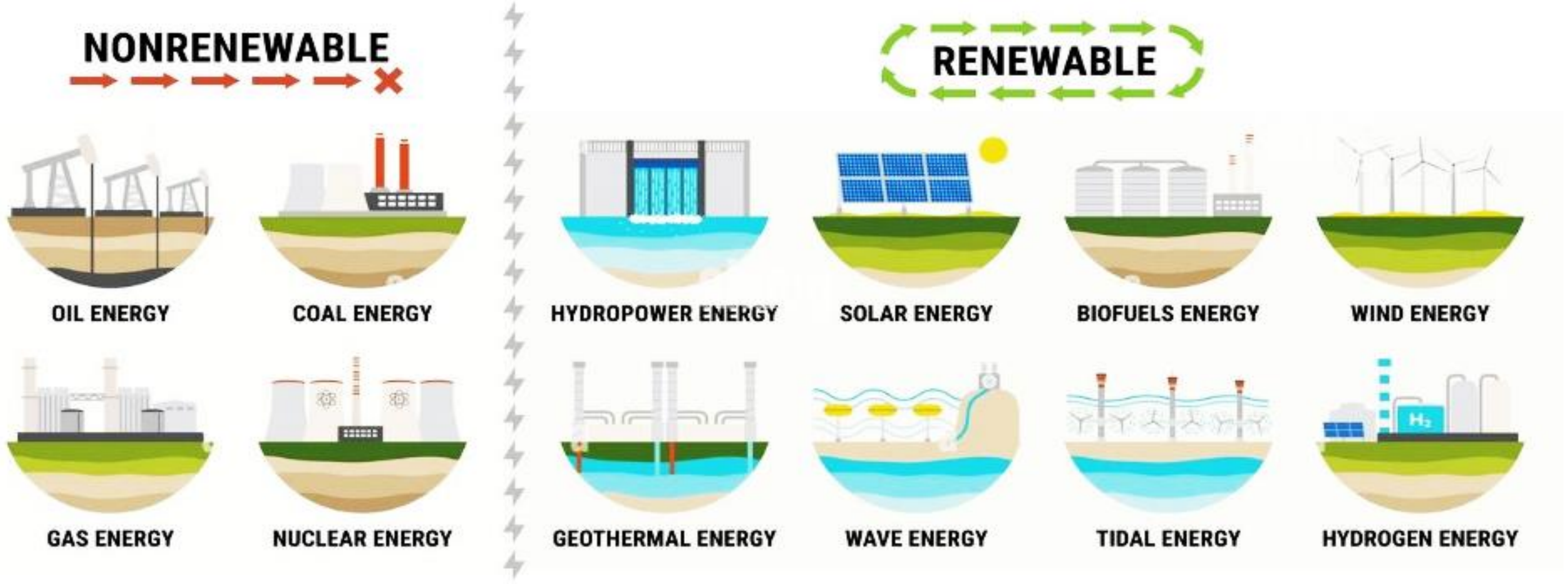
GREEN HYDROGEN: THE ENERGY OF THE FUTURE ESSENTIAL FOR DECARBONISATION

“TIIAME”
National Research University



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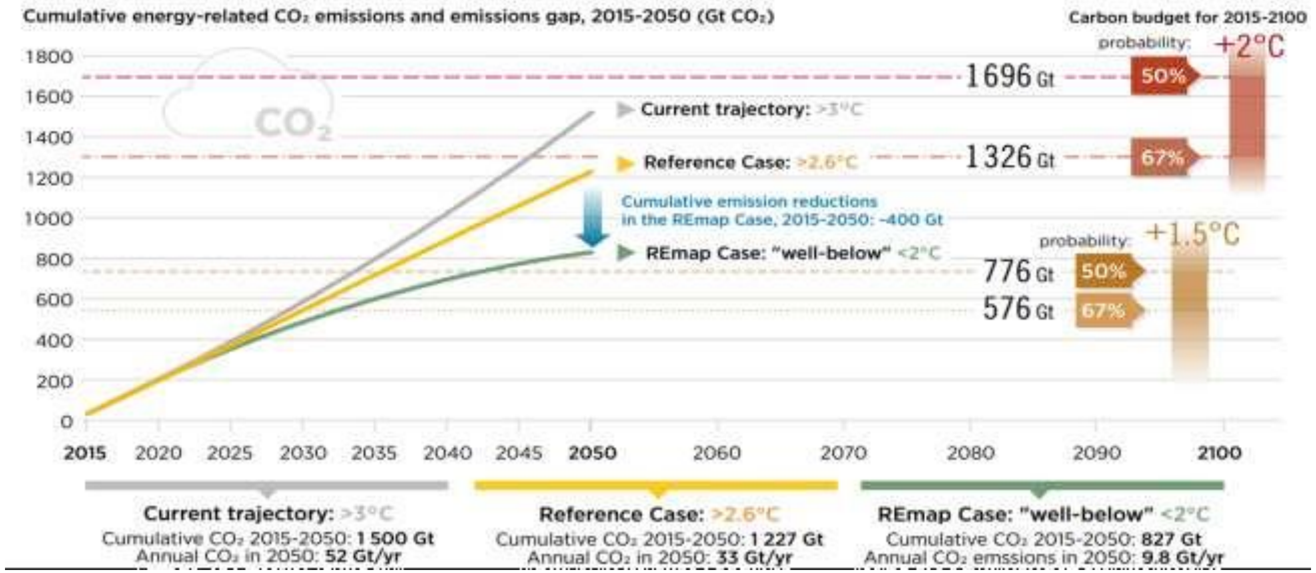
CLIMATE CHANGE ACCELERATION

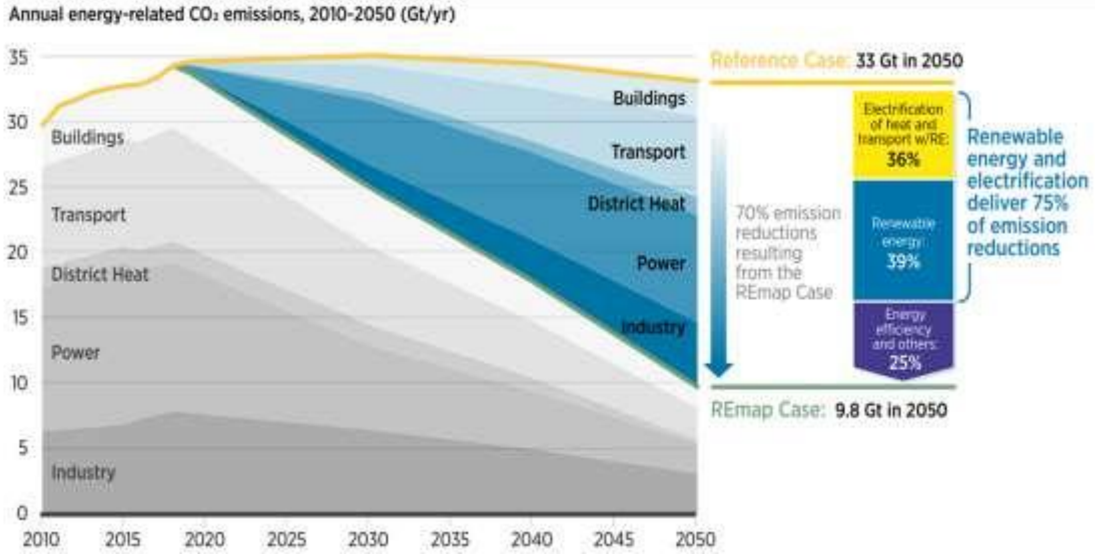
Climate change is accelerating

- CO_2 emission increased 1.5%/year for last 5 years
- Paris agreement: temperature rise less than 2^0C, preferably 1.5^0 C



Ways to achieve net zero

- Energy Intensity/efficiency
- Structural Changes
- Deployment of Renewable Solutions



WHY HYDROGEN & WHY NOW

1 — 1800 — Beginning

Discovery of H2 and production by electrolysis

2 — 1850 — Fuel Cells

Combining H2 & O2 to generate electricity & water

3 — 1900 — Hydrogen engine

- ✓ IC engines for trucks, buses – using Hydrogen and Hydrogen mixtures

4 — 1950 — Space & Aviation

- ✓ Flights from Germany to US.
- ✓ Formation of NASA largest known consumer of LH2

5 — 1975 — Hydrogen Economy

- ✓ OPEC Oil Embargo
- ✓ International Energy Agency (IEA) for R&D of H2 Technologies

6 — 2000 — Green Hydrogen

- ✓ Solar powered Hydrogen
- ✓ Fuel Cell vehicle
- ✓ H2 Fuel station in Germany

7 — 2016 — Climate Accords

Paris Climate Agreement for

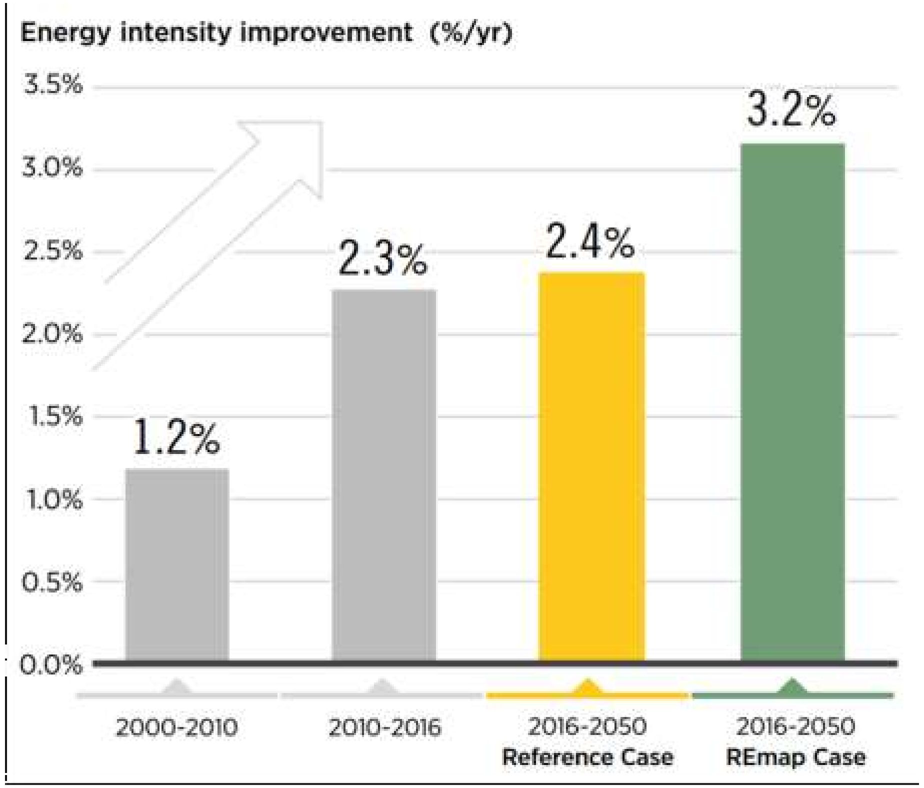
- ✓ Reduction of Emission and
- ✓ Net zero by mid 21st Century

8 — 2023 — GHM Of INDIA

- ✓ Energy independent by 2047
- ✓ Net zero by 2070

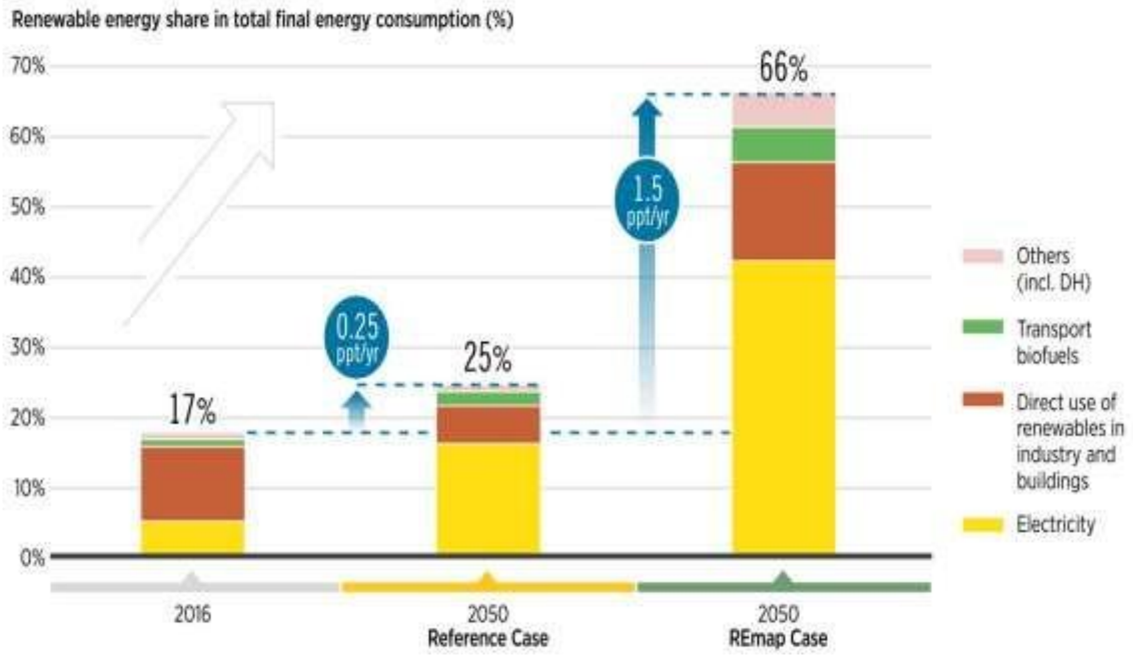
Information source: Fact sheet series – 1, The history of hydrogen by Hydrogen association. For more details see reference section.

PROJECTED ENERGY INTENSITY AND RENEWABLE ENERGY SHARE



- The energy intensity improvement rate would need to increase to 3.2% per year. This is higher than the improvements in recent years (2.3%) or projected in the Reference Case (2.4%).

Renewables share in total final end-use consumption needs to 66%



Hydrogen as renewable energy can catalyse disruptive technology to combat global warming

IRENA Global Energy Transformation,2019

WHY HYDROGEN?

Energy Efficient

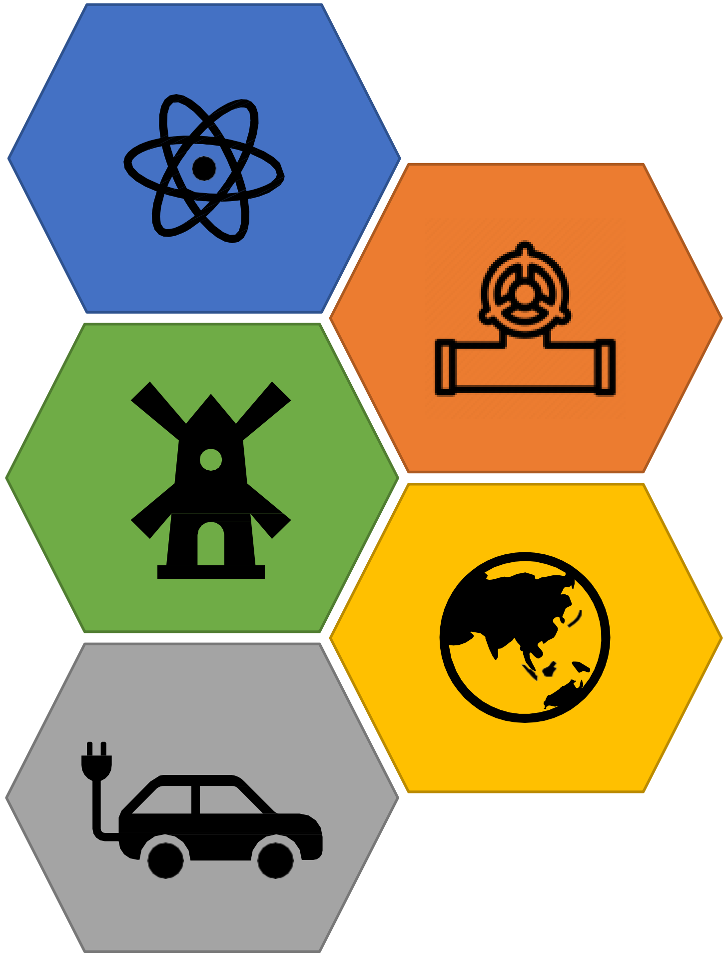
- Gaseous hydrogen contains nearly three times more energy per unit mass than gasoline: **141.90MJ/Kg of H_2 vs 47.40MJ/Kg of gasoline**

Zero Emissions fuel

- Leaves no carbon footprint
- Ideal for future zero-carbon power supply demands.

Fast Charging and Long Usage

- Hydrogen fuel cells can be recharged in under five minutes, in contrast to electric vehicles takes 30 to several hours for same driving range.



Versatile

- Hydrogen fuel cells will be able to supply power for:

  Mobile

  Stationary

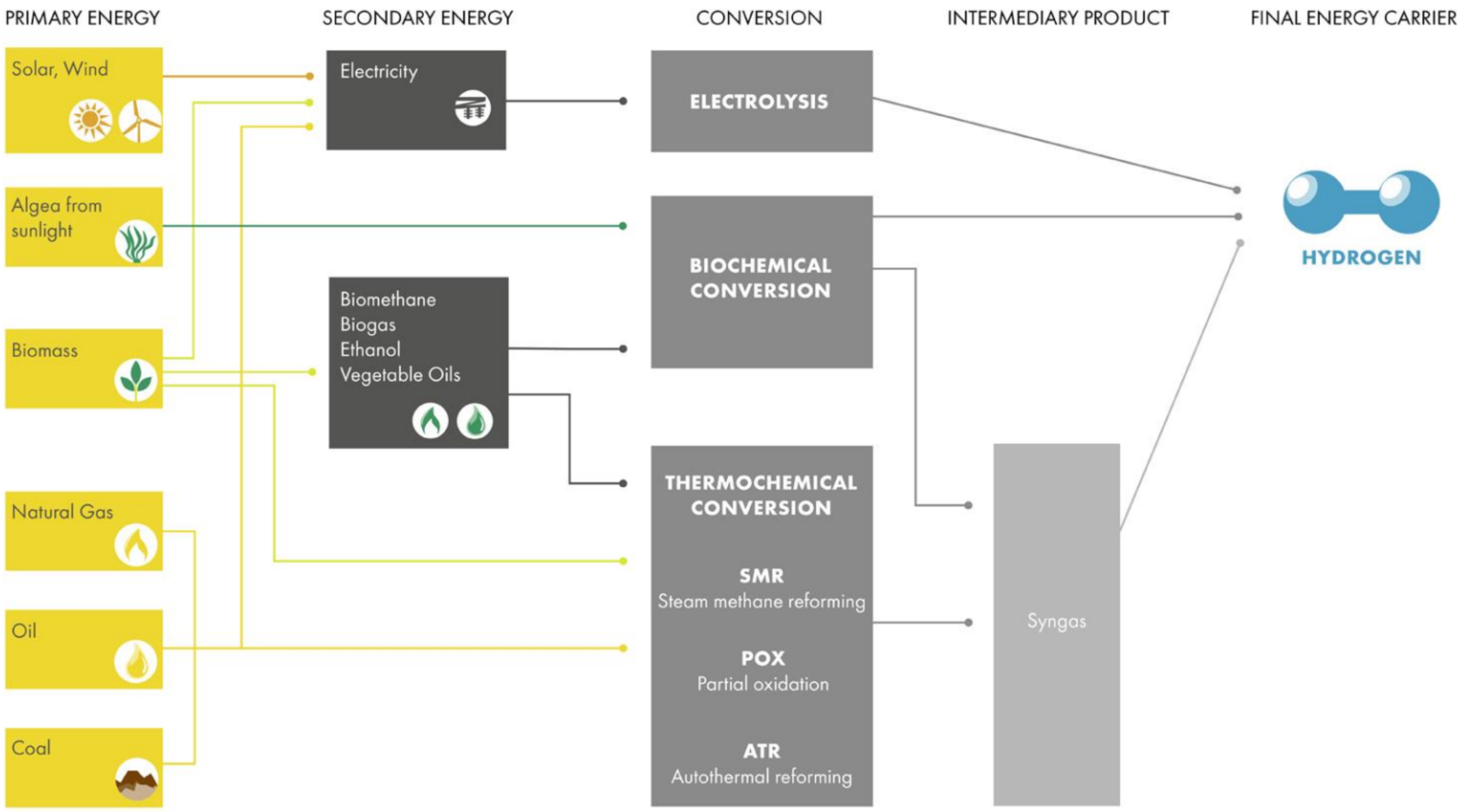
  Transportation: Pipelines and Tube trailers

Energy self-reliance

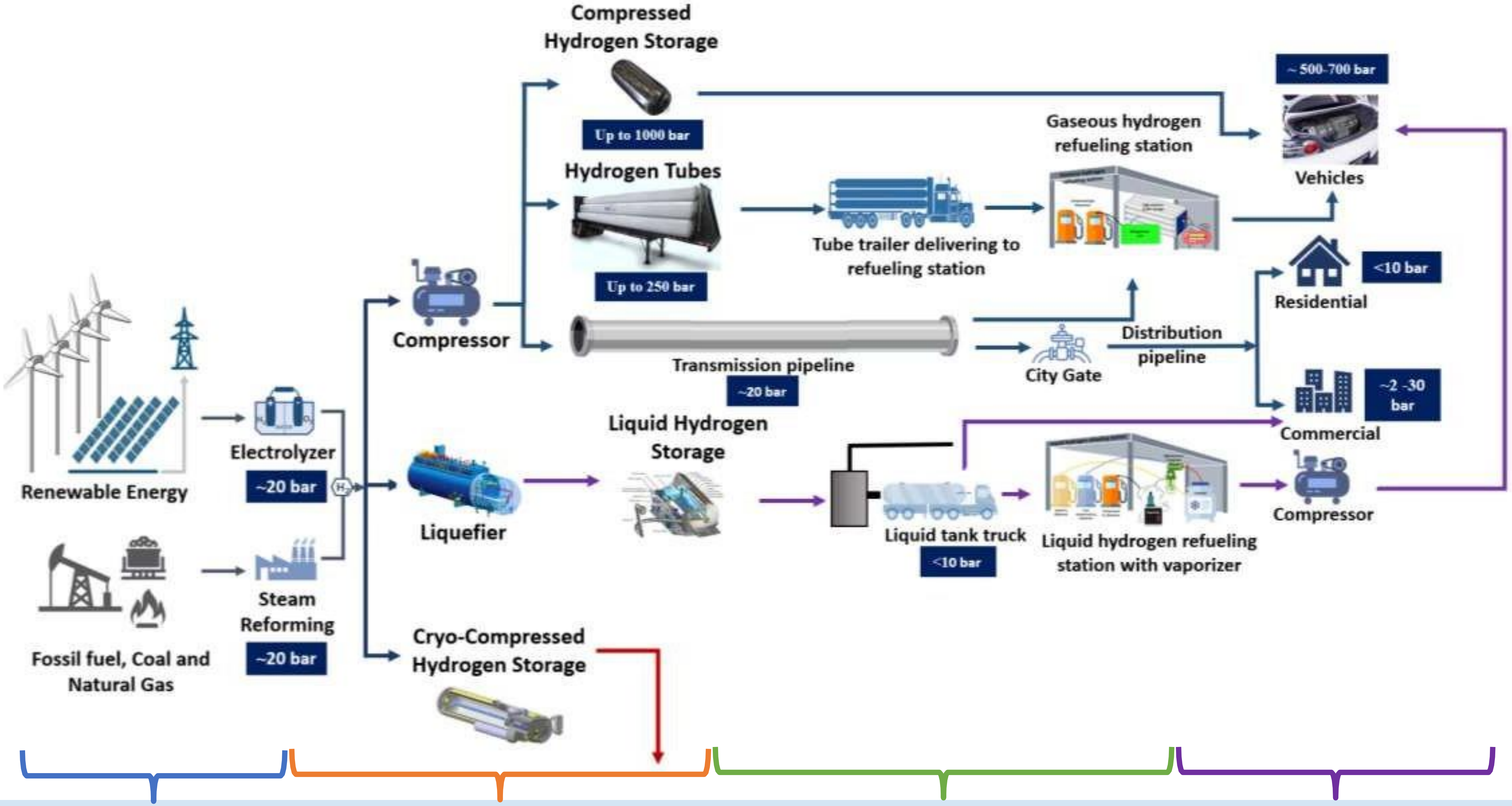
- Reduce the nation's reliance on fossil fuels.

One of the prime objective of the **Nation Hydrogen Energy Mission**

PROCESSES FOR PRODUCING HYDROGEN



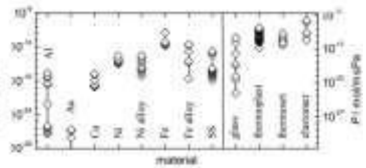
ENERGY SQUARE: HYDROGEN PATHWAYS



HYDROGEN STORAGE & DISTRIBUTION: TECHNICAL CHALLENGES

Molecular Size

- Smallest in size
- Easily pass through metallic and non-metallic material

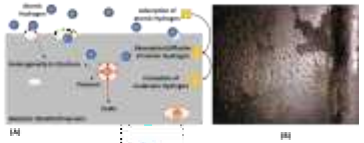


Hydrogen Permeation

Diffusivity

- Four-time higher diffusion coefficient compared to natural gas
- Rapid gas escape forming flammable gas in air

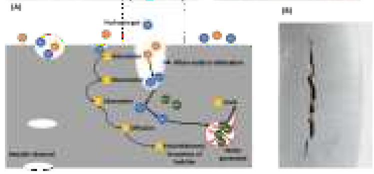
Fire Safety Issue



Hydrogen Blistering

Reactivity

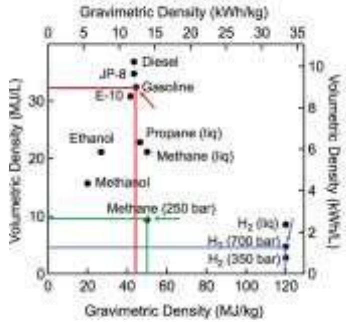
- Highly reactive
- Combines with most elements to form hydride



Hydrogen Embrittlement

Density

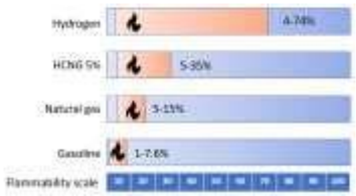
- Seven times lighter than natural gas
- Low volumetric energy density



High gravimetric but low volumetric density

Flammability

- Highly flammable gas
- Flammability range of 4-74 vol% in air

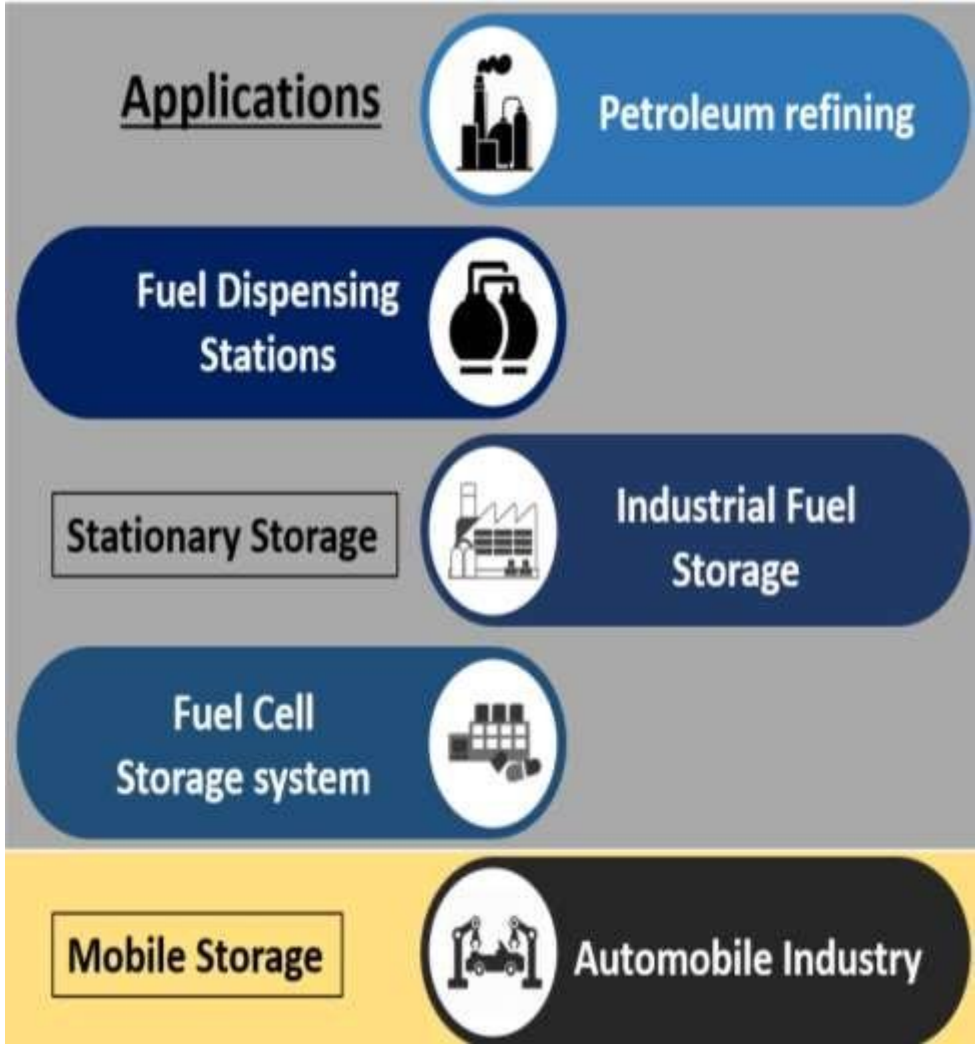


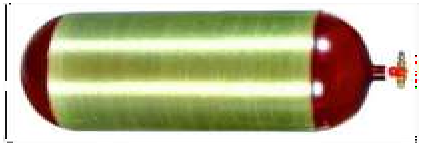
Flammable hydrogen clouds formation

COMPRESSED HYDROGEN STORAGE: PRESSURE VESSELS

Pressure vessels are the containers for storing energy fluids under high pressure.

Single phase (Gaseous). Operating pressure: up to 1000 bar. Operating temperature: -40 to 85°C



Type	Vessel Geometry	Description	Material of construction	Operating Pressure	History
I		Metallic vessel	Stainless-Steel, Aluminium, Iron	upto 300 bar	1880 for military use
II		Metallic vessel/liner + Composite hoop wrapped	**Liner material:** Stainless-Steel, Aluminium, Iron **Composite Material:** Glass, carbon, Kevlar.	No limit	
III		Metallic liner + Composite over wrapped	**Liner material:** Stainless-Steel, Aluminium, Iron **Composite Material:** Glass, carbon, Kevlar.	Upto 700 bar	
IV		Polymeric liner + Composite over wrapped	**Liner material:** Stainless-Steel, Aluminium, Iron **Composite Material:** Glass, carbon, Kevlar.	Upto 1000bar	2001, 1st prototype demonstration
V		Linerless, Fully composite vessel	**Liner material:** No liner **Composite Material:** carbon, other material may be used	Upto 10.3 bar	2010 Developed by Composite Technology Development Inc

TANK SIZE OF HYDROGEN-POWERED DIFFERENT SUB-SECTORS OF THE TRANSPORTATION INDUSTRY

Toyota Mirai car travels 590kms

5Kgs in 120L @70MPa or a 217L tank @35MPa

HGV H_2 truck by TEVVA travels 400kms

35Kgs in six roof-mounted tanks

300L tanks @35MPa

H_2-Trains in China travel 500kms back and forth carrying 1500 passengers

99Kgs in ten tanks

~430L tank @35MPa

Double Decker Bus by Wrightbus travels 450kms

27Kgs in six tanks

~200L tanks @35MPa

CaetanoBus by Toyota travels 400kms

37.5Kgs in five tanks

~325L roof-mounted tank @35MPa

EWRC Hydrail in Germany for 800kms

130Kgs in fifteen tanks

~380L roof-mounted tank @35MPa

Xcient trucks by Hyundai travels 400kms

31Kgs in seven tanks ~200L tank @35MPa

TVS H_2 scooters travels 200kms

0.4Kg in a 10L tank @70MPa

TANK SIZE OF HYDROGEN-POWERED DIFFERENT SUB-SECTORS OF THE TRANSPORTATION INDUSTRY

- Compressed hydrogen gas-powered aircraft for long-duration journeys; **Pathfinder and Helios** (Curry, 2003)
- Aircraft powered using hydrogen fuel cells; by **Boeing, Airbus**, etc (Waddington et al., 2021; Y. Zhang, 2022)

https://www.nasa.gov/centers/armstrong/news/FactSheets/FS-068-DFRC.html

- Public transportation using hydrogen; **Chicago, Vancouver, London, and Beijing**, etc. (Das et. al., 2023)

https://www.bloomberg.com/news/articles/2022-02-14/hydrogen-cars-and-buses-seize-the-spotlight-at-beijing-s-winter-olympic-games

- Fuel cell-powered taxis; **Europe.**
- Hydrogen-powered police fleet vehicles; **United States.** (Police, 2022)

https://www.euractiv.com/section/energy/news/hydrogen-taxis-could-be-the-next-big-thing/

Break Through Applications of Compressed Gaseous Hydrogen

https://www.autonews.com/mobility-report/hyundai-launches-us-hydrogen-fuel-cell-truck-strategy

- Carrier vehicles operating on hydrogen for lifting purposes; **Nikola motors, Hyundai Toyota, Kenworth Truck Company**, etc. (Pedrazzi et al., 2022)

https://www.metrorailnews.in/hydrogen-powered-trains/

- Hydrogen-powered trains; **Germany,** under its **Hydrail project** (Palmer, 2022)

:https://www.nrl.navy.mil/Media/News/Article/2498102/nrls-hybrid-tiger-uav-soars-at-demonstration/#:~:text=Group%202%20UAVs%20are%20typically,its%20longest%20flight%20to%20date.

- Gaseous hydrogen powered air vehicle; **Hybrid Tiger,** 26hr endurance in 2008 in developed nations like the US, Germany, etc. (Stroman et al., 2018)

HYDROGEN STORAGE METHODS

PHYSICAL

- Compressed Gaseous Hydrogen CGH_2 (350, 700 bar)
- Liquefied Hydrogen LH_2
- Cryo-compressed Hydrogen CcH_2
- Slush Hydrogen SH_2

MATERIALS-BASED

- Metal Hydrides
- Liquid Organic Hydrogen Carriers LOHCs
- Sorbents (MOFs, Zeolites, Nanotubes)

HYDROGEN STORAGE

Liquid Hydrogen Storage: Cryo tanks

Single phase (Liquid), Higher storage density than compressed
Operating pressure: <10 bar
Operating temperature: -253°C

Traditional Problems

- Cryo temperature cause most material to become Brittle.
- Traditional material have higher thermal conductivity. Therefore, required more super insulation.
- Heavy in weight
- Low fatigue resistance

- ***Heat Inleak***

Spherical storage tanks to minimize interaction between the tank and outside world.

- ***Vacuum insulation***

Consists of two walls, with a layer of high-vacuum in between. Provides extremely high insulation value and also help contain leak.

- ***Boil-off Losses***

Pre-cooling the cryogenic tank with liquid nitrogen. (Ghaffari-Tabrizi et. al., 2022)

CRYOLOR developed innovative solutions:
• A wide range of sizes: from 20 to 75m^3
• High performance, with a Normal Evaporation Rate (NER) < 1 % per day
• Dedicated design for LH_2 transfer pumps

https://www.cryolor.com/cryogenic-storage-tanks/liquid-hydrogen-storage

Toray Advanced Composites developing a long-life, fully composite liquid hydrogen tank for civil aviation.

https://www.innovationintextiles.com/composite-project-for-liquid-hydrogen/

HYDROGEN STORAGE

- Super-insulated tanks; manufactured by **Air Liquide, Linde**, etc.
- Signature fuel for many space programs and satellite launching (Gomez & Smith, 2019; Kang et al., 2022).

Liquid Hydrogen Tank at NASA's Kennedy Space Center since 1966

https://commons.m.wikimedia.org/wiki/File:Liquid_Hydrogen_Tank_at_NASA%27s_Kennedy_Space_Center.png

- Hydrogen powered commercial rockets; **United Launch Alliance, Blue Origin, Boeing,** etc.
- Liquid oxygen and hydrogen as their rocket propulsion fuel; **European rocket Ariane 5, Atlas, Boeing's Delta III, and Delta IV** (Cecere et. al., 2014)

https://www.esa.int/Enabling_Support/Space_Transportation/Launch_vehicles/Ariane_5

Break Through Applications of Liquid Hydrogen

- Liquid hydrogen powered aircraft for long-duration journeys; **Upgraded Pathfinder and Helios** (Turk et al., 2022)
- Liquid hydrogen powered air vehicle; **Hybrid Tiger,** 48hr endurance in 2010 (Stroman et al., 2018)

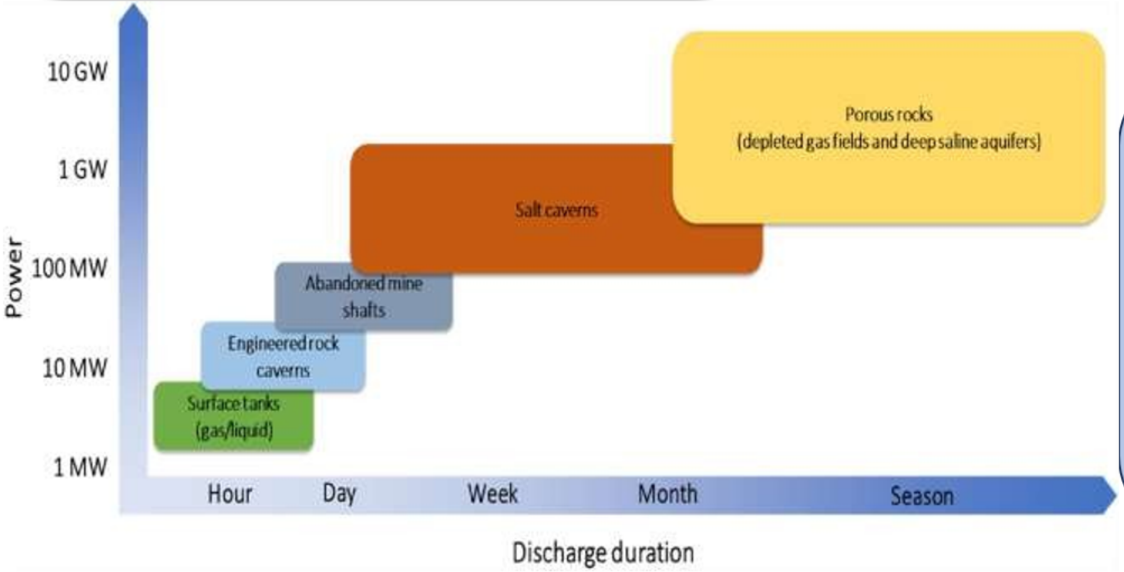
- Powering non-vital parts of the aircraft using liquid hydrogen; **Hycarus project,** a coalition between **Air Liquide, Zodiac Aerospace, Dassault Aviation, and the CEA** (Sparano et. al., 2023)

https://advancedtech.airliquide.com/air-liquide-partner-hycarus-project

HYDROGEN STORAGE

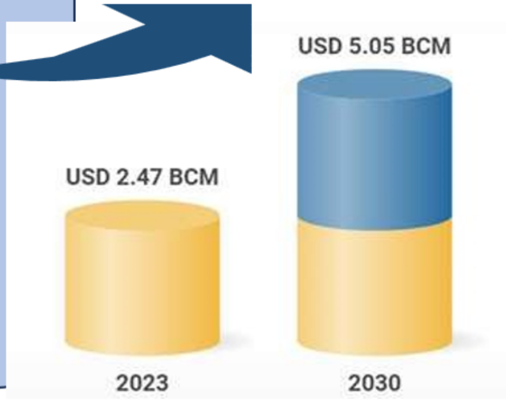
Underground Storage

Excess hydrogen is stored such that it is readily available for its sudden demand or can be set aside without too much processing.



Geological storage options of hydrogen with their corresponding storage power and discharge time. Ranges for each option reflect variations in storage site size and operational management (e.g. number of production wells). (Miocic et. al., 2023)

The global underground hydrogen storage market size; expected to reach 5.05 billion cubic meter by 2030.
Market expansion; compound annual growth rate of 10.7% from 2023 to 2030.



https://www.globenewswire.com/en/news-release/2023/05/19/2672604/28124/en/Global-Underground-Hydrogen-Storage-Market-Report-2023-Players-Include-Linde-Engie-Uniper-and-Texas-Brine.html

- An average cavern is of 60 m in diameter, 300 m in height, and filling pressure of 175 bar can contain 100 million Nm^3 of working gas which is equal to 300 GWh of energy produced by hydrogen (NEA, 2022)
- Till 2010, there were 642 underground hydrogen storages, most of them were located in North America, including 399 in the US and 50 in Canada.
- Europe was in second place with 130, followed by the CIS (Commonwealth of Independent States) countries (50), Asia and Oceania (12), and one facility in South America and one in Argentina (Haratian et al., 2022; Tarkowski, 2019)

HYDROGEN STORAGE

https://hydrogencouncil.com/en/first-eu-supported-large-scale-green-hydrogen-underground-storage-demonstrator-takes-shape/

Construction of the first green hydrogen storage demonstrator in a salt cavern is underway in France.

Break Through Applications of Underground Hydrogen Storage

The **Chevron Phillips Clemens Terminal in Texas** has stored hydrogen since the 1980s in a solution-mined salt cavern.

https://www.cpchem.com/locations/north-america/brazoria-county-texas

Rock cavern hydrogen gas storage facility; HYBRIT's pilot facility at **Svartöberget in Luleå, Sweden** which will test run until 2024.

https://www.ssab.com/en/news/2022/06/hybrit-a-unique-underground-fossilfree-hydrogen-gas-storage-facility-is-being-inaugurated-in-lule

HYDROGEN STORAGE

Type-IV CNG Gas Storage Pressure vessel: Manufacturing and Testing of Developed Prototype

Completed

Type-IV (CNG)
Sponsored by: GAIL India Ltd. (Gas Authority of India Limited)
Vessel Type : Type-IV (CNG)
Liner : Nylon-6
Composite : carbon-epoxy
Volume : 70Lt
Operating pressure: 350 bar
Burst Pressure : >750 bar
Driving Range : 149Km
Patent granted : 2020

Serial Number	Burst Pressure	Average experimental burst pressure	Theoretical burst pressure using model A	Theoretical burst pressure using model B
Prototype 1	773 bar			
Prototype 2	799 bar	797.3 bar	732.5 bar	796.4 bar
Prototype 3	820 bar			

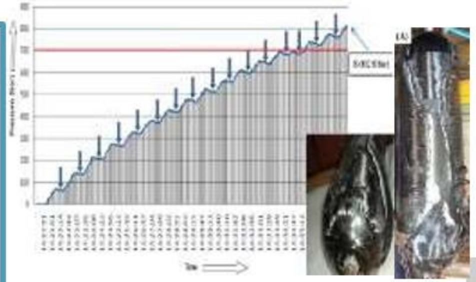
Prototype Burst Test

Final prototype

Type-III H_2 Gas Storage Pressure vessel: Manufacturing and Testing of Developed Prototype

Ongoing

Type-III (H_2)
Sponsored by: IOCL (Indian Oil Corporation Ltd)
Vessel Type : Type-III (H_2)
Liner : Aluminium Alloy
Composite : carbon-epoxy
Volume : 57Lt
Operating pressure: 350 bar
Burst Pressure : >700 bar
Driving Range : 177Km
Patent filed : 2021 (Under revision)

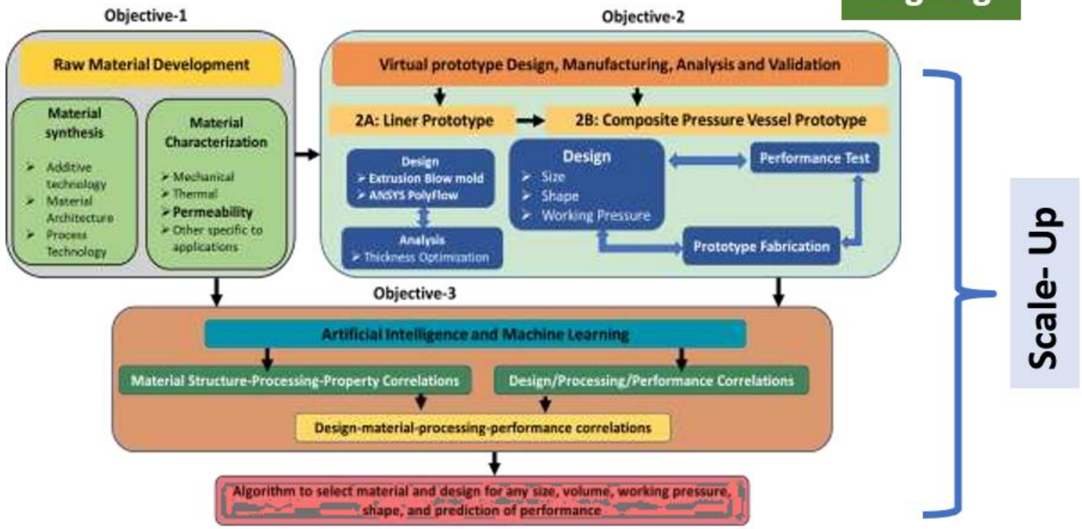


Prototype Burst Test

Final prototype

IC-MAP on Bioenergy and Hydrogen

Ongoing



Liner Development Technology: Type-IV

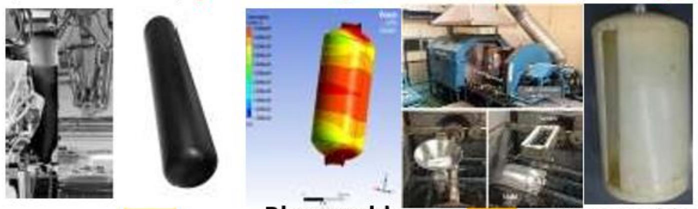
Ongoing

- HDPE/PA6/PET are common materials for liner.
- **HDPE** and **PA6**(Ube nylon 1218IU and DSM FEL 40HP* are commercialised materials.

➢ **Low** hydrogen gas **permeability** **(ISO 15869/ISO 15105/ASTM 1434)**

➢ **Manufacturing**

- Blow mold [A]
- Roto mold [B]
- Injection mold



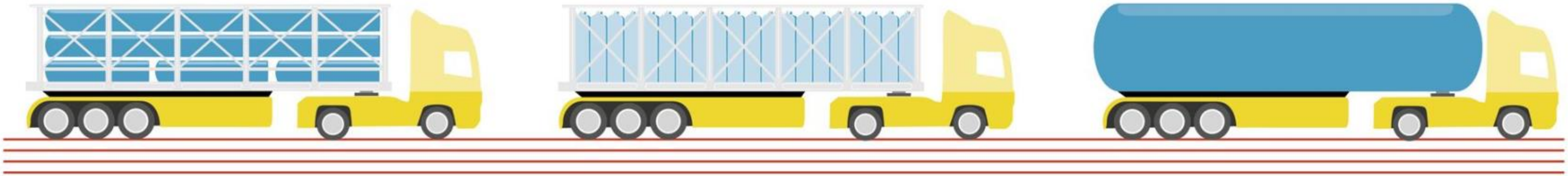
A

Blow mold in ANSYS

B

Roto molded 2li6ner

HYDROGEN ROAD TRANSPORT



TUBE TRAILER

200 – 250 bar, ≈ 500 kg, ambient temperature

CONTAINER TRAILER

500 bar, ≈ 1,000 kg, ambient temperature

LIQUID TRAILER

1 – 4 bar, ≈ 4,000 kg, cryogenic temperature

HYDROGEN DISTRIBUTION SOLUTIONS

Hydrogen Delivery Modes

Gaseous Hydrogen

Tube Trailers

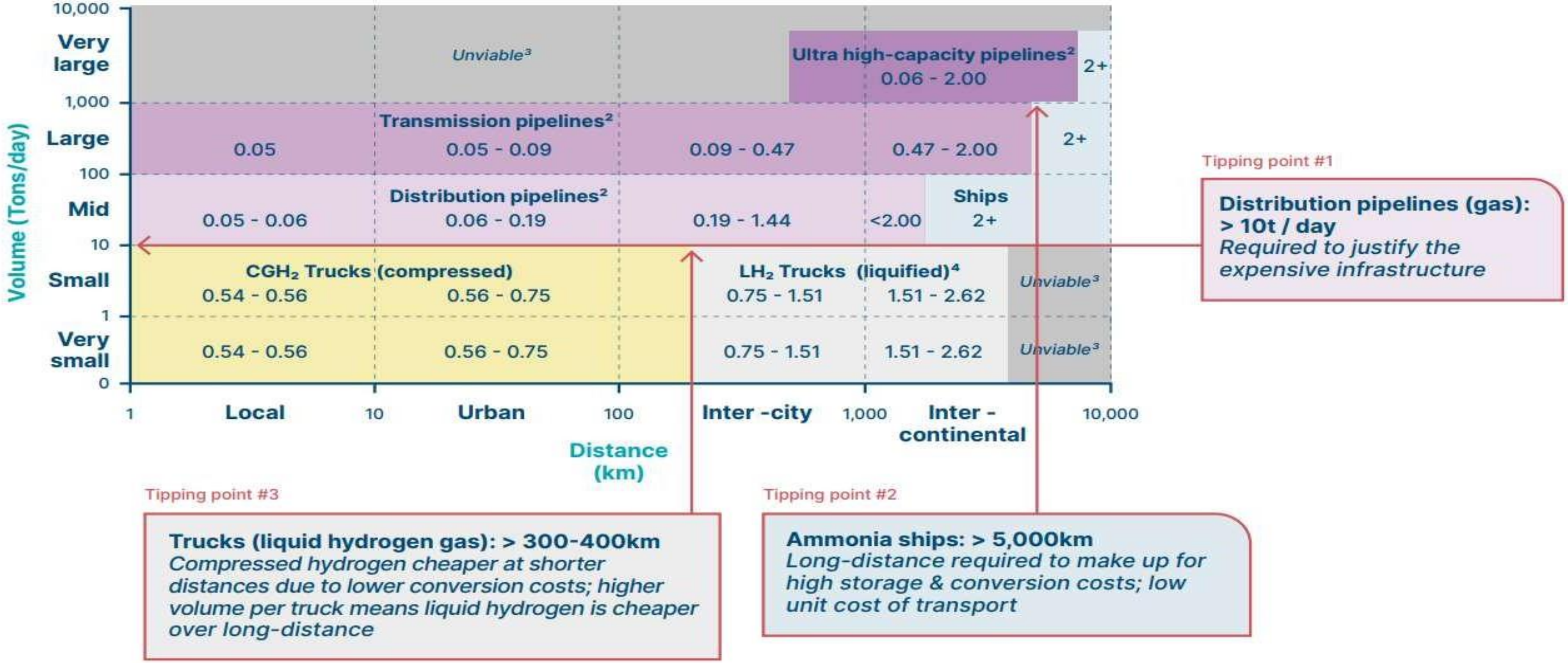
Pipeline

Liquid Hydrogen

Liquid Hydrogen Delivery

DIFFERENT MODES OF HYDROGEN TRANSPORTATION

Lowest cost form of hydrogen transportation[1] based on volume and distance
$/kg H_2

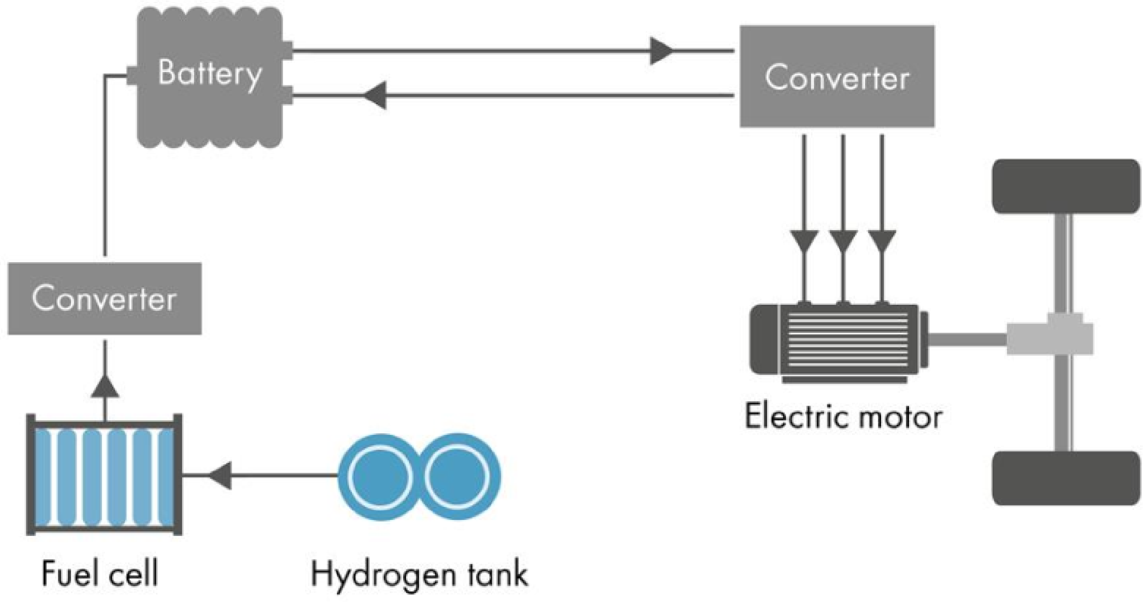


NOTE: [1] Including conversion and storage; [2] Assumes salt cavern storage for pipelines; [3] Ammonia assumed unsuitable at small scale due to its toxicity; [4] While LOHC (liquid organic hydrogen carrier) is cheaper than liquid hydrogen for long distance trucking, it is unlikely to be used as it is not commercially developed.

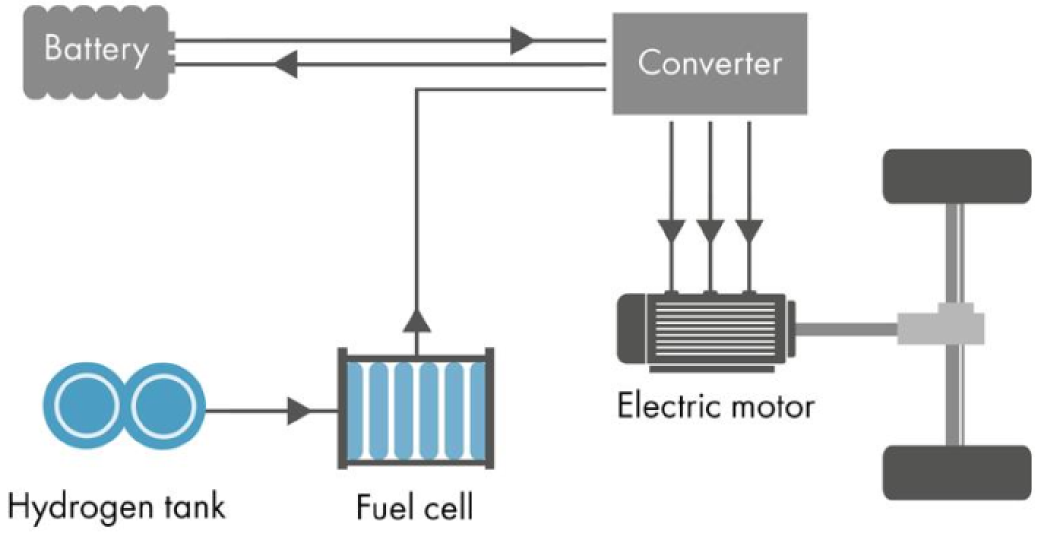
SOURCE: Adapted from BloombergNEF (2019), *Hydrogen: The Economics of Transport & Delivery*, Guidehouse (2020), *European Hydrogen backbone*

FUEL CELL CONCEPTS FOR PASSENGER CARS

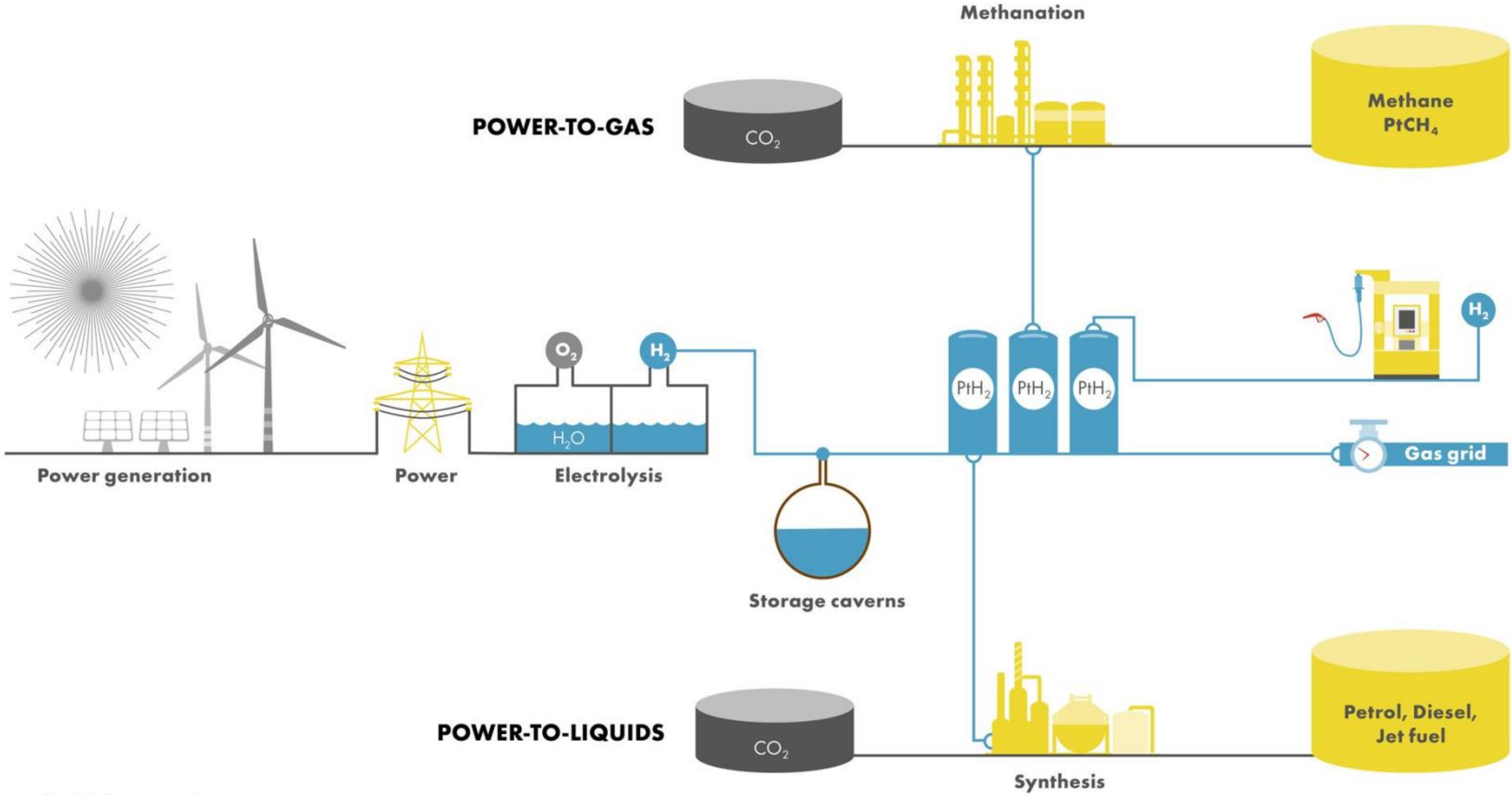
BEV WITH RANGE EXTENDER



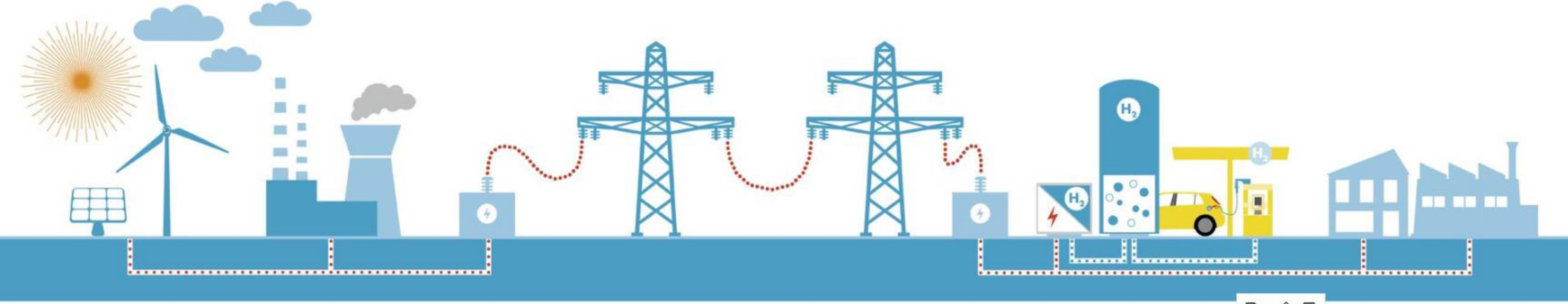
FUEL CELL-DOMINANT SYSTEM



SECTOR COUPLING



SUPPLY PATHWAYS: DECENTRALISED HYDROGEN PRODUCTION ON A RETAIL SITE



HOW DOES IT WORK?

Thank you very much for your attention!

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