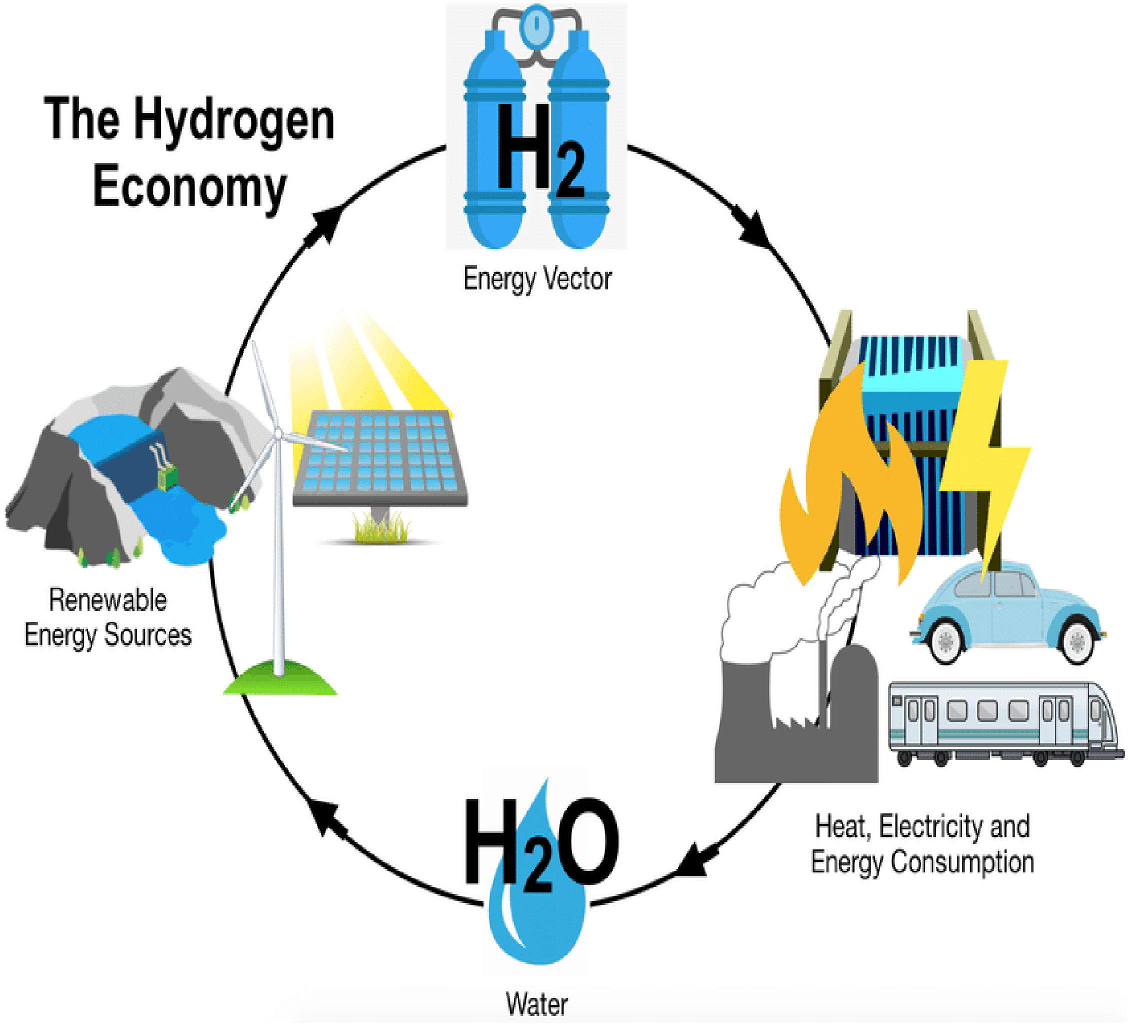
Various Facets of Hydrogen – Status and Challenges

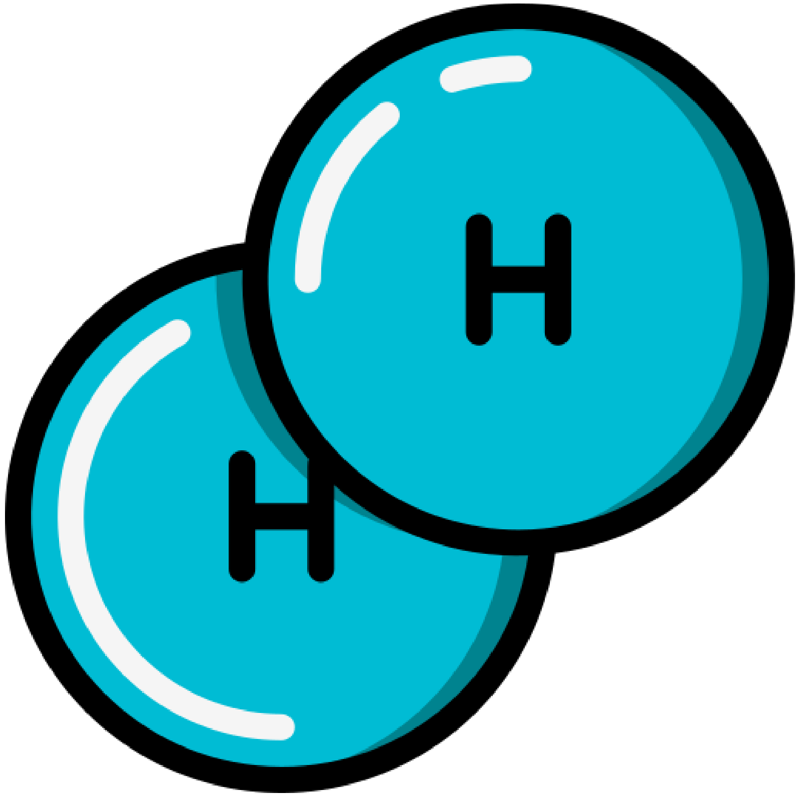


By:-

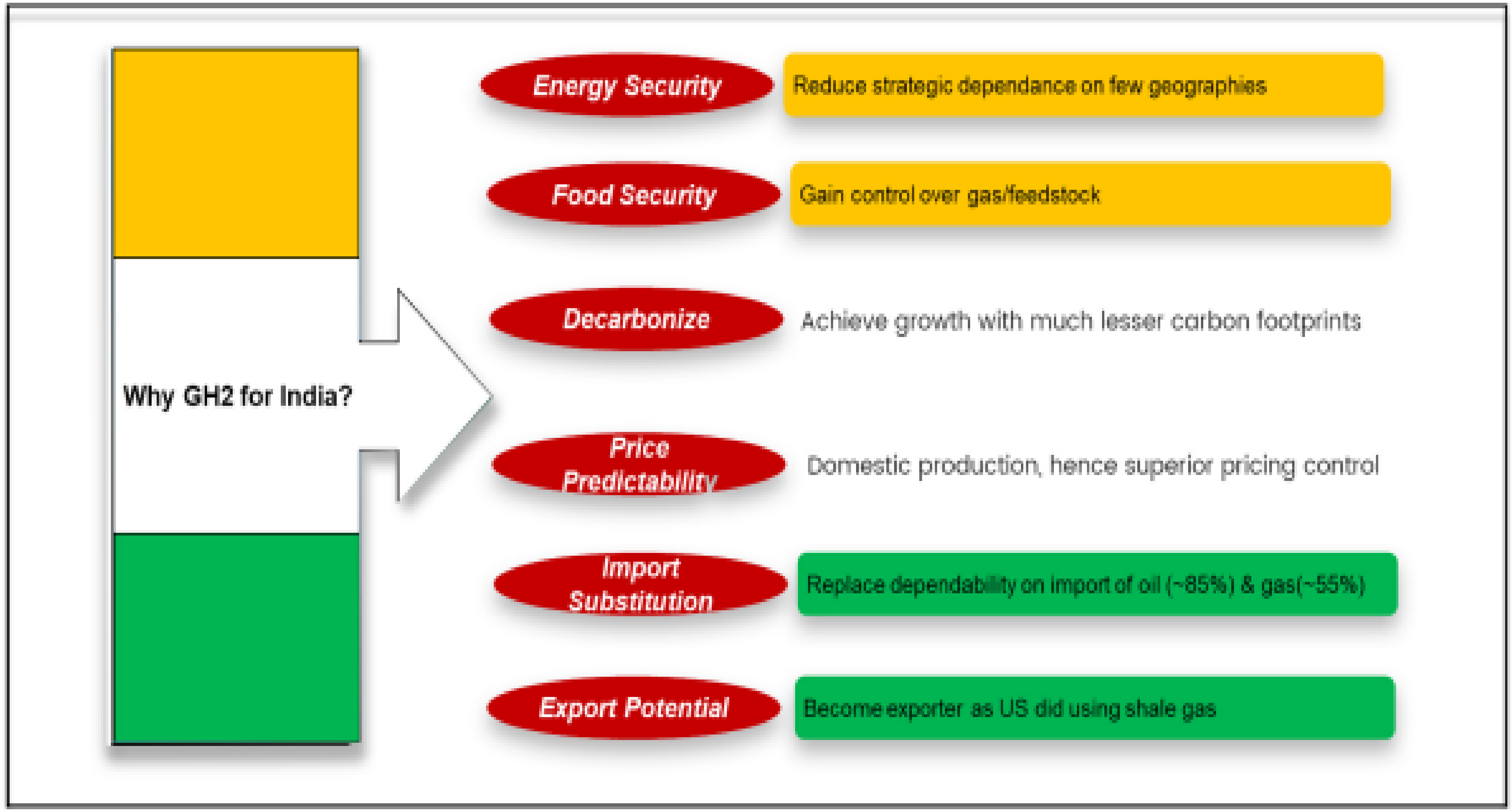
Dr Alok Sharma, Director(R&D)

Indian Oil Corporation Ltd.

Why India should Invest in Green Hydrogen



Below mentioned graphic illustrates strategic reasons why India should invest in GH2:



Green Hydrogen Policy

National Green Hydrogen Mission

- Outlay of ₹ 455 crore up to 2029-30 for **low carbon steel projects**
- Outlay of ₹ 496 crore up to 2025-26 for **mobility pilot projects**
- Outlay of ₹ 115 crore up to 2025-26 for **shipping pilot projects.**
- Other target areas include: decentralized energy applications, hydrogen production from biomass, hydrogen storage technologies, etc.

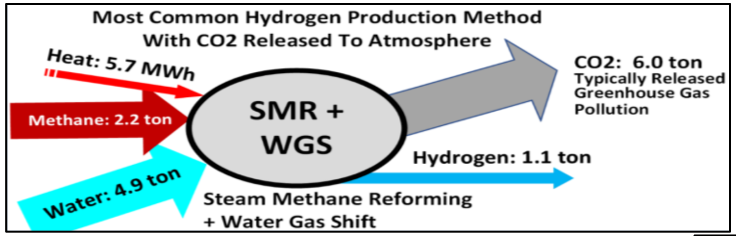
- The Mission will identify and develop regions capable of supporting large scale production and/or utilization of Hydrogen as Green Hydrogen Hubs.
- Development of necessary infrastructure for such hubs will be supported under the Mission.
- It is planned to set up at least two such Green Hydrogen hubs in the initial phase.
- Outlay of **₹ 400 crore** up to 2025-26 for Hubs and other projects.

National Green Hydrogen Mission

- In the initial stage, two distinct financial incentive mechanisms proposed with an **outlay of ₹ 17,490 crore up to 2029-30**

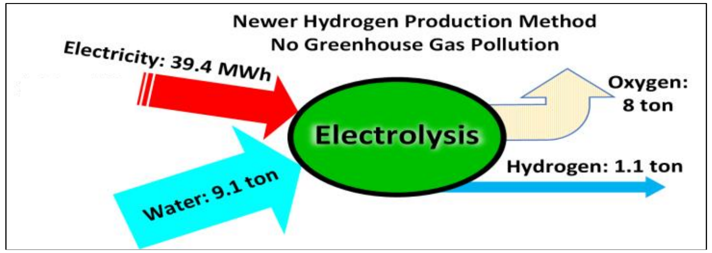
Hydrogen Production Pathways

Each energy path to hydrogen comes with its own set of challenges and opportunities



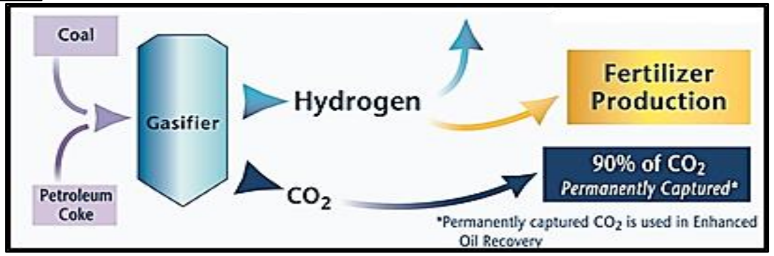
Steam Methane Reforming

But if we are going to get to net-zero emissions, we must start somewhere.



Without carbon capture

with carbon capture



Coal Gasification

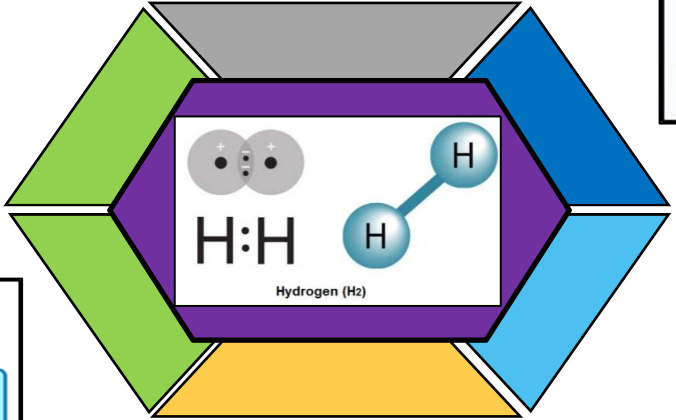
Coal Gasification with carbon capture

Green Power

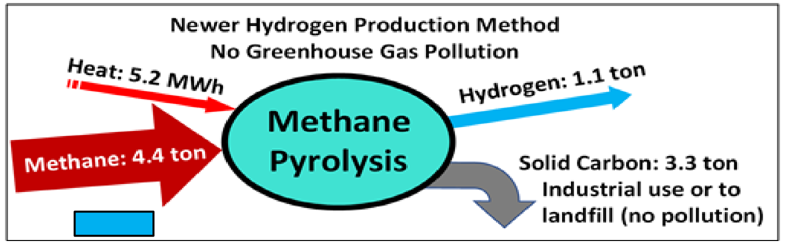
Nuclear Power

Wind Power

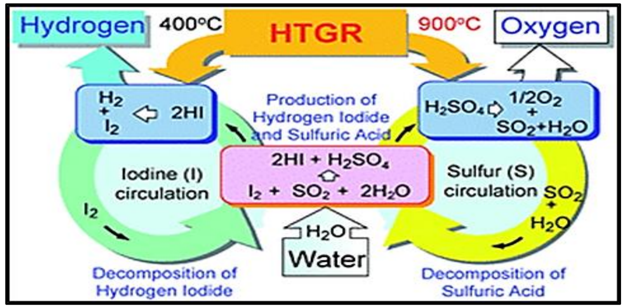
Grid Power



Biomass Gasification



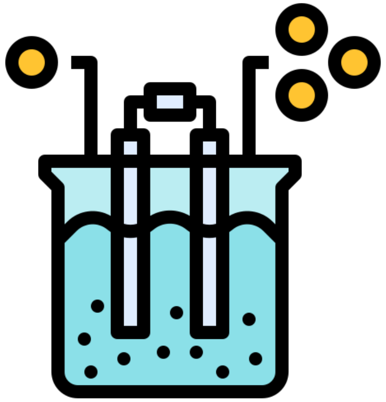
Methane Decomposition of Methane



Thermo chemical water splitting

White Byproduct Hydrogen from Processes

Indian Landscape – Green Hydrogen



Water Electrolysis

- PEM/Alkaline/ SOEC using Solar PV/ Wind Energy (utilization of cheap electricity)
- Water Splitting (Photo-electrochemical) Lab Scale

Waste to Hydrogen

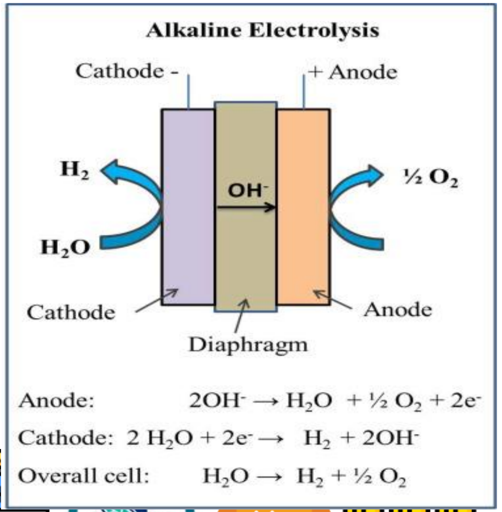
- Biomass Gasification Oxy steam (IOCL & IISc.) and Plasma Gasification (integration with Agro economy)
- Reforming of Compressed Biogas (extension to CBG)

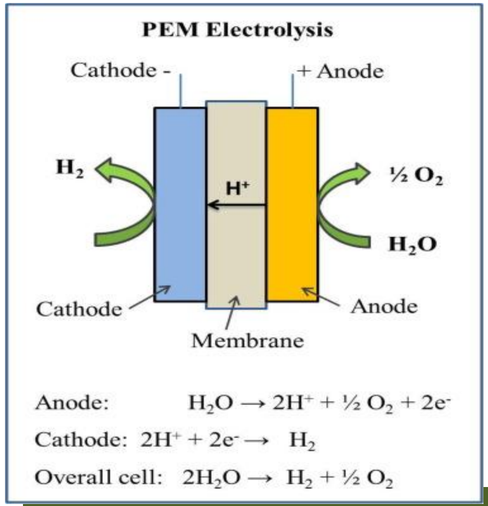
Grey/ Blue hydrogen Already Produced by Refineries / Fertilizers

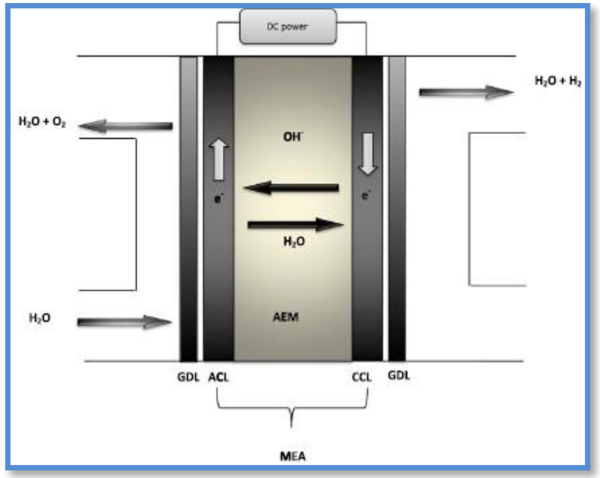
Electrolyzer Types

Water Electrolyzers

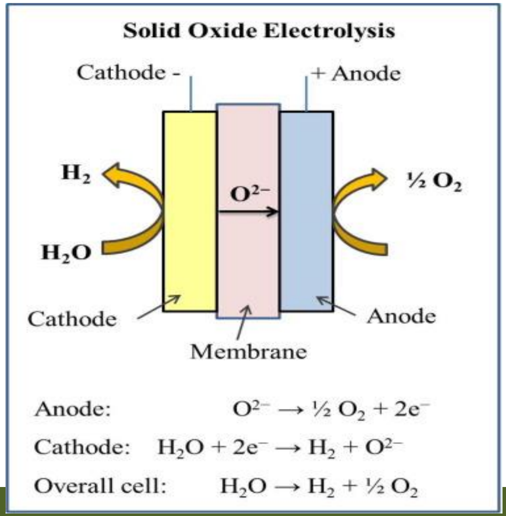
- **Low Temperature Electrolysis**
  - **Alkaline**
  - **Proton Exchange**
  - **Anion Exchange**
- **High Temperature Electrolysis**
  - **Solid Oxide**







Reactions same as alkaline electrolyzer



Ref: https://doi.org/10.1016/j.mset.2019.03.002

Vital Parameters and Specifications

Specification	Units	Alkaline	PEM	AEM	SOE
Technology maturity		Widespread commercialization	Commercialization (small scale)	Under Development	Under Development
Cell temperature	°C	60–80	50–80	50-70	900–1000
Cell pressure	bar	25-30	30-80	~30	<30
Current density	A cm−2	0.2-0.5	1.0–2.0	0.8-1.2	0.3–1.0
Cell voltage	V	1.8–2.4	1.8–2.2	1.8–2.4	0.95–1.3
Current efficiency	%	48-70	48-65	~40	60-80
Specific system energy consumption	kWh Nm−3	4.2–4.8	4.4–5.0	4.2–5	2.5–3.5
System lifetime	year	20–30	10–20	-	-
Hydrogen purity	%	>99.8	99.999	99.99	99.999
Cold start-up time	min	~ 15	<15	-	>60
Investment costs	€ KW-1	800–1500	1400–2100	800–1500	>2000
Electrolyte		20%-30% KOH	Perflurosulfonated acid	1-3M KOH	ZrO2 doped with Y2O3
Charge Carrier		OH-	H+	OH-	O2-
Membrane (separator)		Asbestos	Perflurosulfonated acid	Quaternary ammonia polysulfone	ZrO2 doped with Y2O3
OER Catalyst		Ni2CoO4, La-Sr-CoO3, Co3O4	Ir/ Ru Oxide	Co3O4	Lanthanum strontium manganate
HER Catalyst		Ni	Pt	CeO2-La2O3	Ni doped YSZ

Ref: http://dx.doi.org/10.1016/j.rser.2017.05.258
Ref: https://doi.org/10.1016/j.mset.2019.03.002

Comparison - Advantages & Disadvantages

Alkaline	PEM	AEM	SOE
Advantages			
Mature technology	Higher performance	Non-noble metal catalyst	Higher performance
Non-PGM catalyst	Higher voltage efficiencies	Noncorrosive electrolyte	Higher Efficiencies
Long term stability	Good partial load	Compact cell design	Possibility of Scale up
Low cost	Rapid system response	Low cost	
Megawatt range	Compact cell design	Absence of leaking	Rugged design
Cost effective	Dynamic operation	High operating pressure	Dual inputs (electricity and temperature)
Disadvantages			
Low current densities	High cost of components	Laboratory stage	Laboratory stage
Crossover of gas	Acidic corrosive components	Low current densities	High temperature
Low dynamic	Possible low durability	Durability	Durability
Low operating pressure	Noble metal catalyst	Membrane degradation	Slow start up response
Corrosive liquid electrolyte	Stack below Megawatt range	Excessive catalyst loading	Lack of demonstration on large scale

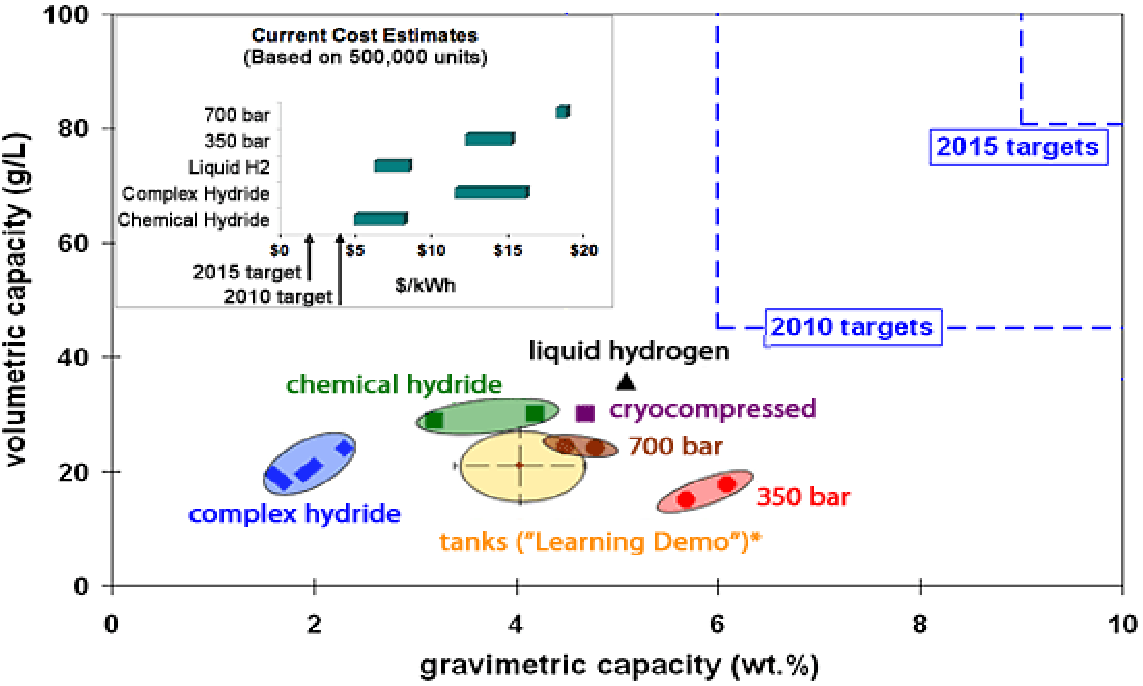
Ref: http://dx.doi.org/10.1016/j.rser.2017.05.258

Comparative Table of Different Process Technologies

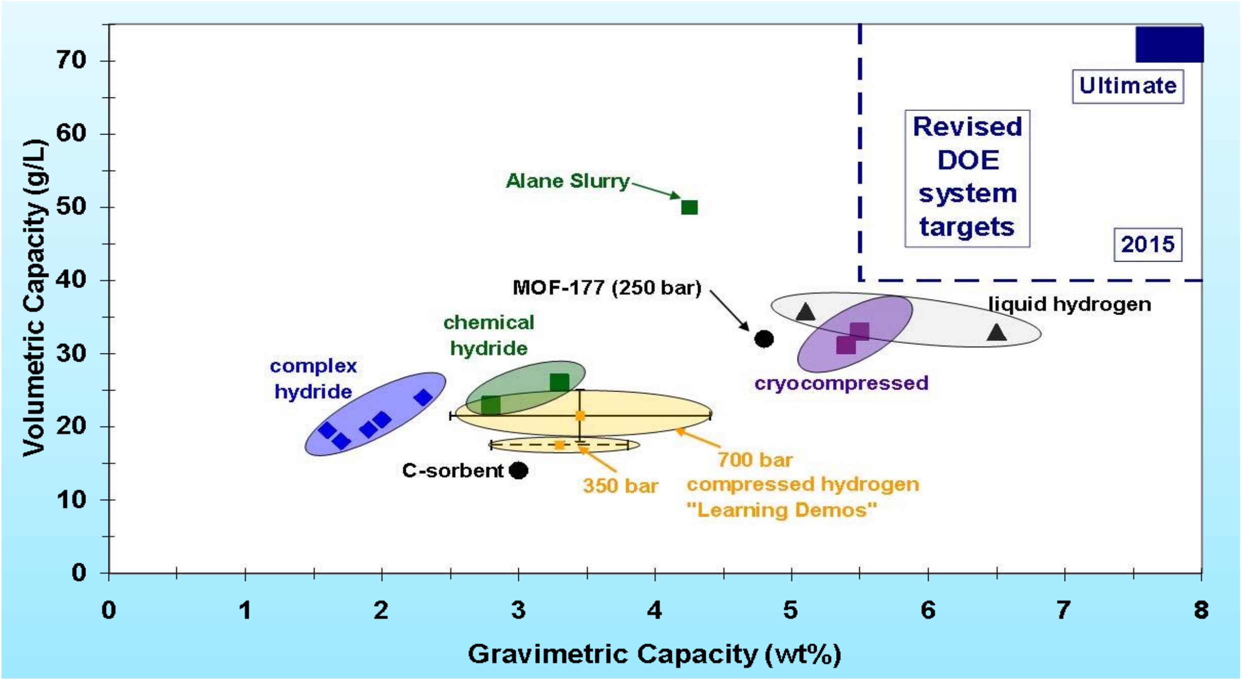
	Feed Type	Feed Cost (₹/ kg)	Efficiency (%) – Feed to H_2	Tentative H_2 cost -mass production (Rs/kg)
Gasification	Biomass	4-5	65-68%	~150-170
Biomethanation to H_2	Agro Residue	3-4	50%	250-270
Natural gas Reformer (If CCUS is added, then ₹ 35-40/kg) will be additional	NG	40	75-80%	140-160
Solar Electrolysis	DI Water (9 litre /kg)	27+ Electricity Cost	~11% (solar to hydrogen)	400-425
Aqueous Phase Methanol Reforming	Coal/NG to methanol to hydrogen	23-25	~32-40%	200-220
Photoelectrochemical Water Splitting Process (Under Development)	DI water	Advantages over other processes: **Completely green hydrogen. Suitable for both centralized and distributed applications**		

DOE Hydrogen Storage Targets

EARLIER



NEW



2025 targets have been **revised** from 9 Wt % to 5.5 wt % with ultimate target of 7.5 wt%

The **Ultimate** targets are intended to facilitate the introduction of hydrogen-fueled propulsion systems across the majority of vehicle classes and models

Material system developed for On-board and Off-board regeneration of H2

Source: DOE

Hydrogen Storage

Most appropriate storage medium depends on the volume to be stored, duration of storage, required speed of discharge, and the geographic availability of different options

Today hydrogen is most commonly stored as a compressed gas or liquid in tanks for small-scale mobile and stationary applications. The majority is either produced and consumed on-site (around 85%) or transported via trucks or pipelines (around 15%)

Large scale storage	Physical storage	Materials based storage
• Geological storage: Salt caverns, depleted natural gas or oil reservoirs and aquifers are all possible options for large scale and long-term hydrogen storage • Storage Tanks	• Compressed Gaseous hydrogen • Liquefied hydrogen • Cryo-compressed Hydrogen • Slush hydrogen (SH2) (stored at Hydrogen's melting point)	• Metal hydride storage systems (with materials such as Palladium, magnesium, etc.) • Liquid hydrogen organic carriers (LOHCs): LOHCs present an option for binding hydrogen chemically • Surface storage system (sorbents): hydrogen can be stored as a sorbate by attachment

Hydrogen Storage Challenges

Gaseous Cylinders

- Cost of compression
- Lower energy density

Liquid Hydrogen

- Boil off losses (as high as 0.5 % /day)
- Lower energy density

Metal / chemical hydride

- Low storage capacity
- Durability of material (1500 cycles)
- Regeneration
- Usage logistics

Besides above codes & standards and public acceptance are also important issues for Hydrogen Storage

Hydrogen Transport

Mostly hydrogen is produced in decentralized locations and transported to place of use

Less than one fourth of world's hydrogen produced centrally and transported through

- **Pipelines – typically the cost of hydrogen pipeline is 80%-100% more than the natural gas pipeline**
- **High pressure cylinders and tube trailers**
- **Liquid hydrogen in cryogenic vessels**

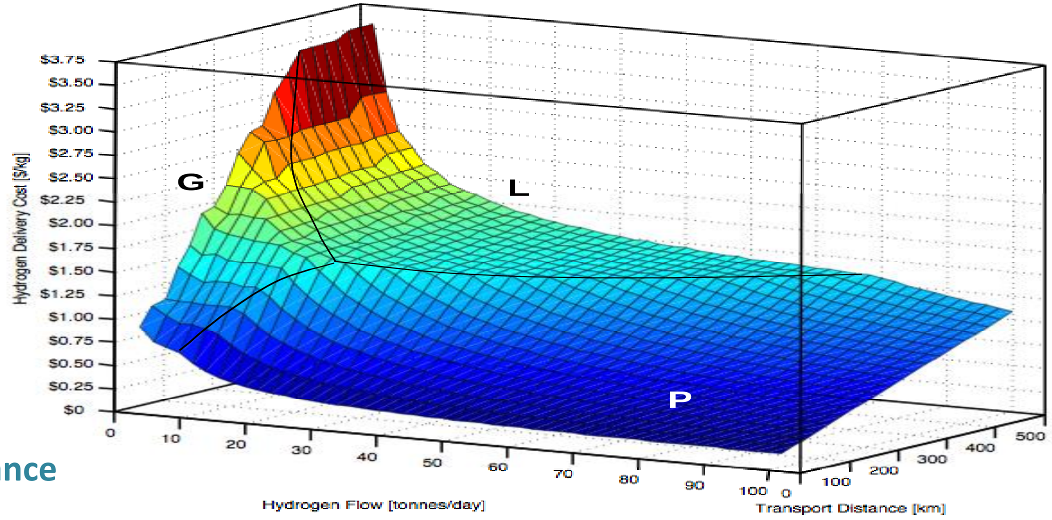
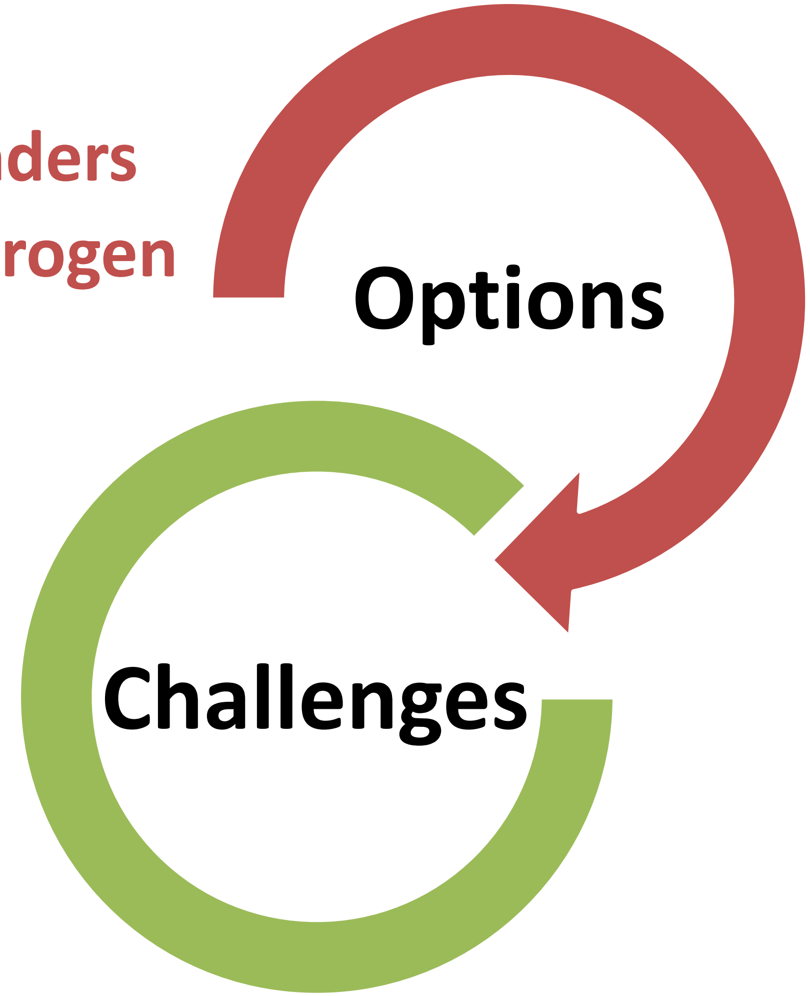


Fig. H_2 Delivery Cost vs. Flow rate and Distance

Hydrogen Transportation Challenges

- Gaseous Cylinders
- Liquefied Hydrogen
- Pipelines



- Capital cost high
- Transportation cost
- Hydrogen embrittlement
- Leak free transport
- Codes & standards
- Regulatory approvals

Hydrogen in Mobility Sector

Hydrogen In Mobility Sector

Hydrogen Blended CNG

(Interim technology, Quantification of Benefits)

Hydrogen IC Engine

(Small Quenching Gap, Backfiring, Embrittlement)

RON= 130 / MON=30

Very low sensitivity

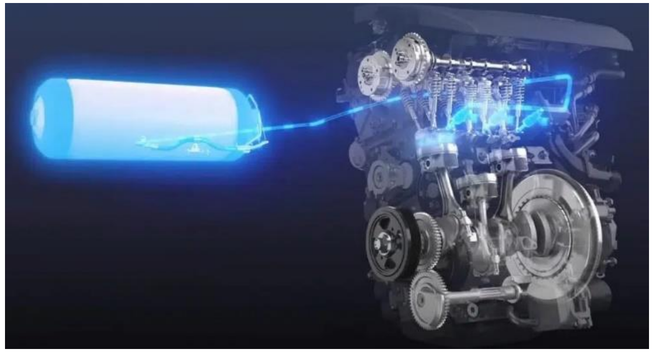
Fuel Cells

(best technology for using hydrogen,

Issues pertaining to cost, durability, fuel quality etc.)

Technology	Desired Cost of Hydrogen	
Hydrogen IC Engine	80-100 Rs/Kg	Great Challenge
Fuel Cell	350-400 Rs/kg	Challenging but can be met

Hydrogen Internal Combustion Engine (HICEs)



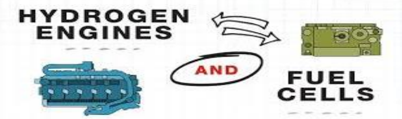
The operation of HICEs is very similar to that of a gasoline engine. Hydrogen is used as fuel and oxygen as oxidant.

- Hydrogen is is stored in a tank with a pressure of 700 bar.
- Hydrogen engine BMW 750hl, which came onto the market in 2000.
- It stores hydrogen in liquid form. This requires a very expensive tank made from materials from the aerospace sector to keep its temperature below -250ºC.
- Hydrogen purity is not a major concerns in HICEs as compared to FCEVs.
- Today, charging hydrogen is faster than charging an electric car battery.

BMW 750hL Hydrogen Engine, (Year-2000)

Hydrogen Internal Combustion Engine (HICEs)

Comparison of the basic parameters between various fuels



S. No.		Gasoline Vehicles	Hydrogen Combustion Vehicles	Hydrogen Fuel Cell Vehicles
1.	Engine type	Internal combustion Engine	Internal combustion engine	Electric motor
2.	Efficiency of the propulsion system	~30–35%	~40–50%	~45–55%
3.	Fuel consumption	approx. 9 L (or 12.8 kg) of gasoline/100 km	approx. 1.4 kg of hydrogen/100 km	approx. 1.0 kg of hydrogen/150 km
4	Cost of fuel	currently low (~0.1)	currently high (~0.9)	currently very high (1.0)
5	Air pollution emissions	high CO2, CO, unburned hydrocarbons, and NOx emissions	minimal/very low CO2 and CO emissions, the same or up to 20% higher NOx emissions compared to gasoline vehicles	minimal/zero CO2 and NOx emissions
6	State of technology	developed (widely used all over the world)	developed, and in diffusion stage (experimental vehicle series)	developed, and in diffusion stage (experimental vehicle series)

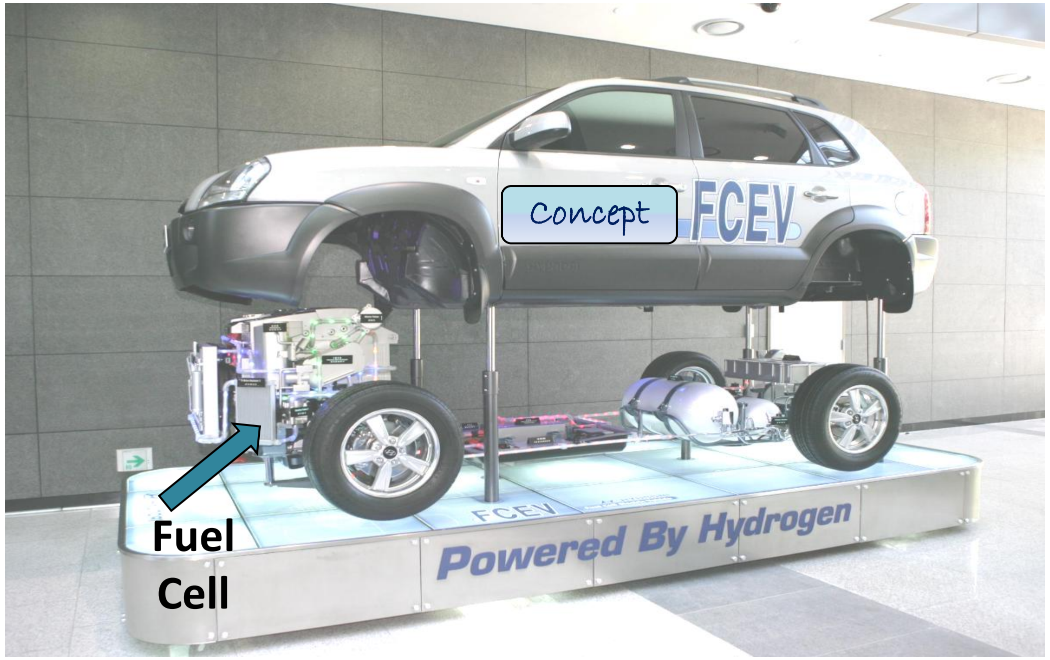
Mitsubishi-Hydrogen-powered V8 engine

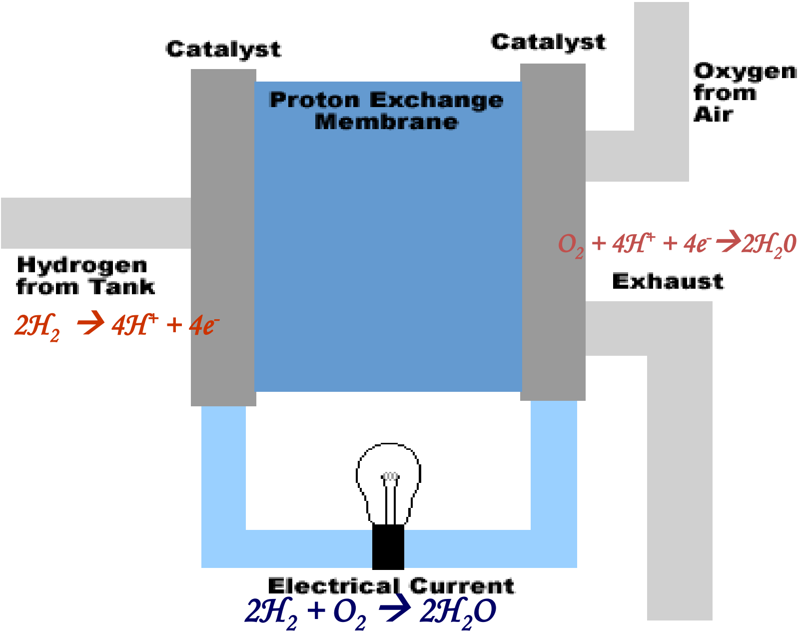
Hydrogen Internal Combustion Engine (HICEs)

Why Hydrogen is suitable for ICEs?

- ❑Wide range of flamability
- ❑Low ignition energy
- ❑Small quenching distance
- ❑High auto-ignition temperature
- ❑High flame speed at stoichiometric ratios
- ❑High diffusivity
- ❑Very low density

Fuel Cell Introduction



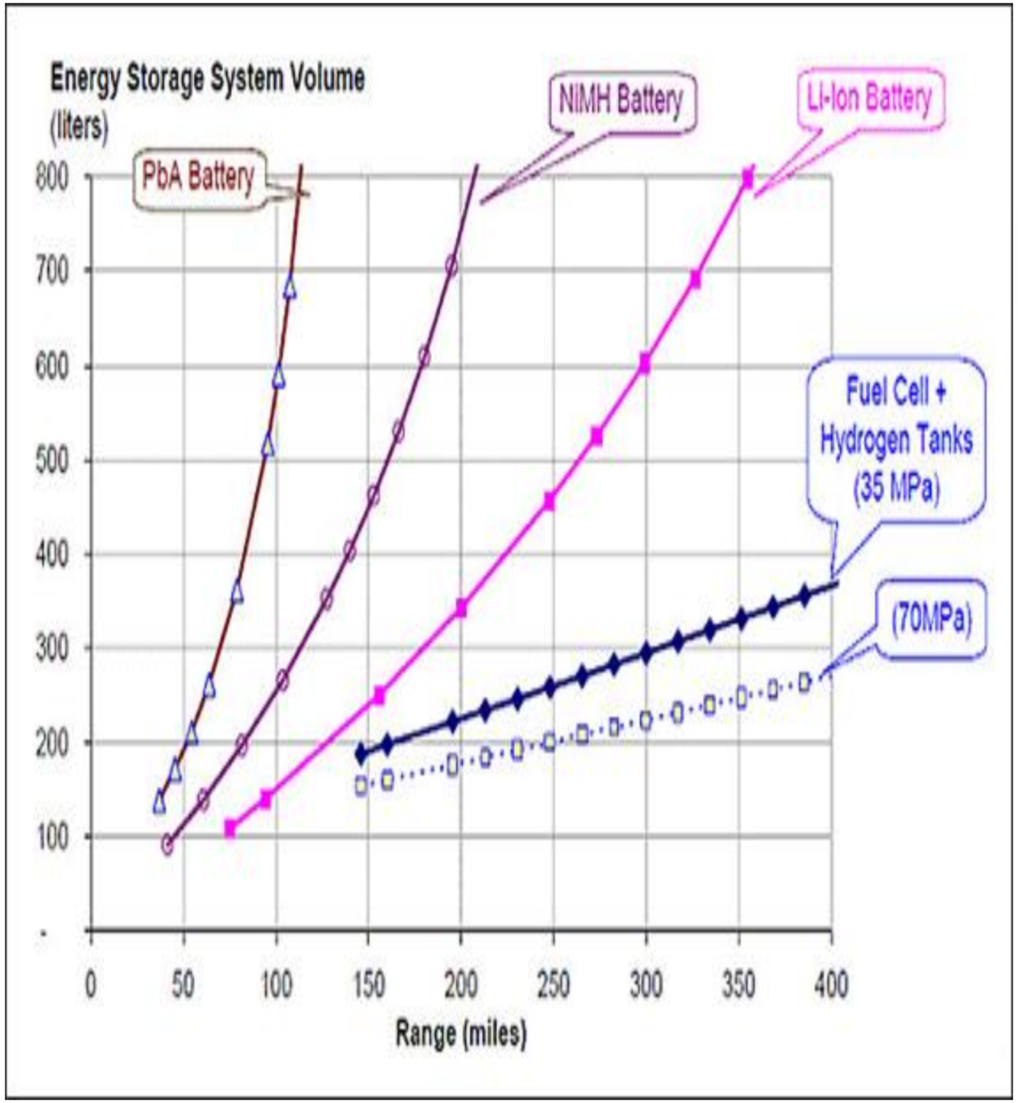


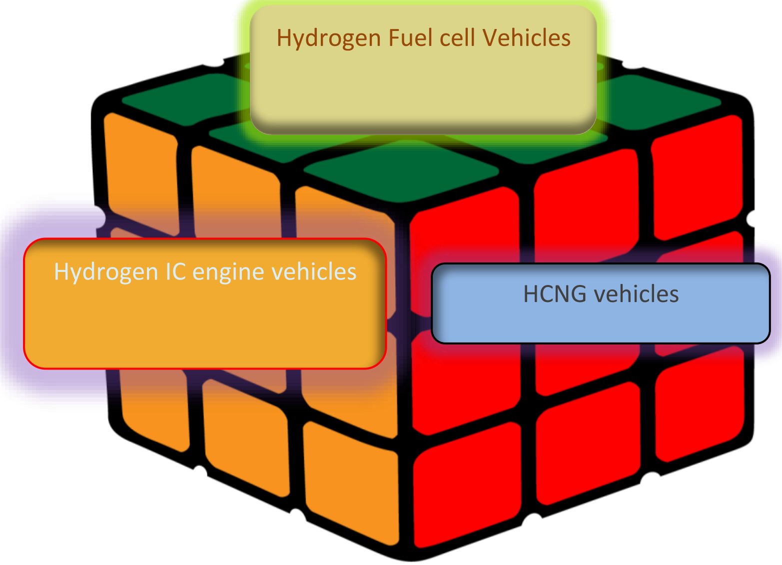
Diesel Car → 18 km/lit. of diesel

Fuel Cell Car → 150 km/kg of Hydrogen

Expanded View - Fuel Cell System

Snapshot – Hydrogen Vehicles





Toyota Mirai
153 HP, **Range: 700 km**, Global 10,000 units

Hyundai ix35
134 HP, **Range: 594km**,

Honda Clarity
174 HP, **Range: 589km**,

Fuel Cell Development - Challenges

Besides technical superiority, fuel cell systems need to be competitive with existing technologies in cost and durability.

Challenges

Cost Current USD 4000/kw Target <USD1000/KW

Durability - DoE 2020 Targets

- **Stationary 80,000 hrs**
- **Transportation 5,000 hrs**

Hydrogen supply to Consumer

Regulatory approvals

Public Acceptance

Safety

Hydrogen Safety- Issues

- Long history of safe use in chemical and aerospace industries

- Safety will be a major issue from the standpoint of commercialization of hydrogen-powered vehicles

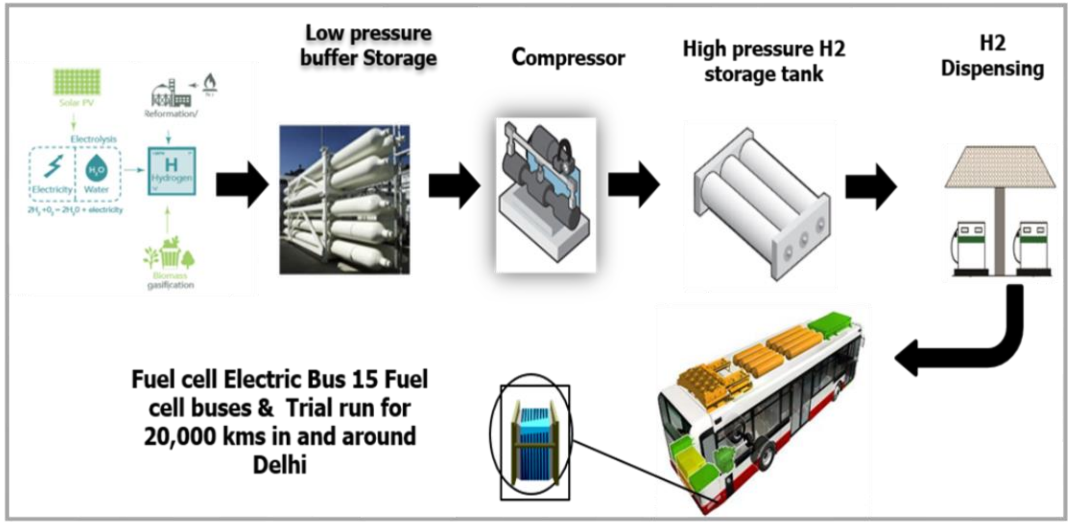
- A particularly salient and under explored issue is that of leakage in enclosed structures, such as garages in homes and commercial establishments.

- Hydrogen safety, from both a technological and a societal perspective, will be one of the major hurdles that must be overcome in order to achieve the hydrogen economy.

OISD /MoPNG is formulating Standard on Hydrogen Safety

Hydrogen & Fuel Cell for E-mobility

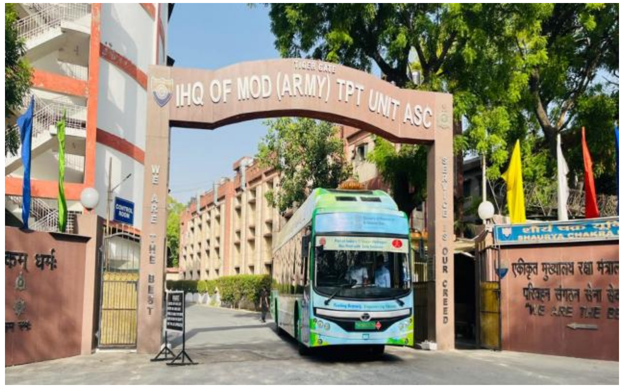
- **Development & demonstration of commercially viable 15 Fuel cell buses with Hydrogen from multiple production pathways**
- **Long term operation of the Fuel Cell buses (20,000 km) for establishing the efficacy, efficiency and sustainability of the FC technology for public transit application.**
- **Hydrogen production pathways comprising of different Electrolyser based H2 production - Alkaline, PEM & SOEC, CBG Reforming & Bio-Mass gasification**



Snapshot of the Project

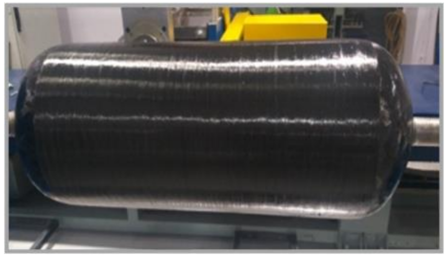
Filling of H2FC Bus from R&D Faridabad

FC Bus for Indian Army



Innovative Insight – Key Initiatives

HCNG –India's 1st tryst with H2 Economy



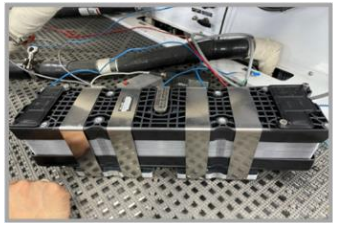
1st Indigenous Type-3 H2 cylinder

Green Hydrogen Production - Biomass Gasification / CBG Reforming & Electrolysis (Anion Exchange Membrane/ Polymer Electrolyte Membrane) Technologies

CO tolerant Fuel cell Technology

1st refueling in Toyota Mirai

India's 1st Hydrogen Fuel cell Forklift



FC stack for 15 buses – 5 kW (Miniaturized version)

Setting up of 10 KTPA Green Hydrogen Production Plant at IOCL Refinery

Challenges for Fuel Cell Technology

1

Cost

automotive internal-combustion engine : \$25–\$35/kW;
a fuel cell system needs to cost \$30/kW competitiveness

2

Durability & Reliability

Automotive: 8,000 hr
Stationary: 40,000 hr

3

System Size

to meet the packaging requirements for automobiles.

4

Air, Thermal & Water Management

Heat exchanger requirement

5

Improved Heat Recovery Systems

Improving Combined Heat & Power Efficiency

6

Platinum Group Metal Catalyst

Cost & Import Dependency

7

Hydrogen Purity

Prone to Contamination: CO, NH3, SO2. High Purity 99.999% H2 requirement

8

H2 Refueling Stations

Availability of Hydrogen Refueling Infrastructures

9

Hydrogen Storage

Light weight-high pressure H_2 storage research

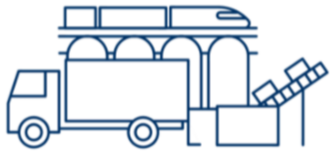
Challenges in Hydrogen Economy: Opportunity for R&D

Hydrogen Production

1. Production under 1 $/ kg
2. Development & Scale up of SOEC
3. High pressure Electrolysis
4. Electrolysis of saline water
5. Syn gas Production
   - Waste / MSW
   - Crude oil residue / Asphalt gasification
   - High ash coal gasification

Hydrogen Storage & Distribution

1. Transportation using CNG pipeline infrastructure
2. High pressure cylinder for storage
3. Materials for hydrogen storage
4. Underground storage
5. Liquefaction
6. HRS : Chicken and Egg



Hydrogen Utilization

1. H2 in IC Engines
2. Fuel cell based applications
3. Electrofuels (CO_2 to fuels/ chemicals using Green Hydrogen)
4. Pilot study for Green Steel
5. Industrial heat

Safety, Codes and Standards

Public Acceptance

ITS HyTIME

Thank you

Ready For Future