Physical Hydrogen Storage and Distribution: Technology Status and Research Activities

INTERNATIONAL CONFERENCE ON GREEN HYDROGEN 2023

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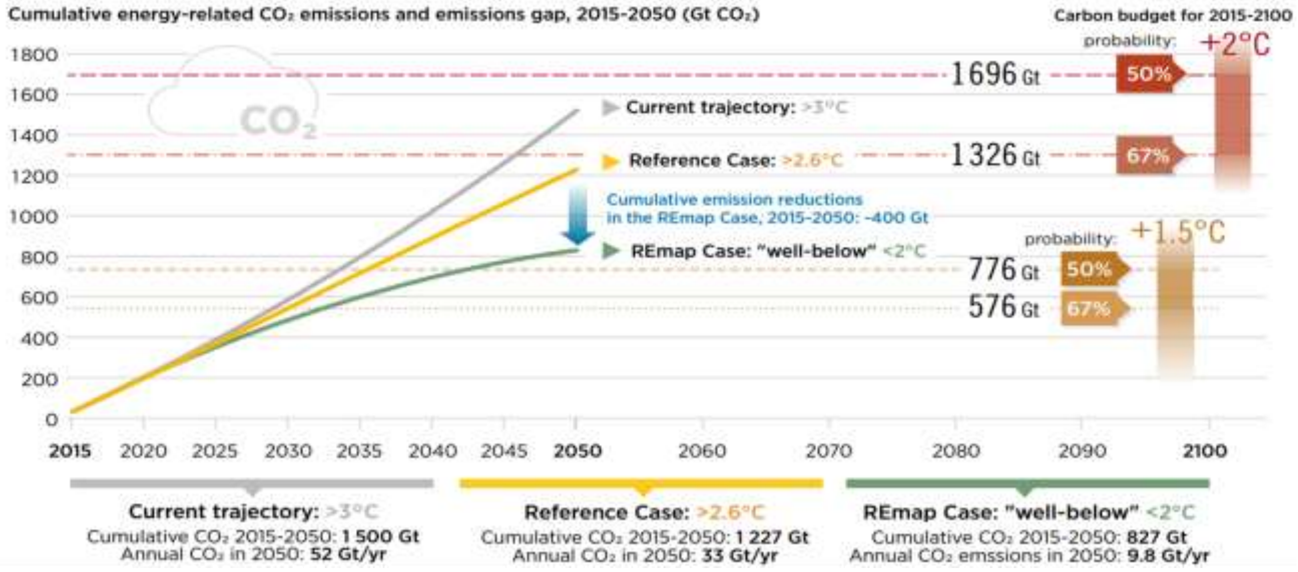
Climate Change Acceleration

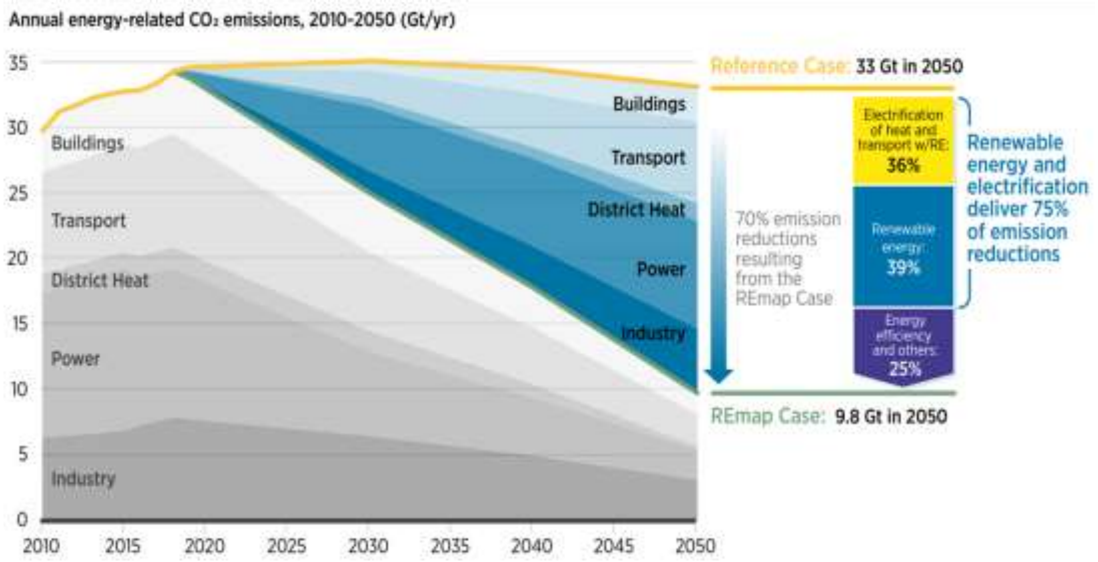
Climate change is accelerating

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

Ways to achieve net zero

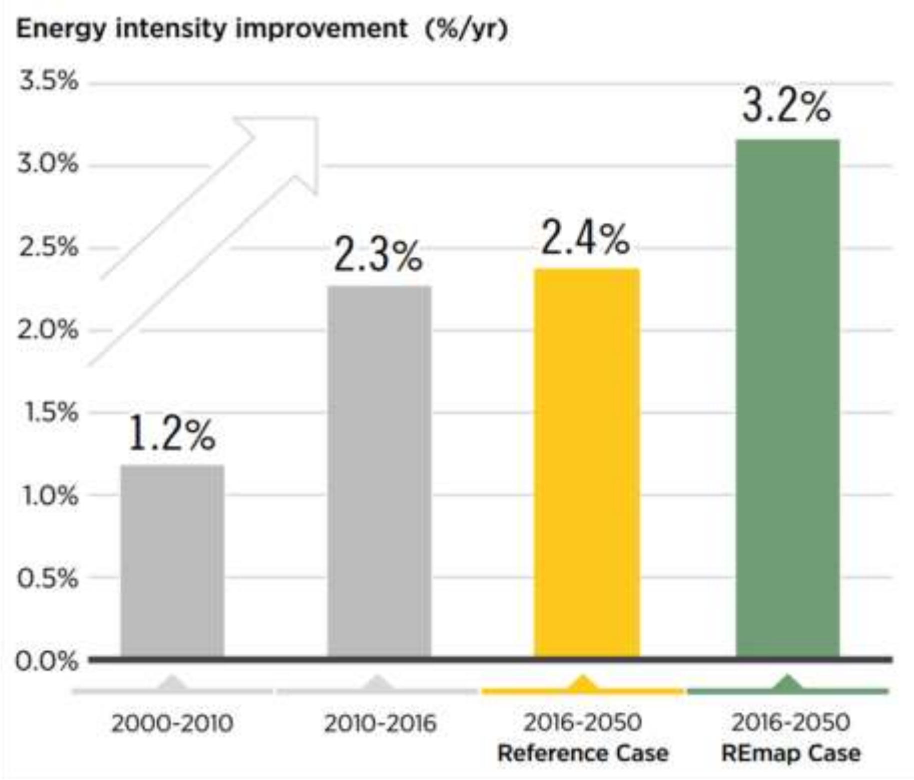
- Energy Intensity/efficiency
- Structural Changes
- Deployment of Renewable Solutions





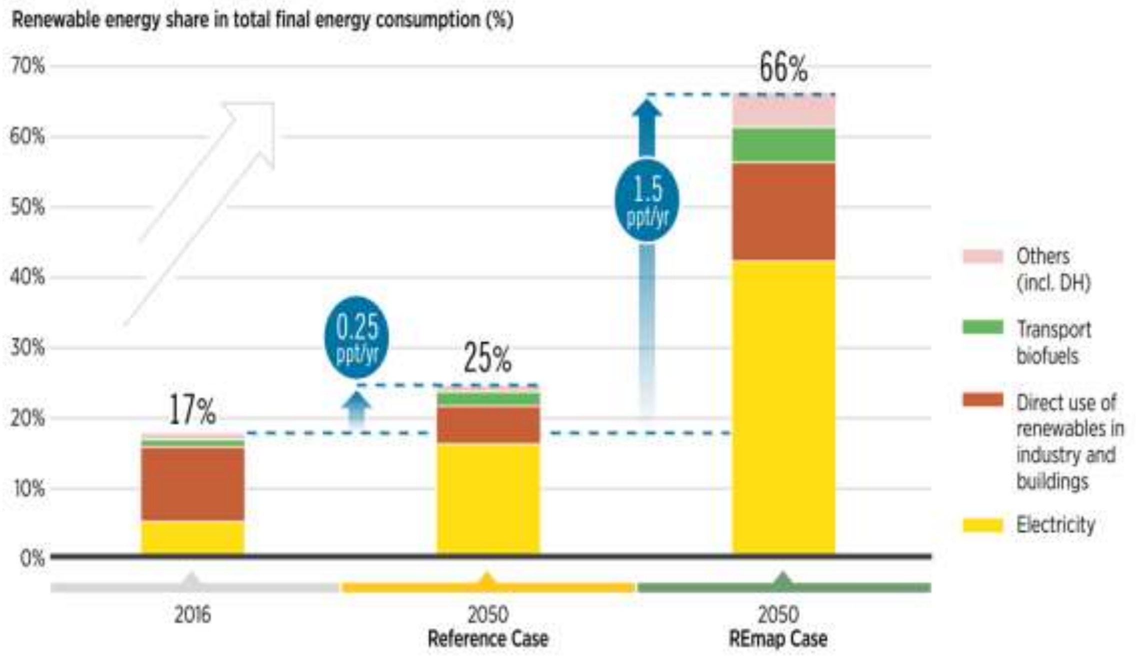
IRENA Global Energy Transformation,2019

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%



IRENA Global Energy Transformation,2019

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

Why Hydrogen?

Energy Efficient

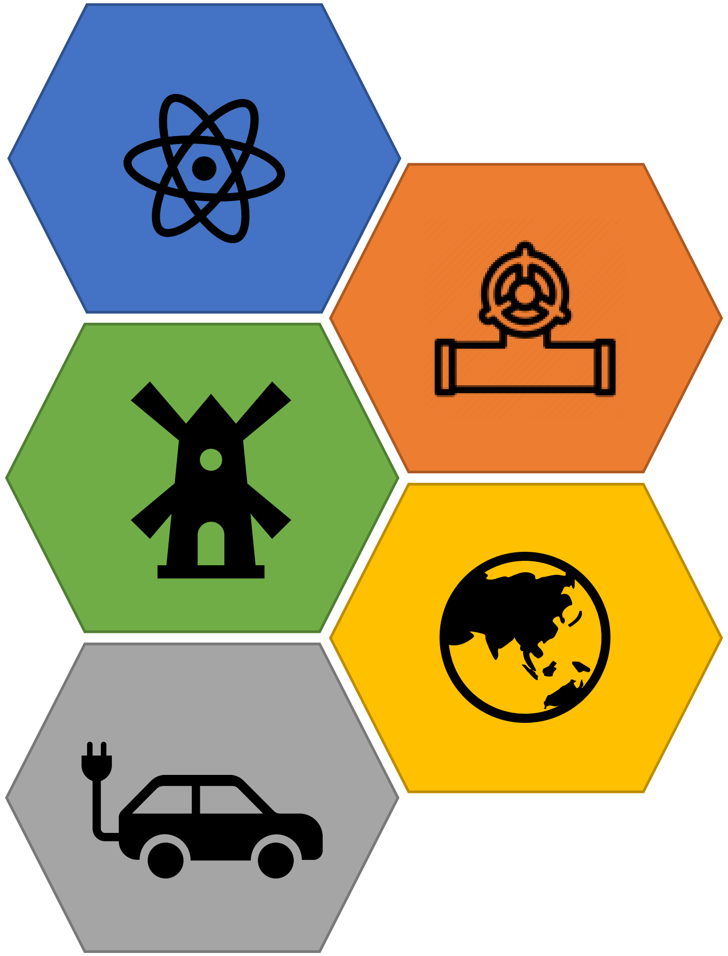
- Gaseous hydrogen contains nearly three times more energy per unit mass than gasoline: **141.90MJ/Kg of H_2 vs 47.40MJ/Kg of gasoline**

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**

NHEM
(National Hydrogen Energy Mission)

Launched on 15th August, 2021 by PM of India

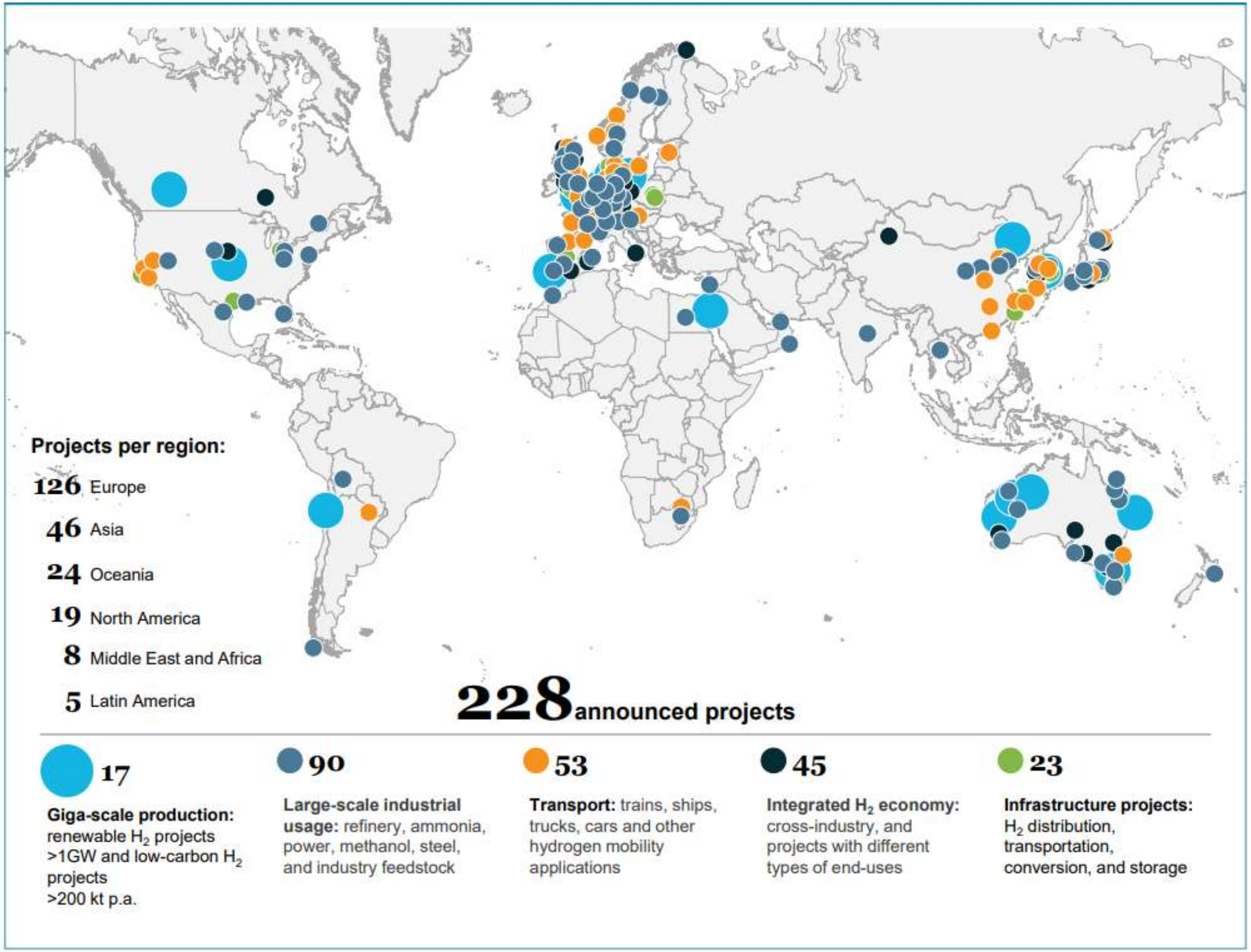
TARGETS

Export of Green Hydrogen	Make India a Global hub for production & export of green hydrogen.
Reduce Dependence	Reduce dependence on imported fossil fuels while enabling decarbonization of economy
Production	Produce 1 million tonne of green hydrogen annually by 2030

Current Scenario

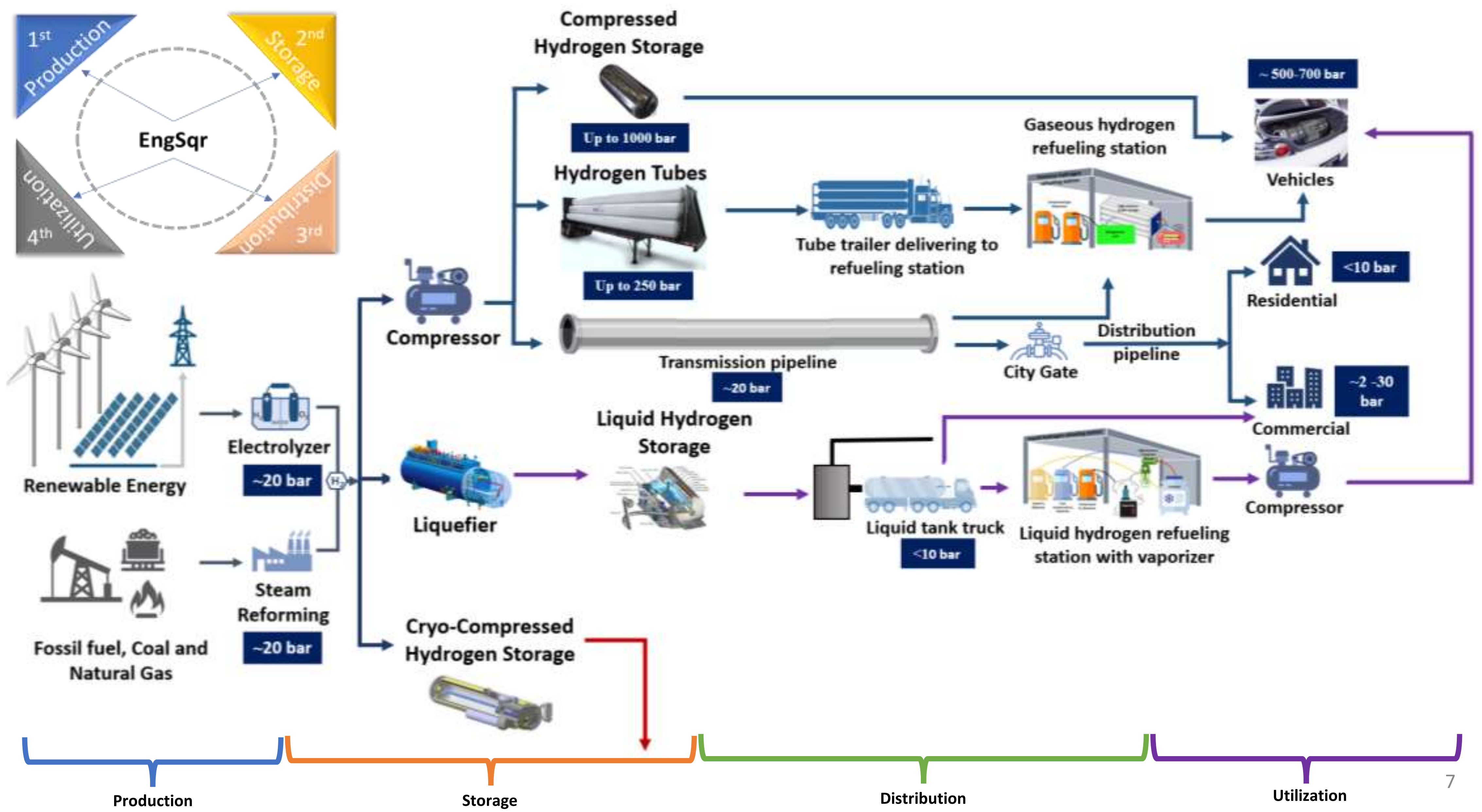
- India's first pure green hydrogen plant commissioned in Jorhat, Assam by IOCL.
  https://pib.gov.in/PressReleasePage.aspx?PRID=1818482
- A Green Hydrogen plant was inaugurated at L&T's A M Naik heavy engineering complex at Hazira in Gujarat's Surat.
  https://www.larsentoubro.com/pressreleases/2022-08-20-lt-commissions-green-hydrogen-plant-at-its-manufacturing-complex-in-hazira/
- NTPC starts India's first green hydrogen blending operation in PNG network.
  https://pib.gov.in/PressReleasePage.aspx?PRID=1888334
- **Other projects are under progress**

Global Hydrogen Projects



Hydrogen Council Report , 2021

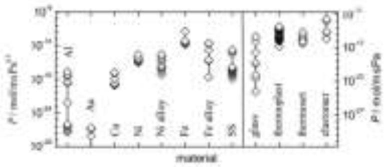
Energy Square: Hydrogen Pathways



Hydrogen Storage & Distribution: Technical Challenges

Molecular Size

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

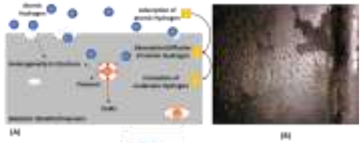


Hydrogen Permeation

Diffusivity

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

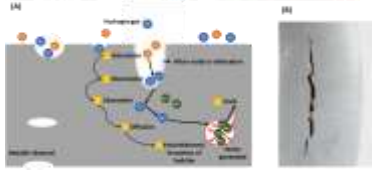
Fire Safety Issue



Hydrogen Blistering

Reactivity

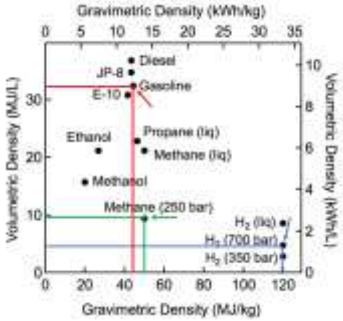
- Highly reactive
- Combines with most elements to form hydride



Hydrogen Embrittlement

Density

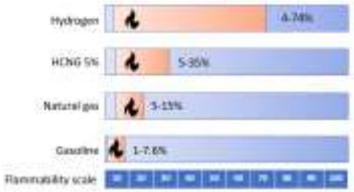
- Seven times lighter than natural gas
- Low volumetric energy density



High gravimetric but low volumetric density

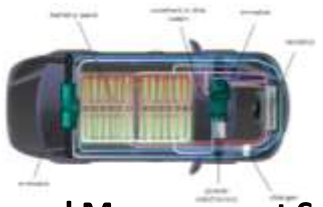
Flammability

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



Flammable hydrogen clouds formation

Physical vs Material Hydrogen Storage

Physical Hydrogen Storage		*Material Hydrogen Storage*
Easy Thermal Management System	 Thermal Management Systems	Complex Thermal Management System
No Catalysts Required	 Catalyst	Expensive Catalysts
No Chemical Reactions	 Chemical Reaction	Unwanted Chemical Reactions
Easy rate of extraction of hydrogen fuel	 Extraction the hydrogen fuel	Low rate of extraction of hydrogen fuel
Safety Problems, High Pressure Storage	 Storage	Low Pressure Storage
Small amount of H_2 can be stored	 Quantity of Fuel	Comparatively higher amount of H_2 stored

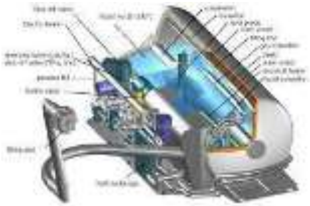
Physical Hydrogen Storage Solutions

Physical Based Storage

Compressed Hydrogen

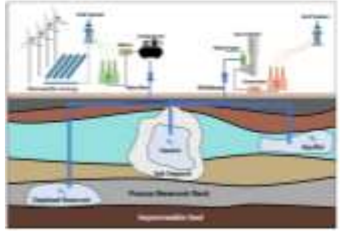
Advantages	• Provide direct usable hydrogen
Disadvantages	• Very low volumetric storage density • Required high compression energy

Liquid Hydrogen



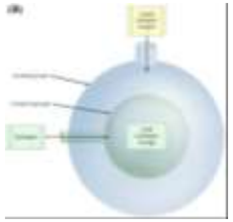
Advantages	• Moderate volumetric storage density • Easy to transport
Disadvantages	• Boil off issue • Complex thermal management • Degradation of insulation

Underground Storage



Advantages	• Cost-effective storage of hydrogen • mitigates the risk of hydrogen gas leaks
Disadvantages	• Risk of hydrogen-consuming reactions • Still in technological infancy

Cold Gas Storage



Advantages	• Higher amounts of hydrogen gas can be stored without adding extra cooling energy
Disadvantages	• Boil off issue • Degradation of insulation

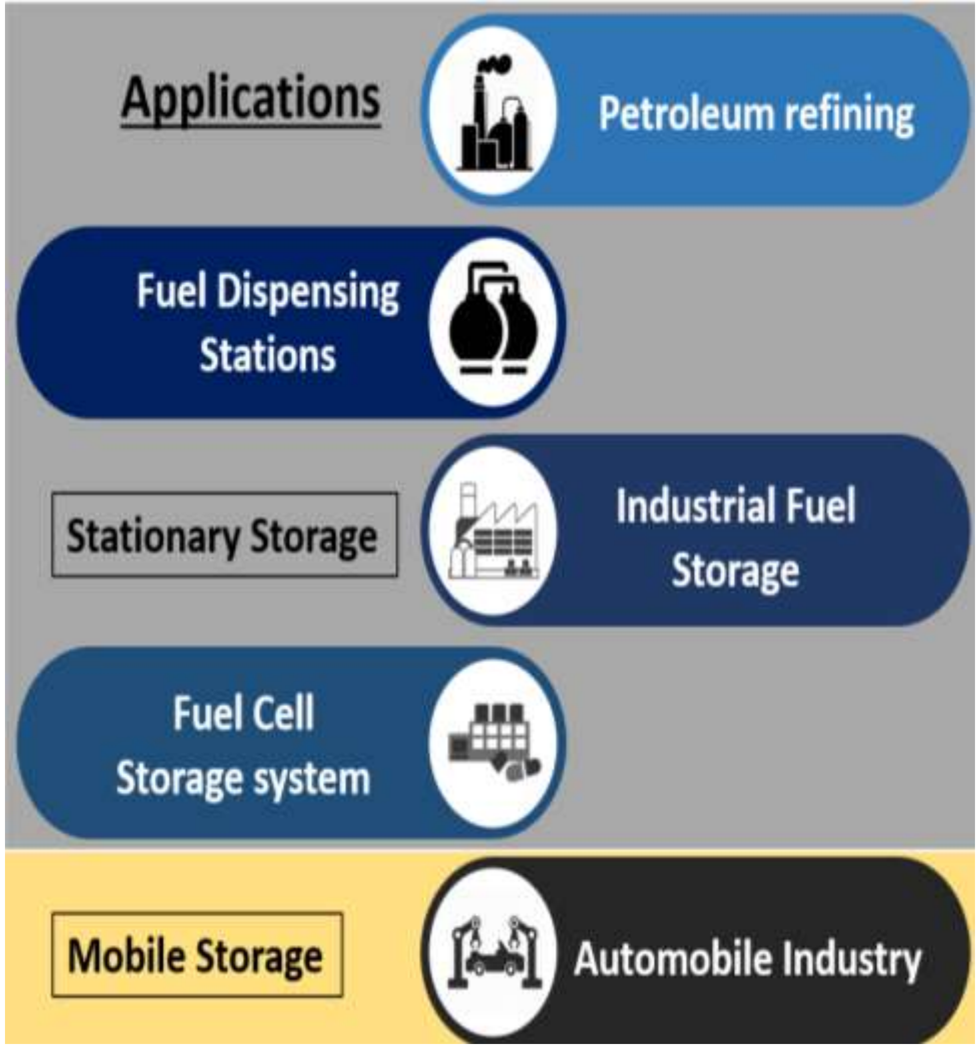
Cold / Cryo Compressed

Advantages	• High volumetric storage density
Disadvantages	• Required high compression energy • Boil off issue • complex thermal management • Degradation of insulation

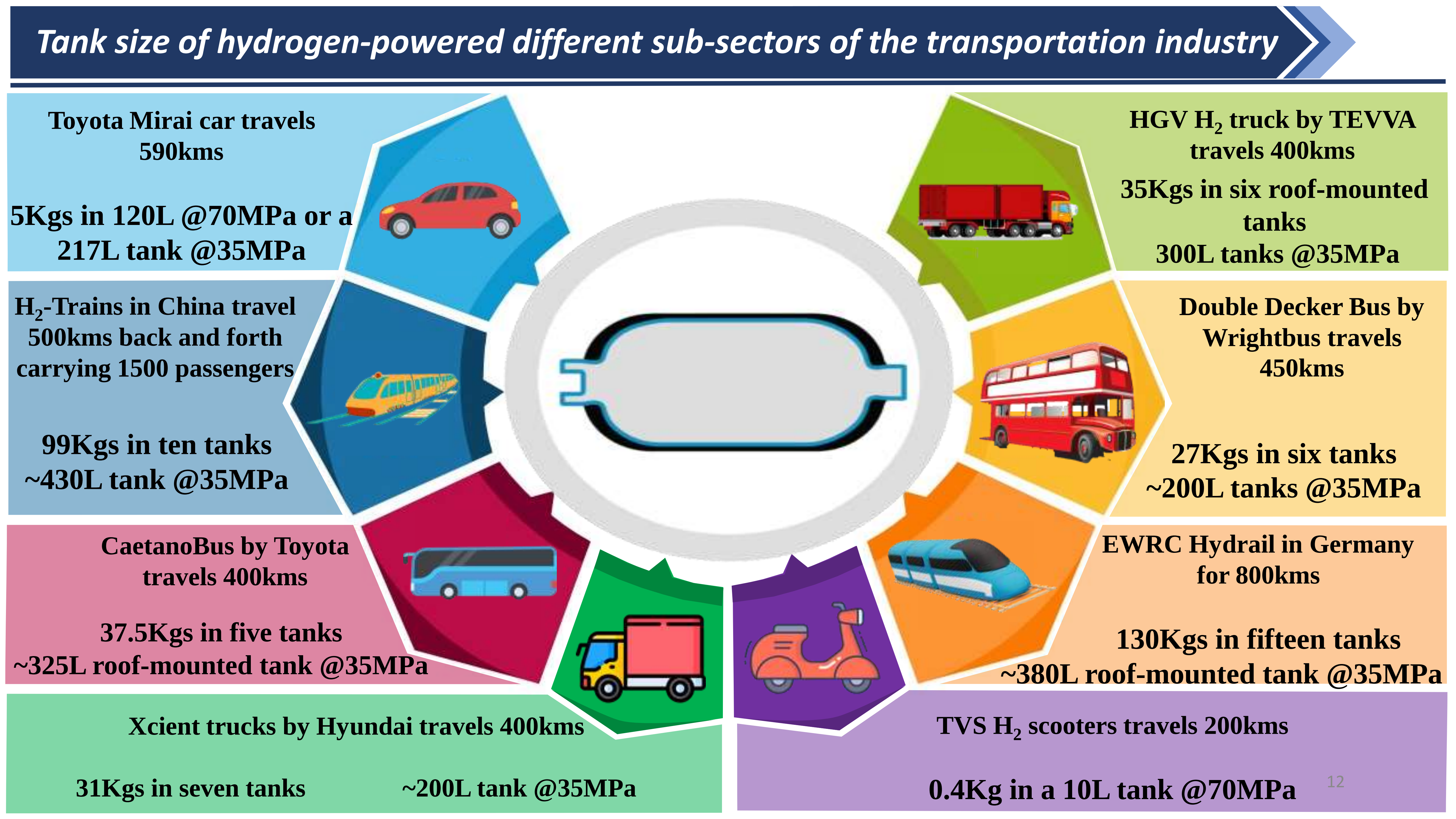
Compressed Hydrogen Storage: Pressure Vessels

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

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



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

- 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)

Compressed Hydrogen

Type	Manufacturer	Mass of gas (Kg)	Working Pressure (bar)	Applications
Type III	**Dynetek (Canada)**	-	700	-
	Faber (Italy)	-	700	Heavy duty
	SteelHead	0.39 - 5	700	Transportation
	Nissan	-	700	Car fuel
	Luxfer (UK)	1.64 - 4.93	350	(FC/ internal combustion
	Dynetek	-	350	vehicles)
	Worthington Industries	-	310	Industrial gas storage
	Dynetek (Canada, Germany)	230	450	Transport heavy duty
	Catalina composites	-	-	-
	Vinjamuri Innovations LLC	0.46 – 1.71	350,700	-
Type IV	**Quantum Technologies**	6	700	Toyota Mirai
	Lincoln composites	1.6	700	Light Duty
	Ullit (France)	-	700	-
	MAHYTEC	1.5	700	Light duty vehicles
	Hexagon Lincoln	7.5	350	Heavy duty

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/

Break Through Applications of Liquid Hydrogen

- 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

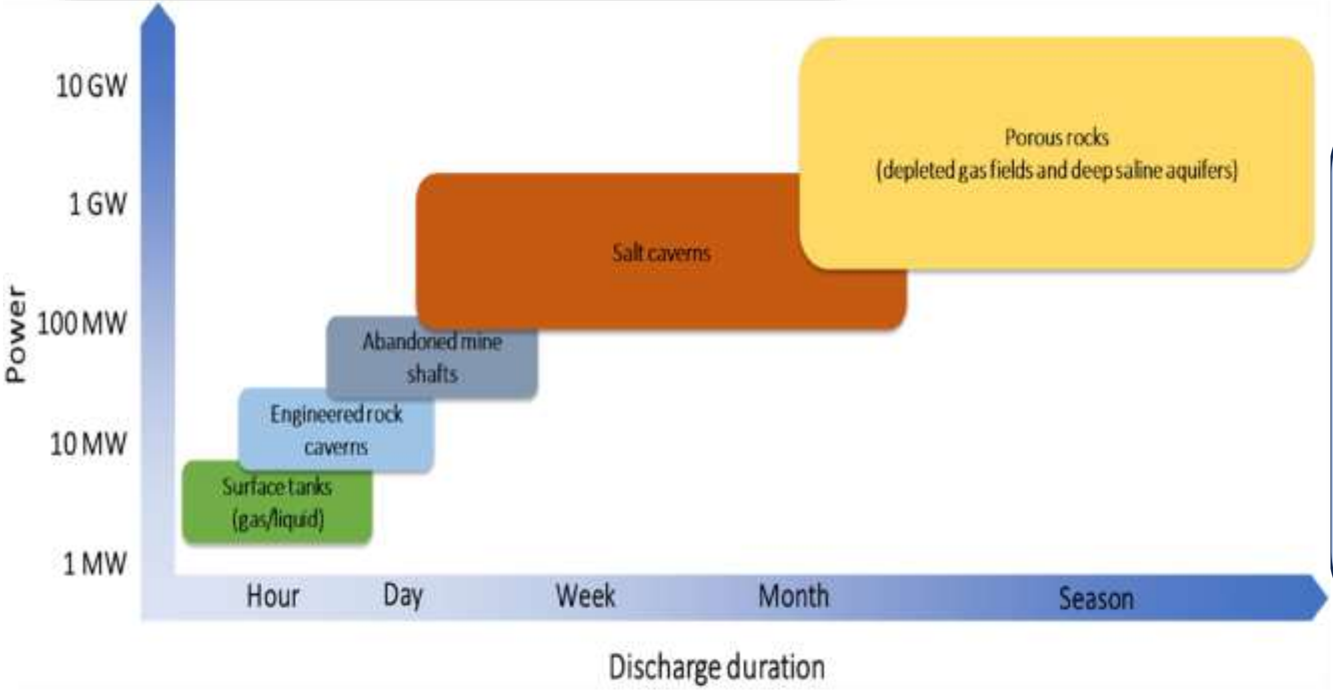
- Liquid hydrogen powered aircraft for long-duration journeys; **Upgraded Pathfinder and Helios** (Turk et al., 2022)
- Liquid hydrogen powered air vehicle; **Hybrid Tiger,** 48hr endurance in 2010 (Stroman et al., 2018)

- 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

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)

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.

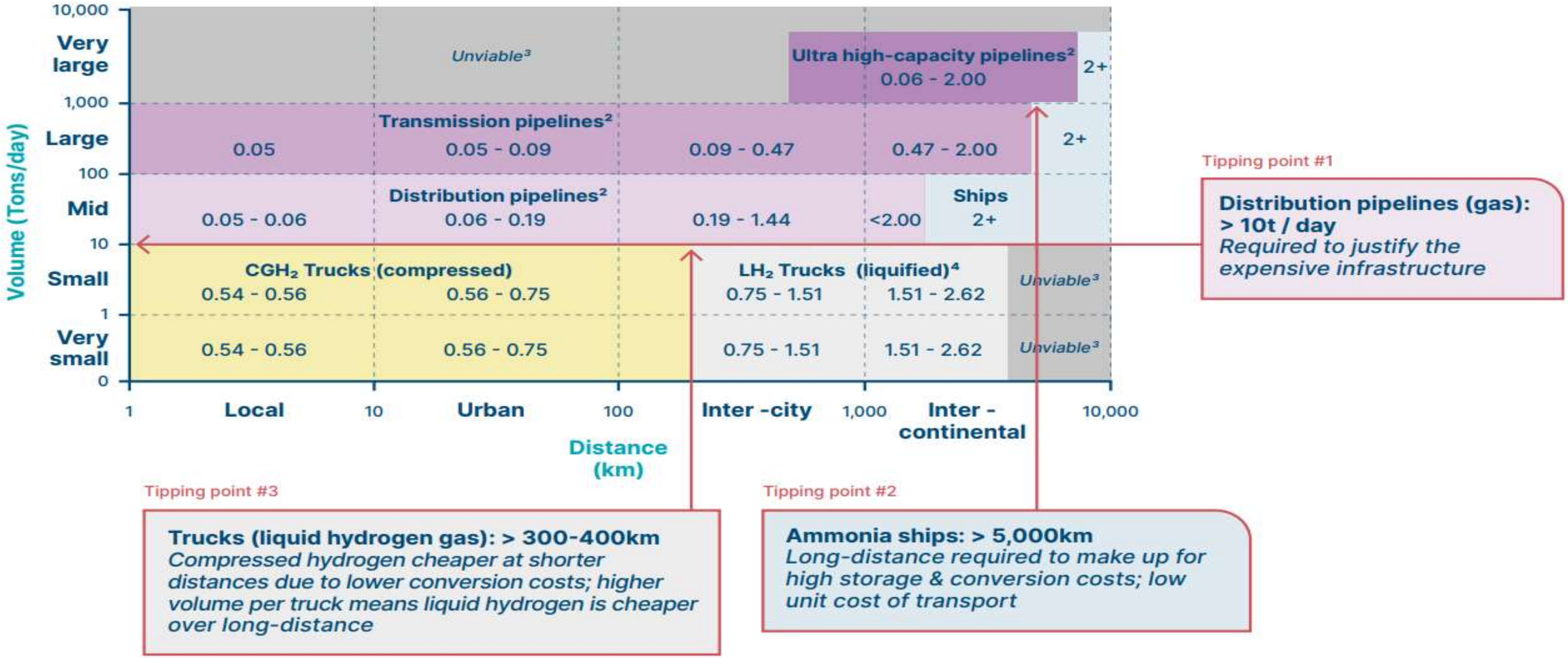
https://www.ssab.com/en/news/2022/06/hybrit-a-unique-underground-fossilfree-hydrogen-gas-storage-facility-is-being-inaugurated-in-lule

Hydrogen Distribution Solutions

- Hydrogen Delivery Modes
  - Gaseous Hydrogen
    - Tube Trailers
    - Pipeline
  - Liquid Hydrogen
    - Liquid Hydrogen Delivery

Different Modes of Hydrogen Transportation, (EUA, 2021)

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



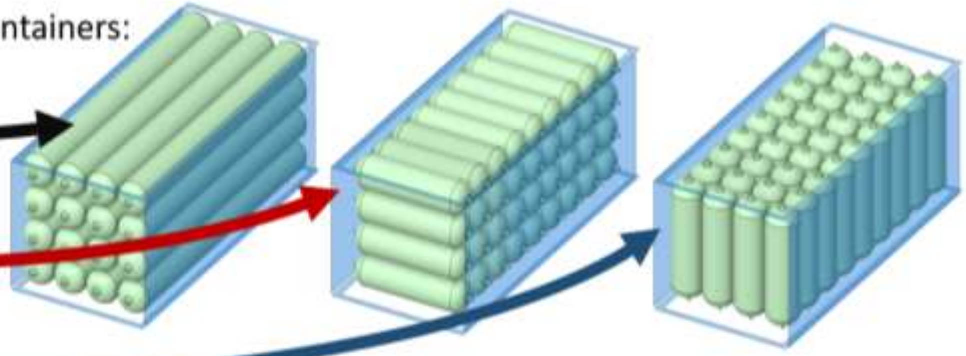
NOTE: [1] Including conversion and storage; [2] Assumes salt cavern storage for pipelines; [3] Ammonia assumed unsuitable at small scale due to its toxicity; [4] While LOHC (liquid organic hydrogen carrier) is cheaper than liquid hydrogen for long distance trucking, it is unlikely to be used as it is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

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

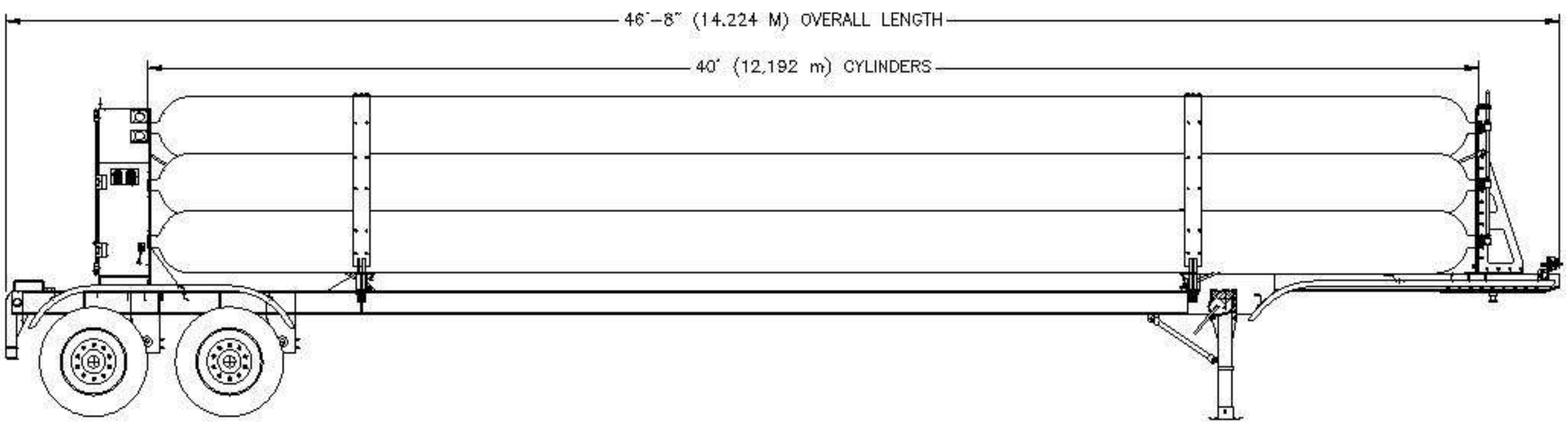
Tube Trailers

Tube trailers are used for distance up to 350 kms, 142-300 kg H_2/trailer
Operating pressure: up to 250 bar
Operating temperature: -40 to 85°C

- Placement of hydrogen tanks in 10ft, 20ft, and 40ft containers:
  - Along length
  - Along width
  - Along height



Tanks attached with valves, manifolds, and necessary fixtures for dispensing hydrogen



Leading Companies

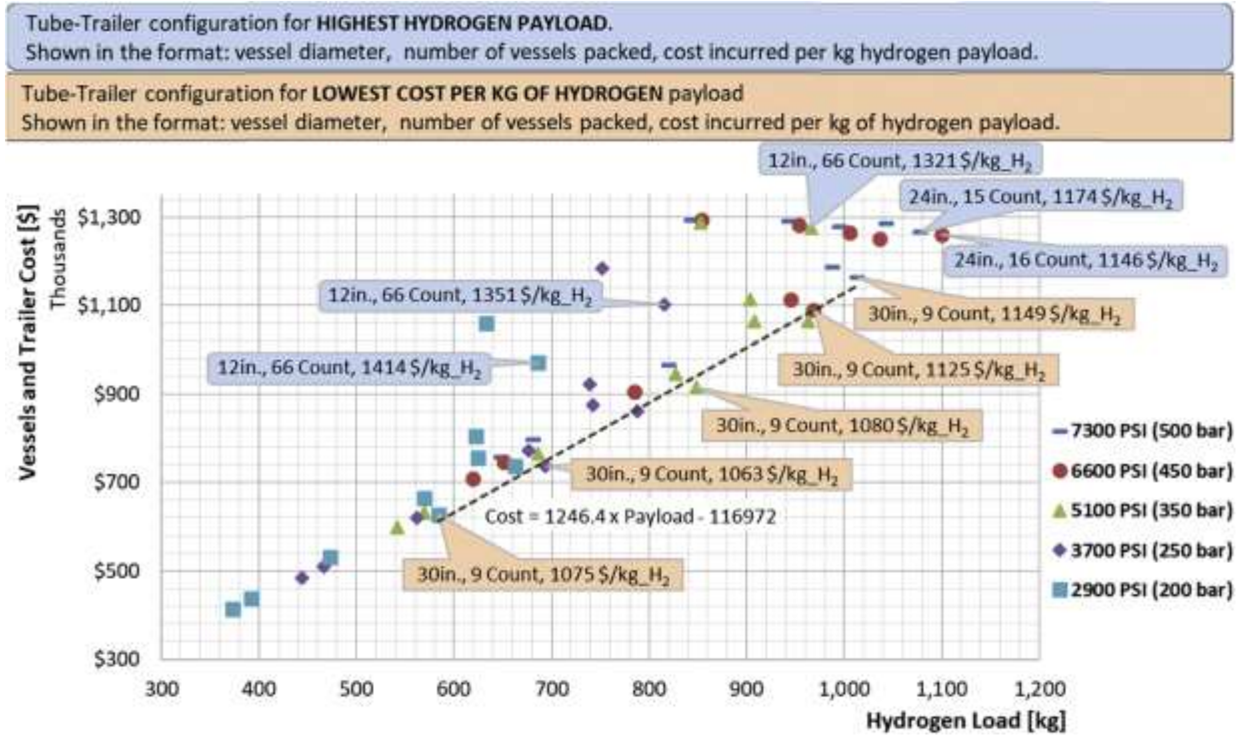
- **Air Liquide**
- **Linde AG**
- **Air Products and Chemicals, Inc.**
- **Roberts Oxygen Company, Inc.**
- **Calvera**
- **Composite Advanced Technologies, LLC**
- **Hexagon Composites ASA**
- **Zhejiang Rein Gas Equipment Co., Ltd.**
- **FIBA Technologies, Inc**
- **Matar Srl.**
- **Weldship Corporation**

According to Fairfield Market Research, the **global hydrogen tube trailer market was valued at US$ 276.3 Mn in 2020 and is anticipated to be worth US$498.6 Mn in 2026**, **registering a CAGR of 10.3% between 2021 and 2026**.

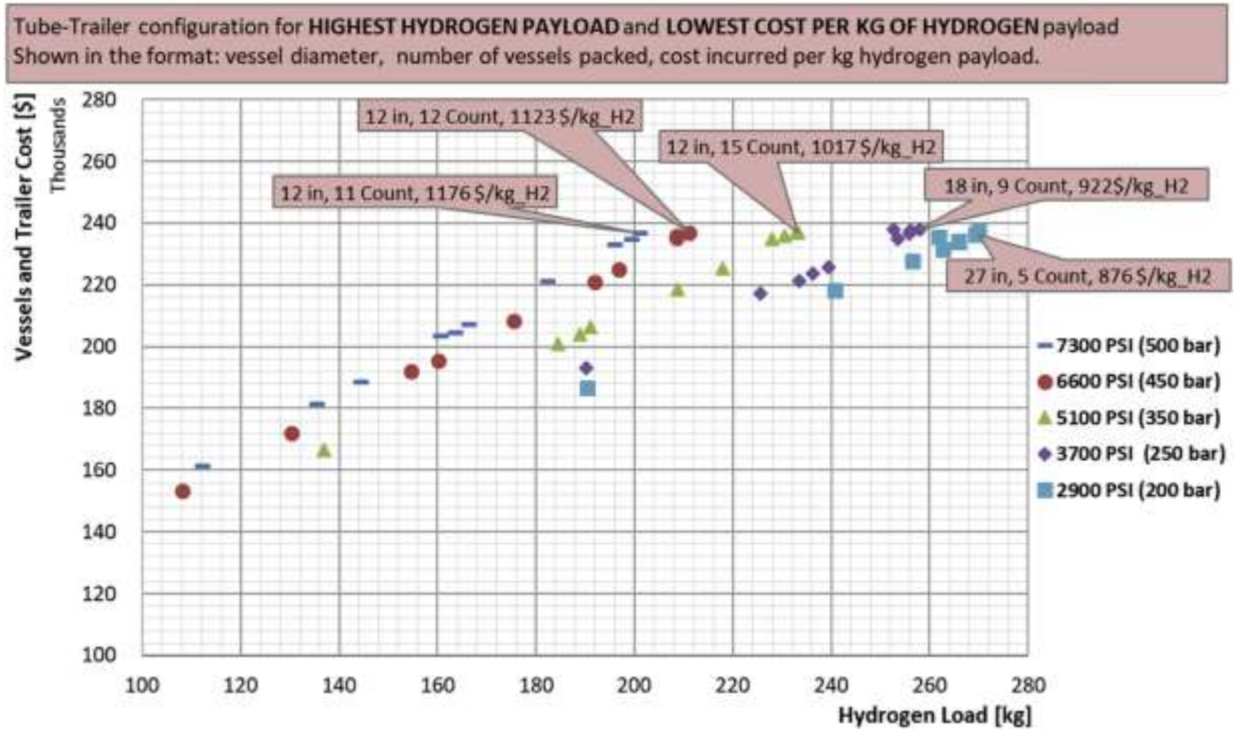
https://www.fairfieldmarketresearch.com/report/hydrogen-tube-trailer-market

https://cmwelding.com/configuration/hydrogen-h2-tube-trailer-9-tubes-dot-3aax-2400psi-40-ft

Tube Trailers cost comparison

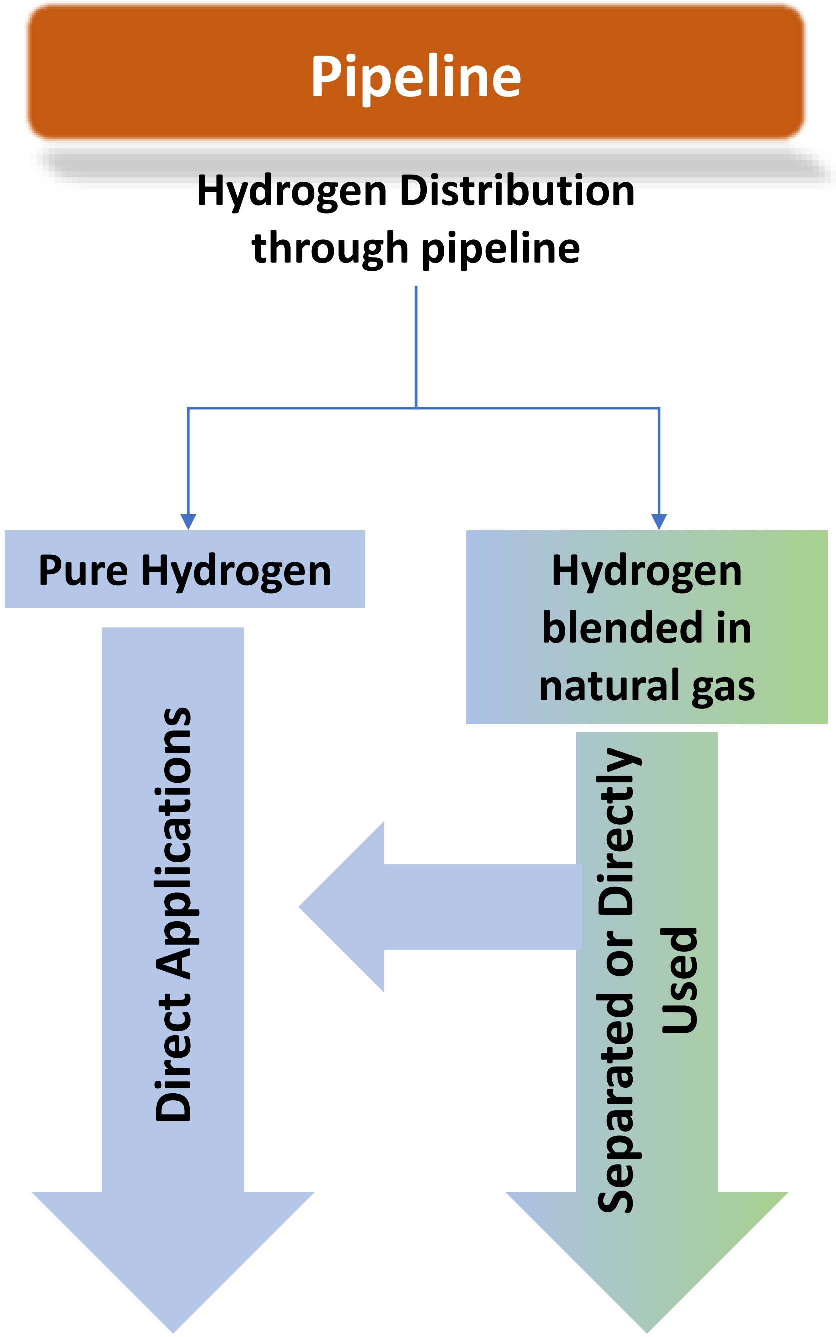


Deliverable hydrogen payload and resulting cost of the trailer and composite vessels for various combinations of working pressures and vessel outer diameters.

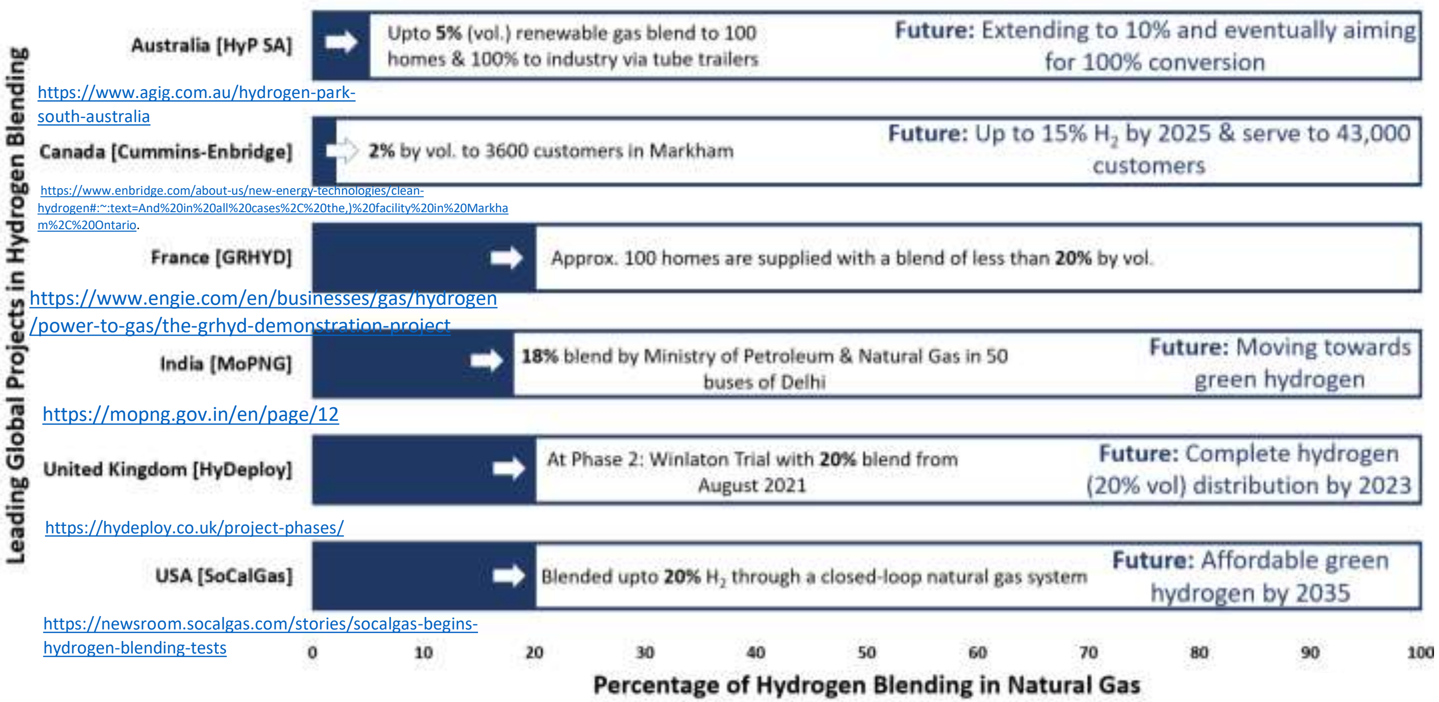


Deliverable hydrogen payload and resulting cost of the trailer and steel vessels for various combinations of working pressures and vessel outer diameters.

- **Composite tube trailers** can transport large hydrogen payloads, up to 1100 kg at 500 bar working pressure.
- **Steel tube trailer** may transport a maximum hydrogen payload of approximately 270 kg. (Reddi et. al., 2018)



Global Status of Hydrogen Blending Projects in Natural Gas



https://www.agig.com.au/hydrogen-park-south-australia

https://www.enbridge.com/about-us/new-energy-technologies/clean-hydrogen#:~:text=And%20in%20all%20cases%2C%20the,)%20facility%20in%20Markham%2C%20Ontario.

https://www.engie.com/en/businesses/gas/hydrogen/power-to-gas/the-grhyd-demonstration-project

https://mopng.gov.in/en/page/12

https://hydeploy.co.uk/project-phases/

https://newsroom.socalgas.com/stories/socalgas-begins-hydrogen-blending-tests

Indigenous Scenario of Hydrogen Blending Projects in Natural Gas

- **GAIL** had commenced India's first-of-it's-kind project of mixing Hydrogen into Natural Gas system.

  https://pib.gov.in/PressReleasePage.aspx?PRID=1794428
- **NTPC** starts India's first green hydrogen blending operation in PNG network.

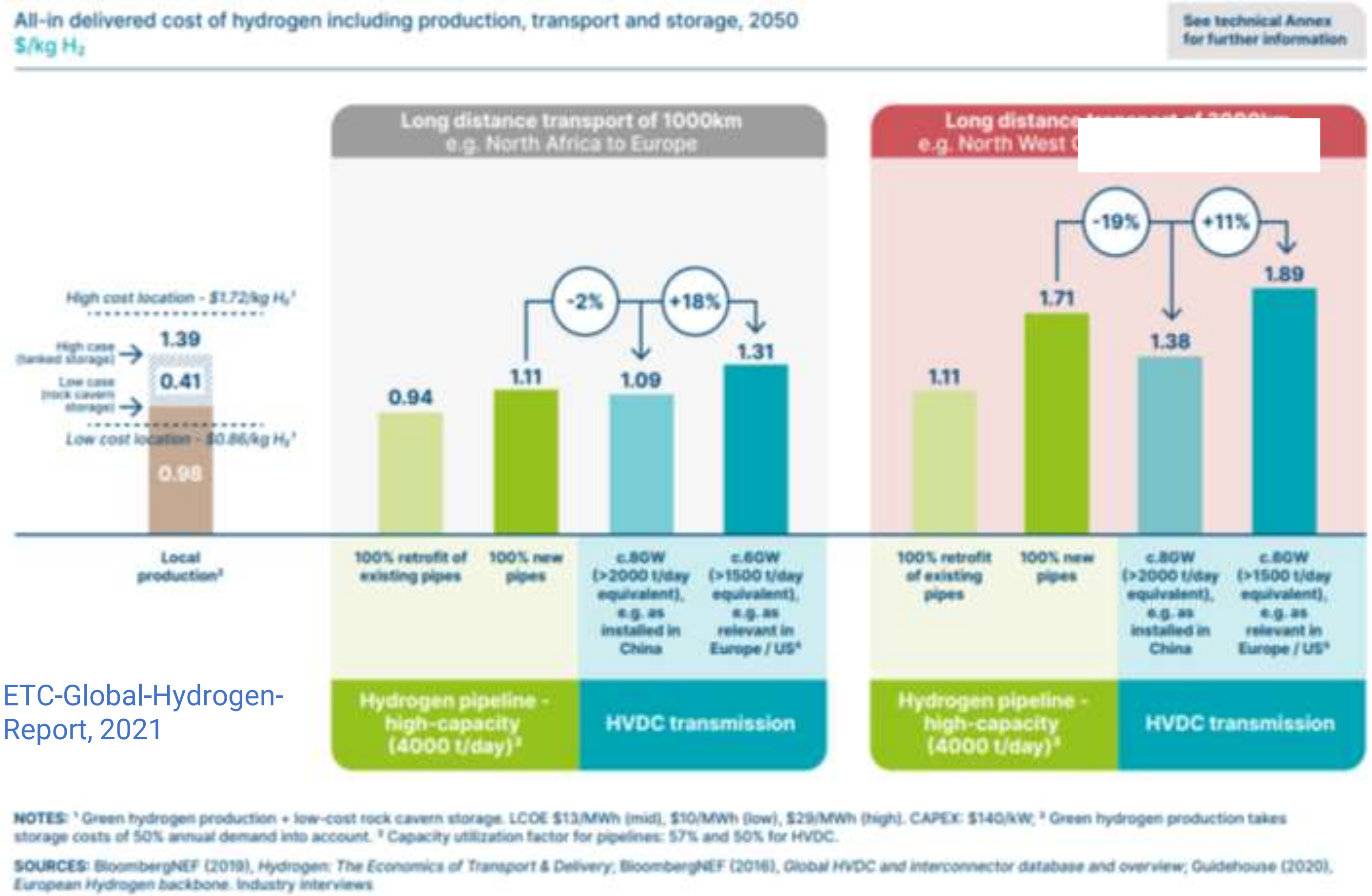
  https://pib.gov.in/PressReleasePage.aspx?PRID=1888334
- **Indian Oil Corporation (IOCL)** plans to conduct testing of natural gas pipelines nationwide for their ability to carry hydrogen.

  https://www.projectstoday.com/News/IOCL-to-test-gas-pipelines-for-hydrogen-carrying-potential-soon

Pipeline

Transport of gaseous hydrogen over long distances
Operating pressure: up to 20 bar
Operating temperature: -40 to 85°C

- More than 4,500 km of hydrogen pipelines are already in use worldwide (Capurso et al., 2022), mostly for moving hydrogen between facilities in the chemical process industry.
- The United States' Louisiana and Texas have the longest operating pipelines, followed by Belgium and Germany (Sircar, et. al., 2022).



ETC-Global-Hydrogen-Report, 2021

ttps://www.everycrsreport.com/files/2021-03-02_R46700_294547743ff4516b1d562f7c4dae166186f1833e.pdf

https://www.energy.gov/sites/default/files/2017/09/f37/fcto_webinarslides_lowering_costs_h2_pipelines_097217.pdf

- Fiber-reinforced polymer (FRP) pipelines for the distribution of hydrogen are one possible remedy. The installation costs for FRP pipelines are around 20% lower than those for steel pipelines.
  https://www.energy.gov/eere/fuelcells/hydrogen-pipelines

Today's research focuses on technical pipeline transmission issues, such as

- the potential for hydrogen to embrittle the steel and welds used to construct the pipelines
- the need to stop hydrogen leaks and permeation and
- the demand for more affordable, dependable, and long-lasting hydrogen compression technology. (Kar et. al., 2022).

Liquid Hydrogen Delivery

LH_2 tanks can be used for delivery up to 4000 kms.
Operating pressure: <10 bar
Operating temperature: -253°C

- For longer distances, hydrogen is transported as a liquid in super-insulated, cryogenic tanker trucks to distribution sites where it is vaporized to a high-pressure gaseous product for dispensing.
- Over long distances, trucking liquid hydrogen is more economical than trucking gaseous hydrogen because a liquid tanker truck can hold a much larger mass of hydrogen than a gaseous tube trailer can.

https://www.energy.gov/eere/fuelcells/liquid-hydrogen-delivery#:~:text=Hydrogen%20is%20most%20commonly%20transported,temperatures%20through%20a%20liquefaction%20process.

Advantages	• Higher volumetric storage capacity than compressed gas. • Fewer evaporation losses than typical compression mechanisms
Disadvantages	• Liquefaction requires complex technical plant. • Liquefied hydrogen incurs boil-off losses.

Examples of Liquid Hydrogen Delivery (Ustolin et.al., 2020)

Transportation method	Transport distance (km)	Pressure (bar)	Hydrogen content	Hydrogen amount	Tank volume (m³)	Example
Road	Mid-range distance	Up to 7	100%	4 tons per truck	<64	**Air Products** delivers LH_2 by means of semitrailer with a capacity of 17,000 gal (64 m³).
Railway	> 10³	Up to 7	100%	7 ton per rail car	105	In 2009, **NREL** estimated that hydrogen railway delivery might be a more efficient method compared with CGH_2 and LH_2 trucks and pipelines for long distances and large H_2 amount
Maritime	Transoceanic delivery	Up to 7	100%	60 ton per tank	900	LH_2 was transported in 900 m³ containers onboard of barges to the **NASA** Space Center during the Apollo space program

- The world's first liquid hydrogen tanker; launched on the **Suiso Frontier** in **Kobe, Japan**, 2019. (Lloyd'sRegister, 2020).

https://www.hydrogenenergysupplychain.com/supply-chain/the-suiso-frontier/

Research Activities at IITKGP: 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			

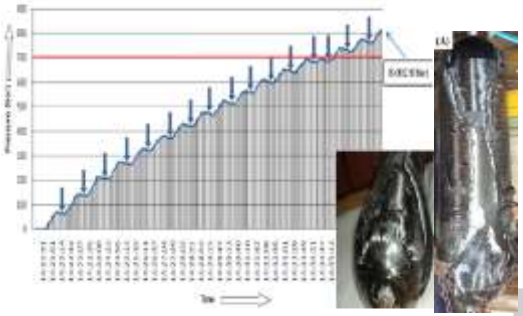
Prototype Burst Test

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)

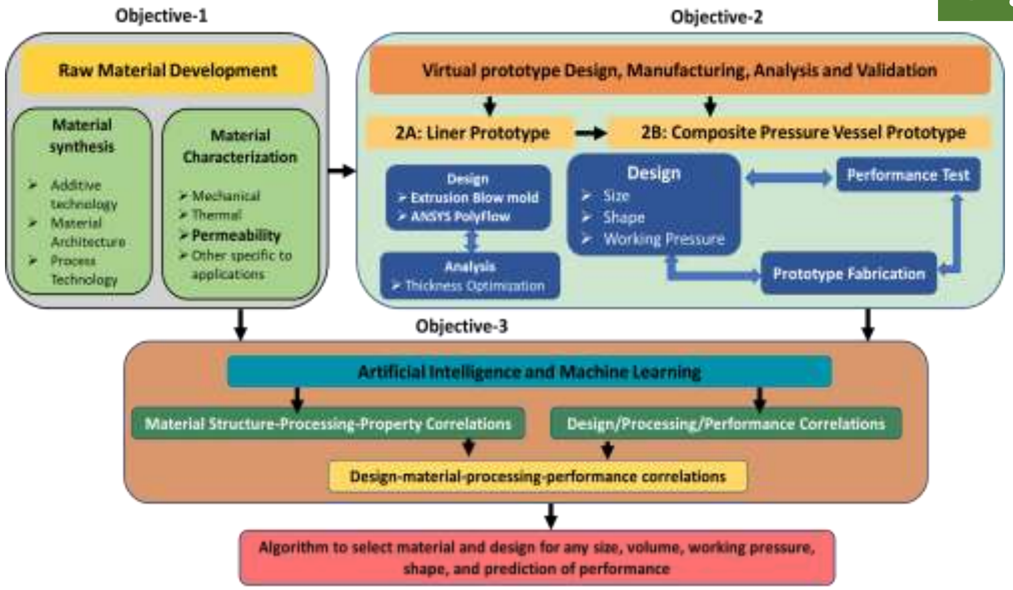


Prototype Burst Test

Final prototype

IC-MAP on Bioenergy and Hydrogen

Ongoing



Scale- Up

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 liner**

Research Activities at IITKGP: Hydrogen Distribution

H_2 Distribution System: Composite Tube trailer

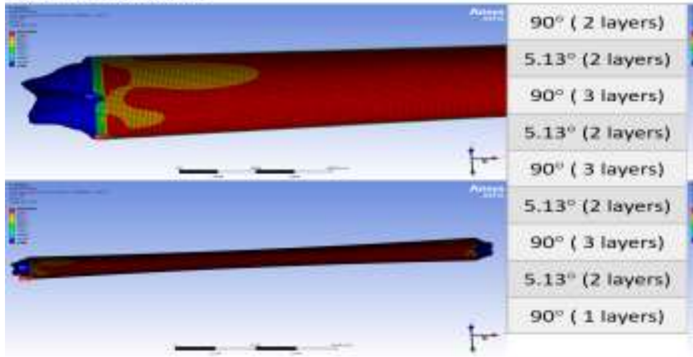
Composite Tubes

Vessel Type	: Type-IV (H_2)
Liner	: HDPE
Composite	: carbon-epoxy
Volume	: 3257 m^3
Operating pressure	: 175 bar
Burst Pressure	: >412 bar

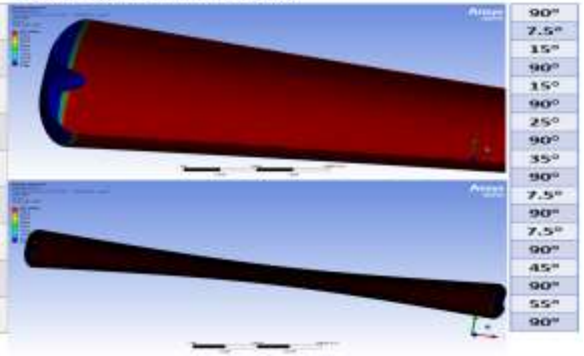
Ongoing

	Simulated Composite Tube Trailer	Designed By Netting Analysis	Commercial Metallic Tube Trailer
Maximum Allowable Working Pressure (bar)	175	175	175
Tube Length	10.97 m	10.97 m	10.97 m
Tube Diameter	22 in	22 in	22 in
Capacity (m^3)	2643	2643	3257
Number of Winding Layers	18	20	-
Tube Weight (kg)	374.97	413.65	1945.911

By Netting Analysis



Sequence 1 (Trial and Error)

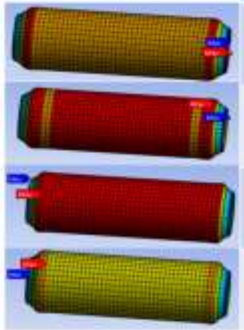


H_2 Distribution System: Composite Pipeline

Parameters	Glass-fiber reinforced pipes
Inner Diameter	110 mm
Length	450 mm
Wall Thickness	3.8 mm
Composite	E-glass fiber and Epoxy

Ongoing

FEA Simulation of Pipe



Winding Angles	Experimental Burst Pressure (Mpa)	Simulated Burst Pressure(Mpa)
$[\pm 45]_{3s}$	-	30.78
$[\pm 55]_{3s}$	5.6	34.44
$[\pm 63]_{3s}$	3.4	36.19
[±63/±45/±55]	2.3	29.37

Analysis

- **Burst Performance**
- **Tensile and compressive characteristics**
- **Fatigue behavior**
- **Impact response**

Knowledge Base and Infrastructure Developed at CAL, IITKGP

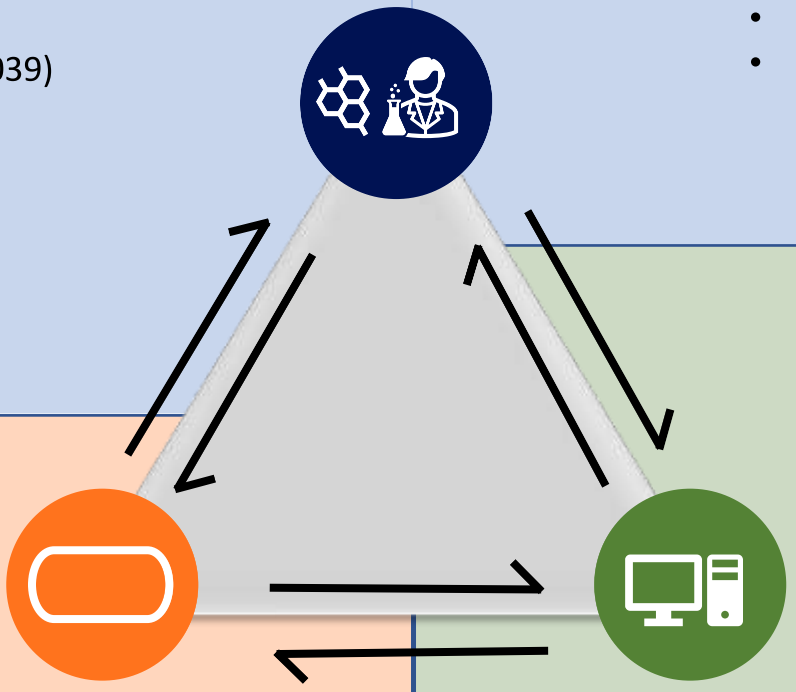
Material characterisation /methodology

Composite material characterisation facility

- Density (ISO 1183)
- Fiber volume fraction (ASTM D2584)
- Hoop tensile strength: NOL ring (ASTM D2290)
- Tensile strength with thermal condition (ASTM D3039)
- Poisson's ratio
- Compressive strength (ASTM D14126)
- Flexural strength (ASTM D14125)
- Resin cure kinetics: DSC
- Fracture toughness (ASTM D15024)

Liner material characterisation facility

- High pressure hydrogen gas permeability test (up to 200 bar)
- Molecular weight: GPC
- Rheological properties: DMTA



Manufacturing technology

Manufacturing technology

- Filament winding
  - Winding speed
  - Winding band width
  - Winding tension
  - Fiber volume fraction
- Liner forming technology
  - Roto mold: polymeric liner
  - Spinning: metallic liner

Virtual processing /testing platform

Virtual platform for design and performance

- Optimisation of winding layers: hoop and helical layers
- Optimisation of winding parameters
  - Winding angle/tension/band width
- Optimisation of liner geometry

- Burst pressure analysis/ Fatigue analysis/ Fracture analysis
- AI & ML to create correlation among material, design, and performance.
- Resin flow out mold
- Polymeric liner forming technique

CAL Group

Current Research Scholars

Energy Storage/Distribution Group


Pranjali


Akash


Ananya


Saurav (M.Tech)

Bio Composite


Sangeeta

TPS Group


Yash


Abhiram (M.Tech)

Armour Group


Rinku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Rohan


Sarga (M.Tech)

Prof. Swati Neogi
PI of CAL
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"Taking Composites Mainstream"

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Hafijul Hossain Sardar
Technical Superintendent


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Rohan Roy
Lab assistant

Alumni


Dr. Raghu Raja


Dr. Victor


Dr. Santoshi


Dr. Yashwanth


Dr. Nitai


Jigyasa


Monika


Saksham

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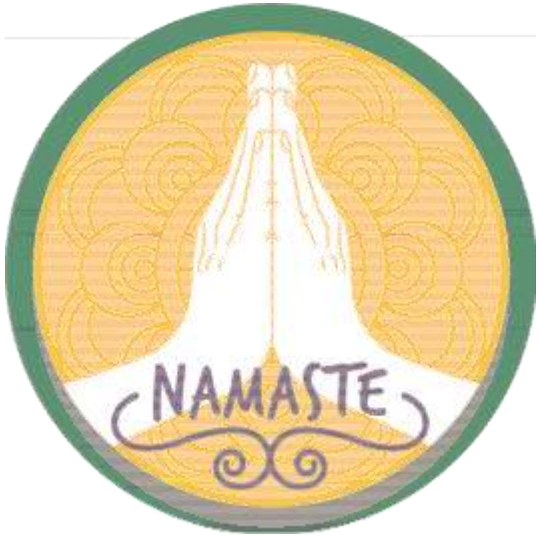
Thank You



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