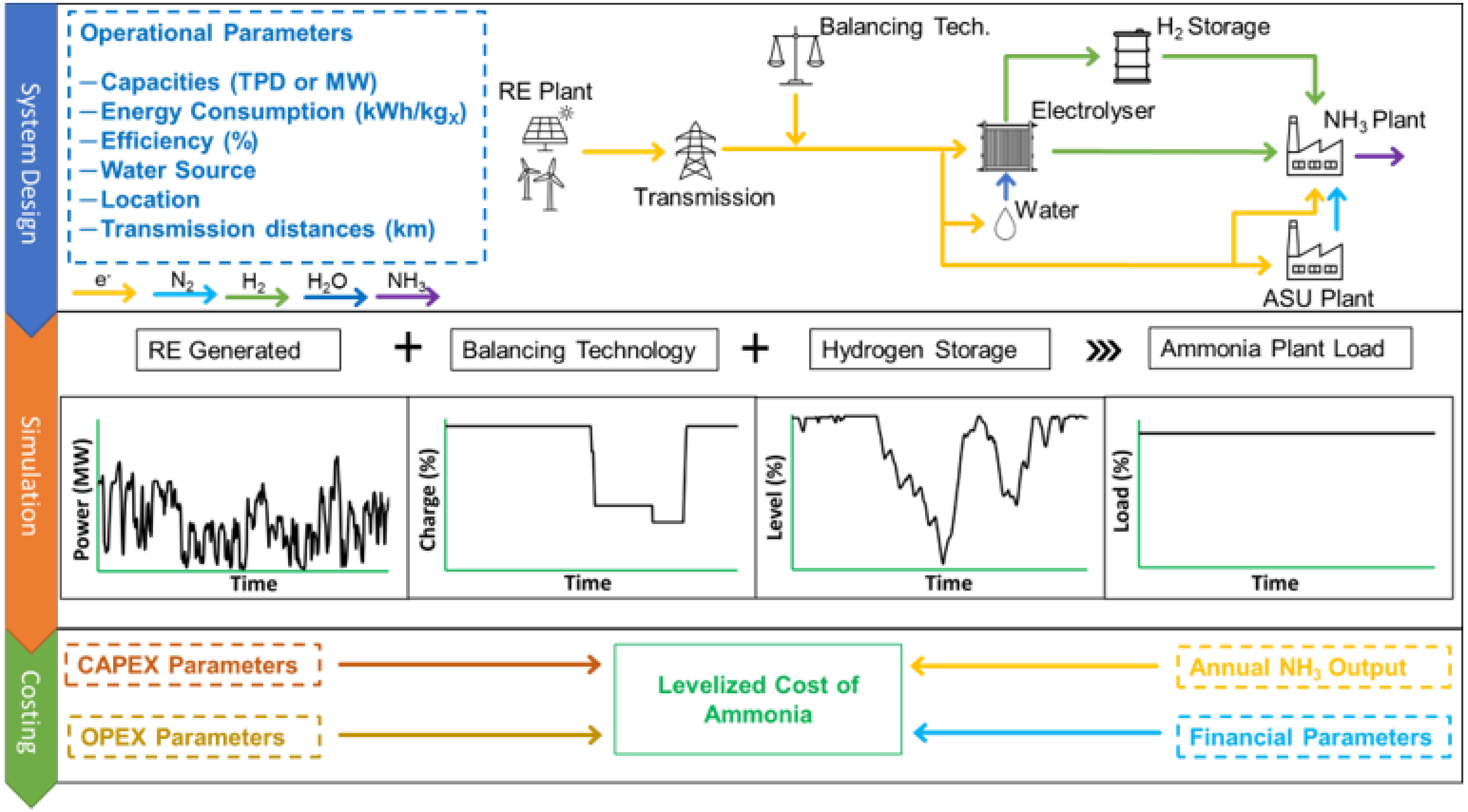


Figure: Summary of the framework used to assess the feasibility of green ammonia projects. The first level involves system design to define the operational parameters. The second level simulates the chosen design with outputs displayed graphically to determine the viability of the project. The third level uses the production output and pre-defined cost parameters to generate a Levelized Cost of Ammonia (LCOA).

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Power to Ammonia (5/5)

Cost Challenges

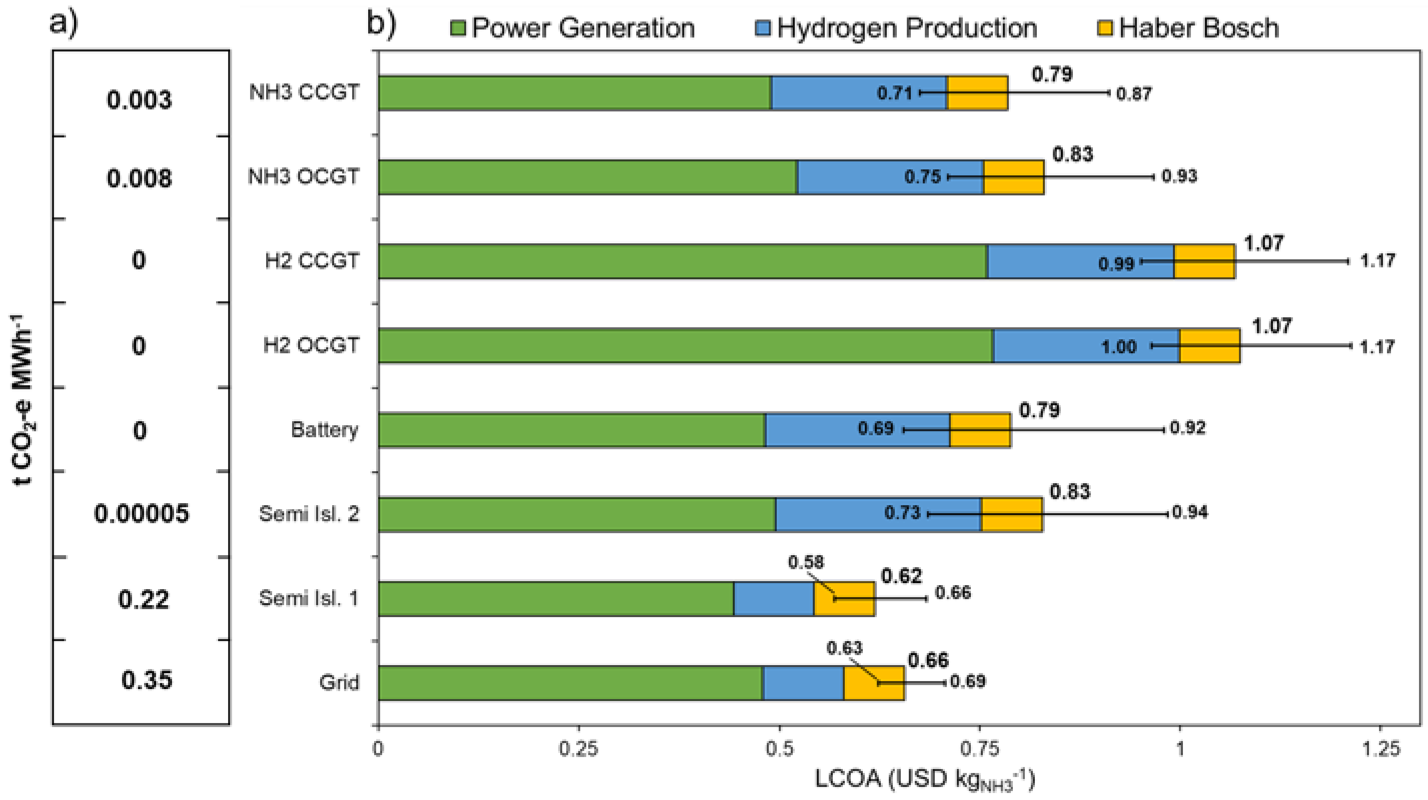
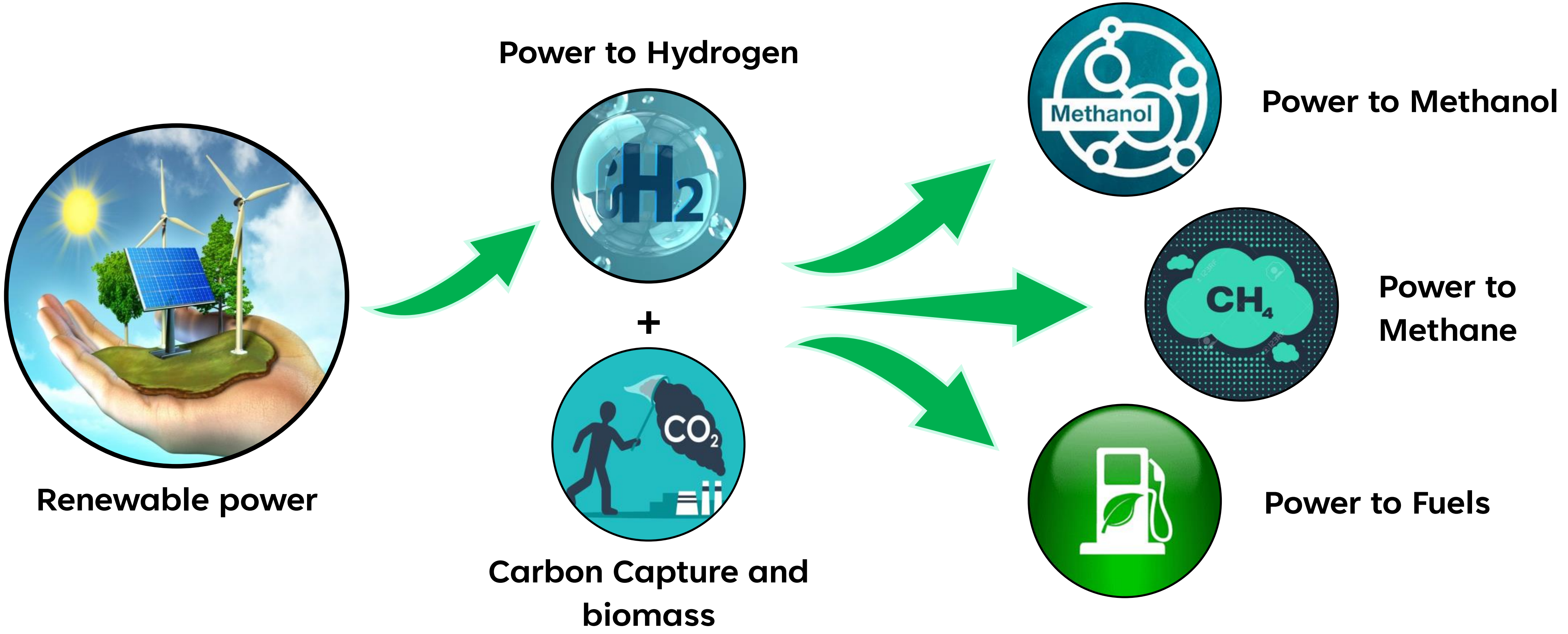


Figure: Power source and balancing technology comparison for 1 MMTPA ammonia plant in 2030. (a) Estimated carbon intensity for scope 1 and 2 emissions for different power sources and balancing technologies assessed. (b) Breakdown of costs covering power generation, hydrogen production and Haber Bosch for each of the power sources and balancing technologies assessed.

Power to Synthetic Fuel



Clean energy carriers
Green fuels
Green chemicals and products

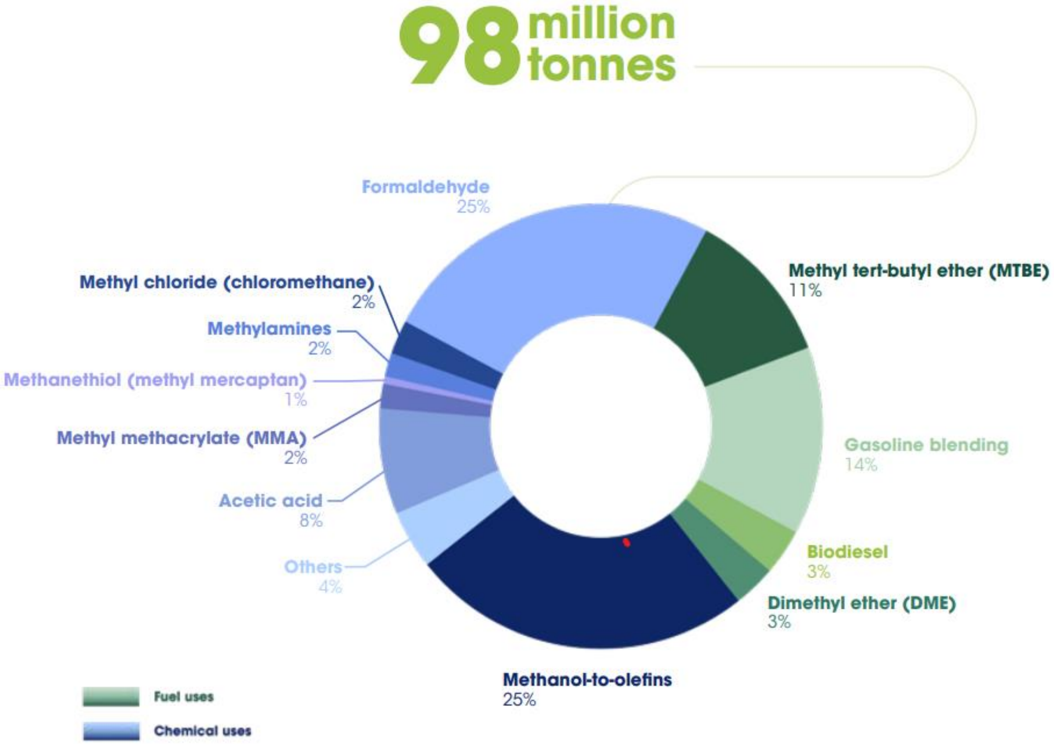
Closing the carbon loop

Clean energy storage
Decarbonising the value chain
Trade and export

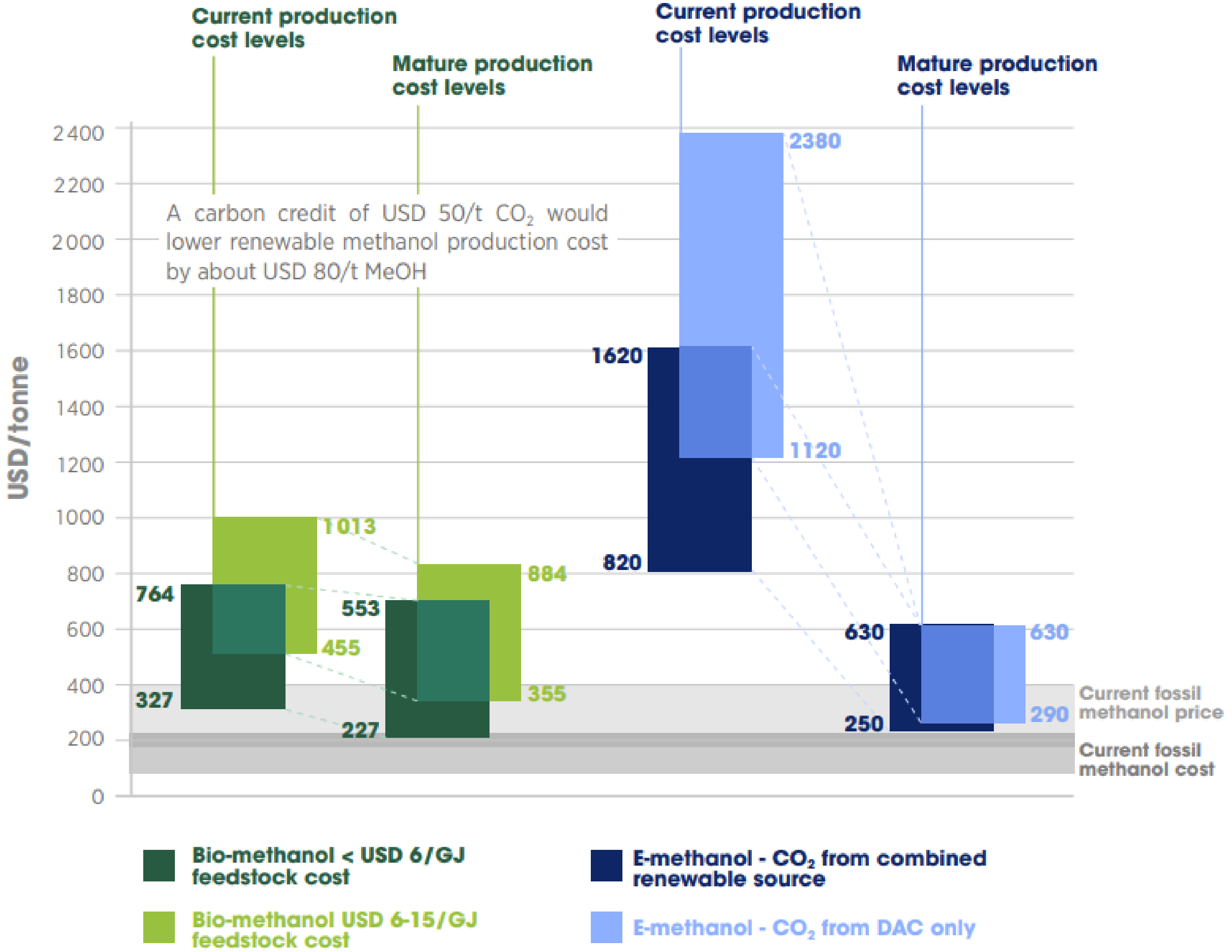
UNSW. Sydney, "NSW Power to X (P2X) Industry Pre- Feasibility Study A Roadmap for a P2X economy in NSW."

Power to Methanol (1/5)

Established Trade in Methanol



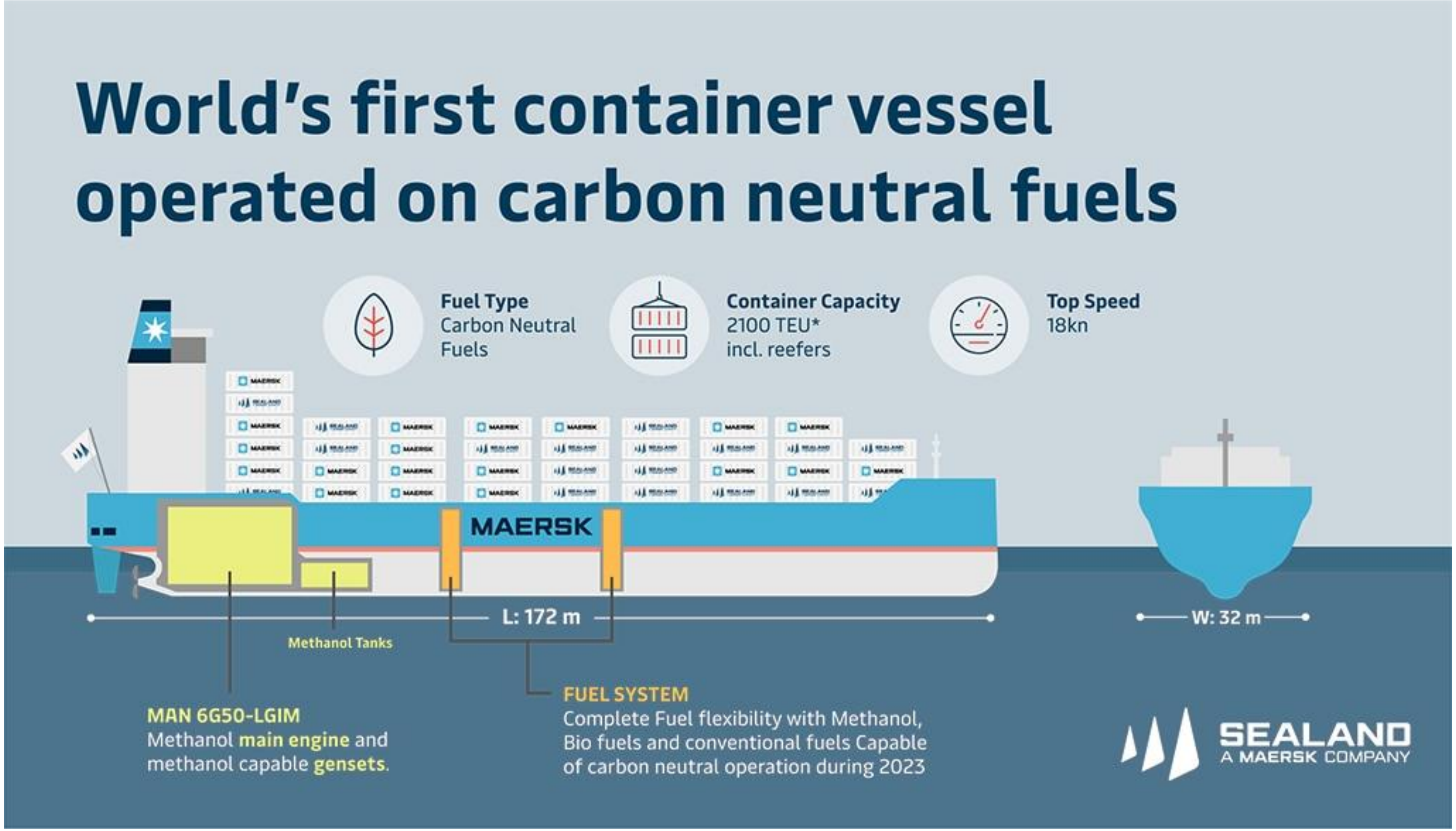
Source: *Based on data from MMSA (2020)*



Notes: *MeOH = methanol. Costs do not incorporate any carbon credit that might be available. Current fossil methanol cost and price are from coal and natural gas feedstock in 2020. Exchange rate used in this figure is USD 1 = EUR 0.9.*

Power to Methanol (2/5)

Emerging Uses as Bunker Fuels

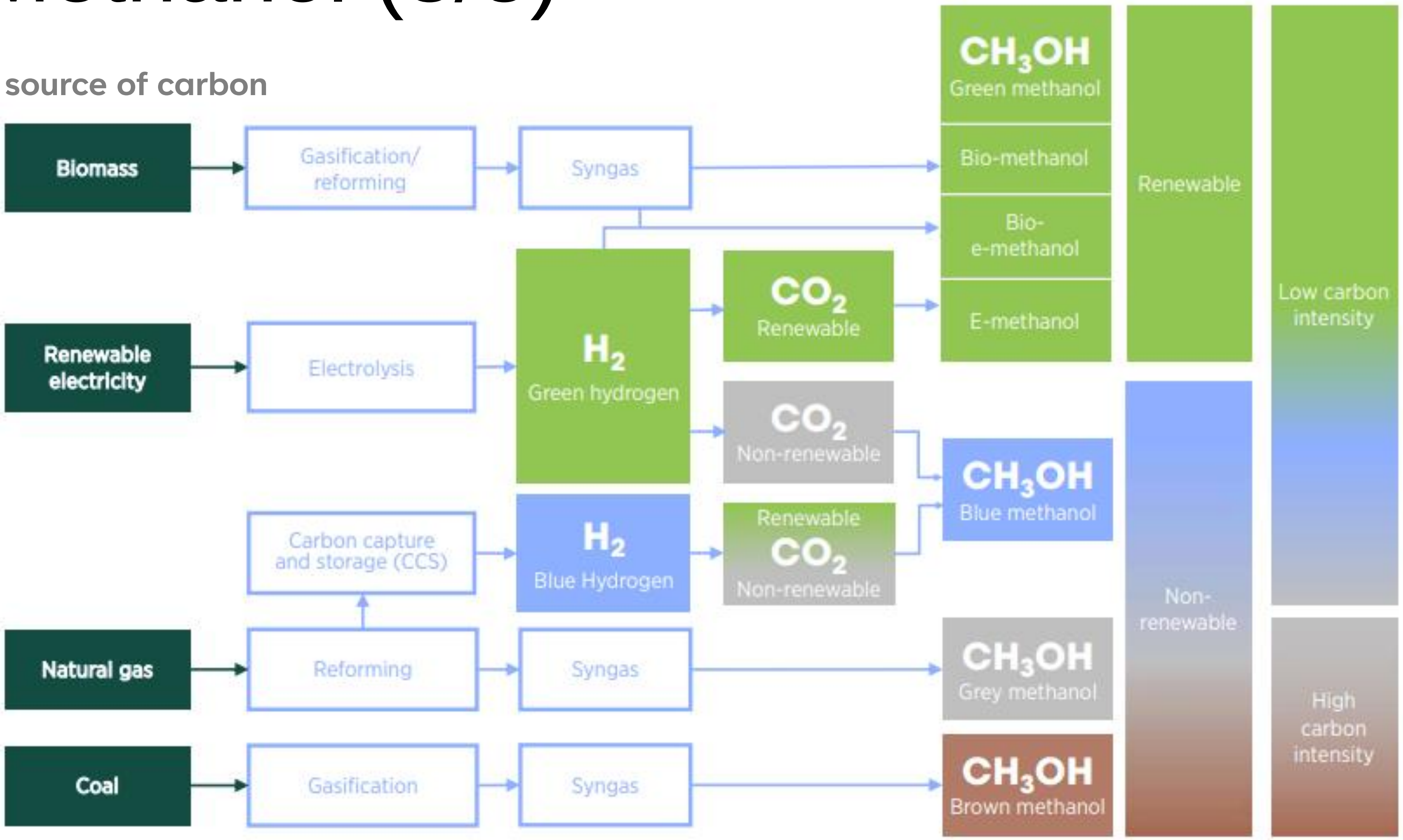


Renewable Methanol – (250 Mt/y – 2050)

- Marine transport fuel
- Chemical Feedstock (MTO, DME, etc.)
- Renewable energy trade and export
- Fuel cell backup power

Power to Methanol (3/5)

Production pathways and source of carbon



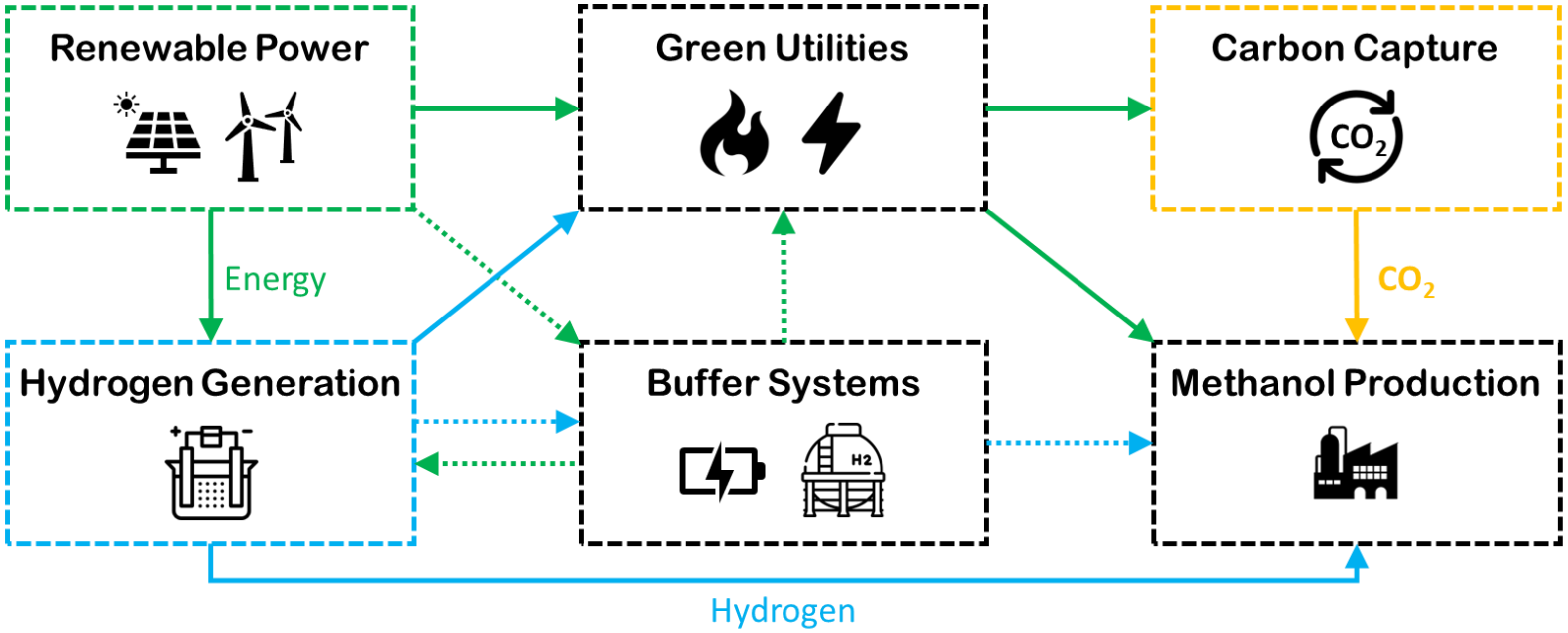
Renewable CO_2: *from bio-origin and through direct air capture (DAC)*

Non-renewable CO_2: *from fossil origin, industry*

While there is not a standard colour code for the different types of methanol production processes; this illustration of various types of methanol according to feedstock and energy sources is an initial proposition that is meant to be a basis for further discussion with stakeholders

Power to Methanol (4/5)

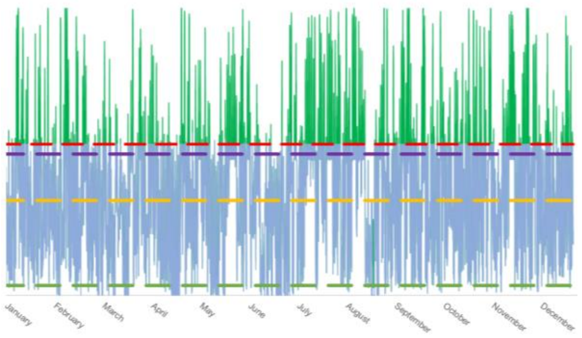
Cost Framework



Dynamic modelling

Configuration analysis

Buffer systems



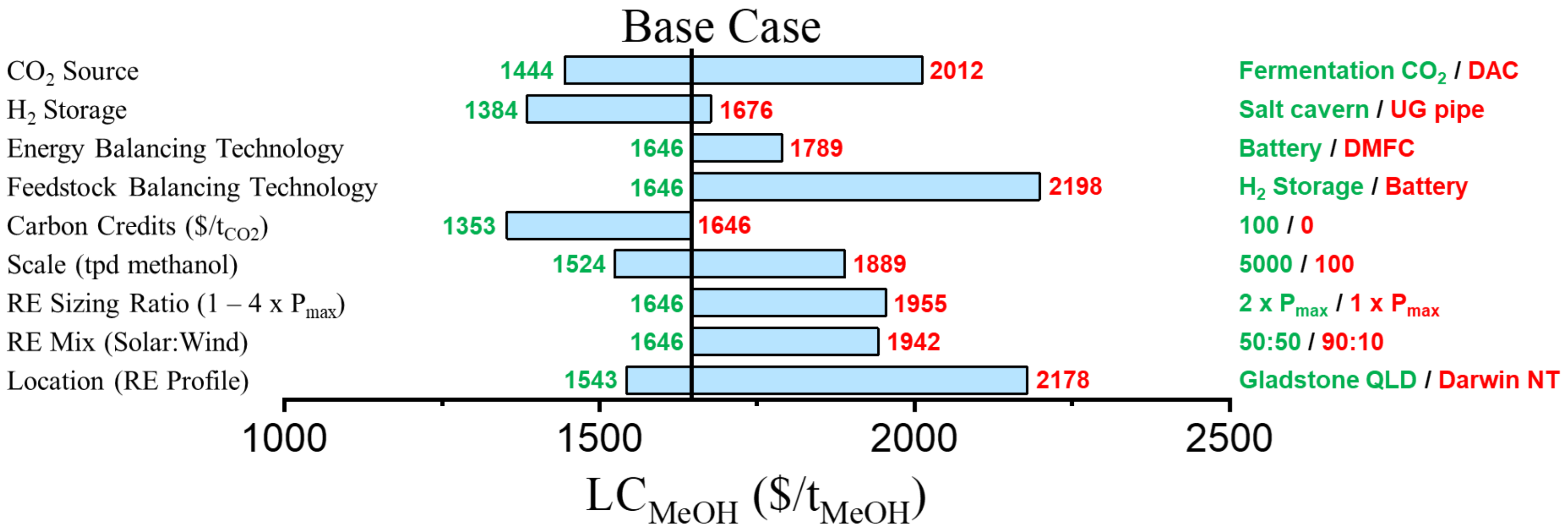
Open-source tool

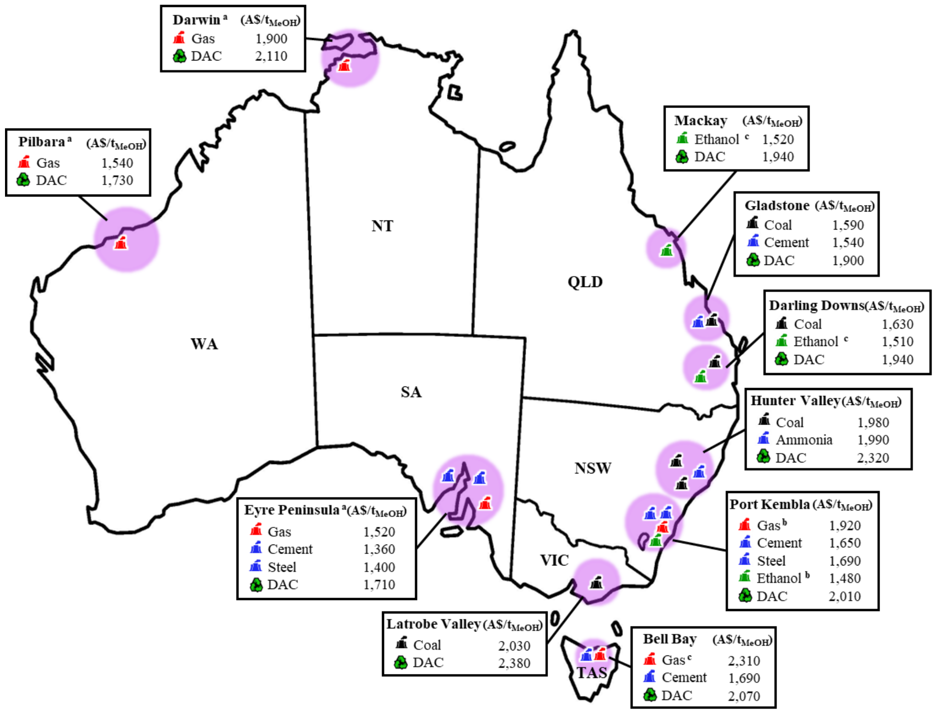
Location specific results

CO_2 point source types

Power to Methanol (5/5)

Cost Framework





e1 Marine’s Technology in the Marshall Islands

- e1 Marine's M-series methanol to hydrogen generator has received Approval in Principle (AiP) for marine applications from the Republic of the Marshall Islands (RMI) Maritime Administrator on any vessel type.
- Through e1 Marine’s hydrogen generation technology, fuel cell-grade hydrogen is safely and cost-effectively generated from methanol and water. It can be delivered on-site, onboard, and on-demand, and it provides an immediately viable pathway to green energy.
- In the Marshall Island’s Rebbelib 2050 decarbonisation framework, the potential for the deployment of green electro-fuels (ammonia, methane, hydrogen) are discussed for decarbonisation of transport.

Figure: e1 Marine's methanol to hydrogen generator M18.

Reference: https://www.e1marine.com/resource/approval-in-principle-certification-from-the-marshall-islands-marks-increasing-support-for-e1-marine

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Power to Sustainable Aviation Fuel (1/3)

Sustainable aviation fuel (SAF) is the main term used by the aviation industry to describe a sustainable, non-conventional, alternative to fossil-based jet fuel.

Current SAF focused on so-called ‘drop-in fuels’

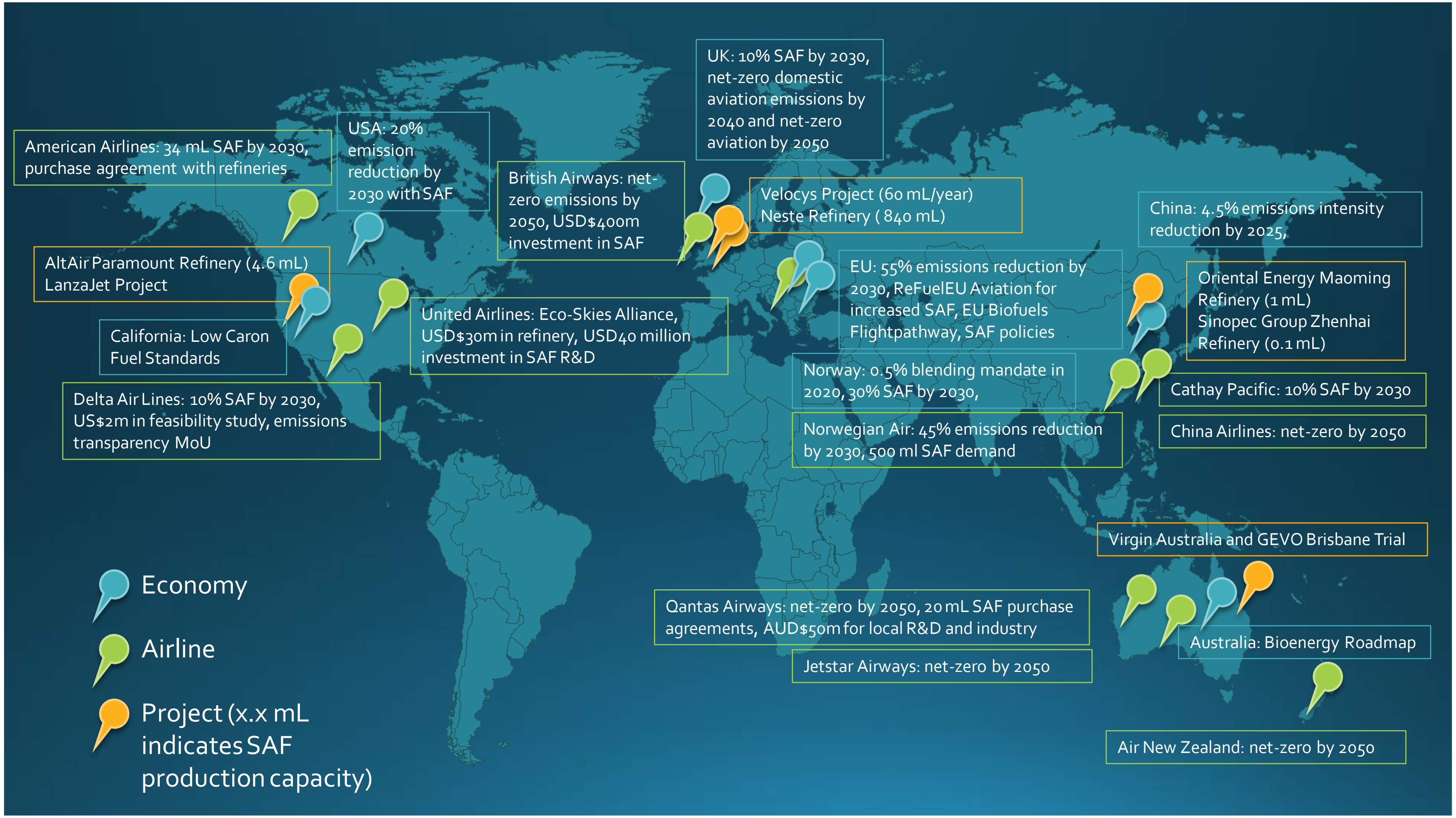
- Physical and chemical characteristics are almost identical to conventional fossil based jet fuel and can therefore be safely mixed (at various blend ratios).
- Uses the same fuel supply infrastructure and doesn’t require adaptation of current global fleet.

- Over **450,000 flights** have taken to the skies using SAF
- **7 technical pathways** exist
- Over **300 million litres** of SAF were produced in 2022
- SAF can **reduce emissions by up to 80%** during its full lifecycle
- Around **17 billion US dollars** of SAF are in forward purchase agreements in 2022
- More than **50 airlines** now have experience with SAF

Decarbonisation Technology Pathways	**Sustainable aviation fuel**	**Battery-electricity**	**Hydrogen (fuel cell and turbine)**
Emissions reduction potential	Medium to High, depends on blending ratio	Low to Medium, if powered by renewable electricity but restricted for short-haul flights	Medium to High, restricted for short-haul flights and depending on hydrogen production pathways
Aircraft design impact	Minor design changes	Medium to High, new design for battery and control system	Medium impacts on design
Range and type	Applications to full range and both cargo and commuter flights	Restricted applications between 500 km and 1000 km, commuter flights only	Restricted applications between 500 km and 10,000 km, both cargo and commuter flights
Aircraft refuelling infrastructure impact	Low Impact, existing infrastructure can be used	High Impact, energy storage, transmission and fast-charging infrastructure required	High Impact, liquid hydrogen storage and distribution infrastructure required
Technology Readiness Level and deployment timeframe	6-9, deploying with commercial projects	3-4, R&D and early piloting, to be deployed post-2040	3-4, R&D and early piloting, to be deployed post-2040

Power to Sustainable Aviation Fuel (2/3)

Global Commitments and Projects



Power to Sustainable Aviation Fuel (3/3)

How is it made?

Pathways Processes	Feedstock	Date of Approval	Blending Limit
Fischer-Tropsch Synthetic Paraffinic Kerosene (FT-SPK)	Biomass (forestry residues, grasses, municipal solid waste)	2009	up to 50%
Hydroprocessed Esters and Fatty Acids (HEFA-SPK)	Oil-bearing biomass, e.g., algae, jatropha, camelina, carinata	2011	up to 50%
Hydroprocessed Fermented Sugars to Synthetic Isoparaffins (HFS-SIP)	Microbial conversion of sugars to hydrocarbon	2014	up to 10%
FT-SPK with aromatics (FT-SPK/A)	Renewable biomass such as municipal solid waste, agricultural wastes and forestry residues, wood and energy crops	2015	up to 50%
Alcohol-to-Jet Synthetic Paraffinic Kerosene (ATJ-SPK)	Agricultural wastes products (stover, grasses, forestry slash, crop straws)	2016	up to 30%
Hydroprocessed Esters and Fatty Acids Plus (HEFA +)	Oil-bearing biomass, e.g., algae, jatropha, camelina, carinata	To be determined. *It is expected to be approved by ASTM by the middle of 2018.*	up to 50%

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Use of SAF in New Aircraft

- Airlines in the PICT region are yet to announce any SAF procurement targets.
- However, Air Niugini has purchased 4 Trent 1000 engines to power two new Boeing 787-8 Dreamliner aircrafts, which can technically operate at up to 50% sustainable aviation fuel blend.
- SAF is set to be the primary avenue for decarbonisation of the aviation sector over the next decades.

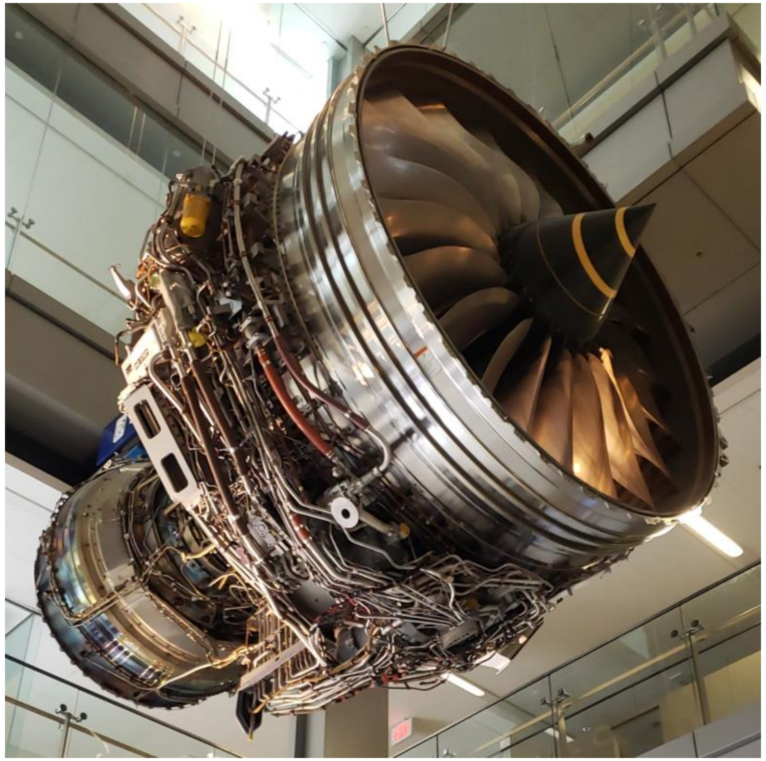

Figure: Rolls-Royce Trent 1000 engine.

Reference: https://www.rolls-royce.com/media/our-stories/discover/2023/poweroftrent-rr-welcomes-air-niugini-as-new-trent-1000-customer-following-selection.aspx