Renewable Hydrogen for the Pacific

Lecture 3: Hydrogen Safety and Economics

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Hydrogen Safety and Economics

- This lecture will cover:
  - Hazards associated with gaseous and liquefied hydrogen
  - Safety protocols for hydrogen production, storage, and transportation
  - An introduction to hydrogen economics

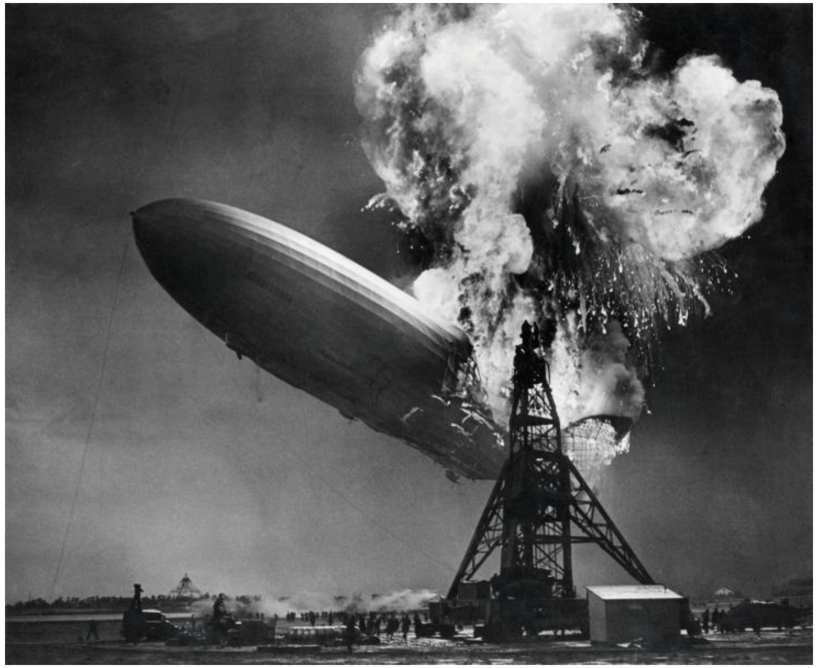
Hydrogen Safety

Hydrogen Properties: Comparison

	Hydrogen Gas	Natural Gas	Gasoline
Color	No	No	Yes
Toxicity	None	Some	High
Odor	Odorless	Yes (mercaptan)	Yes (benzene)
Buoyancy *Relative to **Air***	14X Lighter	2X Lighter	3.75X Heavier
Energy by Weight	2.8X > Gasoline	~1.2X > Gasoline	43 MJ/kg
Energy by Volume	4X < Gasoline	1.5X < Gasoline	120 MJ/Gallon

The Hindenburg Disaster

- The Hindenburg airship caught fire and was destroyed on May 6th 1937, causing 35 fatalities of the 97 on board
- The most accepted theory is that static electricity ignited both the canvas (painted in an incendiary mixture) and leaking hydrogen, eventually reaching the hydrogen stores
- Public confidence in airships (and hydrogen) was shattered



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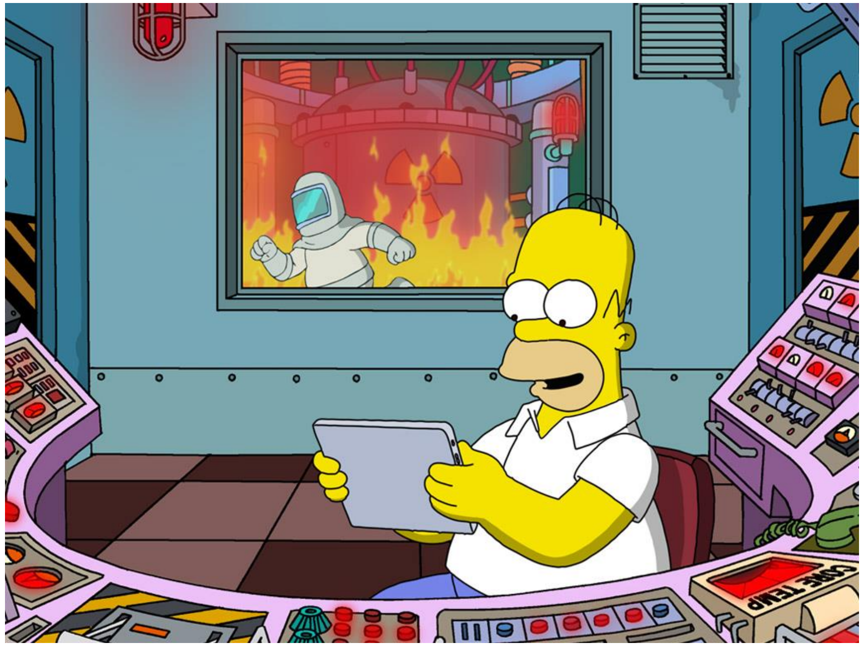
Other Incidents

- Many other hydrogen-related incidents have occurred:
  - 1948: Hydrogen explosion at synthetic liquid fuels laboratory
  - 2008: Fatal accident due to bacterial hydrogen production in atmospheric storage tank
  - 2011: Hydrogen explosion and iron dust flash fires in powdered metals plant
  - 2011: Fukushima Daiichi nuclear disaster hydrogen explosions
  - 2020: Hydrogen tanker crash and explosion

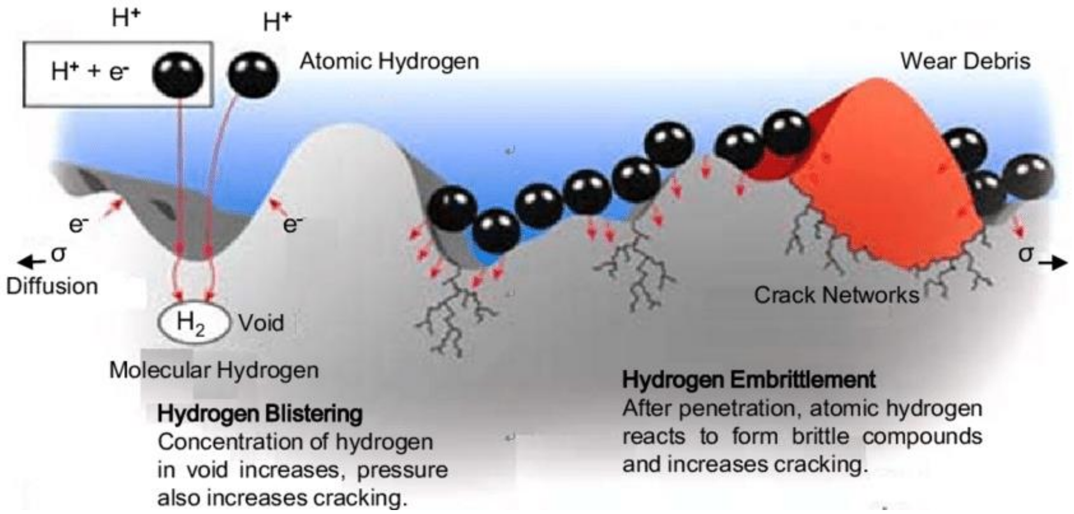
Common Causes of Hydrogen-Related Incidents

- Equipment failure
- Human factors/errors
- Design errors, such as lack of leak detection, insufficient purging, incompatible materials etc.
- Insufficient maintenance
- Flaws in/failure to follow training including operating procedures
- Poor management of change
- Insufficient storage/monitoring protocol
- Flammable mixtures in confined space
- Collisions



Hydrogen Leakage

- Molecular hydrogen is the smallest and lightest of all gases
- It has a very high tendency to leak, and a fast escape rate
- Metals or alloys exposed to hydrogen can degrade or crack, causing hydrogen leakage
- This is known as hydrogen embrittlement or hydrogen attack



Hydrogen Leakage

- Odourants are added to natural gas to assist in detecting leaks
  - Natural gas for public gas supplies typically contains 5-10 mg of mercaptans, alkyl sulfides or cyclic sulfides per cubic meter of gas
- However, sulfur acts as a poison for the noble metal catalysts used in hydrogen fuel cells. Removal of the odorant would add significant expense
- Odorants also cause issues with hydrogen storage. For example:
  - Odorants will condense prior to condensation of hydrogen in cryogenic hydrogen storage
  - Odorants may strongly adsorb and block adsorption sites in metal hydrides and adsorbent-based storage

Hydrogen Leakage

- Alternative detection includes:
  - Hydrogen detection devices are costly, cumbersome, and require constant calibration
  - Devices can have:
    - Detection sensitivity of +/- 0.25% by volume of H_2 in air
    - Response time of <1 second at 1% H_2 in air
  - Non sulfur-based odorants, such as ammonia or ethyl isobutyrate. Fuel cell performance degradation is still an issue with these alternatives

Hydrogen Gas Detection Technologies

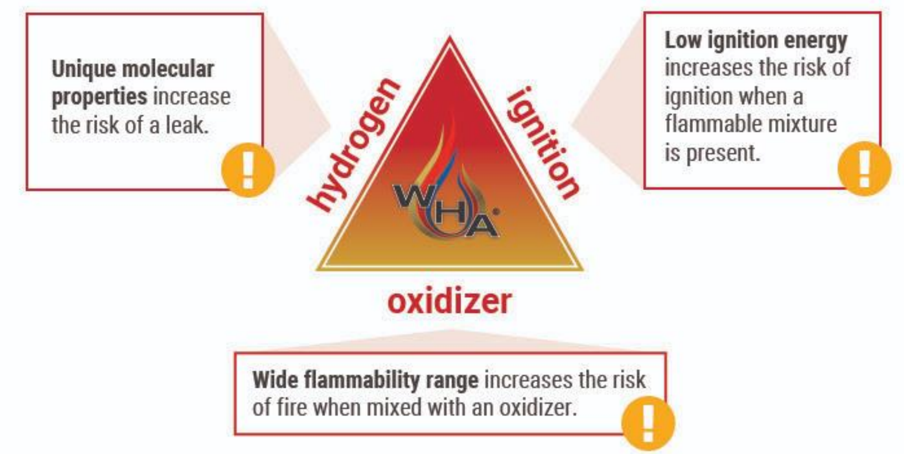
- Pellistor (or catalytic bead)
  - Use of a catalyst that causes flammable gas within the sensor to ignite at a much lower temperature than usual. Typically used as a general "catch-all" technology for flammable gas detection
- Electrochemical
  - Hydrogen is reacted with an electrolyte, producing a current, allows for much more sensitive hydrogen gas detection compared to pellistor sensors (0-1000 ppm)
- Semiconductor
  - Typically respond to a wide range of other gases and vapours.
- Thermal conductivity
  - Low sensitivity and selectivity render them poor for hydrogen detection applications
- Infrared
  - Unable to detect hydrogen since diatomic molecules like hydrogen don't absorb infrared radiation

Pellistor detector

Hydrogen Flammability

- Hydrogen leakage is an issue due to the extreme flammability of hydrogen
- Hydrogen has a very wide flammability range
    - From 4% to 74% in air, even more in atmosphere rich in oxygen or chlorine
- Hydrogen has a very low ignition energy
- Hydrogen burns with a pale blue flame, that is nearly invisible in daylight. Thermal and optical sensors should be used
- The risk of fire and explosion is therefore very high in some applications

	Hydrogen	Gasoline Vapor	Natural Gas
Flammability Limits (in air)	4-74%	1.4-7.6%	5.3-15%
Explosion Limits (in air)	18.3-59.0%	1.1-3.3%	5.7-14%
Ignition Energy (mJ)	0.02	0.20	0.29
Flame Temp. in air (°C)	2045	2197	1875
Stoichiometric Mixture (most easily ignited in air)	29%	2%	9%

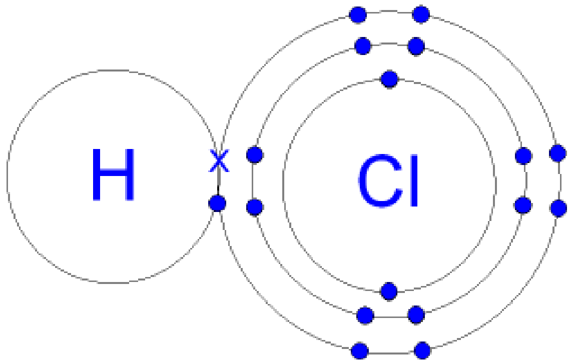


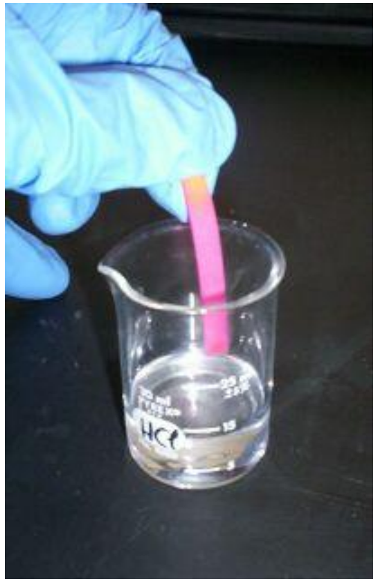
Reaction with Chlorine

- Hydrogen reacts spontaneously with chlorine:

$$H_2 + Cl_2 \rightarrow 2HCl$$

- The reaction is slow in the absence of light but explosive when light or heat are present
- Hydrogen chloride is a colourless gas that forms hydrochloric acid upon contact with atmospheric humidity





Accidental Hydrogen Production

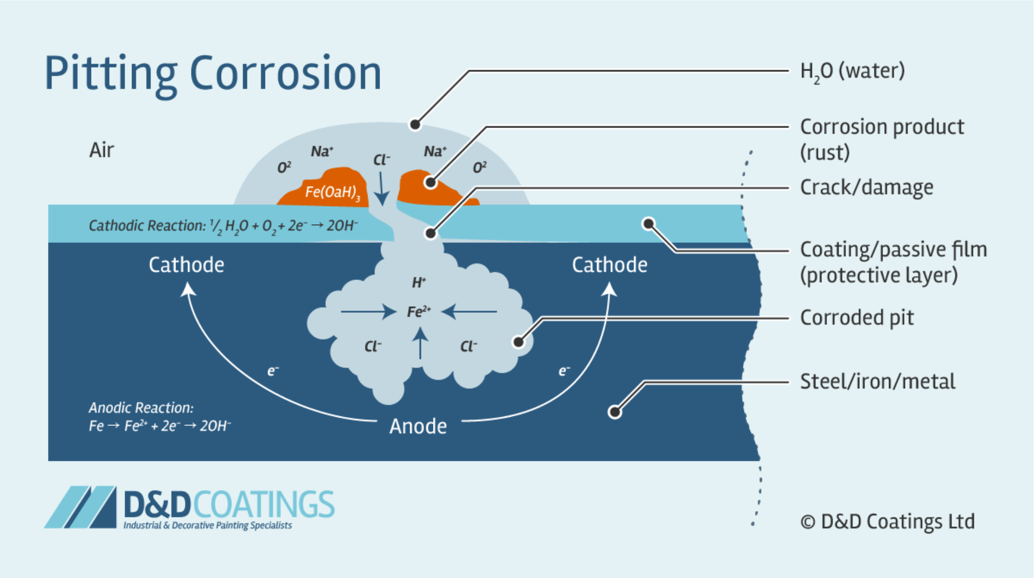
- Hydrogen may be accidentally produced through several pathways, resulting in documented industry accidents
- Via corrosion of steel:
  - Steel is attacked by weak acids, releasing hydrogen

    $$Fe + 2H^+ \rightarrow Fe_2^+ + H_2$$

  - Steel is especially sensitive to pitting corrosion in the presence of aqueous solutions charged with chlorine, bromine, or hypochlorite ions
- Reactions of water or acids with metals
  - Alkaline metals (Li, Na, K etc.) react rather violently with water and generate hydrogen

    $$2Na + 2H_2O \rightarrow 2NaOH + H_2$$

- Formation of water gas
  - Water gas (H_2 and CO), is formed when carbonaceous materials at very high temperatures (1000°C) come into contact with water



Other Hazards

- Gaseous Hydrogen
  - ➢ No odour or taste, making leaks difficult to detect
  - ➢ Non-toxic but can be an asphyxiant if it dilutes or displaces air
- Liquid Hydrogen
  - ➢ Low temperature, causing damage to delicate tissue
  - ➢ Loss of hydrogen to boil-off, drastically increasing pressure within the vessel
  - ➢ Causes the condensation of other gases, e.g. causing solidified air to plug pipes and orifices and jam valves

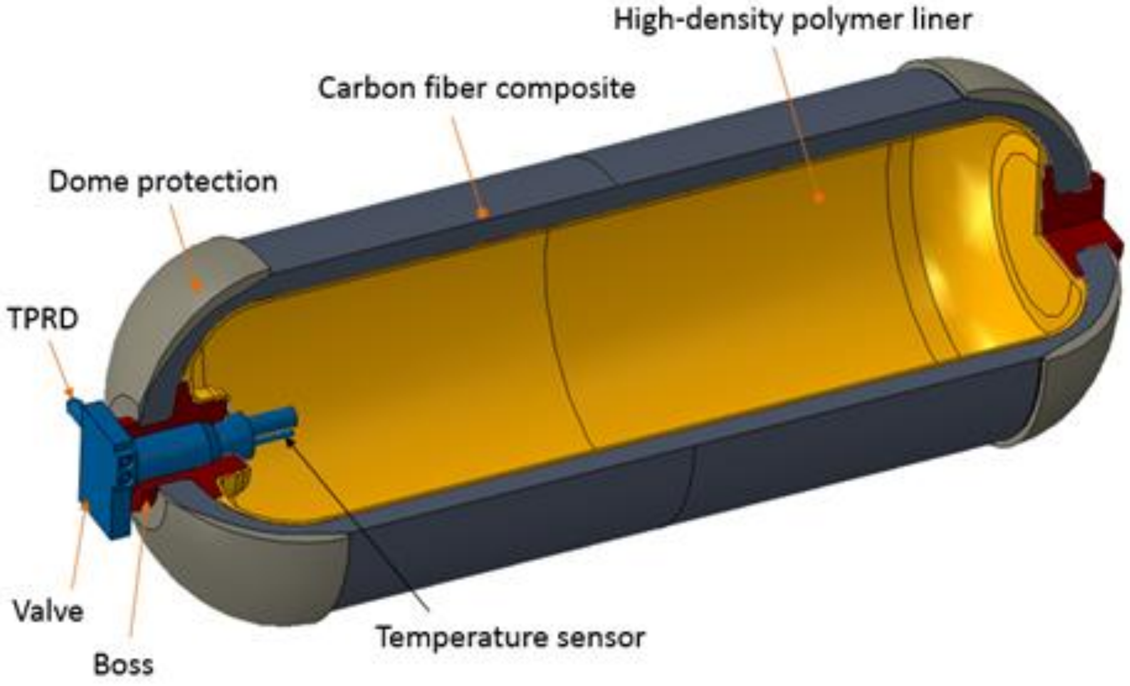
Advantageous Properties of Hydrogen

- Hydrogen exhibits several safety-related advantages compared to conventional fuels:
  - Hydrogen is non-toxic
  - Combustion of hydrogen produces only water, compared to carbon monoxide released through incomplete combustion of carbon-based fuels
  - The low density of hydrogen (14 times lighter than air and 57 times lighter than gasoline vapour) causes it to rapidly dissipate in air if leaked

Why is Hydrogen Safety Important?

- Hydrogen is intrinsically hazardous
- As hydrogen use becomes more widespread in industry and the community, management is critical to ensure safety during:
  - Production
  - Storage
  - Handling and transport
  - End use
- Therefore, safety rules, regulations, and standards are required to prevent dangerous incidents from occurring

A Typical Compressed Hydrogen Storage Tank

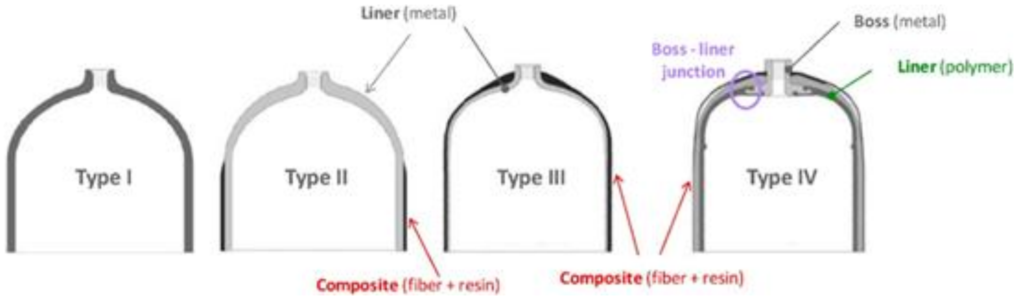


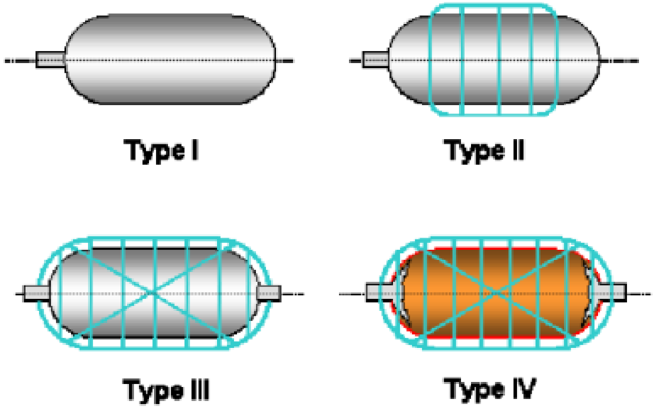
TPRD = Thermally Activated Pressure Relief Device

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

Existing Safety Controls for Compressed Hydrogen

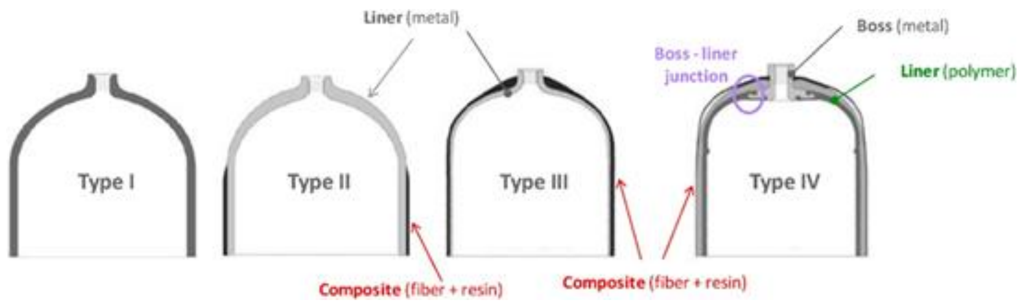
- Type I:
  - Composed of metal
  - Cheap but low maximum pressures
- Type II:
  - Metallic liner with a composite fiber and resin overwrap
  - Improved mechanical strength but high cost
- Type III:
  - Carbon fiber composite pressure vessel with a metal liner
  - Improved mechanical strength but high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

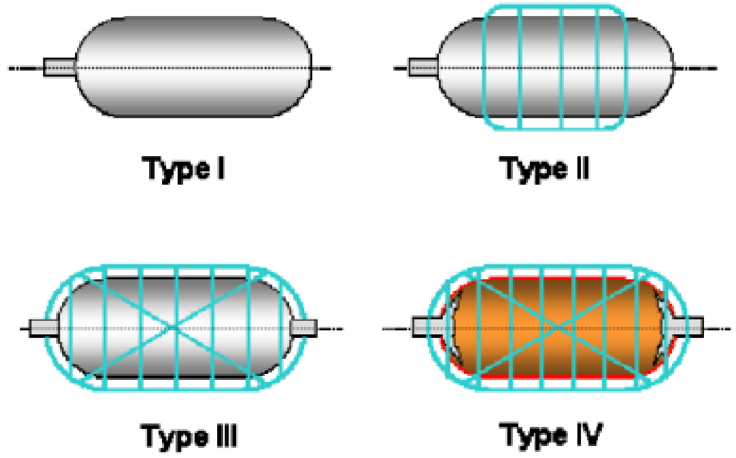




Existing Safety Controls for Compressed Hydrogen

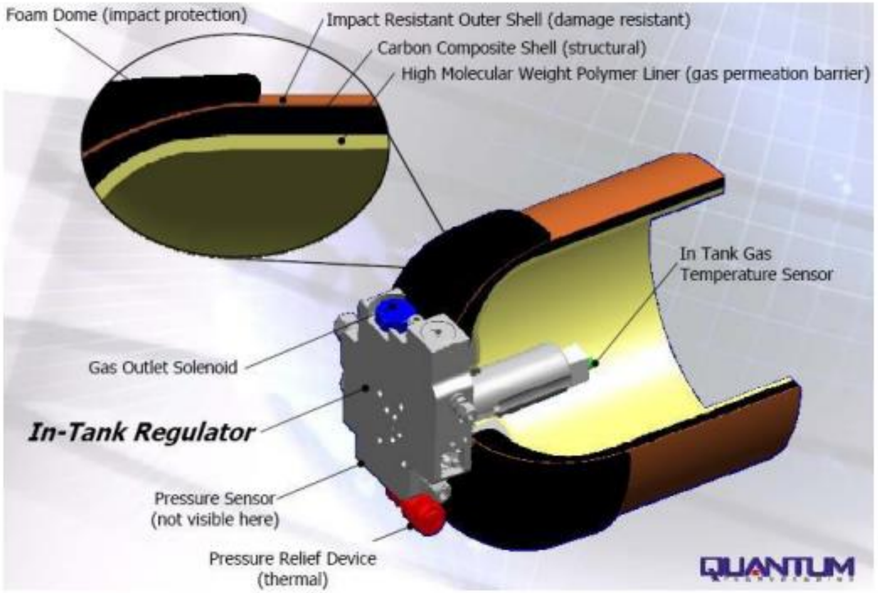
- Metals used are generally aluminium or steel
- Polymers used are generally high-density polyethylene or polyamide
- Carbon fibre is commonly used





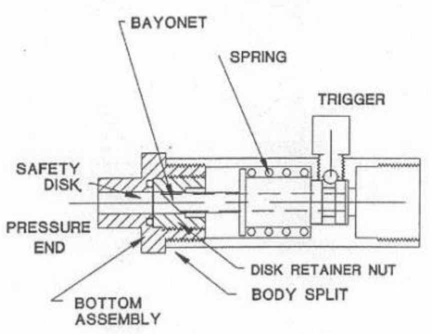
A Type IV tank produced by Quantum Technologies

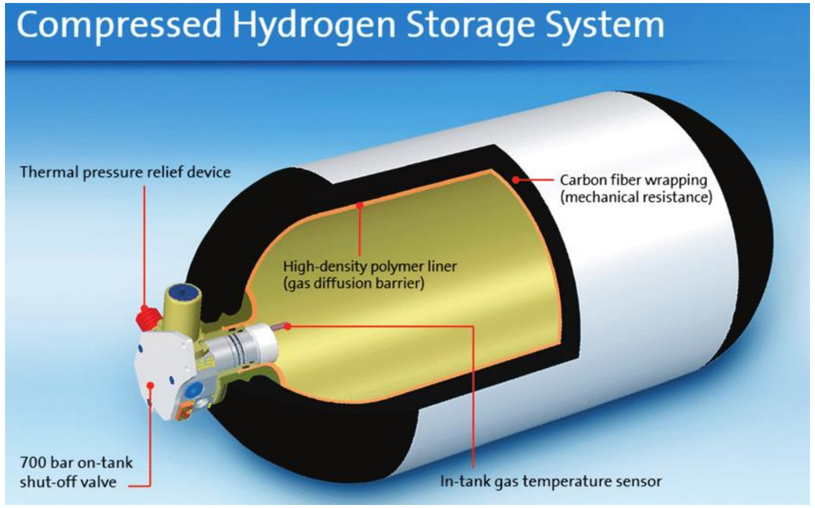
- Features:
  - ➢ An impact-resistant foam dome
  - ➢ An impact resistant outer shell, which is bullet-proof and provides the tank with cut/abrasion resistance
  - ➢ A carbon fibre reinforced plastic (CFRP) shell
  - ➢ A polymeric liner
  - ➢ Pressure and temperature sensors
  - ➢ Pressure relief device



Pressure Relief Devices

- PRDs are the main safety feature for compressed hydrogen storage
- A PRD protects against a failure of a storage vessel by releasing some or the entire tank content in the event of high temperatures, high pressures, or both
- Thermally-activated PRDs release hydrogen from a high-pressure storage container before its walls are weakened by high temperatures





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Indoor Storage - Safety Considerations

Safety considerations for indoor storage or use of bulk gaseous hydrogen include:

- Buildings shall be constructed of non-combustible materials.
- Hydrogen sensors shall be installed at ceiling level near ventilation exhaust.
- Install automatic shutoff that activates if a leak or fire is detected in the facility that is being supplied with hydrogen.
- Avoid ignition sources in storage areas.
- Classified electrical equipment shall be in close proximity to storage systems.
- Gaseous hydrogen system components shall be electrically bonded and grounded.

Reference: https://h2tools.org/sites/default/files/IntroToH2FCandSafetyConsiderations_Sept2018.pdf

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Outdoor Storage - Safety Considerations

- Hydrogen cylinders and storage tanks should be stored outside at a safe distance from structures, ventilation intakes, and vehicle routes
- Separation distance requirements based on quantity of hydrogen
- A bulk hydrogen compressed gas system has a capacity of more than 5,000 scf and consists of:
  - storage containers
  - pressure regulators
  - pressure relief devices
  - compressors
  - manifolds and piping

Reference: https://h2tools.org/sites/default/files/IntroToH2FCandSafetyConsiderations_Sept2018.pdf

Other Safety Controls for Hydrogen

- Storage of hydrogen must take into consideration location and volume of hydrogen, with the preference to have the system outdoors to allow for ventilation if required
- Controls are further detailed in existing safety Standards and include:
  - Material selection and design
  - Administrative e.g., standard operating procedures, risk assessments, training, emergency procedures
  - Ignition source control e.g., electrical installation, explosion proof equipment, electrical grounding, lightning protection, prohibit welding etc.
  - Ventilation
  - Exclusion zones
  - Hydrogen venting and flare system
  - Labelling, barricades and access control
  - Instrumentation for monitoring and alarming e.g., hydrogen leak detection, fire detection
  - Testing and auditing
  - Fire protection e.g., automatic/manual shutdown, deluge or sprinkler systems, etc.


GHS02


GHS04

Australian Standards for Hydrogen

- Need uniform and comprehensive legislation across all levels of Government
- Australian Standards managed by the ME-093 Hydrogen Technologies committee
- Adopted the ISO standards for hydrogen to assist with safe and regulated use of hydrogen within Australia
- Need to address the following key areas:
  - Safety
  - Environment
  - Trade
  - Education

STANDARDS Australia

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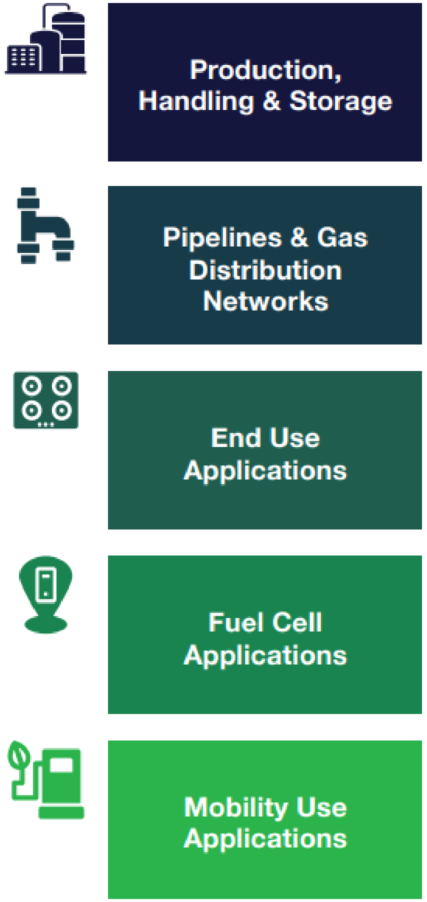
Australian Standards for Hydrogen

- Five working groups within the ME-093 Technical Committee
  1. Production, Handling and Storage
  2. Pipeline and Gas Distribution Networks
  3. End Use Applications
  4. Fuel Cell Applications
  5. Mobility Applications



Examples of Current Standards

- AS 16110.1:2020, Hydrogen generators using fuel processing technologies
- AS ISO 14687:2020, Hydrogen fuel quality – Product specification
- AS 22734:2020, Hydrogen generators using water electrolysis – Industrial, commercial, and residential applications
- SA TS 19883:2020, Safety of pressure swing adsorption systems for hydrogen separation and purification
- AS ISO 16111:2020, Transportable gas storage devices – Hydrogen absorbed in reversible metal hydride
- AS ISO 19881:2020, Gaseous hydrogen – Land vehicle fuel containers
- AS 19880:2020, Gaseous hydrogen – Fuelling stations
- AS 26142:2020 Hydrogen detection apparatus – stationary applications

Codes and Standards for FCEVs

Vehicle

Refueling Guidelines
SAE J2601

Interface Standards
HGV 4.3 – Temperature Comp.
SAE J2719
OIML and NIST Handbook 44

Station

Dispenser Component Standards
CSA HGV 4.1 - Dispenser
CSA HGV 4.2 - Hose
CSA HGV 4.4 - Breakaway
CSA HGV 4.5 - Priority and Sequencing
CSA HGV 4.6 - Manual Valves
CSA HGV 4.7 - Automated Valves

Fuel Cell Vehicle System
GTR (harmonized with ISO and SAE J2978)
FMVSS
SAE J2615 – System Performance
SAE J2572 – Fuel Consumption Measurement
SAE J2574 – General Vehicle Safety
SAE J2617 – Stack Performance
SAE J2574 – Design for Recycling PEM stacks

Compression & Storage
NFPA 2 and Local Codes
ASME BPVC - Storage
CSA HGV 4.8 – Compressors

Installation
NFPA 2 and Local Codes
NEC
ASME 31.12
CSA HGV 4.9 - Stations
ISO 19880-1

Reference: Air Liquide USA

Other Relevant Standards

- Hydrogen can be store in alternate chemicals (such as ammonia, methane, and methanol)
- Standards exist for these chemicals:
  - AS 1940:2017 The storage and handling of flammable and combustible liquids
  - AS/NZS 2022:2003 Anhydrous ammonia - Storage and handling
  - AS/NZS 60079 Equipment for Explosive Atmospheres
  - See: https://www.standards.org.au/

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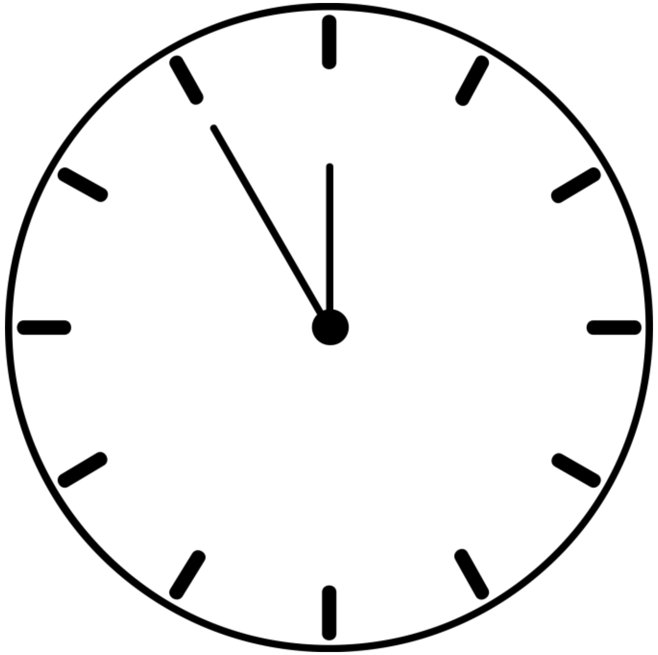
Future Regulations and Challenges

- Regulators still need to utilise standards as law
- Further development of technical standards in each of the five focus areas
- Hydrogen technology is an evolving field, new methods of generation, application and storage are rapidly emerging
- Need to develop and maintain relevant standards which provide clear guidance in its safe use and to ensure its benefits are
- Committees must be proactive to match with rate of growth and allow fast-tracked application of hydrogen within Australia



Hydrogen Economics

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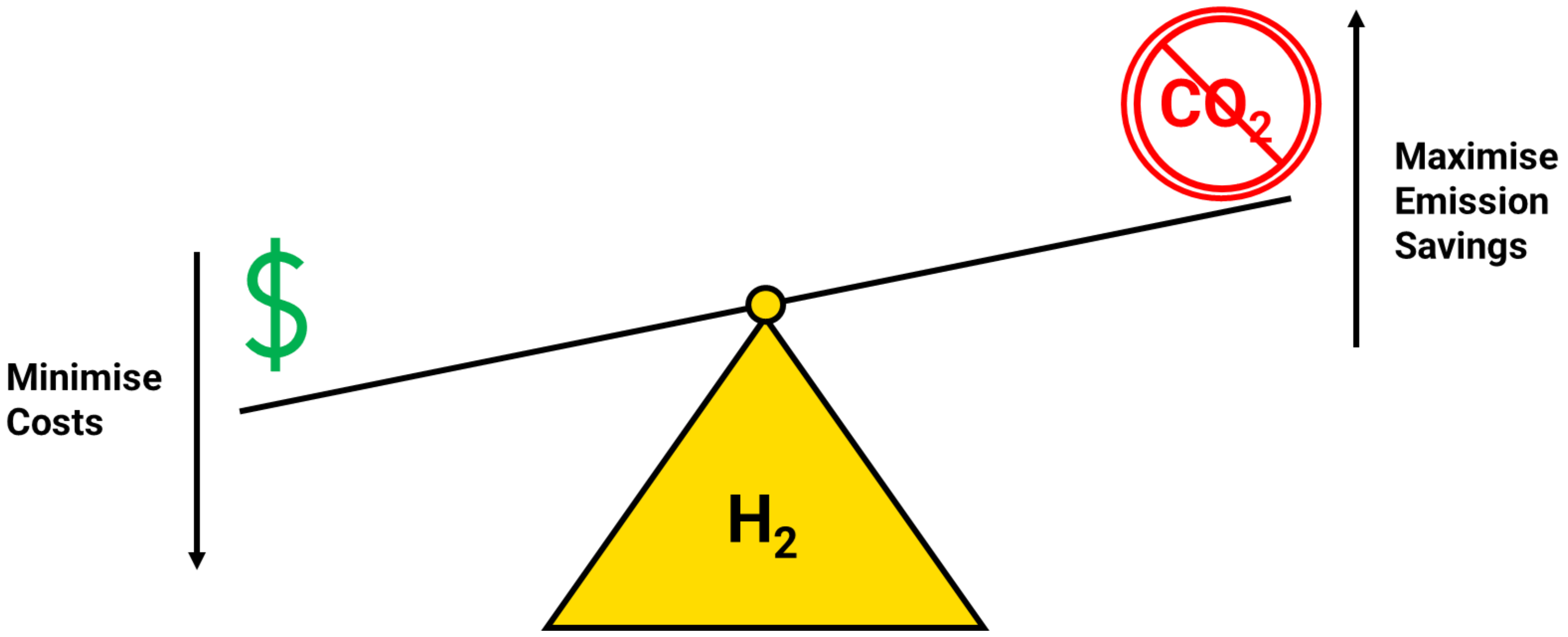
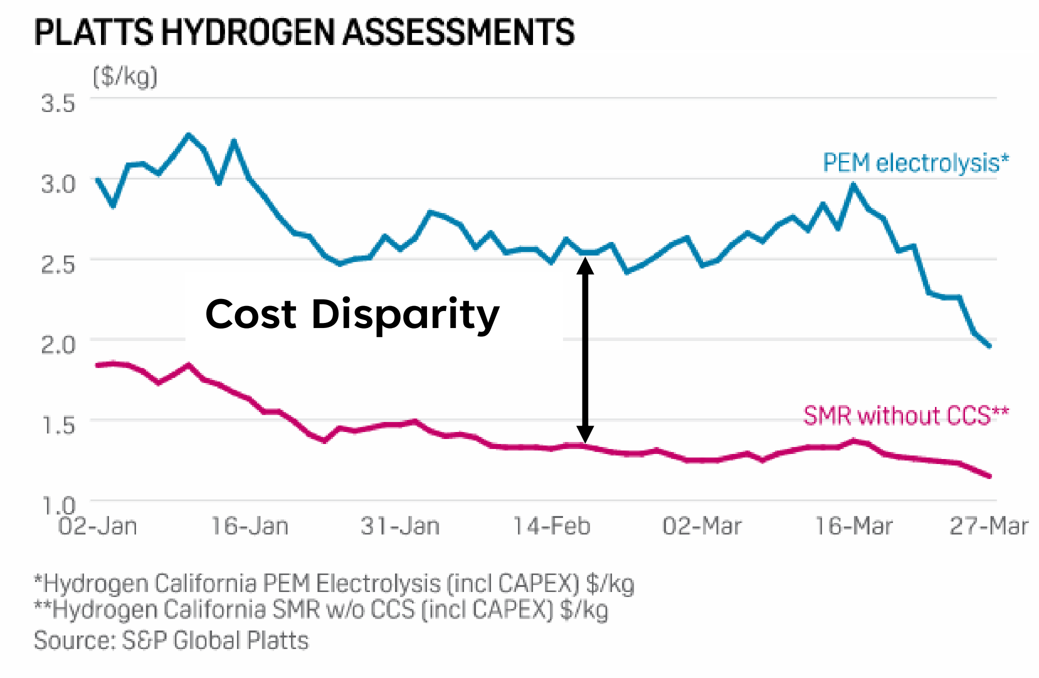
Hydrogen Economics - 101

End Goal: Hydrogen must be viable with the end-use sectors and yield benefits



Hydrogen Economics - 101

End Goal: Economically H_2 needs to achieve certain cost barriers to become economically viable



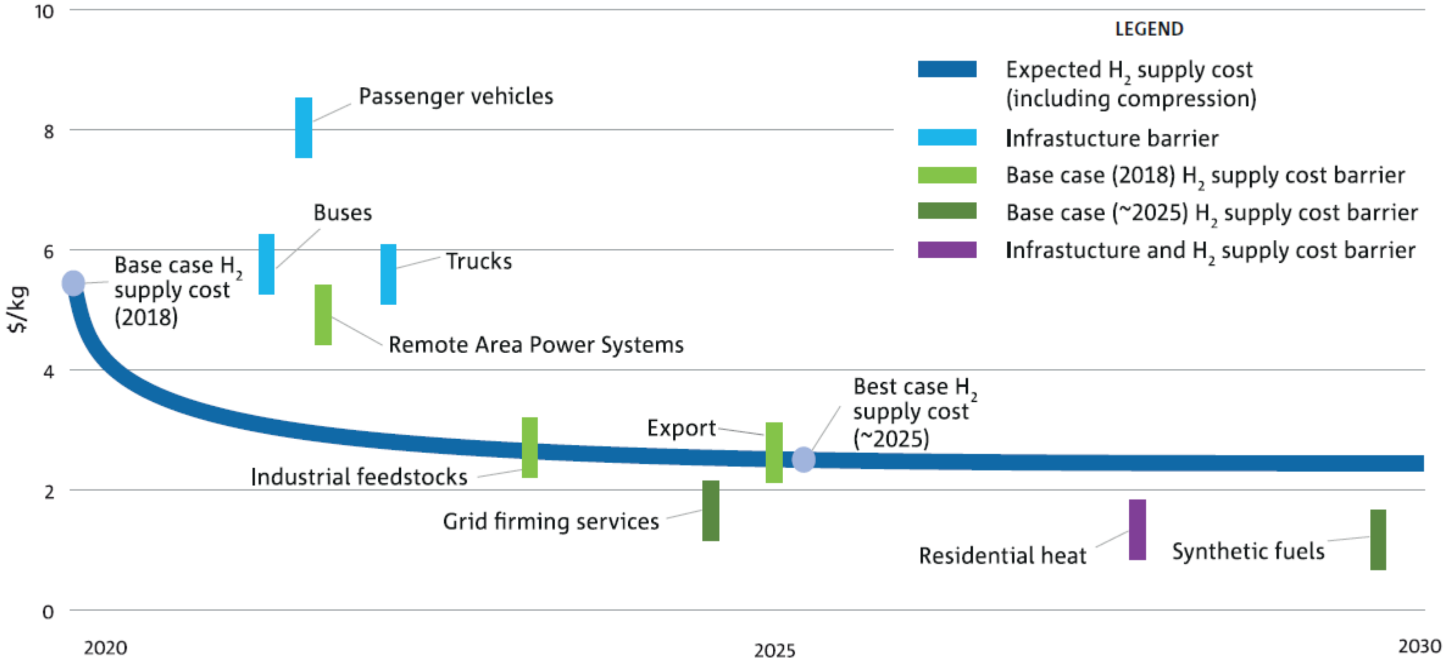
Reference: Platts Hydrogen Price Wall

H_2 Industry

- E.g., for the H_2 industry a standard cost barrier is set by fossil-based hydrogen generation
- **Creating a race to US$1.5 (or A$2) per kg H_2**

Hydrogen Economics - 101

Importance of A$2/kg



At a cost value of <A$2/kg, Hydrogen would become viable for large-scale industry offtake and export

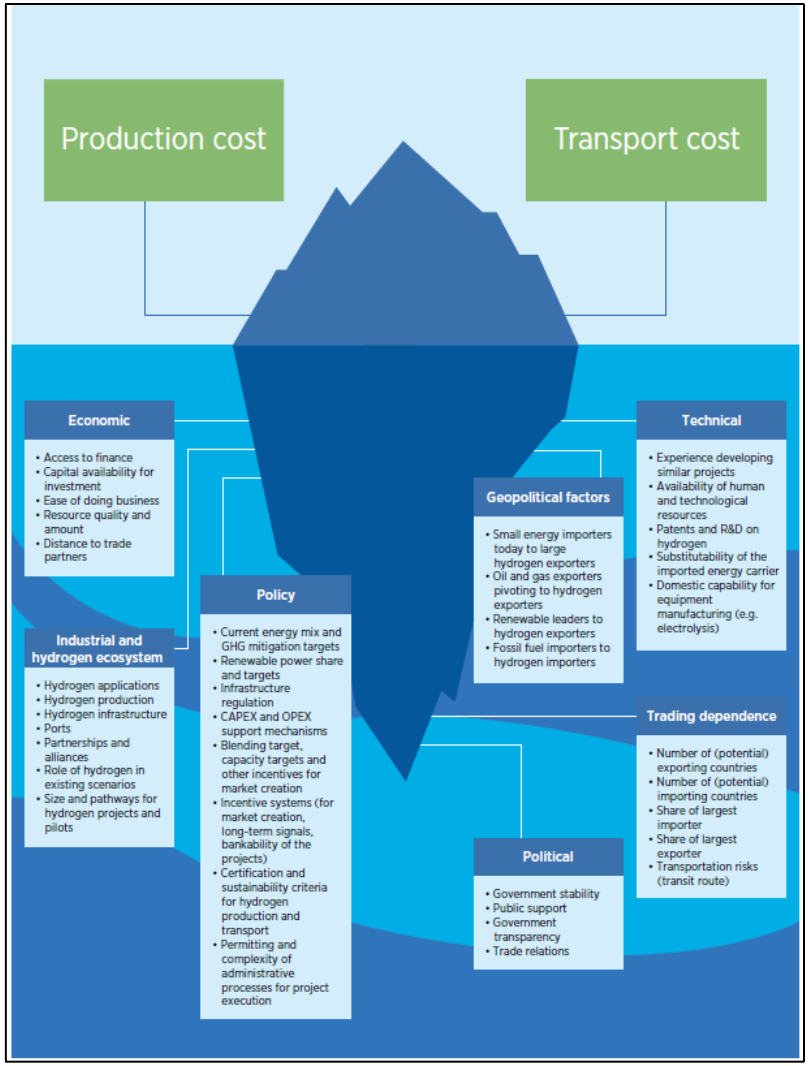
Reference: [National Hydrogen Roadmap, CSIRO]()

Additional Reading Material on H_2 Costs across different sectors in Australia: [Advisian Australian Hydrogen Market Study]()

Hydrogen Economics - 101

The economics is not so straightforward

It's like an iceberg – but hopefully, one that does not sink the H_2 Ship



Reference: https://www.irena.org/publications/2022/Jul/Global-Hydrogen-Trade-Outlook

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Levelised Cost of Hydrogen

$$\textbf{Levelised Cost of Product (A\$/kg)} = \frac{\textbf{Net Present Value of Investment}}{\textit{Net Present Value of Lifetime Production}}$$

The Levelised Cost of Product: Represents the average revenue per unit of product that would have to be generated that would be required to recover the investment cost into constructing and operating the Power to X facility, an assumed financial life and duty cycle.

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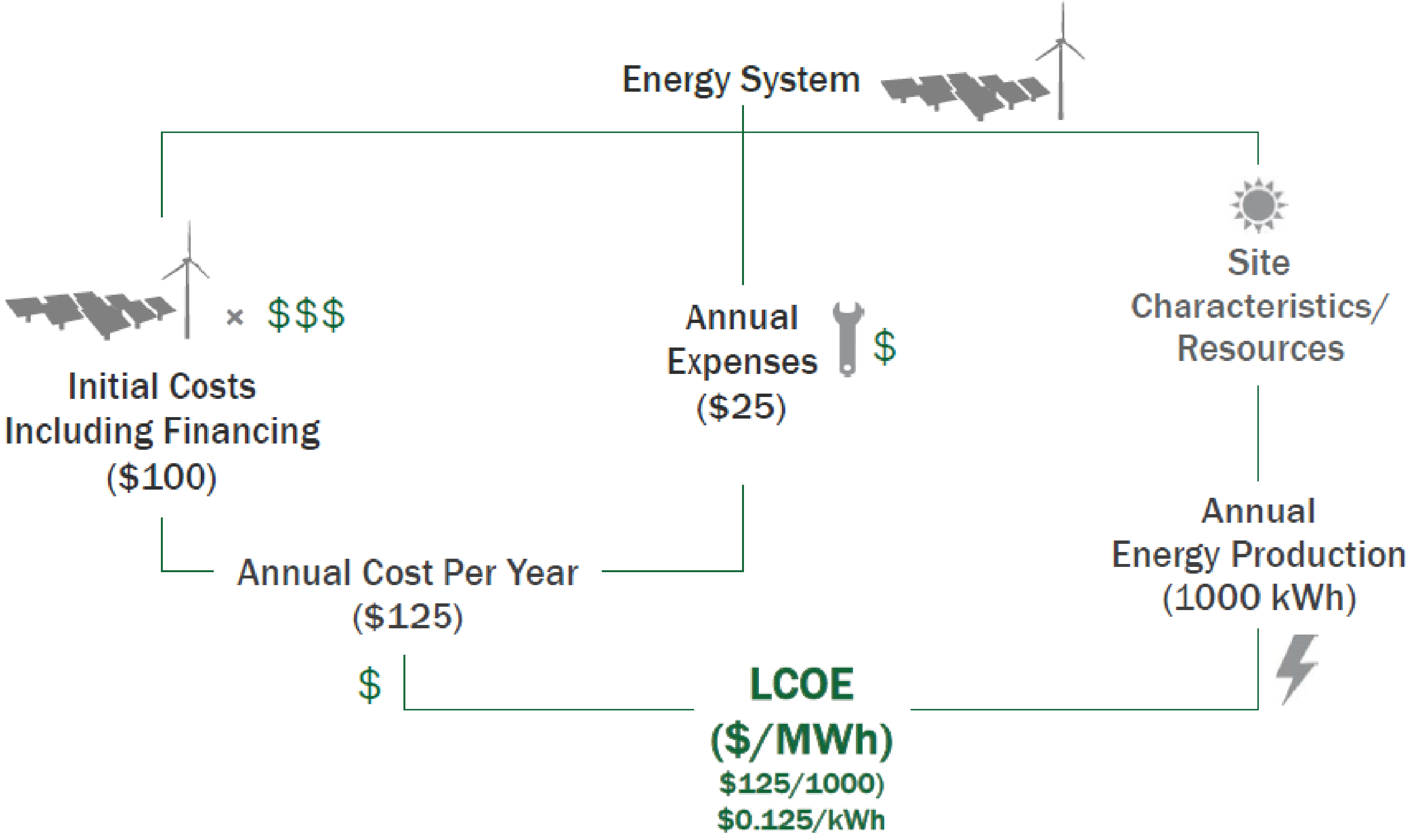
Levelised Cost of Hydrogen



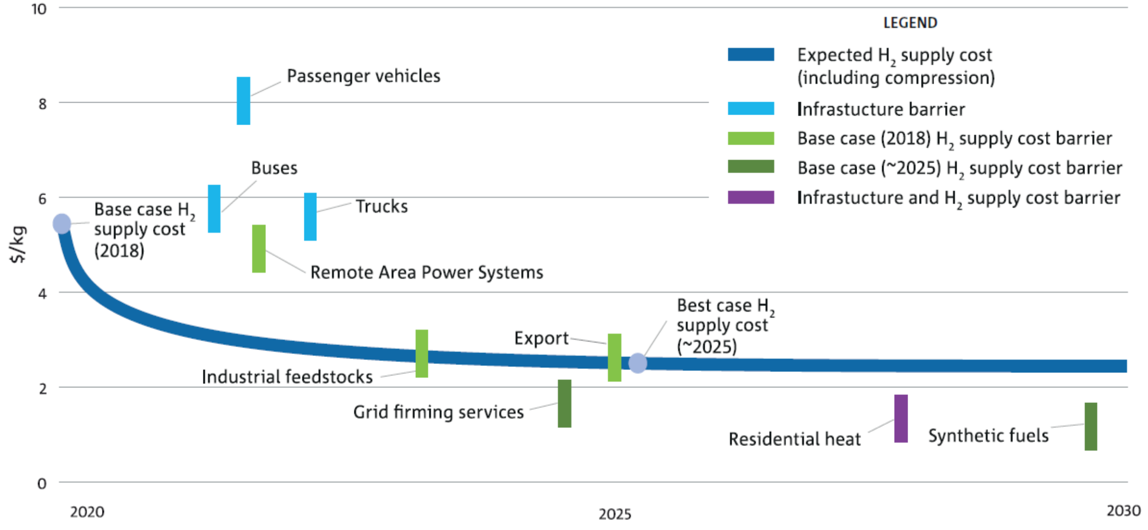
Just like you pay a unit price for electricity.

Hydrogen users will pay a unit price per kg/MWh of H_2 that will cover the producer's costs

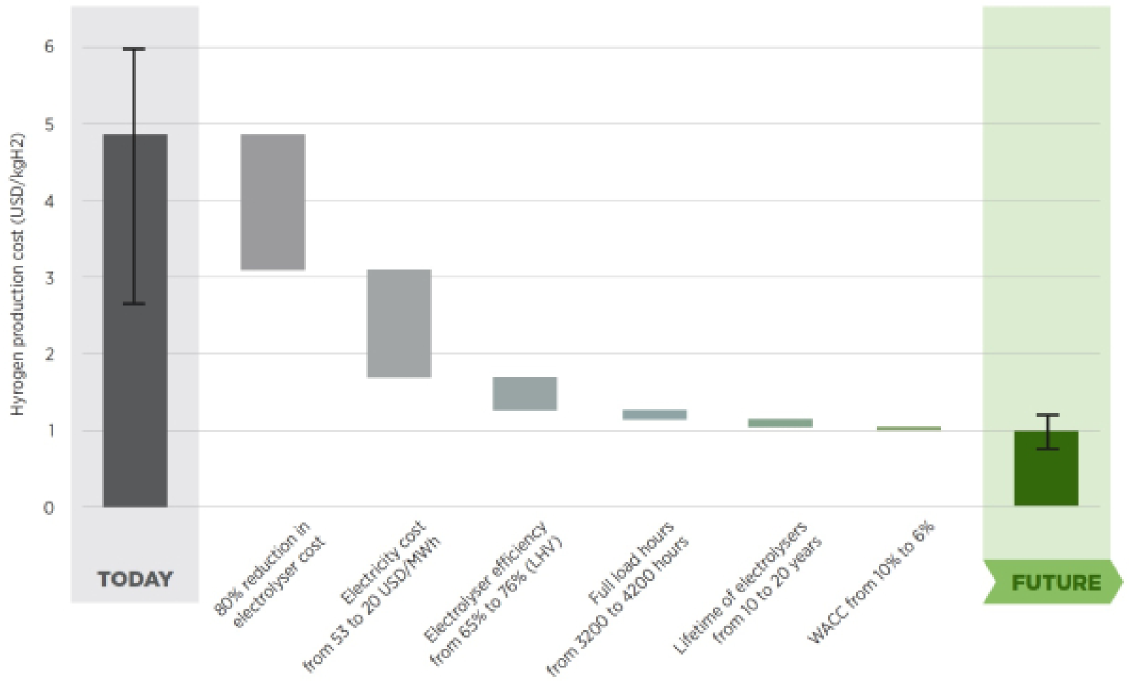
Image Courtesy of US NREL: [NREL Video on LCOE]

Levelised Cost of Hydrogen

Benchmarking Offtake Cost Thresholds



Predicting Future Hydrogen Costs



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Levelised Cost of Hydrogen

What Makes Up A Levelised Cost of Hydrogen?

Capital Costs + Feedstock Costs + Maintenance Costs

$$\text{Levelised Cost of Product} = \frac{\sum_{n=1}^{N} \frac{costs_{(n)}}{(1+r)^n}}{\sum_{n=1}^{N} \frac{Product_{(n)}}{(1+r)^n}}$$

Hydrogen production from project mass and energy balance

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Levelised Cost of Hydrogen

What Costs are Involved?

- **Stage 1: Cradle** – Project envisioned, Prefeasibility makes sense and offtake agreement in place
- **Stage 2: H_2 Production and Distribution** – Investment into development of facility/Operations kick off – supply chain established
- **Stage 3: H_2 End Use** – H_2 reaches end user and return on investment begins
- **Stage 4: End of Life** – The project comes to an end and the facility is decommissioned with equipment and material salvaged for reuse.

It's all about the money!

Hydrogen Economics

How are the costs distributed ?

Stage 1-
Cradle

Upstream

- Equipment Purchase
- Financing Costs
- Approvals and Land Acquisition

Stage 2-
H_2 Production and Distribution

Generation → **Storage** → **Transport**

- Operating Costs: Feedstock and energy bills, operational costs (maintenance and overheads), insurance, taxes, interest etc.
- Cost of Distribution: Operating cost of storage and distribution

Stage 3-
End Use

End Use

- Cost of Hydrogen Use (End Use Equipment capital and operating costs)

Stage 4-
End of Life

End of Life

- Decommissioning: Equipment uninstalled and land rehabilitation

Hydrogen Economics

Capital Cost Assessment

Direct Cost

+ Indirect Cost

+ Contingencies

= Total Capital Costs

I. **Direct costs** = material and labor involved in actual installation of complete facility (65–85% of fixed-capital investment)
   A. Equipment + installation + instrumentation + piping + electrical + insulation + painting (50–60% of fixed-capital investment)
      1. Purchased equipment (15–40% of fixed-capital investment)
      2. Installation, including insulation and painting (25–55% of purchased-equipment cost)
      3. Instrumentation and controls, installed (8–50% of purchased-equipment cost)
      4. Piping, installed (10–80% of purchased-equipment cost)
      5. Electrical, installed (10–40% of purchased-equipment cost)
   B. Buildings, process, and auxiliary (10–70% of purchased-equipment cost)
   C. Service facilities and yard improvements (40–100% of purchased-equipment cost)
   D. Land (1–2% of fixed-capital investment or 4–8% of purchased-equipment cost)

II. **Indirect costs** = expenses which are not directly involved with material and labor of actual installation of complete facility (15–35% of fixed-capital investment)
   A. Engineering and supervision (5–30% of direct costs)
   B. Legal expenses (1–3% of fixed-capital investment)
   C. Construction expense and contractor's fee (10–20% of fixed-capital investment)
   D. Contingency (5–15% of fixed-capital investment)

III. **Fixed-capital investment** = direct costs + indirect costs

IV. **Working capital** (10–20% of total capital investment)

V. **Total capital investment** = fixed-capital investment + working capital

Hydrogen Economics

Operating Cost Assessment

Feedstock Costs

+ Operation Costs

+ Maintenance Costs

+ Overheads

= Total Operating Costs

I. **Manufacturing cost** = direct production costs + fixed charges + plant overhead costs
   - A. Direct production costs (about 66% of total product cost)
     1. Raw materials (10–80% of total product cost)
     2. Operating labor (10–20% of total product cost)
     3. Direct supervisory and clerical labor (10–20% of operating labor)
     4. Utilities (10–20% of total product cost)
     5. Maintenance and repairs (2–10% of fixed-capital investment)
     6. Operating supplies (10–20% of maintenance and repair costs, or 0.5–1% of fixed-capital investment)
     7. Laboratory charges (10–20% of operating labor)
     8. Patents and royalties (0–6% of total product cost)
   - B. Fixed charges (10–20% of total product cost)
     1. Depreciation (depends on method of calculation—see Chap. 7)
     2. Local taxes (1–4% of fixed-capital investment)
     3. Insurance (0.4–1% of fixed-capital investment)
     4. Rent (8–12% of value of rented land and buildings)
     5. Financing (interest) (0–10% of total capital investment)
   - C. Plant overhead costs (50–70% of cost for operating labor, supervision, and maintenance; or 5–15% of total product cost) include costs for the following: general plant upkeep and overhead, payroll overhead, packaging, medical services, safety and protection, restaurants, recreation, salvage, laboratories, and storage facilities

II. **General expenses** = administrative costs + distribution and selling costs + research and development costs (15–25% of the total product cost)
   - A. Administrative costs (about 20% of costs of operating labor, supervision, and maintenance; or 2–5% of total product cost) include costs for executive salaries, clerical wages, computer support, legal fees, office supplies, and communications
   - B. Distribution and marketing costs (2–20% of total product cost) include costs for sales offices, salespeople, shipping, and advertising
   - C. Research and development costs (2–5% of every sales dollar, or about 5% of total product cost)

III. **Total product cost**† = manufacturing cost + general expenses

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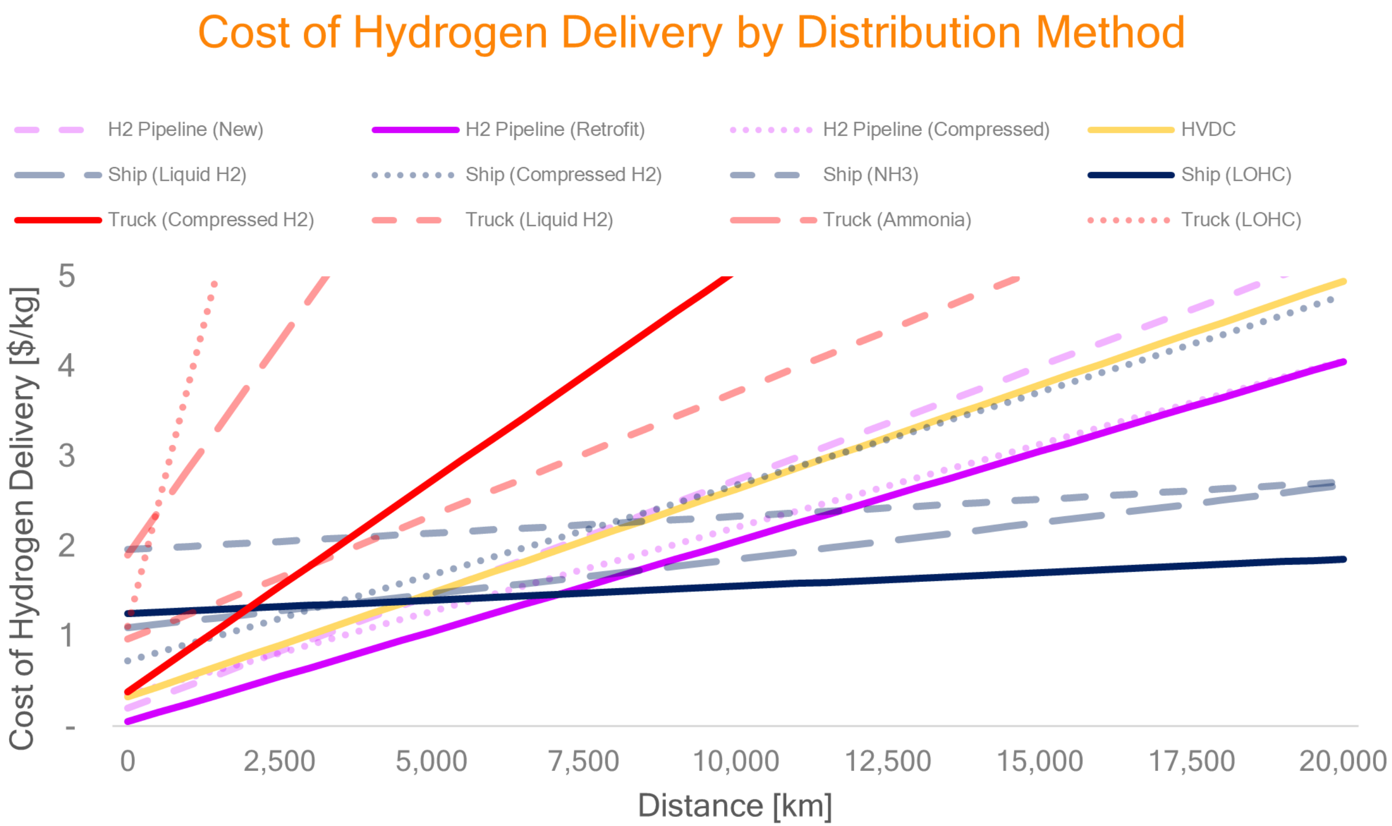
Hydrogen Economics

Distribution Costs

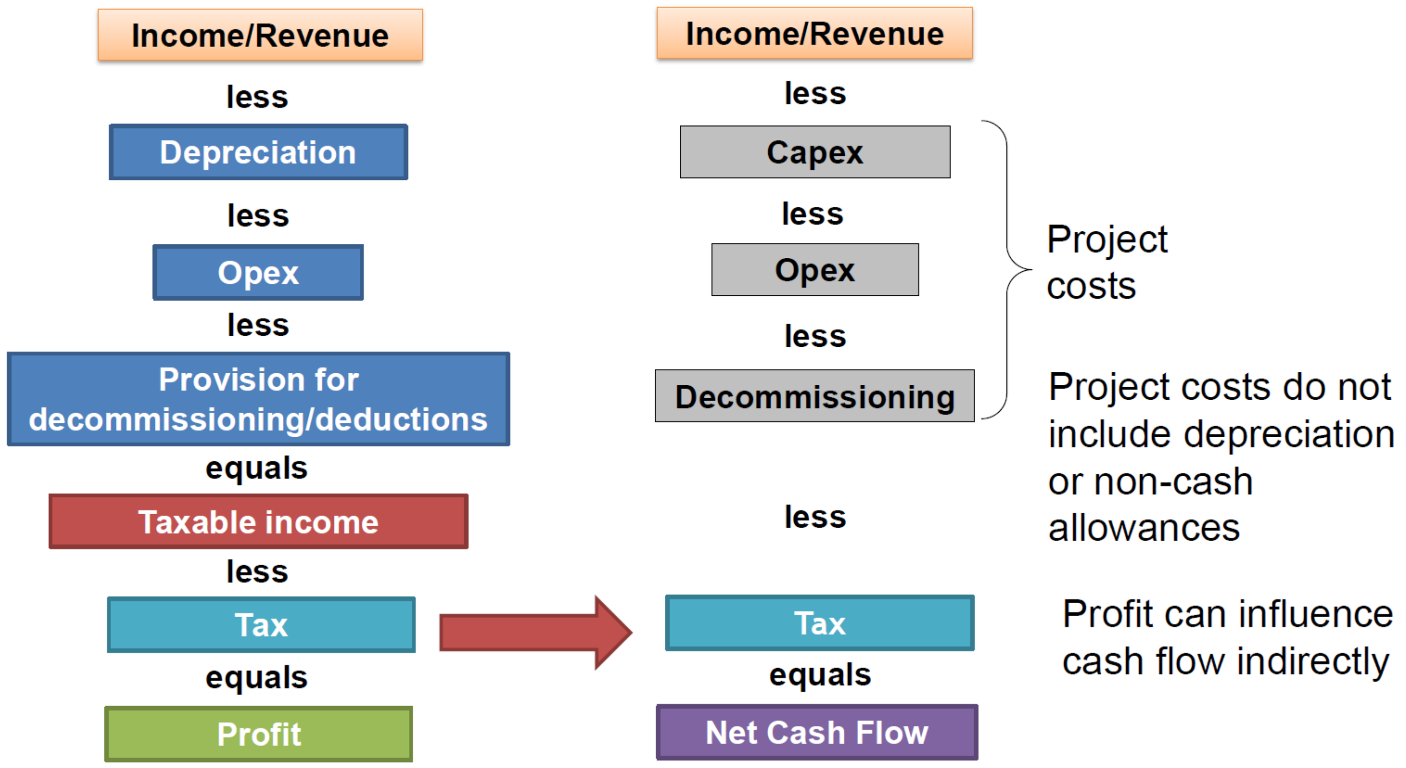
(Storage + Transport)



The cost varies based on the transport medium

Hydrogen Economics

Cash Flow Statement



Cash Flow Statement Functions

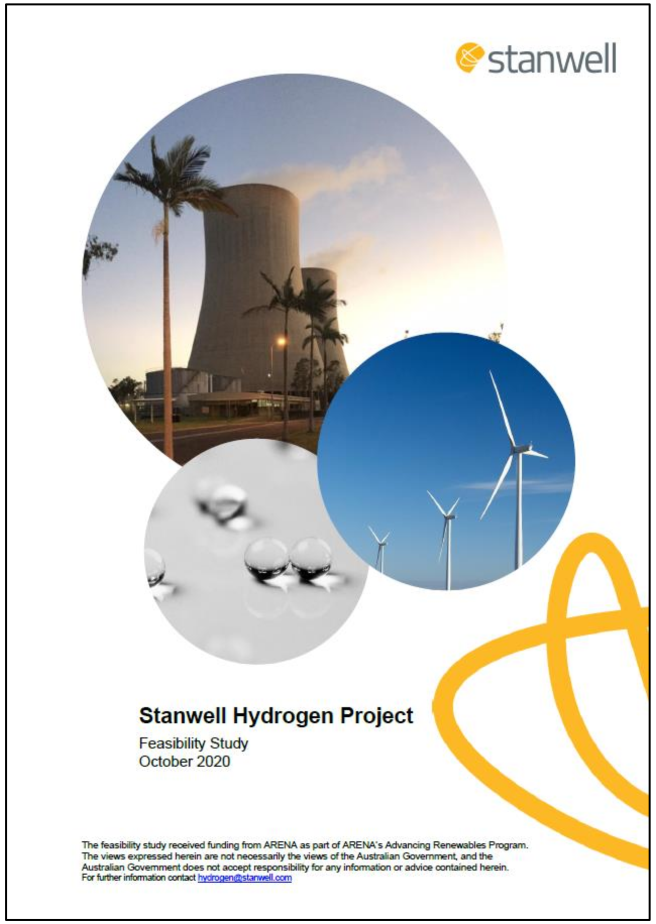
- Tracking of Cash Flows
- Important economic parameters (Profit, Revenue Statement, Breakeven, Net Present Value etc.)

Hydrogen Economics

End Goal: Prefeasibility Study

Pre-feasibility studies involve a design concept of the project is developed and a preliminary cost analysis is conducted.

- **Tools:**
  - ✓ Technical Analysis: Resource Mapping, Mass/Energy Balance
  - ✓ Business Case: Conduct NPV, IRR etc = Economic Attractiveness
  - ✓ Sensitivity Analysis: How flexible the economics are = Robustness of Business Case
  - ✓ Risk Analysis: SWOT – Analysis = Determine Opportunity Costs and Project Risks
  - ✓ Environmental and Social Analysis: Will the Society and Environment be affected?



Further Reading:
https://ens.dk/sites/ens.dk/files/Globalcooperation/prefeasibility_study_guidelines_final.pdf

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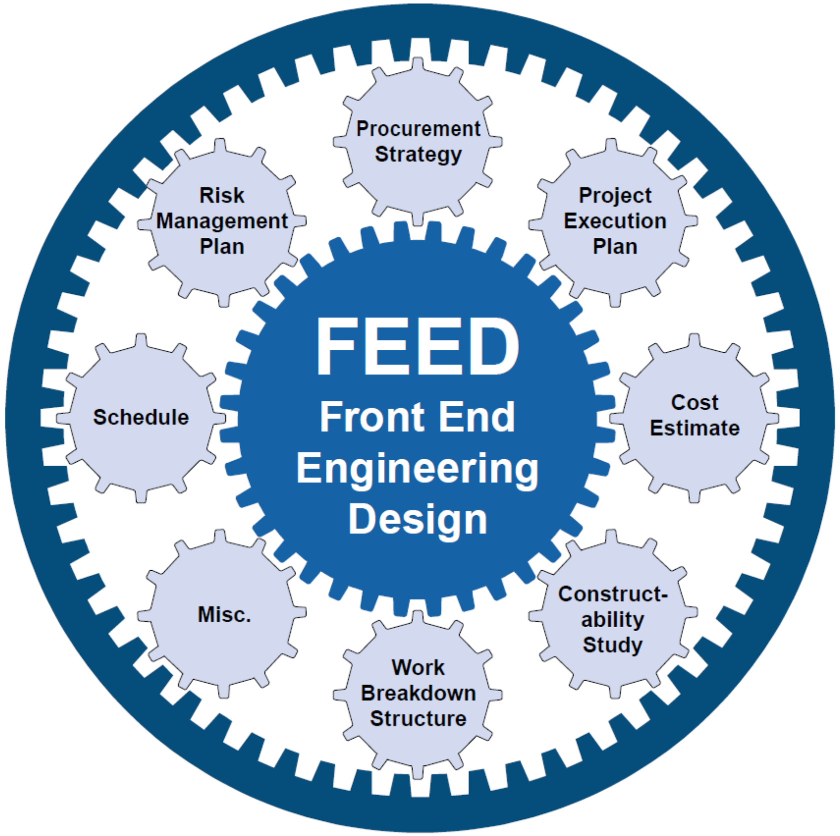
End Goal: FEED Study

- Front End Engineering Design – FEED
- **What is included in FEED:**

✓ Detailed Project Design and Cost Estimates based on quotes from vendors and EPC contractors

✓ Strategies to procure equipment and construct the facility

✓ Workflow and project plan



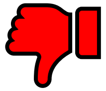
Hydrogen Economics

End Goal: Reaching a Final Investment Decision (aka FID)

How to Make an FID:

- Conduct a **FEED/Pre-Feasibility Study:** Check if design and economics make sense.

If Economics and Design  = FID (+) ive – Go ahead with proposed project

If Economics and Design  = FID (-) ive – Back to the drawing board

Shell gives go-ahead to key renewable hydrogen plant in Holland

A 200 MW electrolyser is to be built on the Tweede Maasvlakte in the port of Rotterdam and will be operational in 2025

8 July 2022 12:20 GMT UPDATED 11 July 2022 18:13 GMT

By **Nishant Ugal**

Supermajor Shell has taken a final investment decision to build a 200-megawatt electrolyser for the Holland Hydrogen I hydrogen plant, in the Netherlands.

The company announced the go-ahead for the development on Wednesday, predicting it would be "Europe's largest renewable-hydrogen plant once operational in 2025".

"The 200 MW electrolyser will be constructed on the Tweede Maasvlakte in the port of Rotterdam and will produce up to 60,000 kilograms of renewable hydrogen per day," it said.

Shell noted that the renewable power for the electrolyser will come from the offshore wind farm Hollandse Kust (Noord), which is partly owned by the company.

Grey to green

Hydrogen Economics

End Goal: Reaching a Positive Final Investment Decision

What makes a Positive FID:

- Prefeasibility Study: Estimates show capital can be raised and return on investment is achievable

- FEED: Results show that the project is technically feasible, socially acceptable and environmentally safe with the project equipment and facility deliverable within available capital limits.

Hydrogen Economics

Challenges

- The cost of low impact H_2 is still significantly high (2 x 3 times higher than fossil fuels).
- Of the US$320 billion worth of committed hydrogen projects only 10% have reached FID.

The Way Forward

- The cost of hydrogen production is decreasing as the cost of electrolyser systems and renewable energy pricing are undergoing a decrease
- There is growing support from governments and industry to incentives and bridge the cost gap to spearhead the development of a hydrogen economy.
- In light of these factors cost of H_2 is likely to reach parity with A$2/kg target by 2030.

Hydrogen Economics

Motivation for Open-Source Modelling

- The infancy of the market – there is a lack of comprehensive tools and transparency.
- Data drives the results – the variables are subjective and will vary from context to context.
- Tools can assist in benchmarking the cost and performance parameters required to achieve project parity.
- Iterative platform to build on – new and emerging technologies can be added

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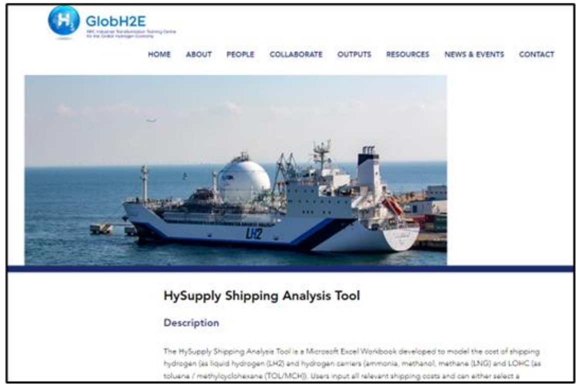
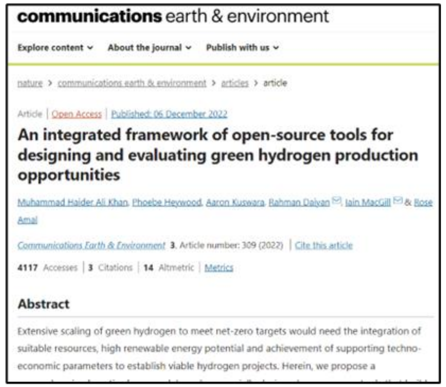
Open-Source Modelling





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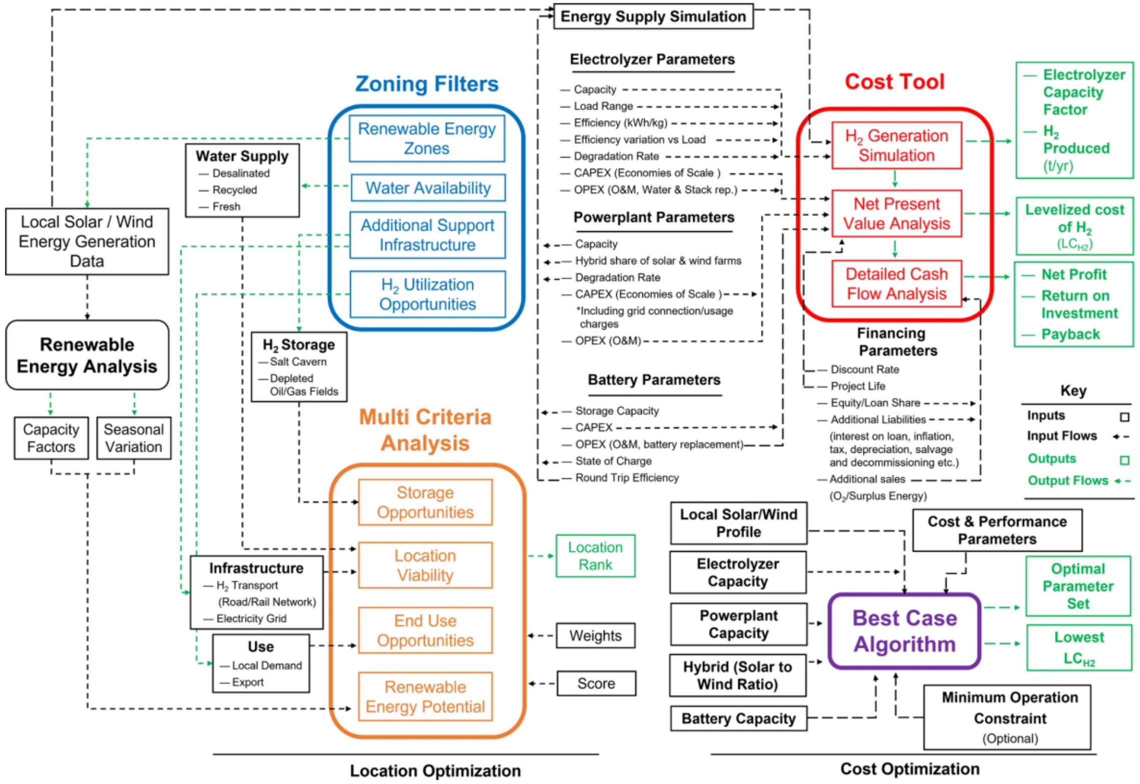
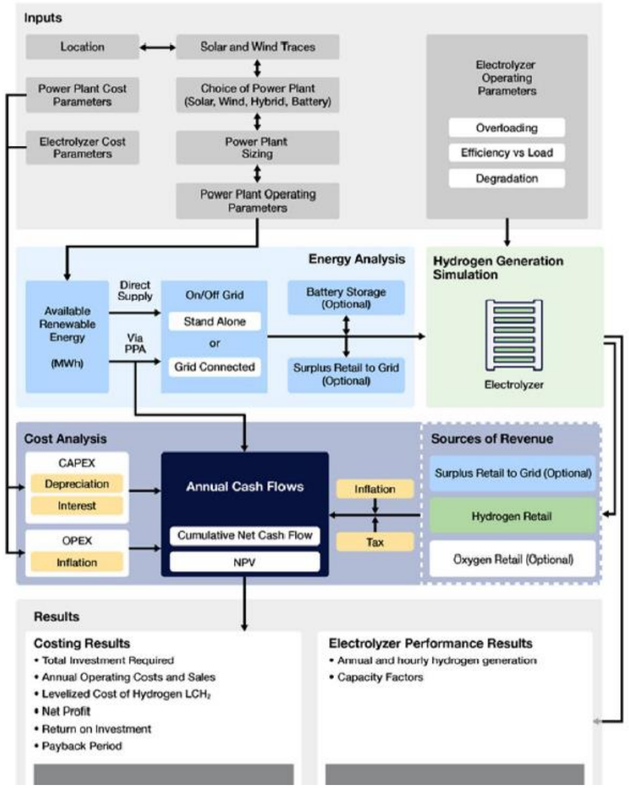
H_2 Modelling and Costing





Reference: https://www.nature.com/articles/s43247-022-00640-1

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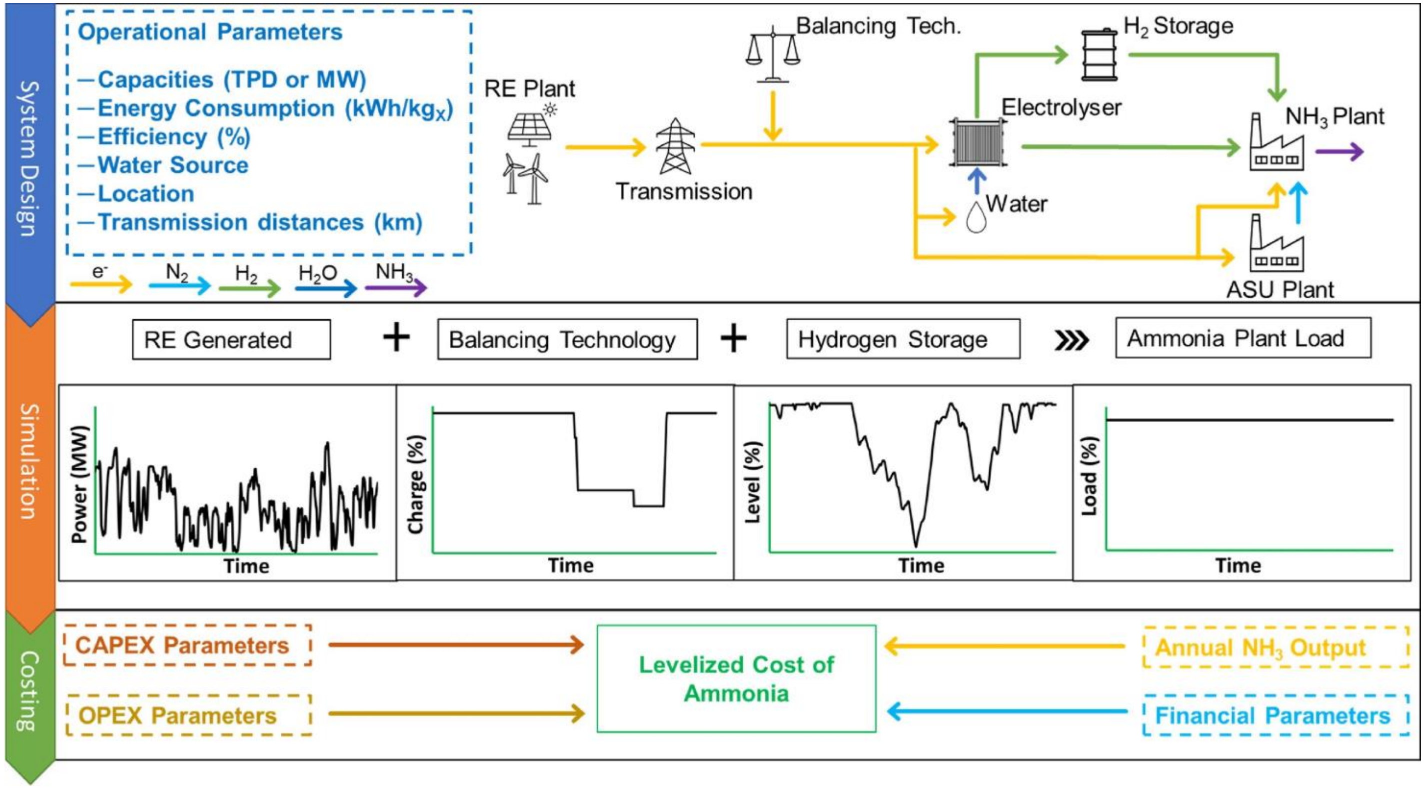
Ammonia Modelling and Costing



Reference: https://www.sciencedirect.com/science/article/pii/S0196890422011918

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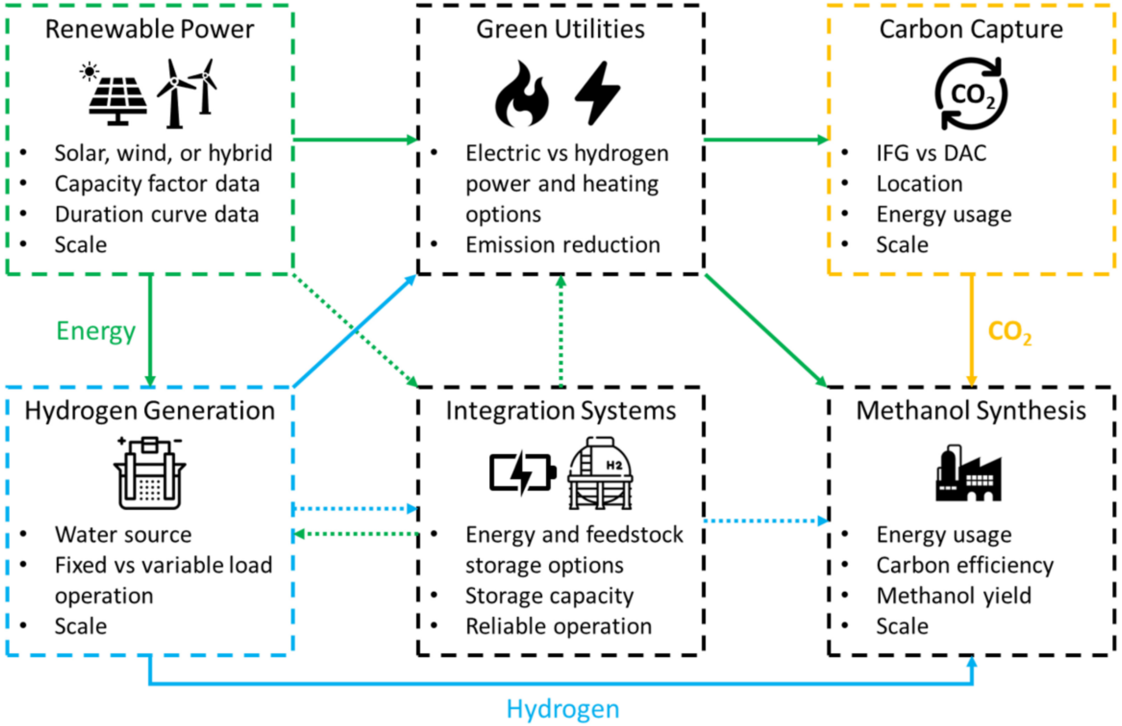
Methanol Modelling and Costing



Reference: https://www.sciencedirect.com/science/article/pii/S0360319923019560

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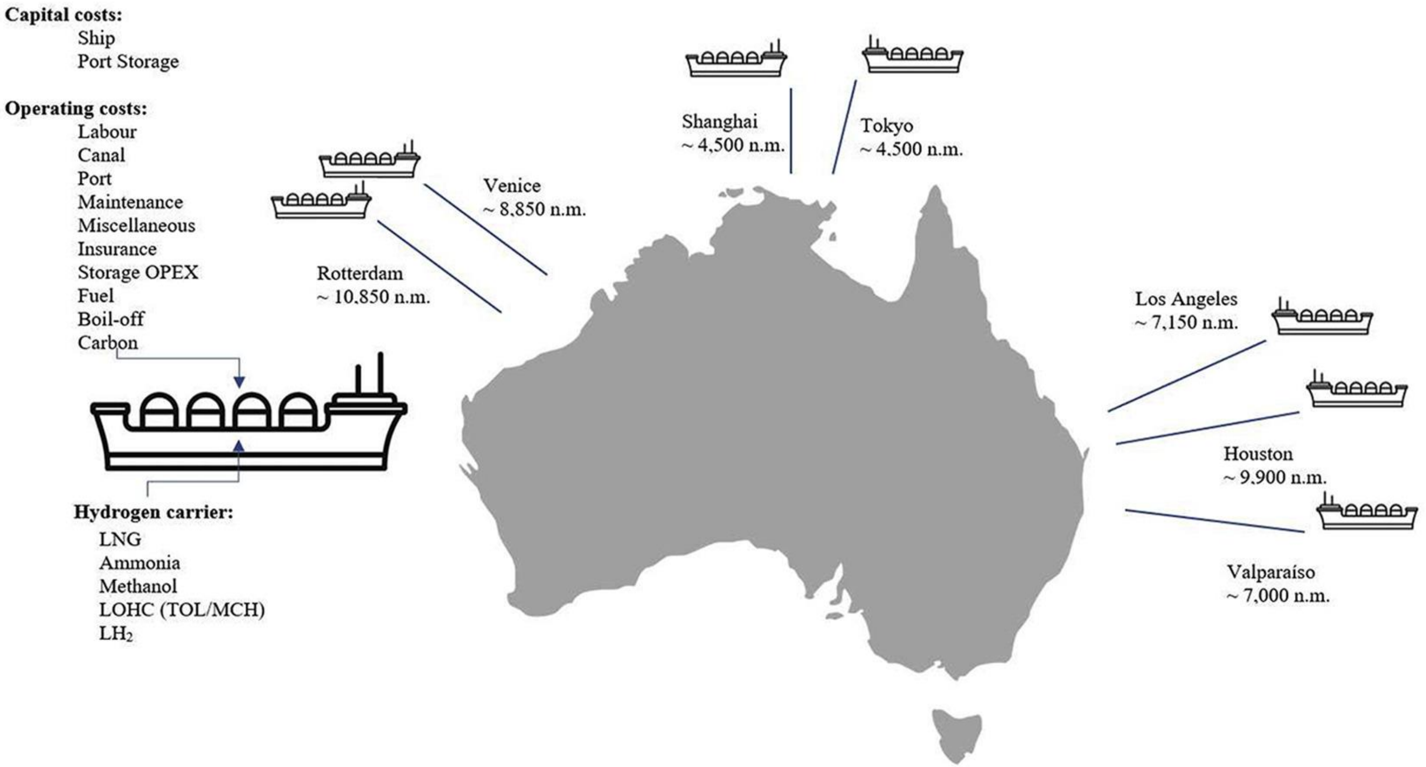
Hydrogen Export Costing



Reference: https://www.sciencedirect.com/science/article/pii/S0360319922017281

Hydrogen Economics

Impact