LH_2 ecosystem, transfer and infrastructures

ELVHyS international stakeholder seminar Bologna 2024

Air Liquide - Safety-Lab

2024.09.30

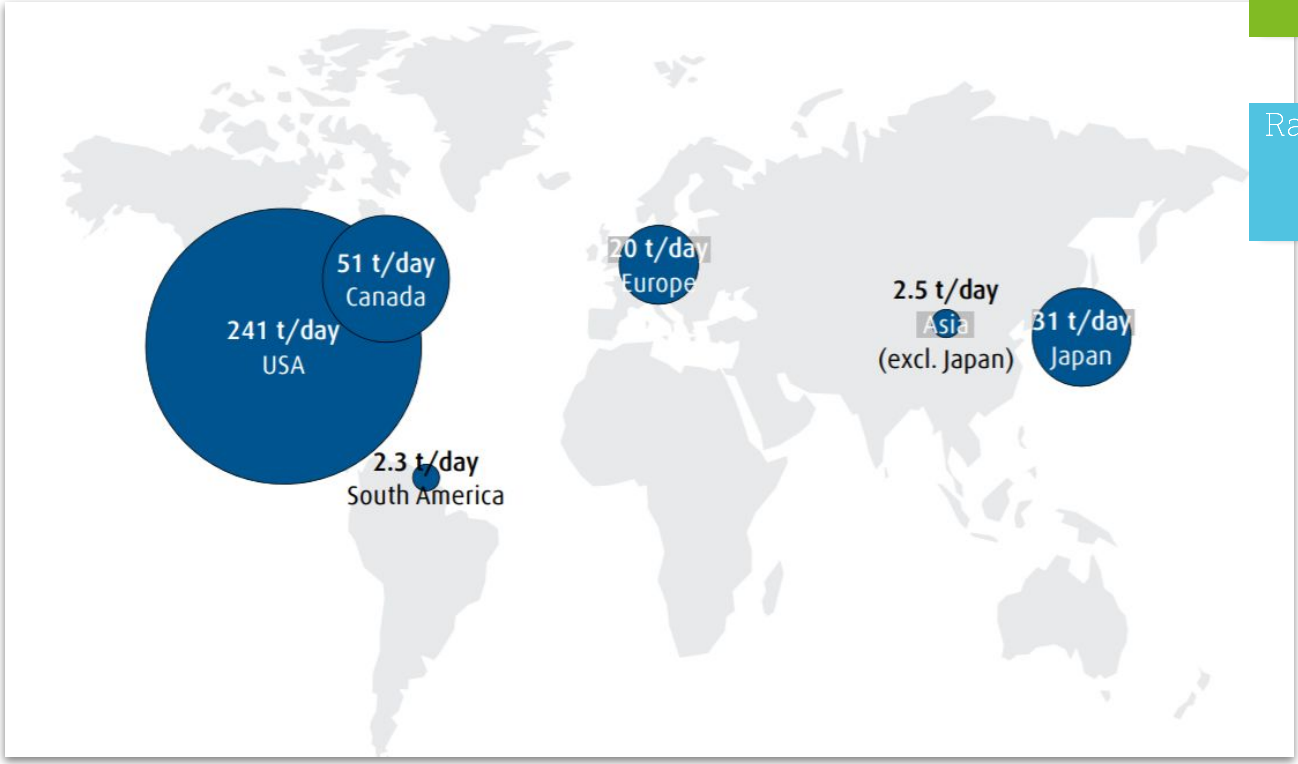
Content & Context

Content

1. H_2 production & Ecosystem development
2. Concretely, why LH_2 ?
3. H_2 liquefaction & Storages
4. Distribution
5. LH_2 refuelling stations & applications

Liquid Hydrogen

Worldwide production capacities



~430 tpd

Ratio LH_2 vs GH_2 prod

0.3%

AL LH_2 references

Hydrogen Liquefiers					
(2025)	FEED Multi trains	South Korea	165	tpd	H2
(2023)	SK E&S GEP 1	South Korea	90	tpd	H2
(2023)	Doosan	South Korea	5	tpd	H2
~~(2022)~~	~~Small scale LH2~~	~~France~~	~~7~~	~~tpd~~	~~H2~~
2022	West Coast	USA	29	tpd	H2
2016	Calvert City	USA	10	tpd	H2
1990	Kourou	French Guiana	2	tpd	H2
1987	Pacific Hydrogen	Japan	1.5	tpd	H2
1987	Hydrogenal	Canada	10	tpd	H2
1987	Waziers	France	10	tpd	H2
1977	Iwatani	Japan	1	tpd	H2
1966	Frais Marais	France	1	tpd	H2
1964	Predicktown	USA	6	tpd	H2

World's largest LH2 plant

Replication of West Coast Cold Boxes
Under Detail Design Study, main equipment ordered and under fabrication

First LH2 plant in South Korea, to feed fleet of city buses

Under Manufacturing in AL's workshop
Equipment delivery Q2 2022

Located in North Las Vegas

To supply Californian market

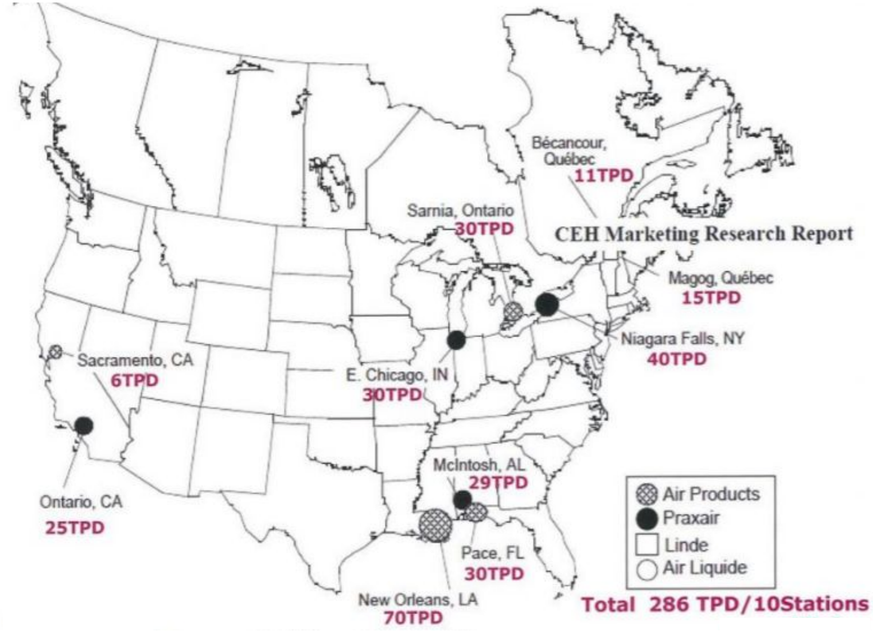
Running since March 2022!

More than 30 years of operation

Still under operation with full availability & reliability

Large scale liquefiers in operation

Focus on the US, from 1960 to now



Site	operated by	Capacity	built
Painsville, OH / USA	Air Products	3 tpd	1957 *
West Palm Beach, FL / USA	Air Products	3.2 tpd	1957 *
	Air Products	27 tpd	1959 *
Long Beach, CA / USA	Air Products	30 tpd	1958
Mississippi (Test Fac.)	Air Products	> 36 tpd	1960 *
Ontario, CA / US	Praxair	20 tpd	1962 *
Sacramento, CA / USA	Union Carbide, Linde Div.	(54) 60 tpd	1966 *
	Air Products	6 tpd	1986
New Orleans, LA / USA	Air Products	34 tpd	1977 (1963)
	Air Products	34 tpd	1978
Niagra Falls, NY / USA	Praxair	18 (40?) tpd	1981
Pace, FL / USA	Air Products	30 tpd	1994 *
McIntosh, AL / USA	Praxair	24 (29?) tpd	1995
East Chicago, IN / USA	Praxair	30 tpd	1997
Sarnia, Ontario / Canada	Air Products	30 tpd	1982
Montreal, Canada	Air Liquide Canada Inc.	10 tpd	1986
Bécancour, Quebec /Can.	Air Liquide	12 tpd	1988
Magog, Quebec /Canada	(BOC) Linde	15 tpd	1989
Kourou, Franz. Guayana	Air Liquide	5 tpd	1990

*stopped

Large scale liquefiers in operation

In the rest of the World

■ Europe

Site	operated by	Capacity	built
Lille (Wazier), France	Air Liquide	10.5 tpd	1985
Rozenburg, Netherlands	Air Products	5 tpd	1986
Ingolstadt, GER	Linde	4.4 tpd	1992 *
Leuna (close to Leipzig, GER)	Linde	5 tpd	2008
	Linde	5 tpd	2021

*stopped

■ Asia

Site	operated by	capacity	built
Amagashi, Japan	Iwatani	1.2 tpd	1978 *
Tashiro, Japan	Mitsubishi Heavy Industr.	0.6 tpd	1984 *
Ooita, Japan	Pacific Hydrogen Co, Jpn.	1.4 tpd	1986
Tane-Ga-Shima, Japan	Jpn Liquid Hydrogen	1.4 tpd	1986
Minamitane, Japan	Jpn Liquid Hydrogen	2.2 tpd	1987
Kimitsu, Japan	Nippon Steel Corp. (Air Products?)	0.2 (0.3?) tpd	2004
Sakai, Japan	Iwatani Gas	1.1 tpd	2006
Osaka, Japan	Iwatani (Hydro Edge)	11.3 tpd	2006
Chiba (Tokio), Japan	Iwatani (built by Linde)	10 (5?) tpd	2008
Yamaguchi, West-Japan	Iwatani (built by Linde)	5 tpd	2008
KHI Akashi, Japan	Kawasaki Heavy Industries → own development!	(5 tpd prototyp)	2015
Indien	Asiatic Oxygen	1.2 tpd	k.A.
Mahendragiri, Indien	ISRO	0.3 tpd	1992
Beijing, China	CALT	0.6 tpd	1995

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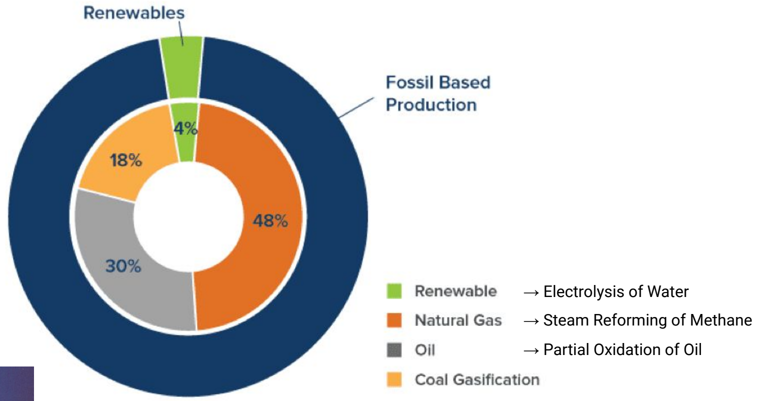
H_2 production & Ecosystem development

Worldwide hydrogen production

Quick reminder

- **Hydrogen is mainly produced from fossil fuels**



Clean and renewable production processes now used for low-C hydrogen needs

Low-Carbon H_2 pathways

**tpd = ton per day*

BioCH$_4$ Reforming

Electrolysis

Low carbon electricity
DK PEM 1.5 MW 0.6 tpd
Canada PEM 20 MW 8 tpd
Taiwan AEM 25 MW 10 tpd
Normandhy PEM 200 MW 80 tpd

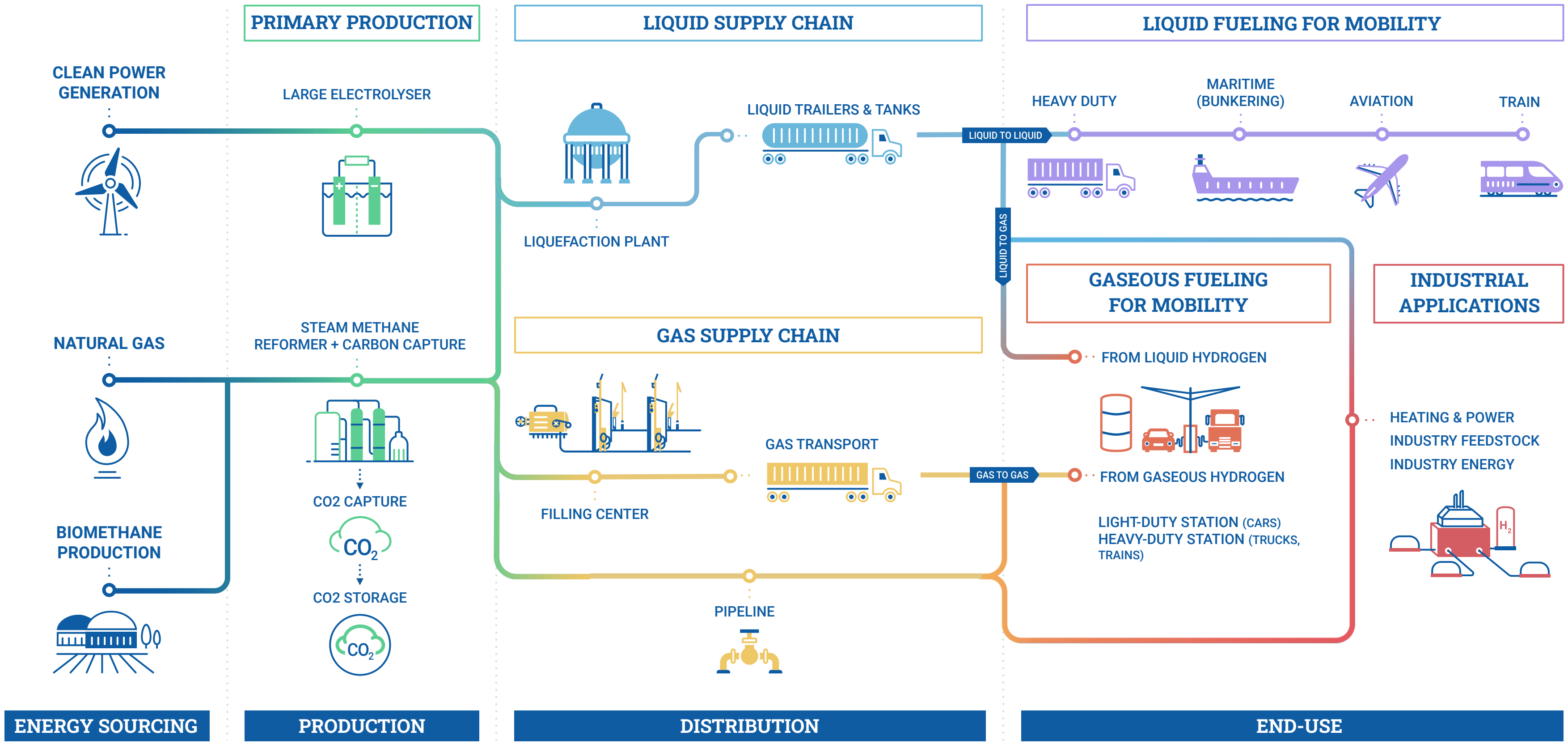
Natural Gas Reforming + Carbon Capture & Sequestration (CCS)

Projects in AL bassins
(Kairos, Antwerp@Sea, Portos,...)
CO_2 shipping OCEOS JV AL-SOGESTRAN

Low Carbon Hydrogen

Hydrogen value chain

From production to end-uses



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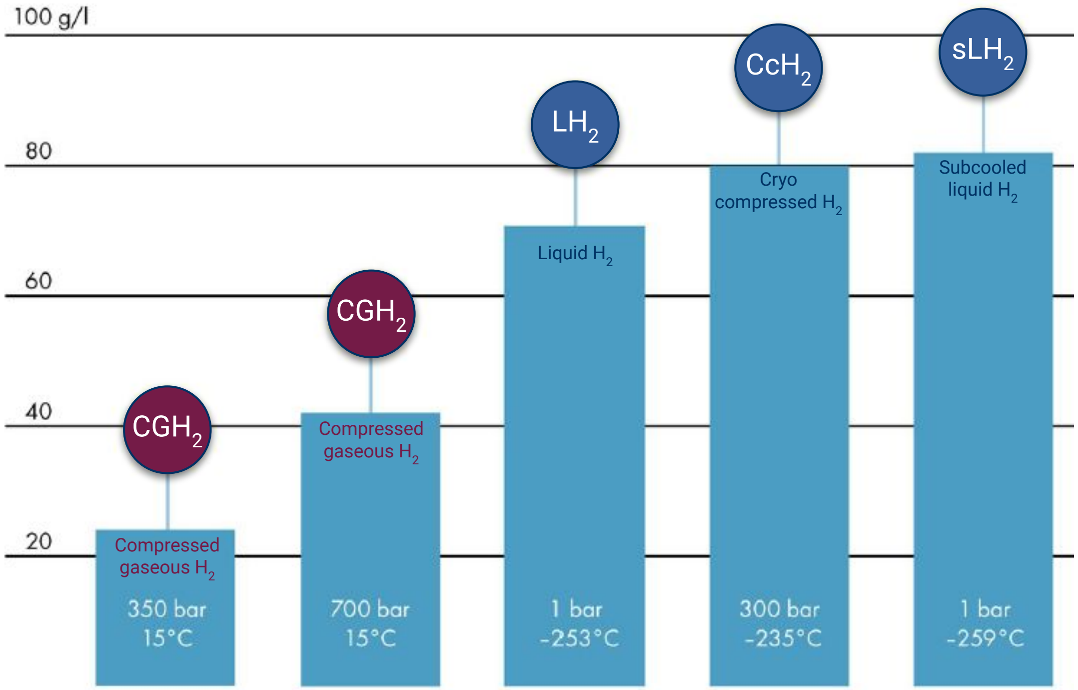
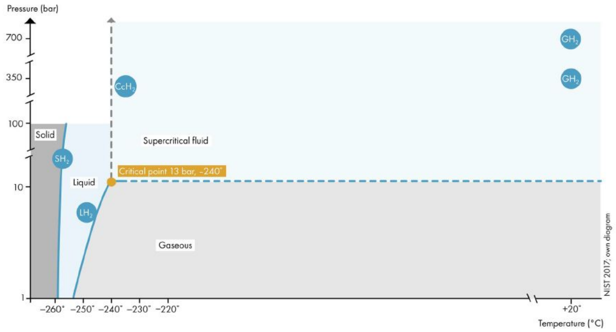
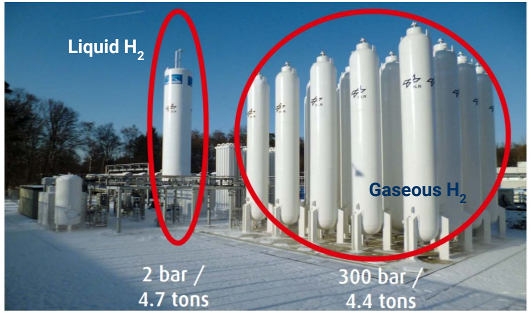
Concretely, why LH_2?

Hydrogen densities

A few numbers







Installation at DLR, Cologne, Germany

Why liquid hydrogen?

Concretely, the benefits

LOGISTIC: MORE VIABLE AT SCALE

LH_2: large amount of H_2 with minimum volume & mass = **minimum storage & transport costs**

Equivalence in usable payload

#1 LH_2	3.6 t	
= #3 635 bar	1.1 t	
= #5 300 bar	0.7 t	
= #16 200 bar	0.2 t	

Usable payload (swap @ 50 bar for GH_2 trailers) based on 2022 prices for GH_2 in Europe and LH_2 in US

ONBOARD: HIGH POWER DENSITY

LH_2 has a role to play for energy intensive mobility applications **with large quantities of energy onboard**

- **Allowing short refueling time:**
  - Example: **Truck fueling** - 60 kg in 10 min = **360 kg.h^{-1} =** 6 times higher flowrate than for H_2 cars
- And **maximum of hydrogen stored in a minimal volume**
  - Example: **Plane Liquid to liquid** - 15 min to refill a turbofan (3.5 tons) = **15 t.h^{-1}**

LAYOUT: REDUCED FOOTPRINT

LH_2 for stationary applications

- **Allowing increasing stored amount of H_2 in urban areas where space is limited**
  - Example: Lower footprint (factor 2) for Light Duty FCV refueling stations

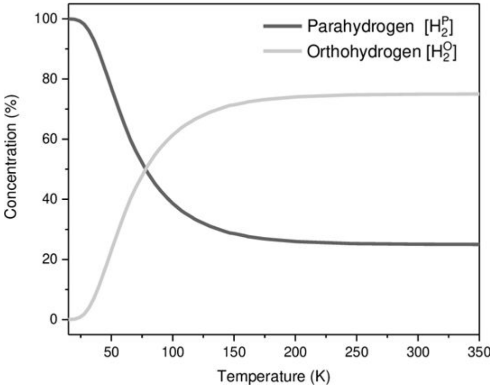
3

H_2 liquefaction & Storages

Hydrogen liquefaction

A few specificities

- **Volumetric capacity of LH_2 is 70 kg.m^{-3} as opposed to 30 kg.m^{-3} for GH_2 tanks at 700 bar**
- **LH_2 stored at cryogenic temperatures and at pressures of around 10-12 bar**
- **LH_2 storage tank is a Dewar, double-walled, vacuum-insulated vessel made of lightweight steel alloys**
  - Insulation: perlite or MLI (Multi Layer Insulation)
- **Boil-off [evaporation of LH_2 due to environmental warm-up] is a major challenge, which can be caused by:**
  - The exothermic ortho-para H_2 conversion
  - Residual thermal entries



Equilibrium concentration of ortho- and para-hydrogen vs. temperature

The conversion from ortho to para is an exothermic reaction with a conversion energy of 270 kJ.kg^{-1} at ambient temperature

Liquid hydrogen storage

Stationary storages

LH_2 storage tanks at Waziers liquefaction plant in France ($10\ t.d^{-1}$)

4 tanks of 250 m^3 each ⇒ Total : 70 t
Int/ext diameter = 4.02 / 5.1 m

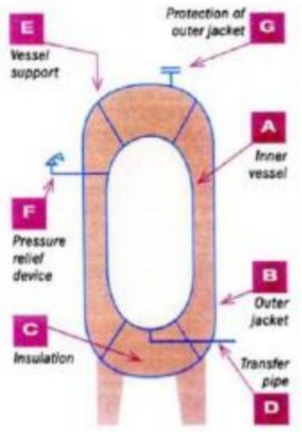
LH_2 storage vessel with 3 800 m^3 capacity at KSC in Florida

World's largest, 3800 m^3 (3 218 m^3 of LH_2)
double-wall vacuum perlite (1.3 m of thickness) insulated spherical (int/ext diameter = 18.75/21.34 m) storage vessel
The tank is operated at a pressure of 0.62 MPa and has a boil-off rate of 0.025%/d.

Liquid hydrogen storage

Stationary storages - Insulation

Double-wall insulation principle
[T_{LH2} = -253°C]



- Vacuum insulated vessels
- Inner vessel for pressure
- External protective jacket to retain perlite

Perlite

- Inorganic amorphous volcanic glass
- Compressed under vacuum between inner vessel and outer jacket
- Good tradeoff between cost and insulation properties

MLI

- Layer of Aluminium/Polymeric sheets
  Mylar, Lydall...
- More efficient than perlite
- Complex to wrap

⇒ Next generation : Aerogel, Foam, ...

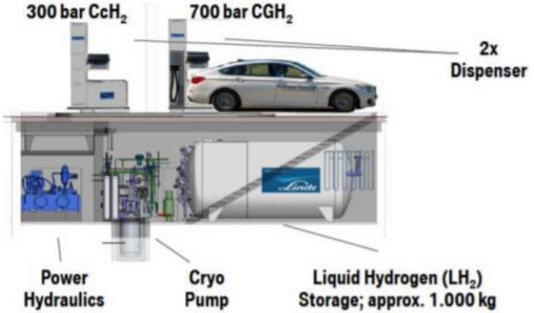
Liquid hydrogen storage

Stationary storages - Location

List of known underground liquid hydrogen storages

Year	Location	Design	Station operator
2004	Washington DC	Vertical, in a sleeve	Shell
2005	London	Vault	BP
2007	Munich	Vault	Total
2010	Berlin	Vault	NA

- **In most of the cases, LH_2 tanks are aerial → Above ground**
- **But a few cases of underground LH_2 storages**
  - buried (LNG, LOx) or vault (LH_2 in Germany)



- **Advantages**

  Footprint/layout reduction, could foster societal acceptance for urban environment…

- **Drawbacks**

  Lack of knowledge/feedback, H_2 confinement, ageing, maintenance…

LH_2 storage
Mobile tanks

HEAVEN FCH JU project
Successful flight summer 2023 Maribor Slovenia

Picture 2: Liquid hydrogen storage module for BMW

10 kg LH_2
M_{tank} = 100 kg

Picture 3: Liquid hydrogen storage module for GM

5.4 kg LH_2
M_{tank} = 50 kg

11 kg LH_2 / V_{tank} = 265 L / M_{tank} = 71 kg

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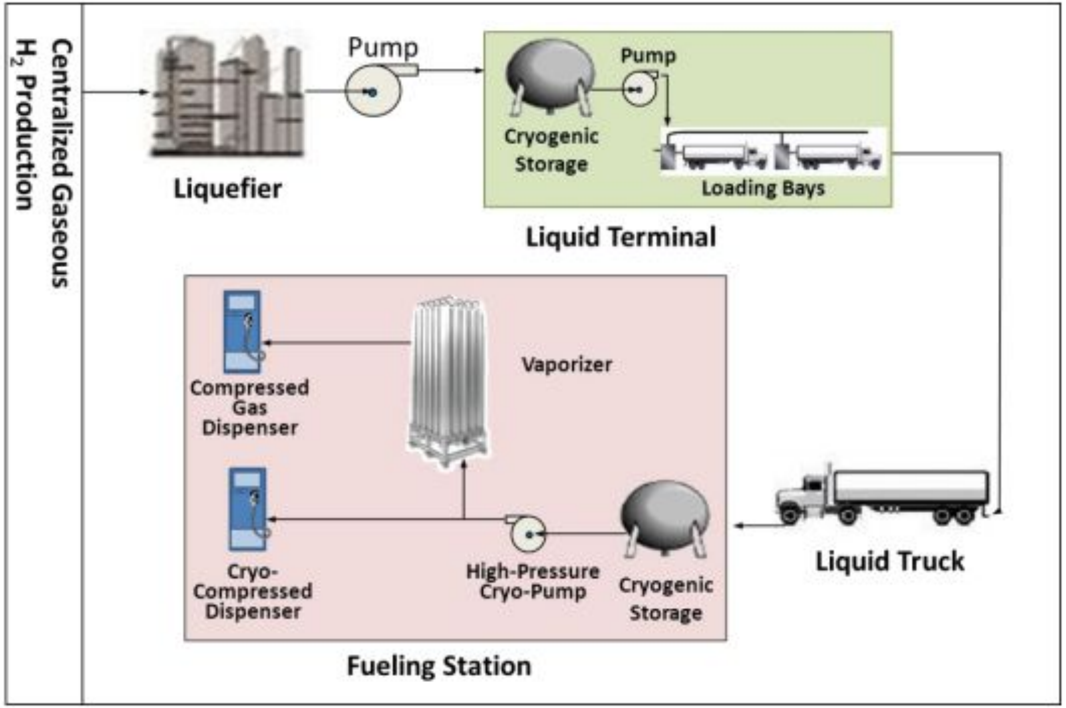
H_2 filling center & Distribution

LH_2 delivery chain

Overview



LH_2 supply chain
Equipment

- **Large trailers**
  - US Jumbo design for Airgas
  - 53' trailers, 66 m^3 ⇒ 4, 35 t payload
- **Short trailers / A-Double train configuration**
  - Specific to US market, complex valve cabinet
- **ISO40' containers**
  - Payload : 2.7 t
  - One way travel time up to 50 days
- **Compact trailers (ISO 20' containers)**
  - Payload 1.2 t
- **On site storages**
  - Sizes from 1 000 to 2 000 m^3 in operation or designed at AL
  - Max 4000 m^3 at NASA
- **Space / Car industry / Aeronautics**
  - Tailored designs
  - Most of them are under strict NDA

Example of Airgas LH_2 Jumbo trailer manufactured by Worthington

Example of A-Double train configuration operated in Canada (LN_2)

ISO 40' LH_2 container

H_2 filling center & transfer with LH_2 trailer

Actually

- LH_2 transfer by pressure build up (small ext HEX)
  - ⇒ P “mother storage” > P “daughter storage”
  - ⇒ “natural” LH_2 transfert
- Drawbacks
  - Slow transfer (1 to 2 t/h)
  - P ↗ in the “mother” storage ⇒ need of venting

Near future

- LH_2 transfer by pumping (no flow limitation) using a centrifugal cryogenic pump
- Drawbacks
  - Cost of the pump
  - Frequent maintenance of the pump

LH_2 distribution

Road transport

- **LH_2 trailers capacity: up to 5 t-H_2 - 12 bar**
- **H_2 boil-off can occur during transport despite the super-insulated design of tankers**
    - potentially 0.5% per day
- **H_2 boil-off up to roughly 5% also occurs when unloading LH_2 on delivery**
- **Boil off can be vented or valorized (compressed, recycled…)**
- **LH_2 tanks on the trailers are insulated using a vacuum super insulation (MLI)**

LH_2 distribution
Ship transport

NASA LH_2 barge fleet
From Louisiana to Florida
5 t capacity since 1990

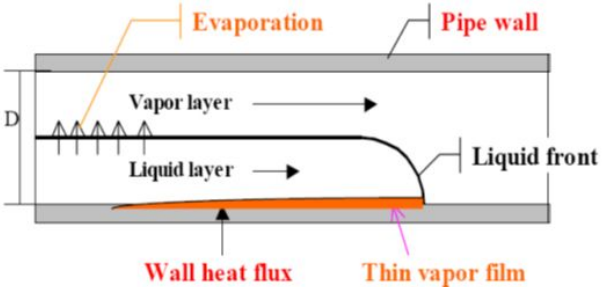
The world's first LH_2 carrier ship SUISO FRONTIER
launched in December 2019 in Kobe, Japan (HySTRA project)

Ship length 116 m, width 19 m
LH_2 tank with a capacity of 1 250 m^3 (90 t)

LH_2 distribution

Pipelines

- **Pipeline transportation of LH_2 at a small scale only**
- **Pipes for transferring cryogenic LH_2 must comply with the extreme low temperature of LH_2 and the associated insulation requirements**
- **Similar to LH_2 storage tanks, pipelines are of double-wall design and vacuum-jacketed**
- **Stainless steel is usually taken for the inner line with low heat conduction spacers as a support in the vacuum jacket**
- **Cryogenic pipes must be sufficiently flexible which can be done by appropriate pipe routing and expansion joints**



➪ *During the period of chill-down of an LH_2 line, a two-phase flow develops which is stratified for horizontal flows*

➪ *This phenomenon is encountered particularly in refuelling lines where chill-down is required before the fuelling process itself begins to avoid the gaseous phase to enter the tank*

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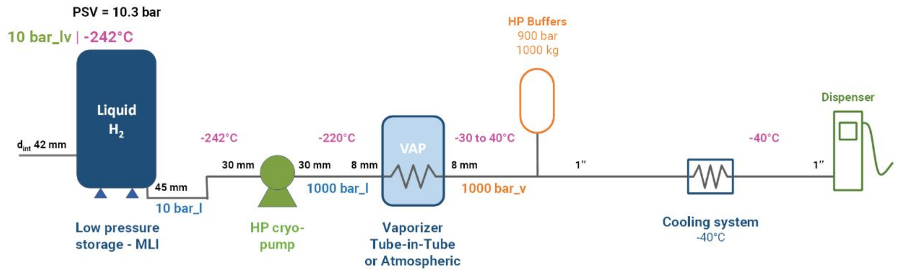
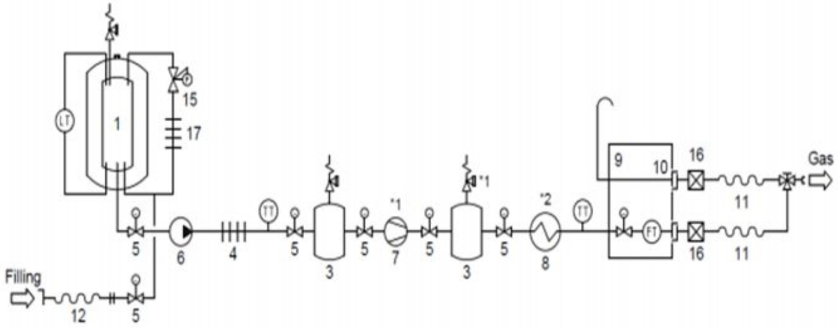
LH_2 refuelling stations & applications

LH_2 storage-based refuelling station

LtG HRS

- **A LH_2-based refueling station basically consists of :**
  - a LH_2 tank (around 20 m^3) with a maximal operating pressure of 10 bar
  - an insulated process line driving LH_2 from the storage tank to a vaporizer
  - a heater to heat up H_2 at 1000 bar
  - 1000 bar gaseous buffers (few m^3)





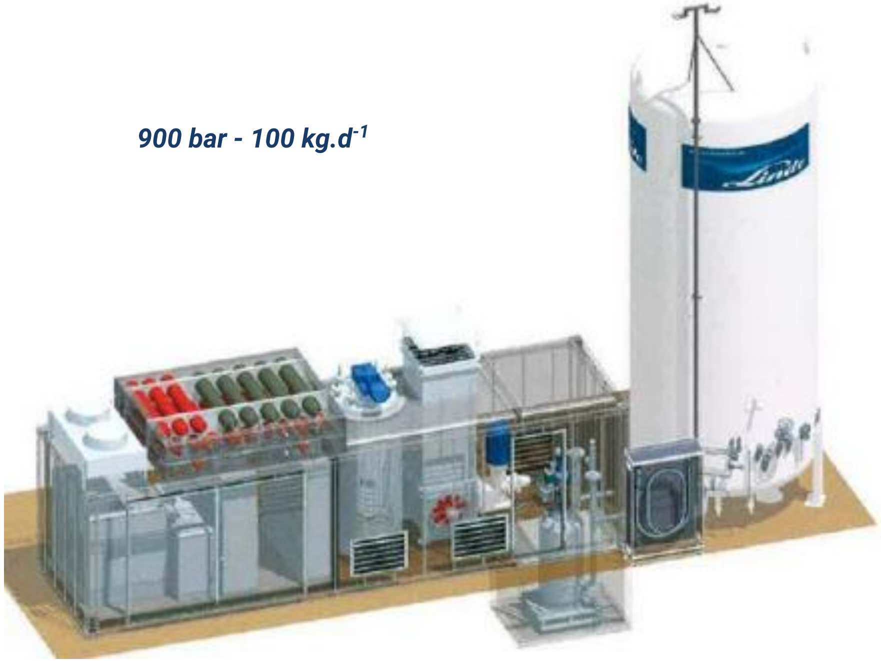
1. liquid hydrogen storage unit	8. chiller	15. pressure regulator
2. gaseous hydrogen storage unit	9. dispenser	16. breakaway coupling
3. intermediate gas storage	10. safety valve	17. pressure build-up evaporator
4. evaporator	11. delivery hose	
5. emergency shutdown system	12. off-loading hose	LT level sensor
6. pump	13. fill	FT flow sensor
7. compressor	14. purifier	TT temperature sensor

Air Liquide

LH_2-based filling station

For FCV and Forklift

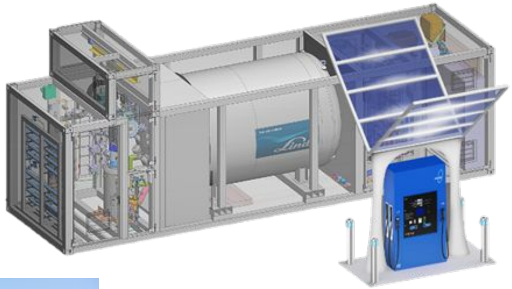
900 bar - 100 kg.d^{-1}

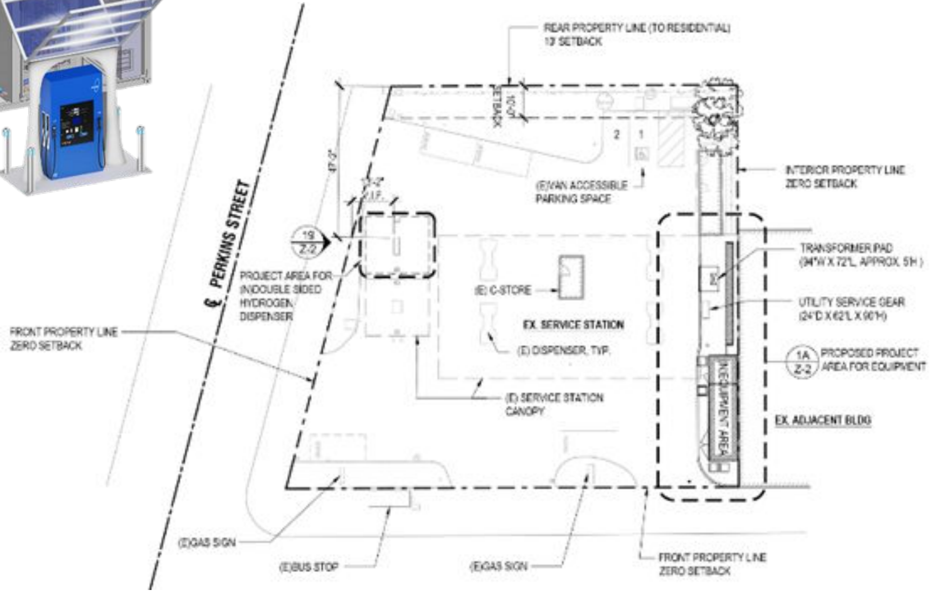


Coca Cola - Charlotte - USA

LH_2-based refueling stations

Oakland (US) First Element Fuel LtG HRS





LH$_2$-based refueling stations

Tobishima (Japan) L-t-G HRS

LH_2 applications

LH_2 system for mobility - Trucks

Musashi-9 LH_2 truck Musashi Institute of Technology (Japan)

H_2-powered engine with a 150 L LH_2 tank
A high pressure LH_2 pump delivers fuel to ICE

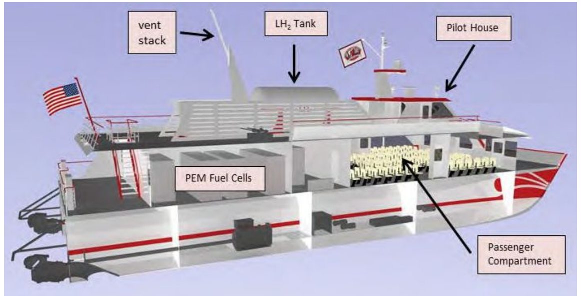
Mercedes FC truck GenH2 concept with LH_2 storage

Total output of 300 kW with 2 FC stacks
1000 km on a single tank filling recently demonstrated

LH_2 applications

LH_2 system for mobility - Ships

- **SF-BREEZE**
  - A zero-emission, H_2 fuel cell, high-speed passenger ferry (California)
  - Designed for 150 passengers - 100 km / day at a top speed of 35 knots (~65 km/h)
  - 1,2 t of LH_2 are stored in a single tank installed on the roof
  - 41 PEMFC racks (4* 30 kW FC stacks) ⇒ 4.92 MW



- **NORLED HYDRA ferry**
  - Power is provided by two 200-kW fuel cell modules
  - The LH_2 tank (3.8 t) will be installed on the roof

- **TOPEKA prototype FC ship**
  - Starting in 2021 the EU project HySHIP with 14 partners and led by the Norwegian shipping operator Wilhelmsen
  - Equipped with a 3 MW PEM fuel cell stack and supported by a 1 MWh battery pack
  - On-board single LH2 tank (6 t installed on the roof)

- **Many others under NDA**

Many thanks

Do business efficiently,
responsibly, sustainably
AND Safely!

Safety Lab