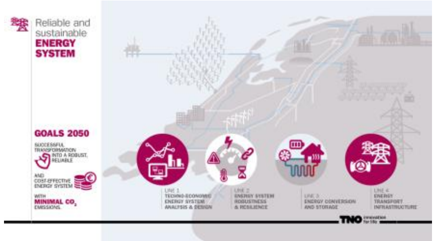
STORAGE AND TRANSPORT OF HYDROGEN

KIVI Jaarcongres ‘Wet, Wetenschap en Werkelijkheid
Sessie Waterstof, online, 1 december 2020

TNO innovation for life

ENERGY TRANSITION STUDIES



CONTACT

Marcel Weeda
Senior Consultant
Energy Transition Studies
TNO Energy Transition
E: marcel.weeda@tno.nl

TKI NIEUW GAS
Topsector Energie

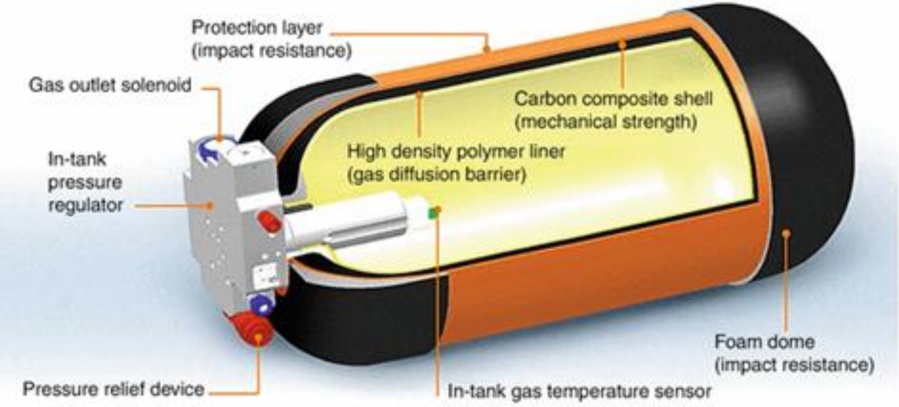
INTRODUCTION

Accelerating the energy transition through research into technical, economic, social and policy aspects of the energy transition for, and in collaboration with, knowledge institutions, governments, companies and social organizations

HYDROGEN STORAGE OPTIONS

Hydrogen holds much promise as an energy carrier and, compared to other forms of energy storage (e.g. electricity in batteries), can be stored in large volumes for long duration. However, being the lightest molecule, the properties of hydrogen make large scale storage challenging:

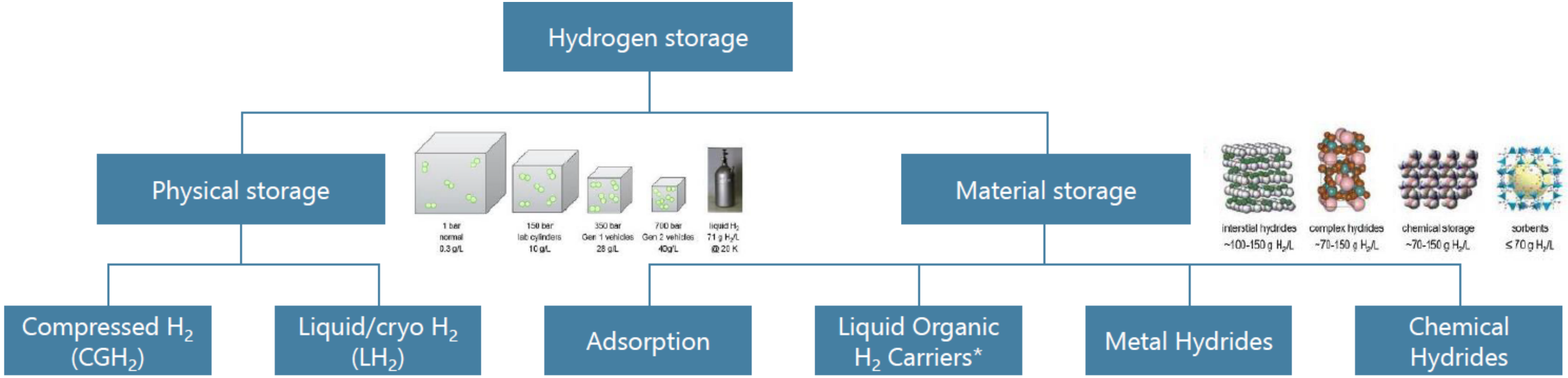
- The volumetric energy density of hydrogen gas is low (10,8 MJ/m^3 at 1 atm), so physical storage requires compression.
  - 1 liter gasoline ≈ 1 m^3 natural gas ≈ 3 m^3 hydrogen ≈ 3000 liter hydrogen
  - Efficiency Fuel Cell Electric Vehicles ≥ 2x gasoline vehicles
  - Compression to 700 bar



Example of a Type IV tank

HYDROGEN STORAGE OPTIONS

Fundamentally, there are two main approaches to H_2 storage: **Physical H_2 storage**, and **Material-based H_2 storage**



Hydrogen storage

Physical storage

Material storage

Compressed H_2 (CGH_2)

- In tanks
- In caverns and depleted gas fields

Liquid/cryo H_2 (LH_2)

- T < -150°C
- In tanks
- Usually also compressed

Adsorption

- Metal-organic frameworks (MOFs)
- Zeolites
- Carbon nanotubes

Liquid Organic H_2 Carriers*

- Dibenzyltoluene (DBT-PDBT)
- Toluene-MCH

** LOHCs are liquid in both dehydrogenated and hydrogenated state*

Metal Hydrides

- Simple metal hydrides: AlH_3, MgH_2, PdH_2,
- Complex metal hydrides: $LiBH_4$, $NaAlH_4$, $LiAlH_4$

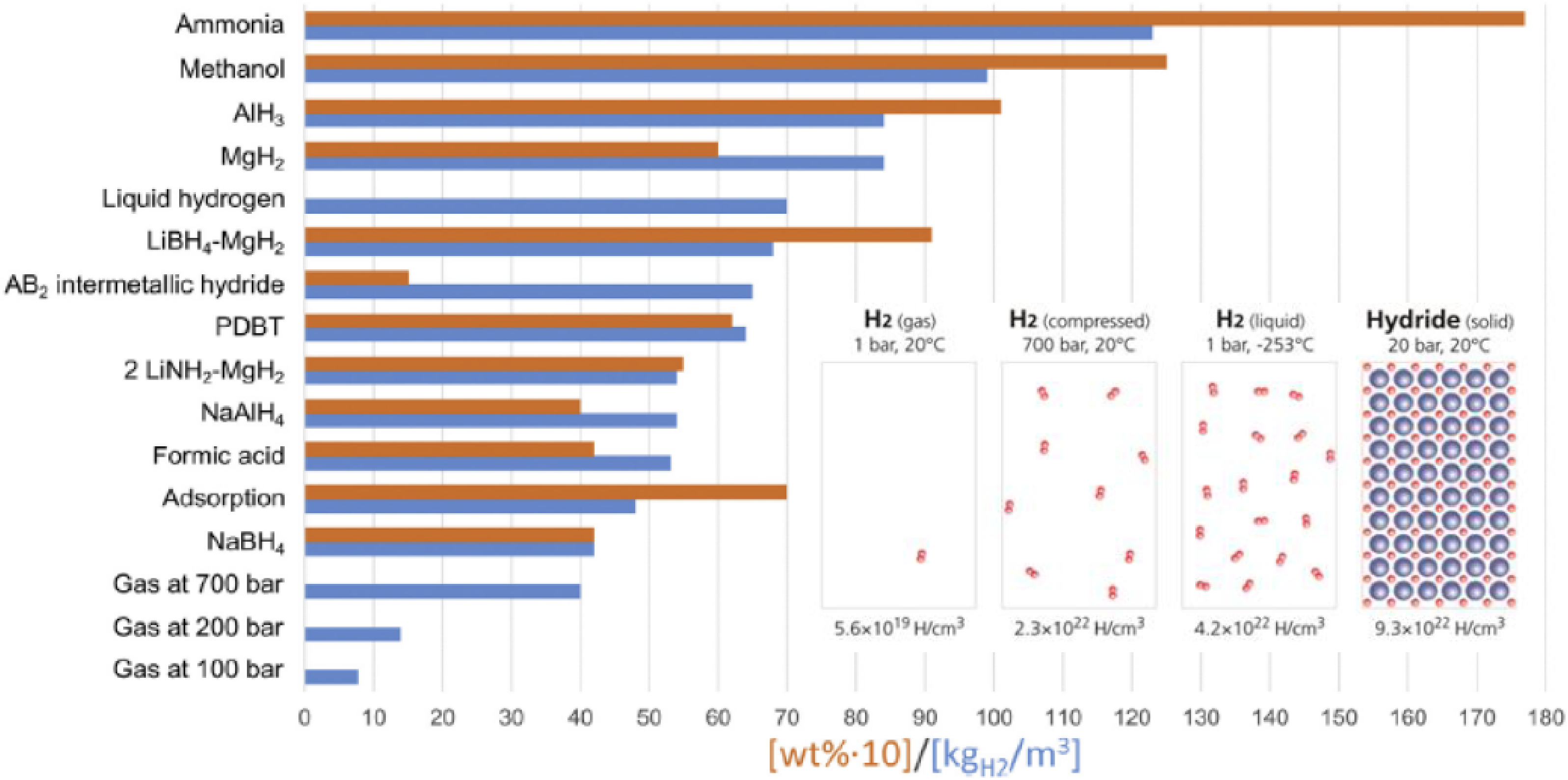
Chemical Hydrides

- NH_3
- MeOH
- HCOOH
- NH_3BH_3

Images taken from Abdalla et al. 2018

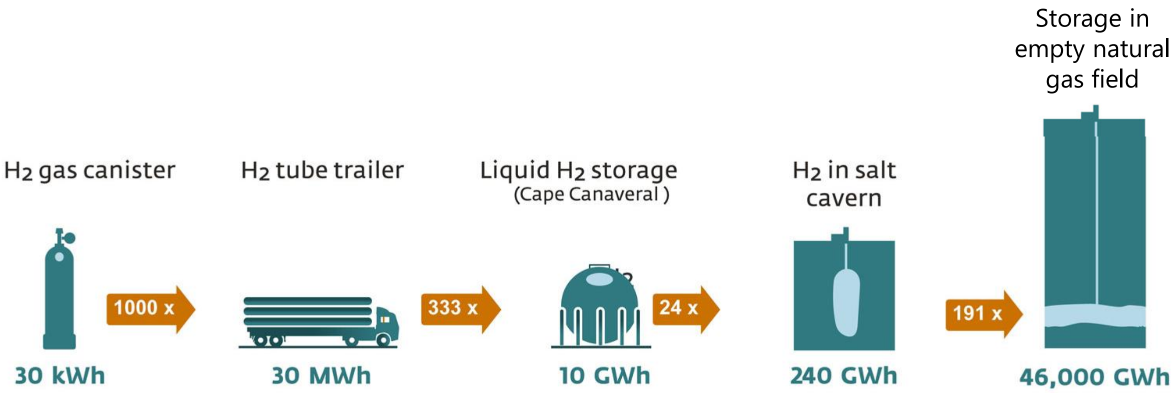
Storage in metal-organic frameworks (MOFs) or carbon nanotubes is technically feasible, but prohibitively expensive at this point. Similarly, concepts based on metal hydrides don't yet show commercial promise.

HYDROGEN STORAGE OPTIONS



J. Andersson & S. Gronkvist, 2019, *Large-scale storage of hydrogen*

TYPICAL CAPACITIES OF HYDROGEN STORAGE OPTIONS



Unit	Cylinder	Tube trailer	Liquid storage	Salt cavern	Gas field
Mass	0.9 kg	900 kg	300 ton	7.2 kton	1.4 Mton
Natural Gas eqv.	3 m^3	3400 m^3	1.1 mln m^3	27 mln m^3	5.2 bcm
Cars	-	7	2,300	55,000	> 10 mln
Houses	-	2 – 3	850	20,000	3,9 mln

Cars: 13,000 km/yr and 1 kg H_2/100 km; houses: 1340 m^3 natural gas per year

MANY SIZES IN COMPRESSED AND CRYOGENIC STORAGE


CGH2 storage Energiepark Mainz, 20-80 bar, 1000 kg

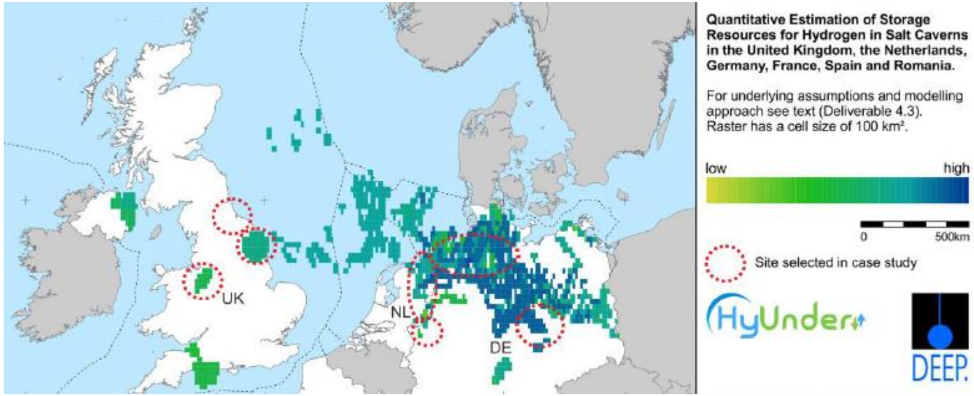

Cryogenic storage tanks


DLR, Germany: LH2 4.7 ton (2 bar) and CGH2 4.4 ton 300 bar

Spherical LH2 tank NASA. Storage up to ~300 ton

HYDROGEN UNDERGROUND STORAGE

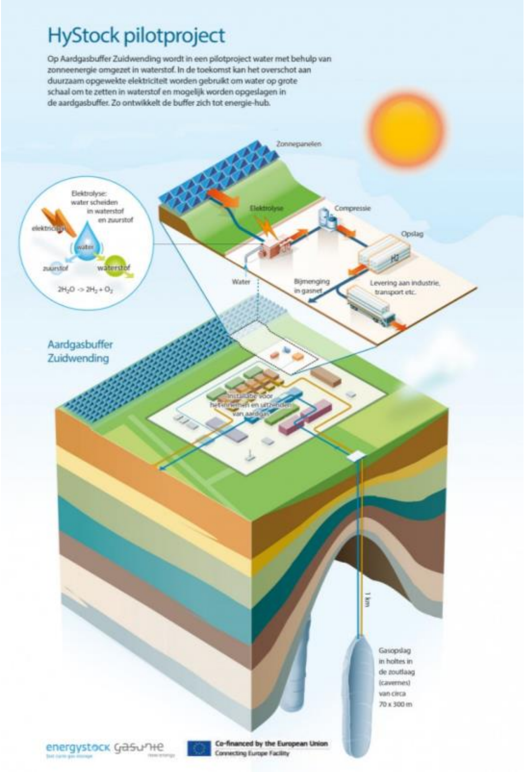
- H_2 storage in salt caverns already operational in 4 locations (US 3x, UK) to secure supply of H_2 to petrochemical clusters – very low cycling frequency



Quantitative Estimation of Storage Resources for Hydrogen in Salt Caverns in the United Kingdom, the Netherlands, Germany, France, Spain and Romania.

For underlying assumptions and modelling approach see text (Deliverable 4.3). Raster has a cell size of 100 km².

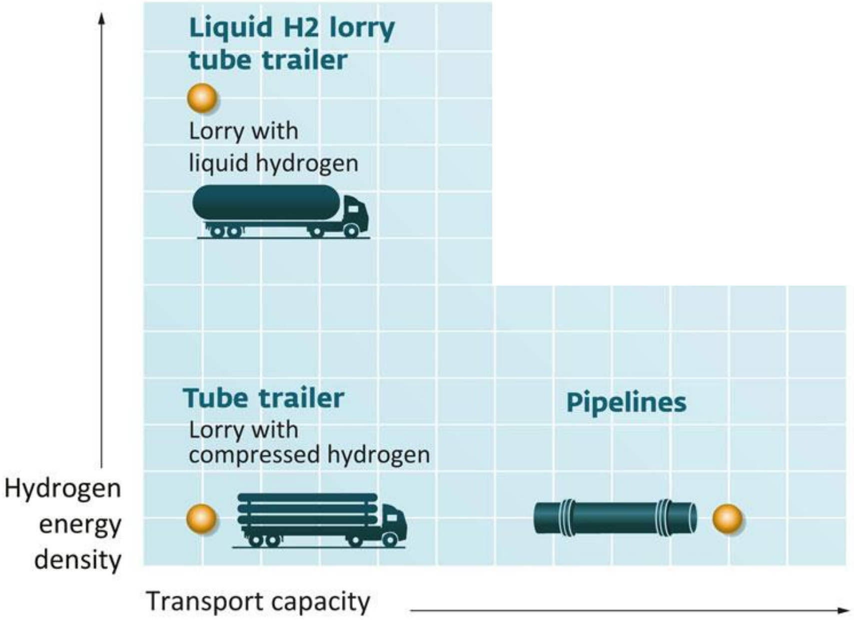
- To provide flexibility to future large-scale power-to-H_2 / H_2-to-power conversion systems, and secure supply of hydrogen, higher cycling frequencies are anticipated.
- Energystock (subsidiary Gasunie) and TNO to conduct field tests (summer 2021) under operational conditions to validate mechanical integrity and leak tightness of materials and components of a H_2 salt cavern storage system .



HyStock pilotproject

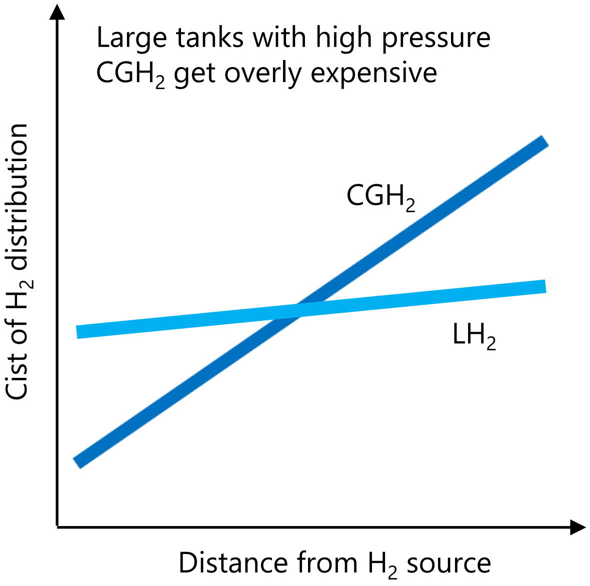
Op Aardgasbuffer Zuidwending wordt in een pilotproject water met behulp van zonneenergie omgezet in waterstof. In de toekomst kan het overschot aan duurzaam opgewekte elektriciteit worden gebruikt om water op grote schaal om te zetten in waterstof en mogelijk worden opgeslagen in de aardgasbuffer. Zo ontwikkelt de buffer zich tot energie-hub.

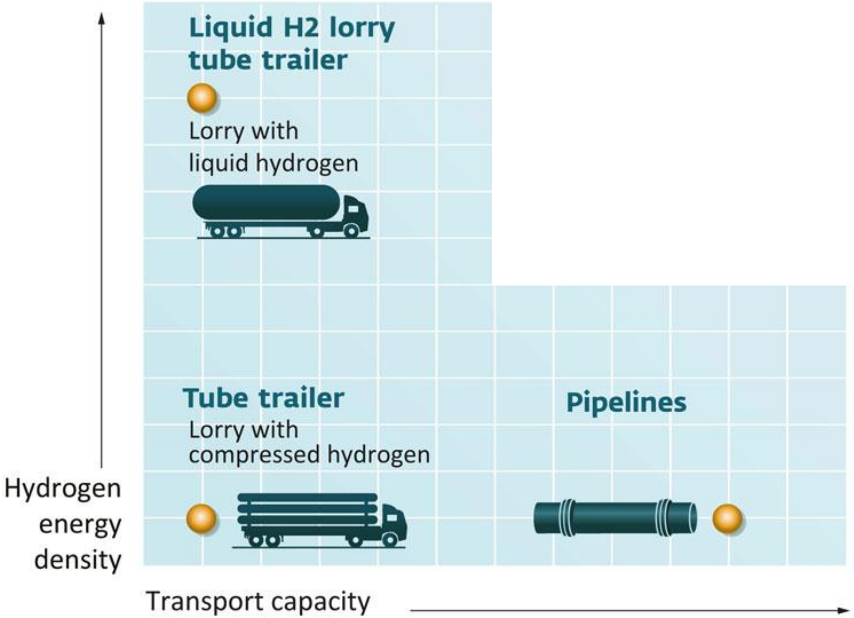
DIFFERENT MODES OF TRANSPORT OF HYDROGEN



Source: https://www.theworldofhydrogen.com/gasunie/infrastructure/

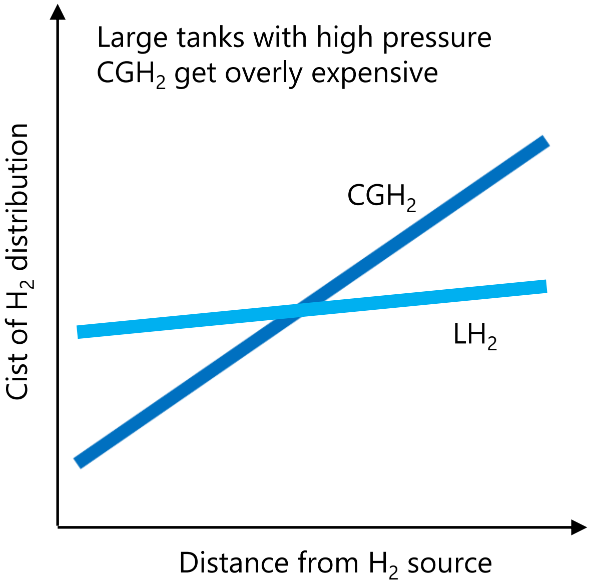
DIFFERENT MODES OF TRANSPORT OF HYDROGEN

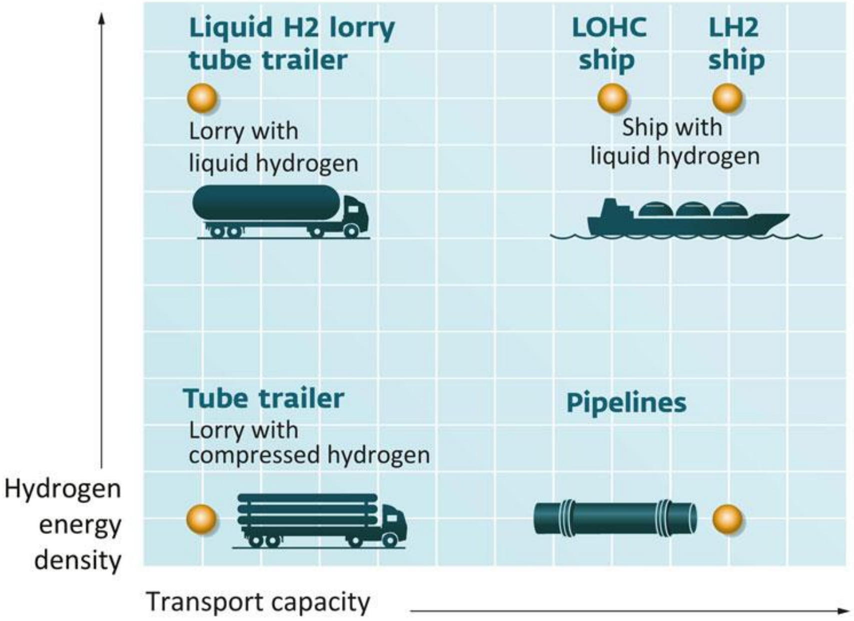




Source: https://www.theworldofhydrogen.com/gasunie/infrastructure/

DIFFERENT MODES OF TRANSPORT OF HYDROGEN





Source: https://www.theworldofhydrogen.com/gasunie/infrastructure/

COMPRESSED GASEOUS HYDROGEN BY TRUCK

Steel cylinder (Pallet 15 Cyld)
200 bar – 0.8 kg (Pallet 15 kg hydrogen)

Conventional steel tubes (tube trailer)
200 bar – 300 kg hydrogen

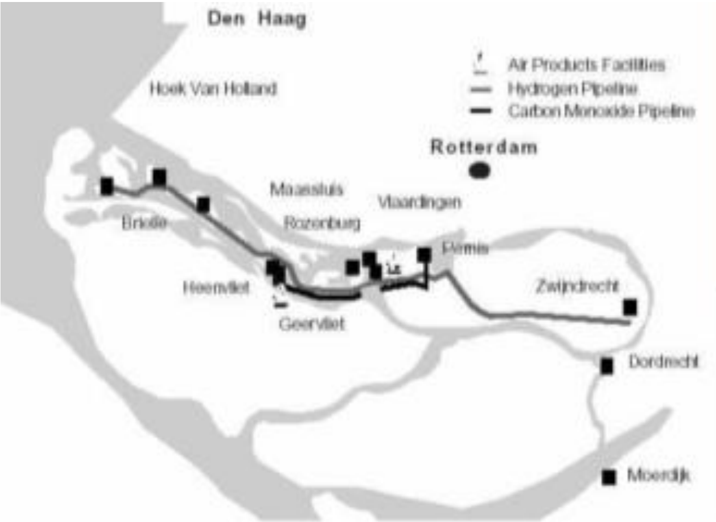
Composite cylinders
up to 500 bar and >1000 kg hydrogen

LIQUID HYDROGEN BY TRAILER AND CONTAINER

Liquid hydrogen tanker
~ 4000 kg hydrogen

Liquid hydrogen container (40 ft)
~ 3000 kg

CURRENT HYDROGEN PIPELINE NETWORK

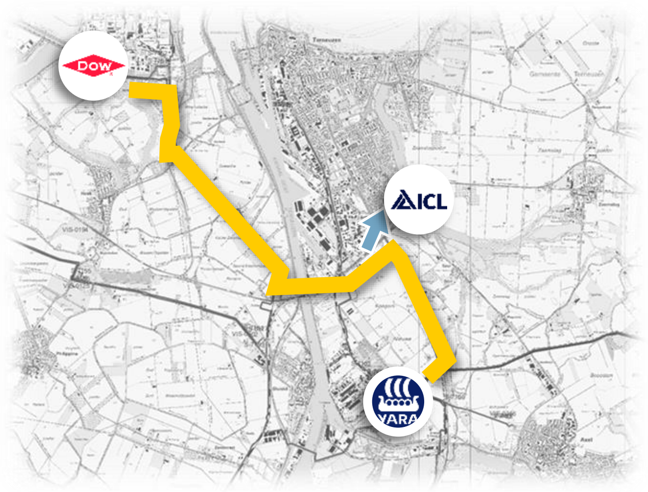


Air Products

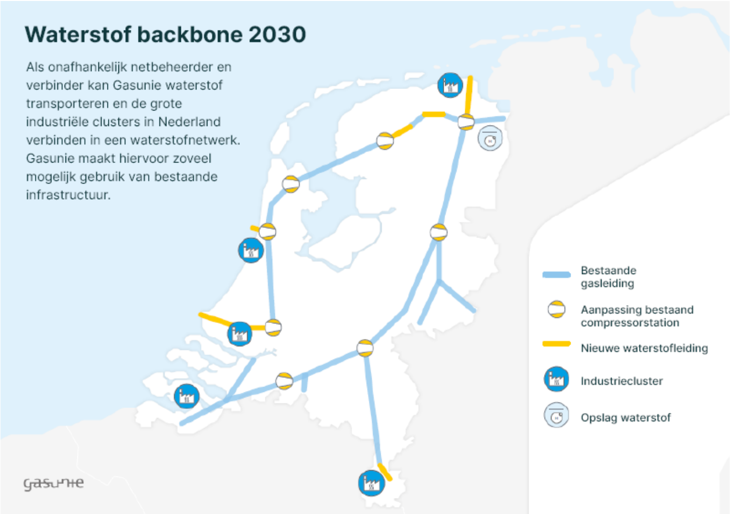
Air Liquide

USE/CONVERSION EXISTING GAS INFRA FOR HYDROGEN

- An existing 12 km gas pipeline between Dow and Yara has been converted into a hydrogen pipeline by Gasunie in 2018.



- Conversion of natural gas infra to hydrogen



Waterstof backbone 2030

Als onafhankelijk netbeheerder en verbinder kan Gasunie waterstof transporteren en de grote industriële clusters in Nederland verbinden in een waterstofnetwerk. Gasunie maakt hiervoor zoveel mogelijk gebruik van bestaande infrastructuur.

- Admixing? Legislation is lagging behind:
  - 0.02% H_2 permitted in transport
  - 0.5% H_2 permitted in distribution

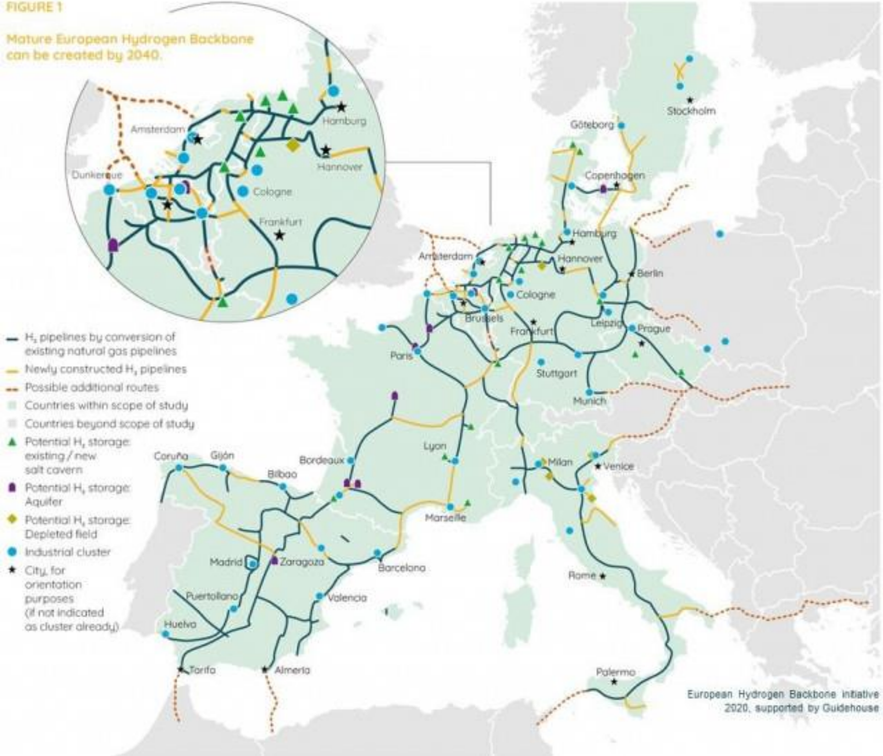
EUROPEAN HYDROGEN BACKBONE PLAN

- In the NL, Gasunie has proposed concrete plans to convert one of their natural gas networks into a backbone network for H_2 transport.

- Gas infrastructure companies published a white paper in July 2020 presenting their plan for a future H_2 backbone network

FIGURE 1

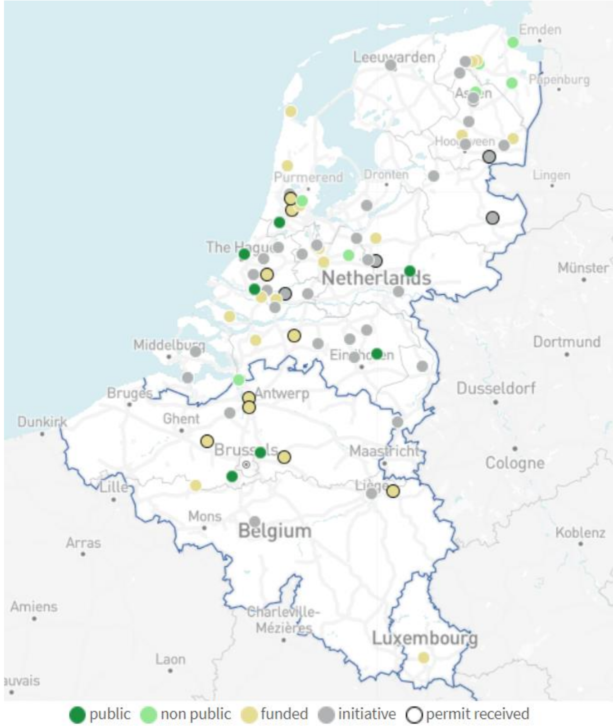
Mature European Hydrogen Backbone can be created by 2040.



European Hydrogen Backbone initiative 2020, supported by Guidehouse

STATUS HYDROGEN REFUELLING STATION NETWORK

	Realised	Planned Short term	Target
Cars	**321 (October 2020)**	n.a.	15.000 (2025)
Buses	8 (R'dam, Arnhem Groningen, Eindhoven)	64	Public transport buses zero-emission as of 2025 "Heavy Duty" total 3000 vehicles in (2025)
Vans	-	Conversion activity	
Garbage trucks	**3**	25	
Trucks	-	2 (27 and 40 ton)	
Inland Ships	-	2 demo's ships are being developed	Contribution to 150 zero-emission ships in 2030
Train	-	1 pilot	-
"Public" refuelling stations	**5**	**See map**	50 (2025)
Other refuelling stations	5	-	-



Source: https://www.waterstofnet.eu/nl/overzicht-waterstoftankstations-benelux

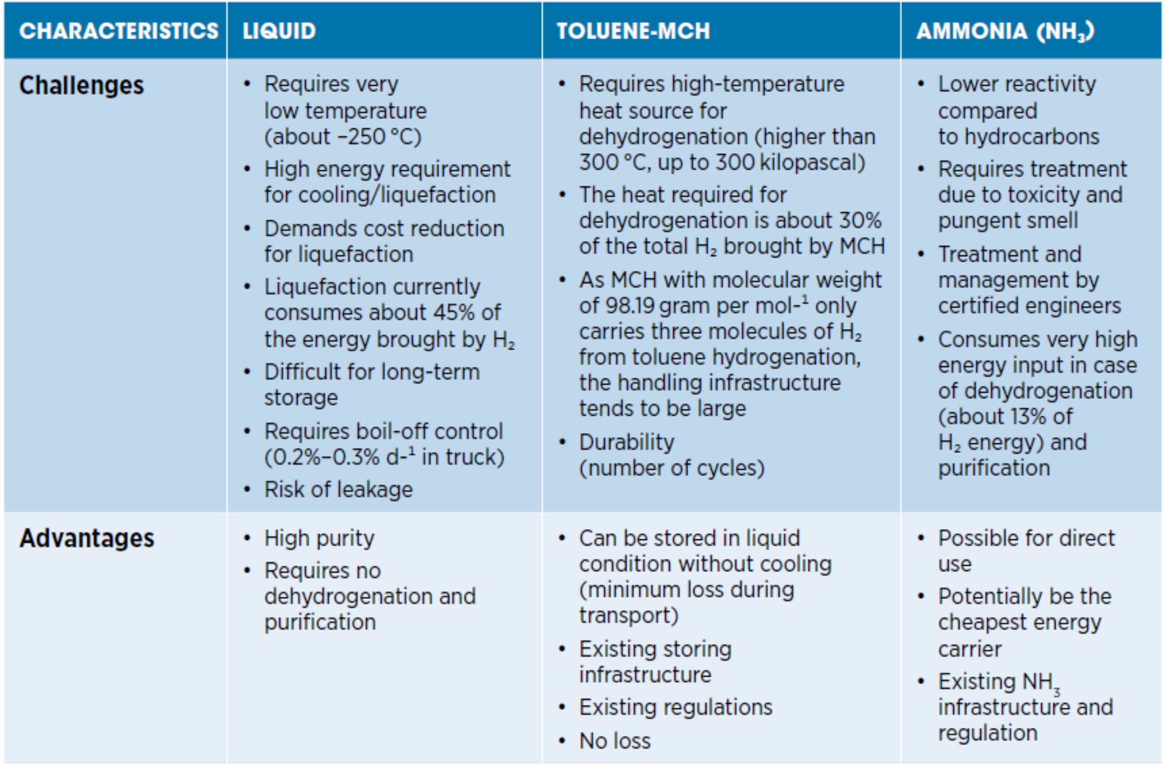
DEVELOPMENT OF THE REFUELLING INFRASTRUCTURE

● in bedrijf ● in realisatie

Source: https://opwegmetwaterstof.nl/tanklocaties/

INTERCONTINENTAL TRANSPORT OF (GREEN) HYDROGEN

- Characteristics of different energy carriers for H_2 supply chains:



CHARACTERISTICS	LIQUID	TOLUENE-MCH	AMMONIA (NH_3)
Challenges	• Requires very low temperature (about −250 °C) • High energy requirement for cooling/liquefaction • Demands cost reduction for liquefaction • Liquefaction currently consumes about 45% of the energy brought by H_2 • Difficult for long-term storage • Requires boil-off control (0.2%–0.3% d^{-1} in truck) • Risk of leakage	• Requires high-temperature heat source for dehydrogenation (higher than 300 °C, up to 300 kilopascal) • The heat required for dehydrogenation is about 30% of the total H_2 brought by MCH • As MCH with molecular weight of 98.19 gram per mol^{-1} only carries three molecules of H_2 from toluene hydrogenation, the handling infrastructure tends to be large • Durability (number of cycles)	• Lower reactivity compared to hydrocarbons • Requires treatment due to toxicity and pungent smell • Treatment and management by certified engineers • Consumes very high energy input in case of dehydrogenation (about 13% of H_2 energy) and purification
Advantages	• High purity • Requires no dehydrogenation and purification	• Can be stored in liquid condition without cooling (minimum loss during transport) • Existing storing infrastructure • Existing regulations • No loss	• Possible for direct use • Potentially be the cheapest energy carrier • Existing NH_3 infrastructure and regulation

Wijayanta, A. T. et al., 2019. *Liquid hydrogen, methylcyclohexane, and ammonia as potential hydrogen storage: Comparison review*. International Journal of Hydrogen Energy, 44(29), pp. 15026-15044.

- No clear winner identified at this point. Techno-economic feasibility strongly influenced by conditions on both sides of the chain
- LH_2, LOHCs and NH_3 appear to be the most promising options for long-distance transport (with the aim of reconversion to H_2)
- In Japan, liquid and LOHC import options are being demonstrated at industrial scale, to gain experience and be better able to compare
- Each option has its merits, and equally each of them presents specific challenges and hurdles towards large-scale deployment

LIQUID HYDROGEN (LH_2)

- Large scale liquid H_2 carriers have yet to be built, but are technically possible and fundamentally similar to large LNG carriers (although the lower boiling point of H_2 does pose additional challenges).

Kawasaki
Powering your potential

Dec 2019 launch of a demo vessel

Image Credits: Kawasaki Group Channel

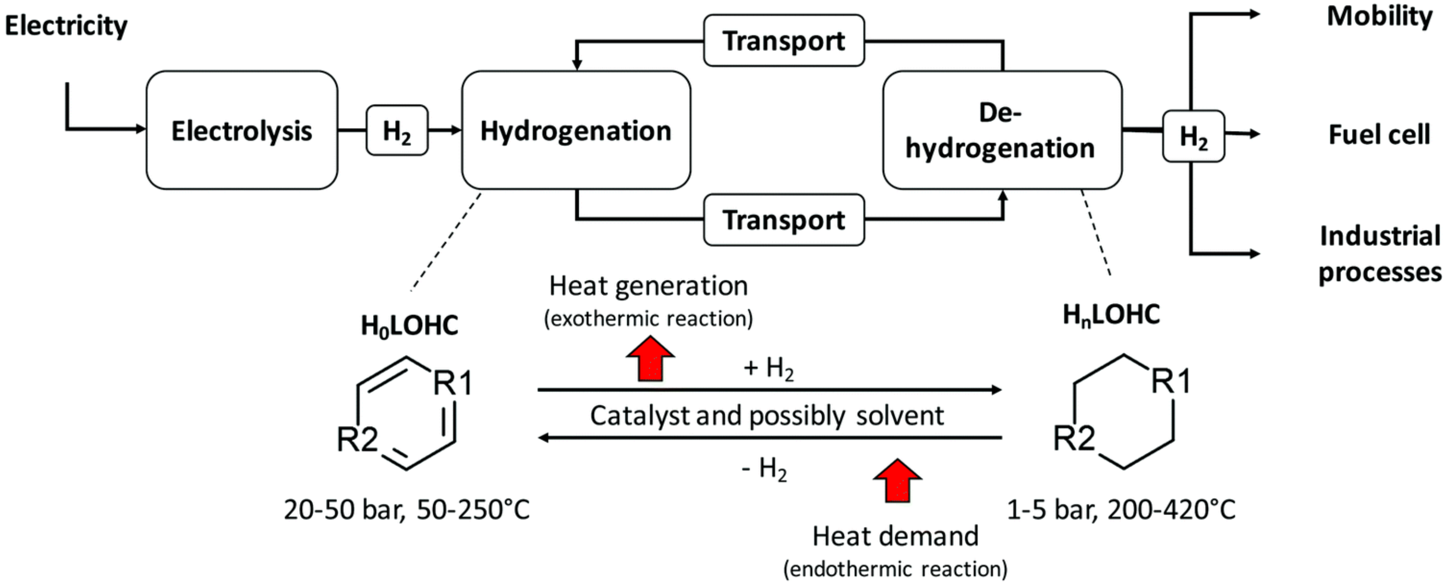
1,250 m^3 capacity: ~89 ton H_2 or 0.01 PJ

160,000 m^3 capacity: ~11.4 kton H_2 or 1.36 PJ

Sources: https://www.marineinsight.com/videos/watch-launch-of-worlds-first-liquefied-hydrogen-carrier-suiso-frontier/
https://global.kawasaki.com/en/stories/articles/vol18/

LIQUID ORGANIC HYDROGEN CARRIERS (LOHCs)

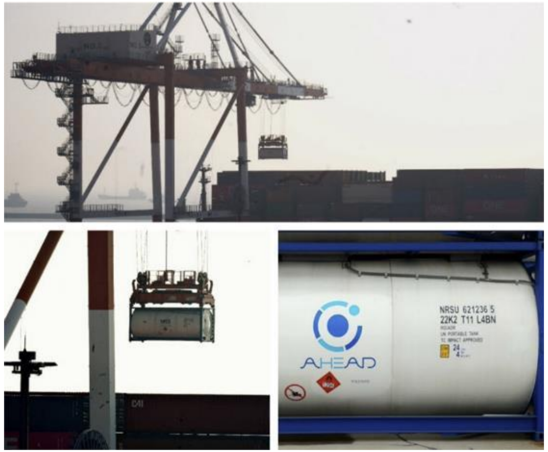
- Typical examples are organic molecules containing aromatic rings, such as toluene, naphthalene, or dibenzyltoluene.
- When hydrogenated, these molecules contain nearly as much hydrogen per cubic meter as liquid hydrogen, without requiring the use of special materials and storage under cryogenic conditions.
- The diagram below illustrates the basic principle of a H_2 supply chain using this approach:

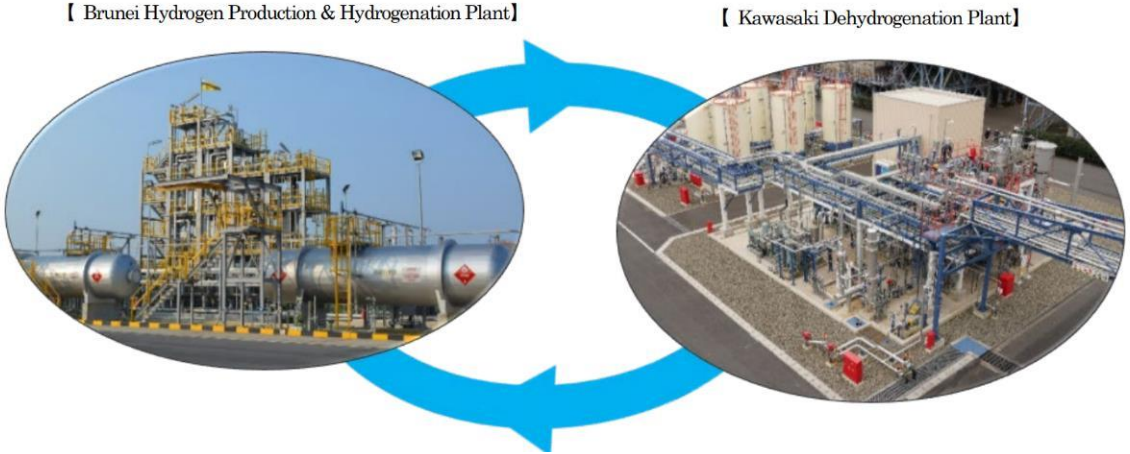


Niermann, M., 2019. Liquid organic hydrogen carriers (LOHCs) – techno-economic analysis of LOHCs in a defined process chain.

LOHC DEMO PROJECT (BRUNEI)

- Collaboration between four Japanese companies to establish the world's first demo scale H_2 import chain based on LOHCs, using Chiyoda's SPERA Hydrogen® Technology. The H_2 is sourced from an SMR near an LNG plant in Brunei.
- First LOHC shipment delivered in Dec 2019, and H_2 was delivered from the dehydrogenation plant to a gas turbine in May.





NEDO AHEAD CHIYODA CORPORATION Mitsubishi Corporation MITSUI&CO. NYK LINE NIPPON YUSEN KAISHA

Source: https://www.ahead.or.jp/en/

OPTIONS FOR THE TRANSPORT OF (GREEN) HYDROGEN

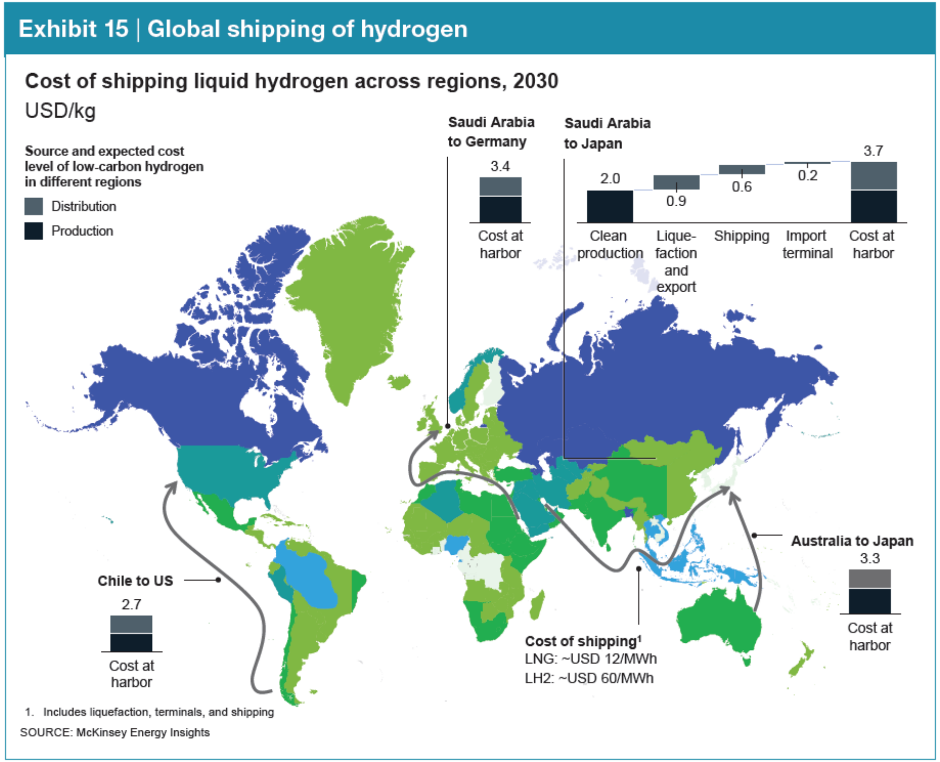


Exhibit 15 | Global shipping of hydrogen

Cost of shipping liquid hydrogen across regions, 2030

1. Includes liquefaction, terminals, and shipping

SOURCE: McKinsey Energy Insights

- The concept of transporting green H_2 internationally, in various forms, has gained traction in recent years
- Several techno-economic evaluations were carried out and published, as a first example the 2020 Hydrogen Council report *Path to hydrogen competitiveness*
- Four cases were evaluated: Chile to US, Saudi Arabia to Germany, Saudi Arabia to Japan, and Australia to Japan
- According to the authors, export costs could be as low as 1.7$/kg H_2 in 2030. Overall delivered H_2 costs range from 2.7 to 3.7 $/kg H_2

Hydrogen Council, 2020. *Path to hydrogen competitiveness, A cost perspective.*

TNO innovation for life

THANK YOU FOR YOUR ATTENTION