Hydrogen, lecture for the Botlek Study Group, 10-06-2021

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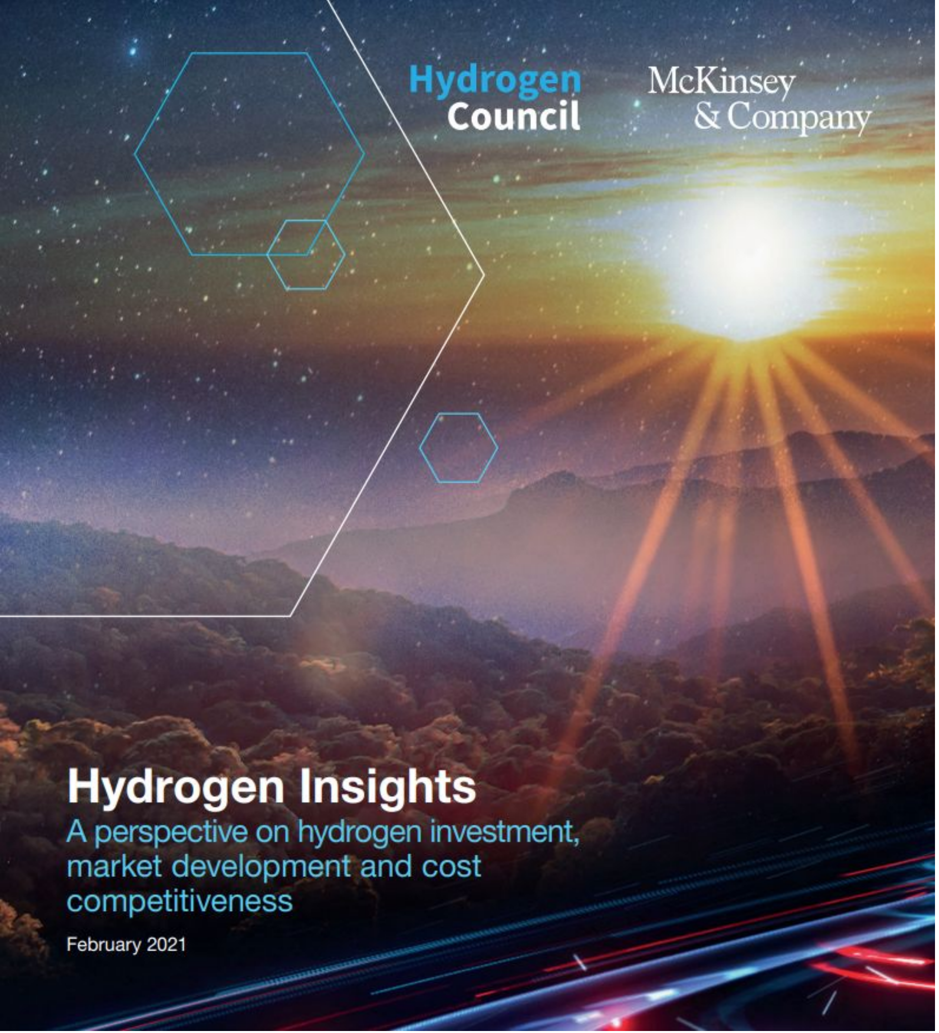


"Anticipating continued growth in scale, the report confirms that – from a total cost of ownership (TCO) perspective – hydrogen can become the most competitive low-carbon solution in more than 20 applications by 2030, including long haul trucking, shipping and steel"

Benoit Potier

Co-Chair of the Hydrogen Council & Chairman and CEO of Air Liquide

Link to Hydrogen Council Report

Leading the Hydrogen Ecosystem Development

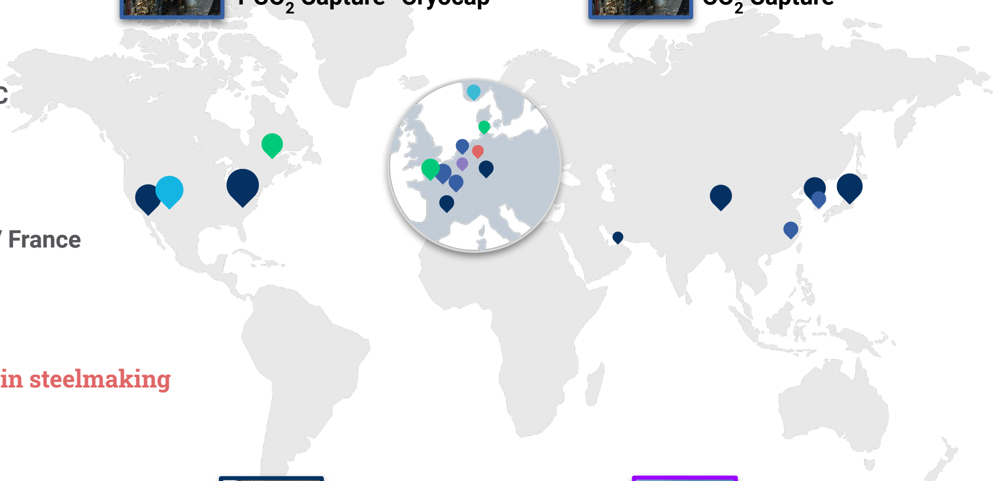
Electrolysis
Denmark
1.2 MW

Electrolysis
Bécancour, QC
1x 20MW

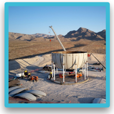
Large scale electrolysis
(In Devt.) H2V France
200 MW

CCU + Low-Carbon H_2
France
1 CO_2 Capture "Cryocap"

CCS + Low-Carbon H_2
(In Devt.) Antwerp / Benelux
CO_2 Capture



H_2 reduction in steelmaking
Germany



Supply Chain
US West Coast
H_2 Liquefier

Supply Chain
(In Devt.) Norway
Liquid H_2 for ships

H_2 Stations for Consumers
70 HRS

H_2 Forklifts
US+EUROPE
9 sites

H_2 Network for trucks
France / Benelux / Germany
HyTrucks

H_2 Bus & Taxi fleets
France / China / Korea

KEY FIGURES

1.2 Mt of H_2/year

1,850 km H_2 pipeline

53 large H_2 / CO plants

20MW PEM Electrolyzer

€2bn sales

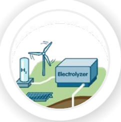
Co-founder of Hydrogen Council

Hydrogen as a Cornerstone of the ET…… and a Tremendous Growth Potential

2050

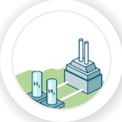
18%
of final energy demand

Power generation, buffering

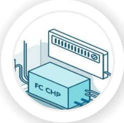


Transportation

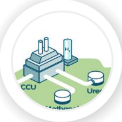
Industry energy



Building heating and power



Industrial feedstock (CCU, DRI)



Our ENGAGEMENT

- **Decarbonize** our **production assets** to develop a competitive low-carbon H_2 offering at large scale.
- **Creating value** by **decarbonizing** our **customer's processes**, leveraging our long-term relationships.
- Be a **key enabler** of the **Hydrogen society** thanks to our assets, technology and expertise.

Becancour Electrolyzer LH2 storage

Source: Hydrogen Council

Air Liquide's Position in reducing CO2 emisions

Group Climate Objective: -30% carbon intensity 2025 vs 2015

AND

Dutch Climate Agreement : -14.3 $MtCO_2/a$ by 2030 vs 1990

\+ **potential CO_2 Tax incentive**

HOW :

- Low-Carbon H_2 (offgas) sources
- CC(U)S **Porthos**
- Green H_2 production through large scale electrolysis
- Steam circularity in the Botlek Area
- Physical actions on the assets (CO_2 recycle, O_2 injection, etc)
- Participation and funding of H-vision, Giga scale electrolyser, Waste to Chemicals

POTENTIAL GAME CHANGERS :

H-Vision: Blue Hydrogen facility in PoR (up to 3M Nm3/hr) targeting power generation and high temperature heat applications in 2030.

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3 ways of storing Hydrogen

Storing Hydrogen

Safety aspects

Hydrogen is a colorless, odorless, tasteless, flammable nontoxic gas which is flammable over a wide range of concentrations. Some of the unique hydrogen properties that contribute to potential hazards (flammability and explosivity) are:

- Hydrogen is combustible over a wide range of concentrations. At atmospheric pressure, hydrogen is combustible at concentrations from 4% to 74.2% by volume.
- Hydrogen has very low ignition energy.
- Hydrogen burns with a nonluminous flame which can be invisible under bright light.
- Due to its small molecular size, Hydrogen can easily pass through porous materials and has the ability to be absorbed by some containment materials. This can eventually result in loss of ductility or embrittlement (this reduces performance of some containment and piping materials such as carbon steel). Loss of ductility/embrittlement is accelerated at elevated temperatures.

But: Hydrogen wants to get away from us as quickly as possible…..

Hydrogen is an ultra-light gas that occupies a substantial volume under standard conditions of pressure, i.e., atmospheric pressure. In order to store and transport hydrogen efficiently, this volume must be significantly reduced.

Hydrogen is the lightest gas in the entire Universe. One liter of this gas weighs only 90 mg under normal atmospheric pressure, which means that it is 11 times lighter than the air we breathe.

A volume of around 11 m^3 (which is the volume of the trunk of a large utility or commercial vehicle) is needed to store just 1 kg of hydrogen, which is the quantity needed to drive 100 km. For this reason, its density must be increased using one of the following techniques:

- High-pressure storage in the gaseous form
- Very low temperature storage in the liquid form
- Hydride-based storage in the solid form

Under pressure

The easiest way to decrease the volume of a gas, at constant temperatures, is to increase its pressure.

So, at 700 bar, which is 700 times normal atmospheric pressure, hydrogen has a density of 42 kg/m^3, compared with 0.090 kg/m^3 under normal pressure and temperature conditions. At this pressure, 5 kg of hydrogen can be stored in a 125-liter tank.

Today, most car manufacturers have opted for the solution that consists in storing hydrogen in the gaseous form, at high pressure. This technology enables us to store enough hydrogen to allow a car that runs on a fuel cell battery to cover between 500 and 600 km between fill-ups.

For easier and more efficient transport, hydrogen is stored in composite tanks or bottles. Air Liquide researchers are working on the mechanical strength of the materials that make up these bottles over time. They perform accelerated fatigue tests by filling and permeability cycles at very high pressure to ensure their perfect tightness. All this research will lay the scientific foundations of the behavior of the materials and allow to determine the criteria of dimensioning of the reservoirs. Thanks to this research, Air Liquide is a decisive player in the definition of safety standards that must be put in place to ensure maximum safety for the user.

Another research area of the Group is the development of bottle control technologies during their use. This step is also essential for the safety of the users and consists in ensuring the absence of defects such as microcracks. For this, researchers appropriate non-destructive testing methods such as acoustic emission to detect this type of anomalies.

In the liquid form

A state-of-theart technique for storing maximum hydrogen in a restricted volume is to convert hydrogen gas to liquid hydrogen by cooling it to a very low temperature.

Hydrogen turns into a liquid when it is cooled to a temperature below -252,87 °C.

At -252.87°C and 1.013 bar, liquid hydrogen has a density of close to 71 kg/m3. At this pressure, 5 kg of hydrogen can be stored in a 75-liter tank.

In order to maintain liquid hydrogen at this temperature, tanks must be perfectly isolated.

Currently, storing hydrogen in the liquid form is being reserved for certain special applications, in high-tech areas such as space travel. For example, the tanks on the Ariane launcher, designed and manufactured by Air Liquide, contain the 28 tons of liquid hydrogen that will provide fuel to the central engine. These tanks are a genuine example of technological prowess: they weigh only 5.5 tons empty and their casing is not more than 1.3 mm thick.

In the solid form

The storage of hydrogen in solid form, i.e. stored in another material, is also a promising avenue of research.

Methods for storing hydrogen in solid form are techniques involving absorption or adsorption mechanisms of hydrogen by a material.

One example is to form solid metallic hydrides through the reaction of hydrogen with certain metal alloys. This absorption is the result of the reversible chemical combination of hydrogen with the atoms that comprise these materials. The most promising materials are composed of magnesium and alanates.

Only a low mass of hydrogen can be stored in these materials, which is currently the major downside of this technology. In fact, the best materials currently generate a ratio of hydrogen weight to the total weight of the tank of not more than 2 to 3%.

Before considering large-scale applications, it is also important to master certain key parameters such as kinetics (cell performance), and the temperature and pressure of the charge and discharge cycles of hydrogen in these materials.

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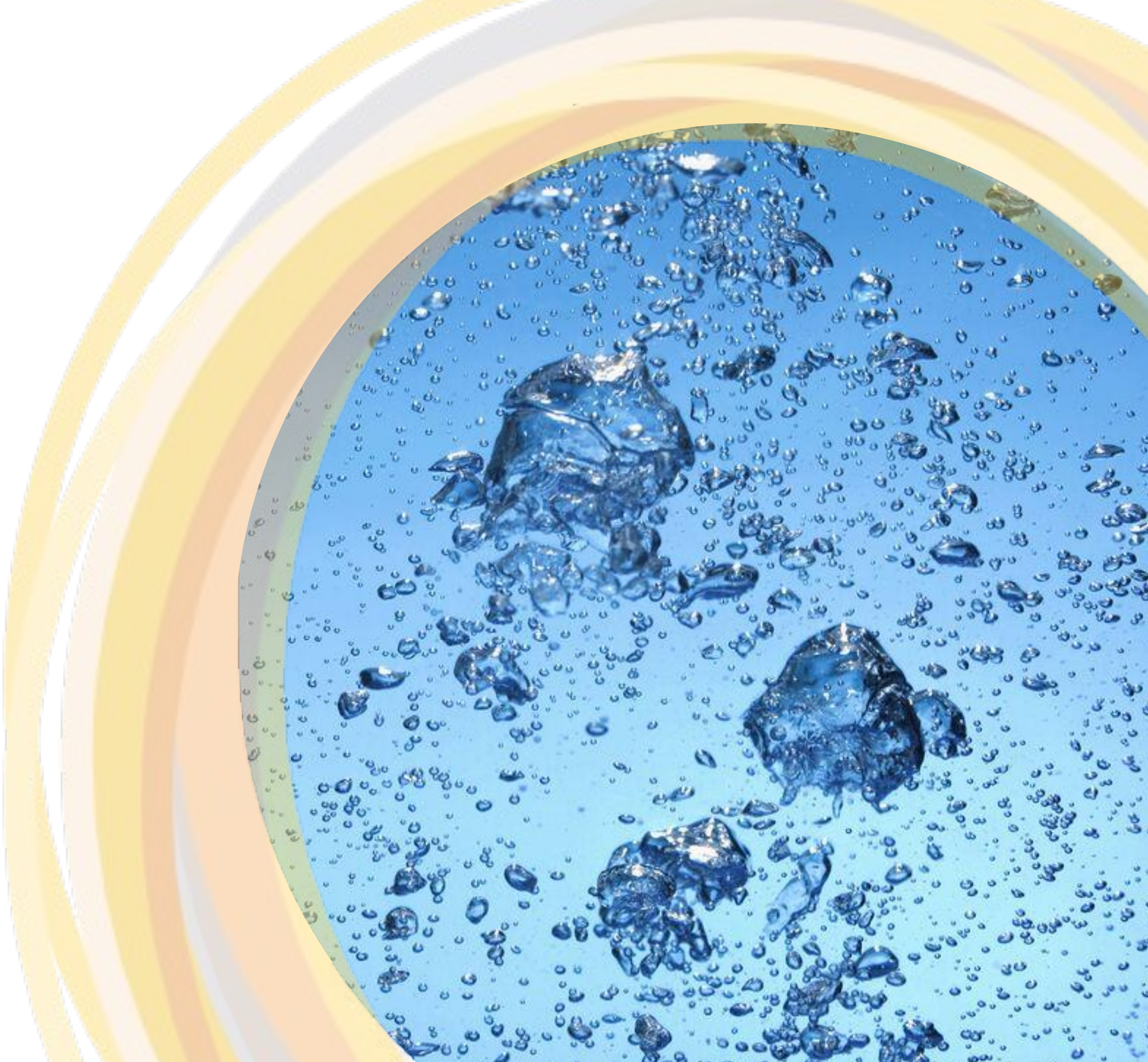
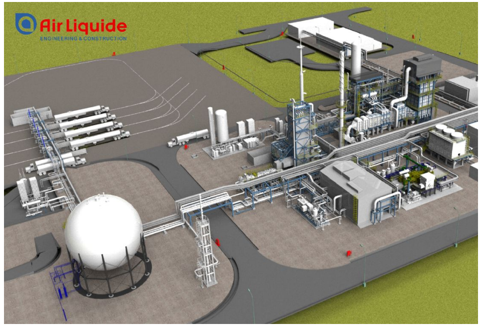
Hydrogen Liquefaction & Storage Expertise



West Coast LH2:

The world biggest H_2 Liquefier dedicated to mobility

- 30 tpd plant, located in North Las Vegas to supply Californian market by Q4 2021.
- 200 MUSD investment to build a liquid hydrogen plant and logistic infrastructure
- AL Proprietary technologies.



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LH2 storage and transport, a little background……..

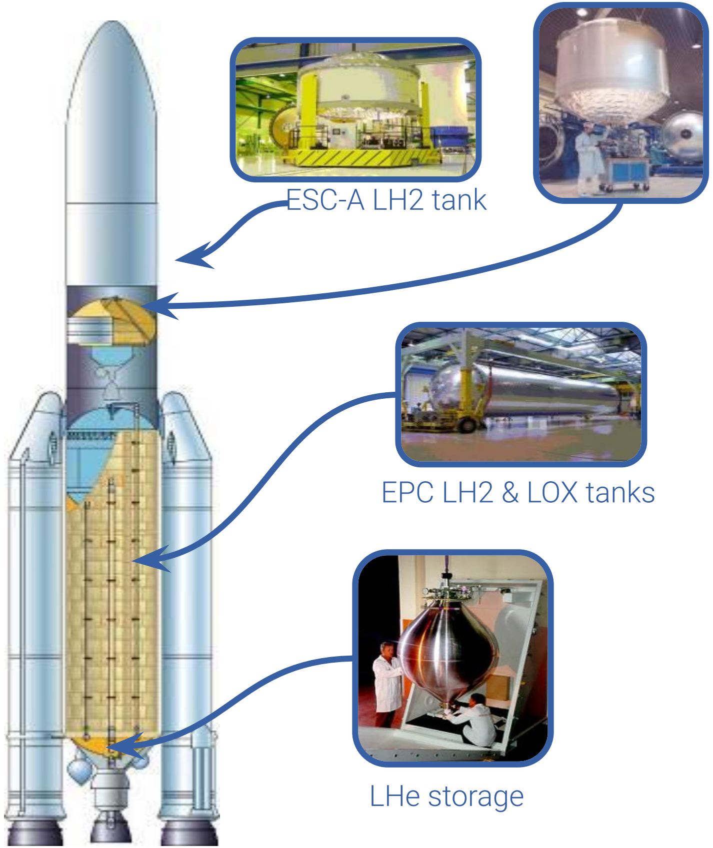
H_2 Storage expertise

AL Hydrogen Storage come from decades of:

- Development & Design capitalization → ARIANE & LH2 Cryolor references

  ARIANE 5 → More than 65 storages manufactured

- Operation experience and capitalization LH2 storages



ARIANE 5 Launcher ; AL Cryo Storage Scope

LH2, general

Al production capacity for LH2 in Kourou (French Guyana) and Waziers (France)

Mainly for ESA rocket launches

Other production locations world wide, amongst the USA.
Vancouver Olympics Public transport was fuelled with AL LH2.

Liquifaction capacity limited, because costly and difficult.

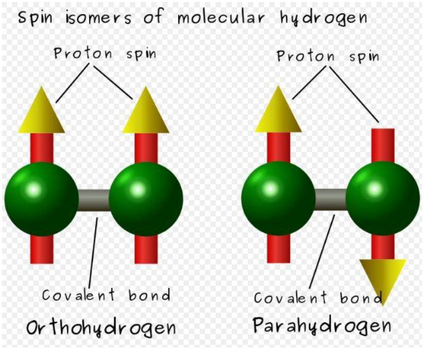
Why???

LH2 boiling point @ 20 K or -253 oC

Molecuulformule (uitleg)	H_2
IUPAC-naam	diwaterstof
Andere namen	LH_2
CAS-nummer	1333-74-0
EG-nummer	215-605-7
PubChem	783
Waarschuwingen en veiligheidsmaatregelen	
 Gevaar	
H-zinnen	H220
EUH-zinnen	*geen*
P-zinnen	P210
VN-nummer	1966 (vloeibaar)
ADR-klasse	Gevarenklasse 2.1
Fysische eigenschappen	
Aggregatietoestand	vloeibaar
Kleur	kleurloos
Dichtheid	0,0678 g/cm³
Smeltpunt	−259,2[1] °C
Kookpunt	−252,8 °C
Zelfontbrandings-temperatuur	571 °C
Onoplosbaar in	water

LH2 Energy effects

	Ortho	Para
@ 295 K	75%	25%
@ 20 K	0.2%	99.8%



Beside the energy needed for compression and cooling, also the conversion from Ortho to Para needs to be executed. Normally a catalytic process with f.i. Iron or Nickel as catalysts.

If you don't execute this step. During storage up till 50% of LH2 will evaporate.

So it is doable but not easy and at high costs………..

Thank you for your attentions, any questions or further clarifications?