Hydrogen storage and transport in a decarbonised Europe

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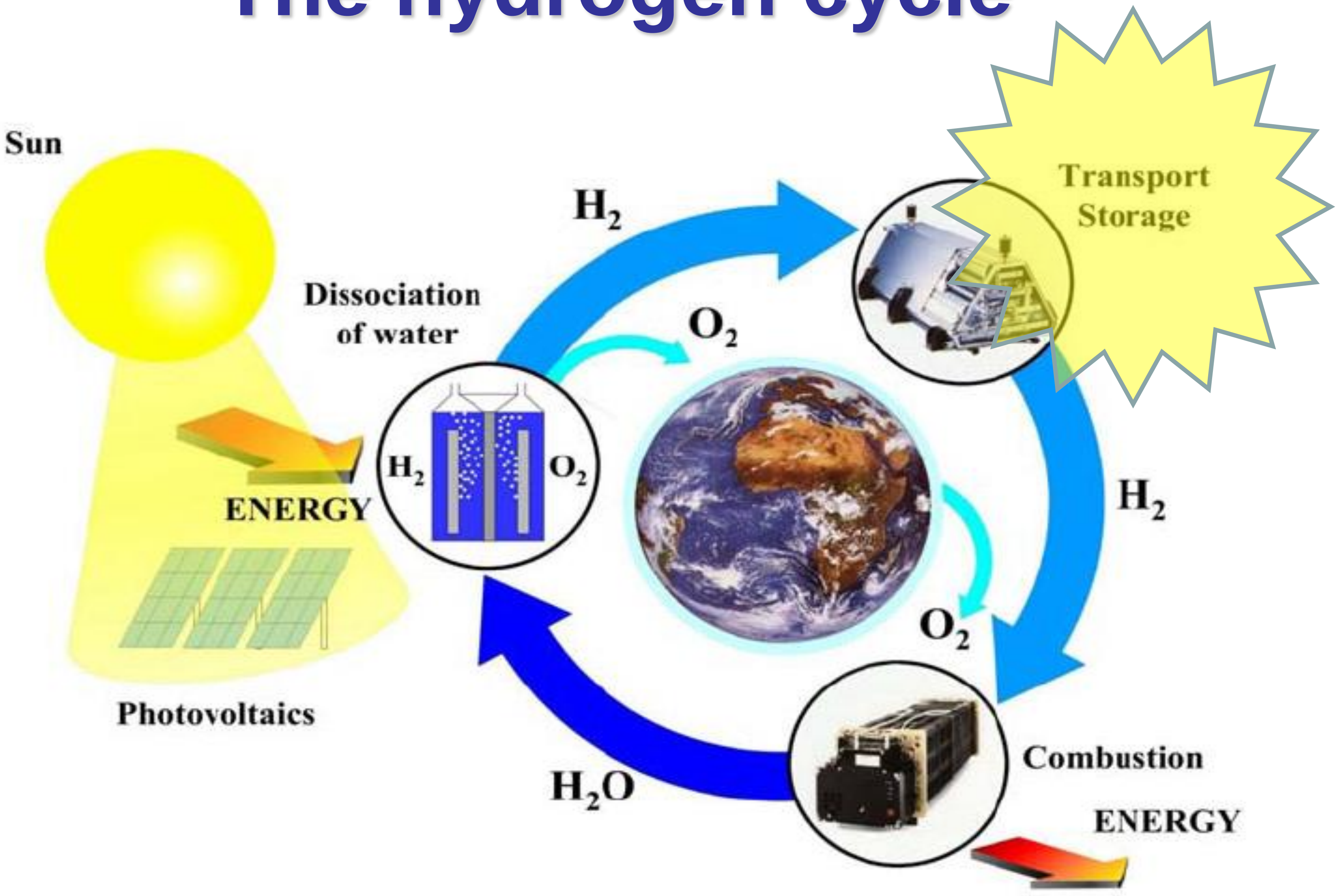
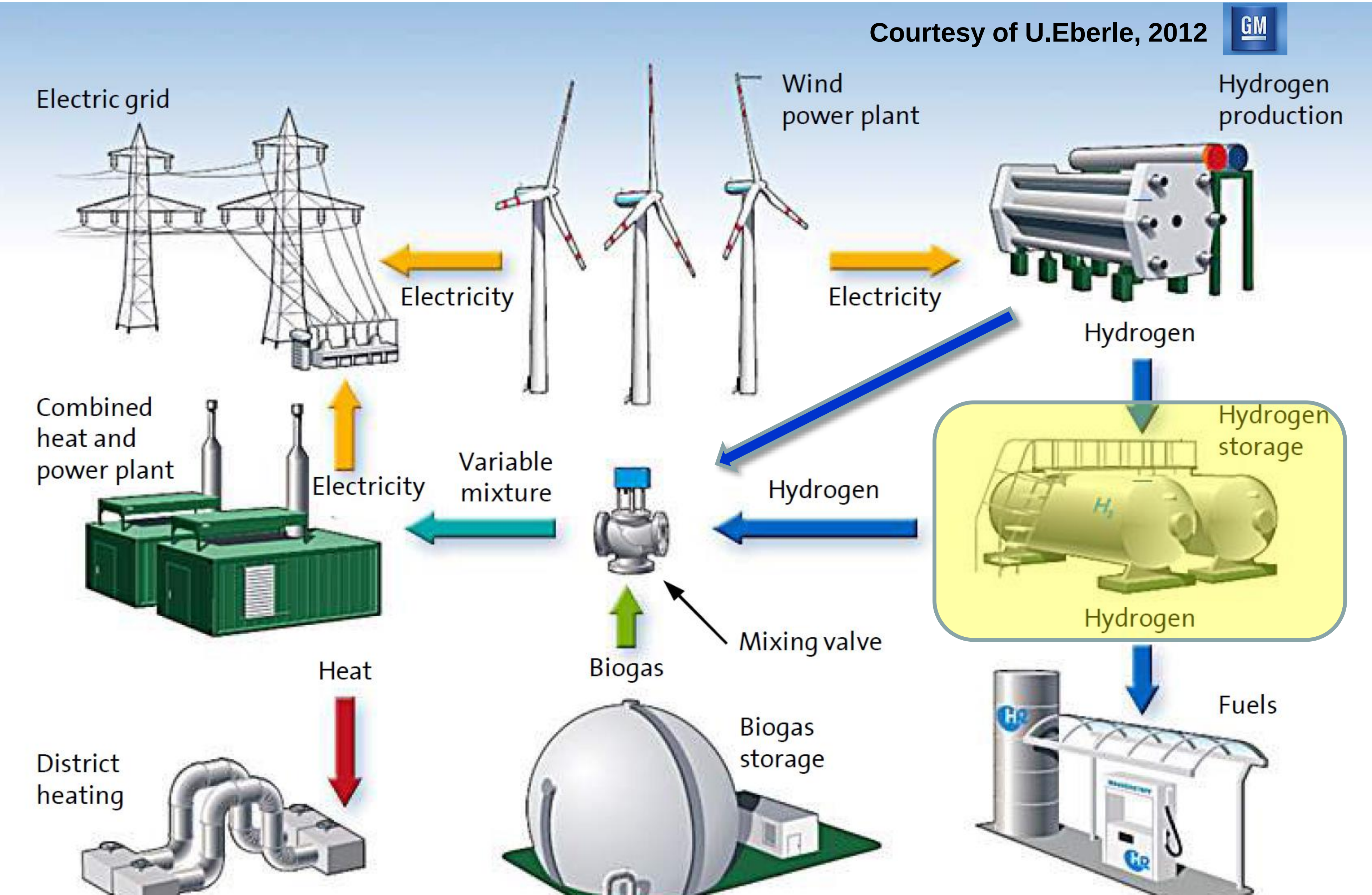
The hydrogen cycle



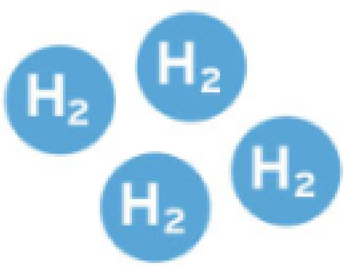
A.Züttel, A.Borgschulte, L. Schlapbach «Hydrogen as a Future Energy Carrier» Wiley-VCH, 2008

Green hydrogen from renewables



Hydrogen handling

- **Storage**
- **Transport**
- **Purification**
- **Compression**



Reduction of volume of gas (1 kg H_2 in N.C. about 11 m^3) by:

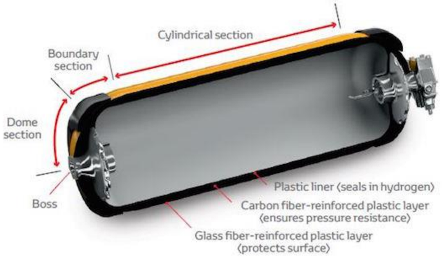
1. **Compression**
2. **Temperature below critical point**
3. **Reduction of repulsion by interaction with solids**
4. **Reversible reactions (no C-H covalent bonds)**

Fuel Cells and Hydrogen

SP 6 Hydrogen Production and Handling

SP 7 Hydrogen Storage

EERA European Energy Research Alliance



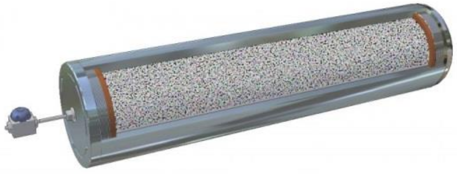
gas

Hydrogen handling requirements

liquid

- High gravimetric and volumetric density
- Temperatures and pressures close to ambient conditions
- High number of charge/discharge cycles
- Fast kinetics of charge/discharge
- Safe and at low cost

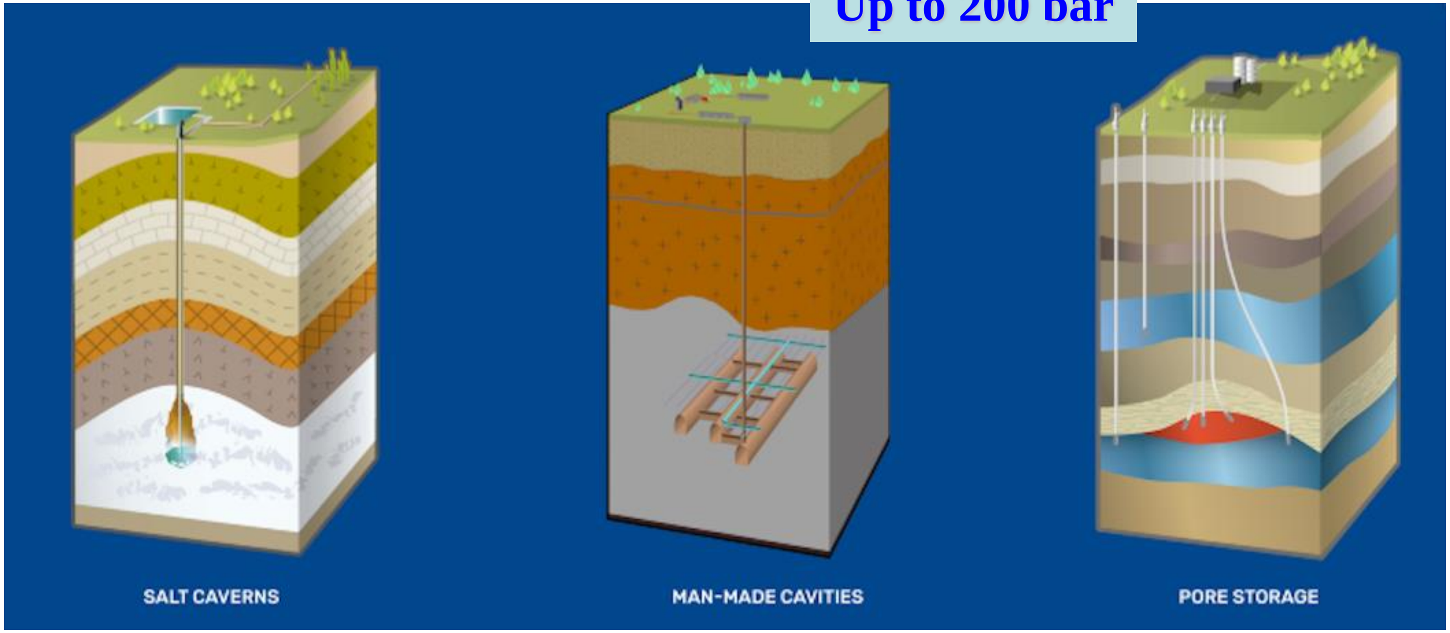
carriers



Low-pressure gas

- Salt caverns
- Man-made cavities
- Piping
- Lined rock cavern

Up to 200 bar



CH_2ANGE from Geostock

- Low construction costs
- Low leakage rates
- Low contaminations
- Projects running

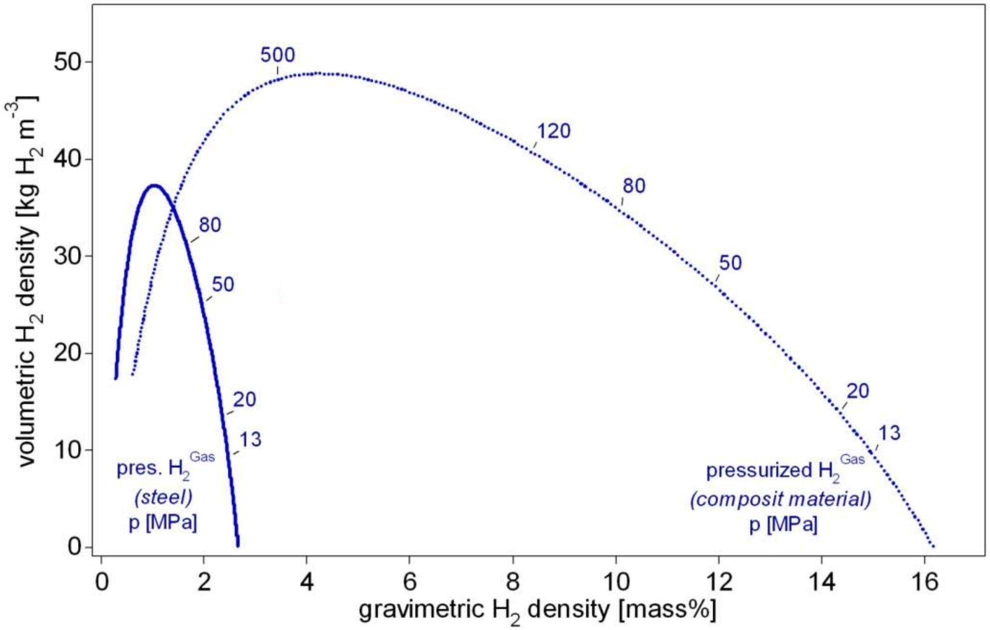
- Storage at tons level
- Low compression costs

High-pressure gas

700 bar!

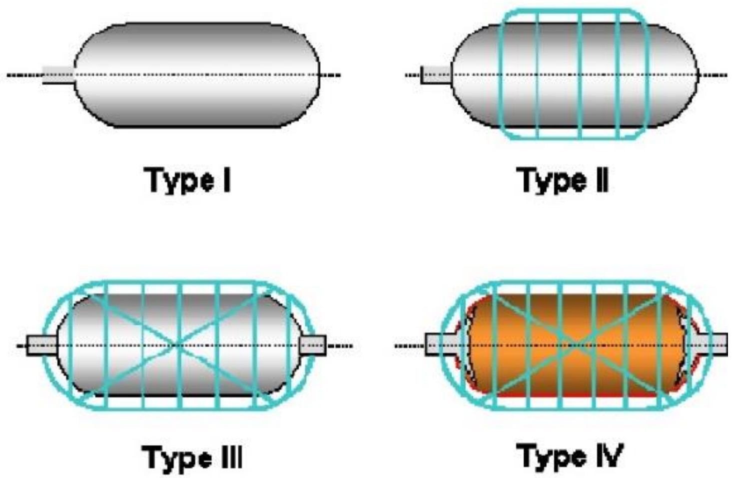
- Commercially available
- Storage capacity depends on the container material

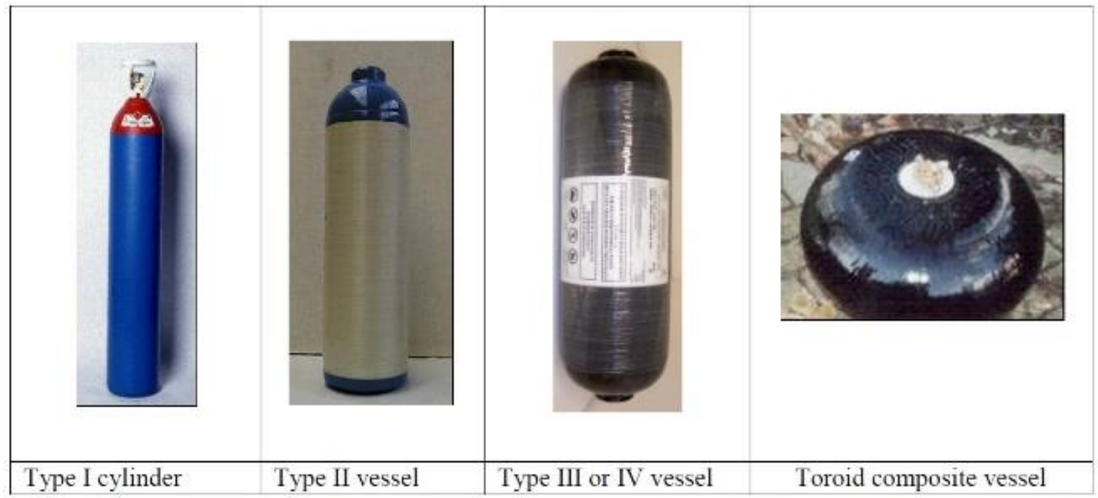
- Energy loss for compression (about 12%)
- Safety
- Pressure dropping
- Gravimetric density decreases with increasing pressure

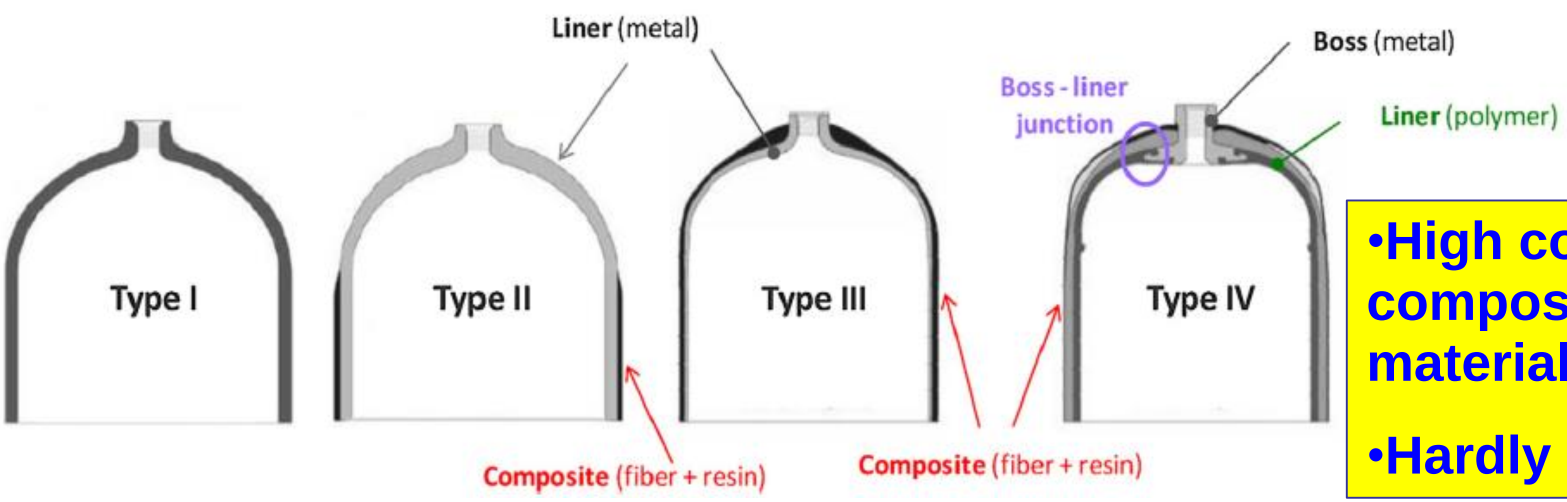


F. Vollrath & D. P. Knight, NATURE 410 (2001), pp. 541-549

High-pressure gas







- **High cost of composite materials**
- **Hardly recyclable**

Liquid Hydrogen

- Commercially available
- Storage as cryogenic liquid below the boiling point of 21.2 K
- Gravimetric density depends on the size of the container →100%

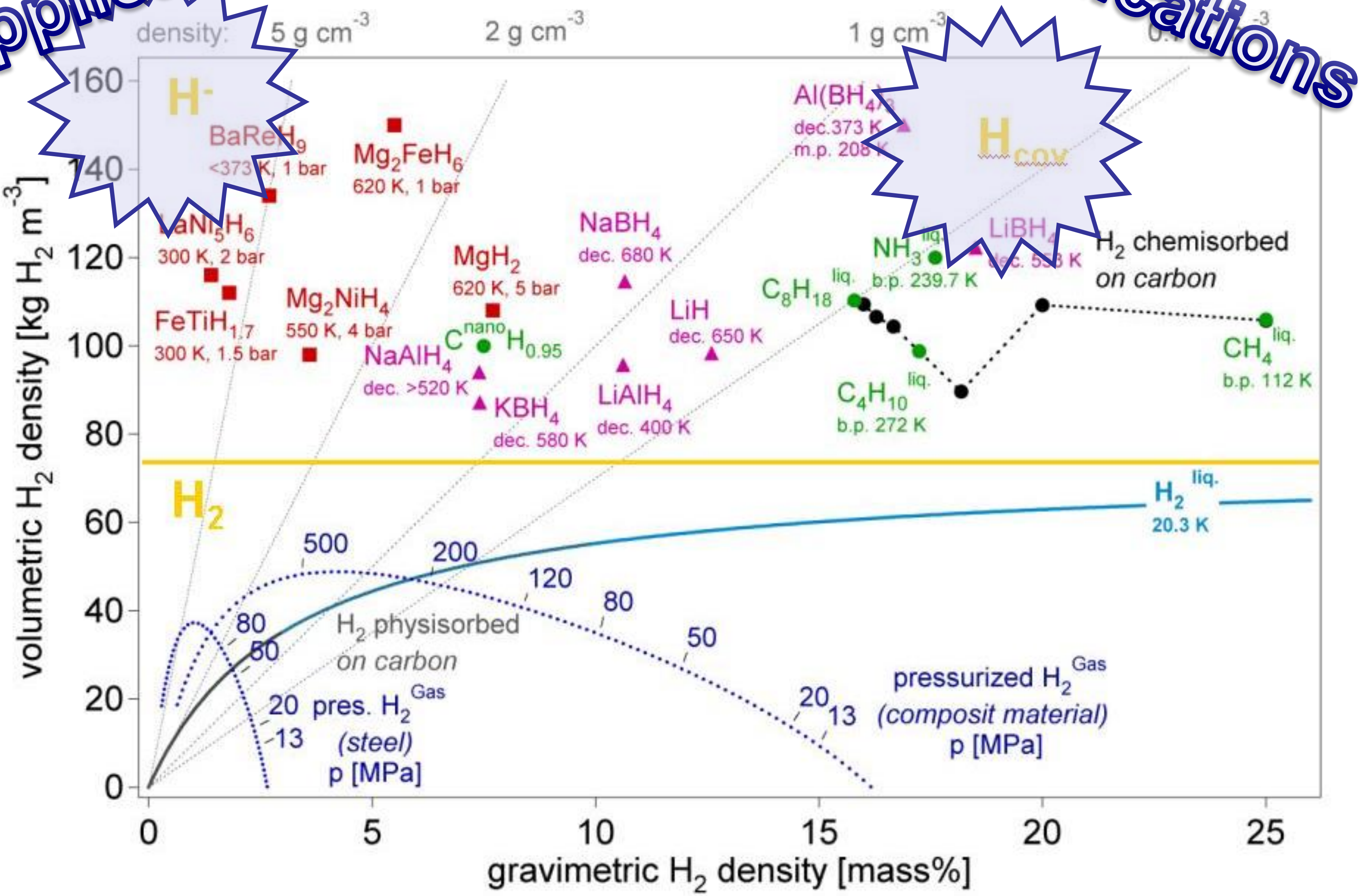
- Energy loss for liquefaction (about 30%)
- Boil-off: continuous loss of few % per day
- Needs of big-sized tanks

- Density (H_2 liq.) = 70.8 kg·m^{-3}

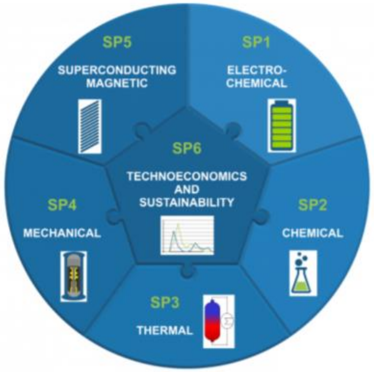
H_2 carriers

stationary applications

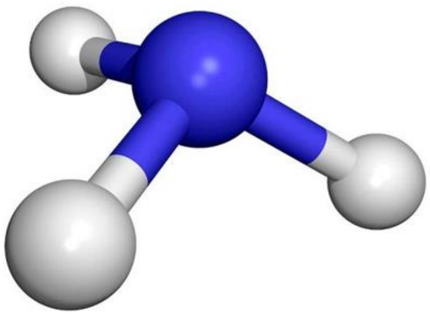
mobile applications



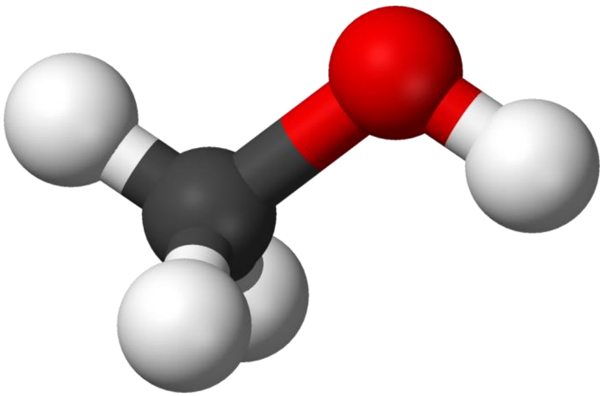
Ref: A. Züttel, "Materials for hydrogen storage", materials today, September (2003), pp. 18-27



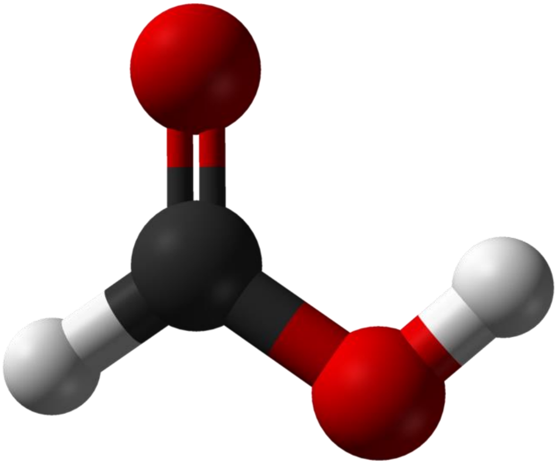
Chemical hydrides



Ammonia



Methanol



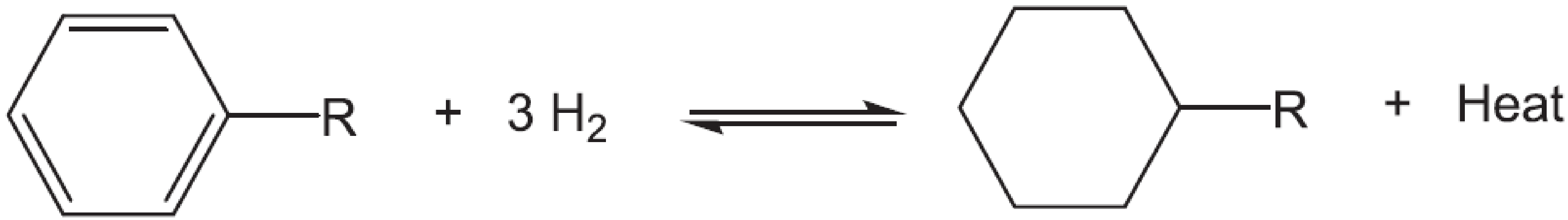
Formic acid

- Liquid at normal conditions
- High gravimetric density
- Catalysts are necessary
- Commercially available

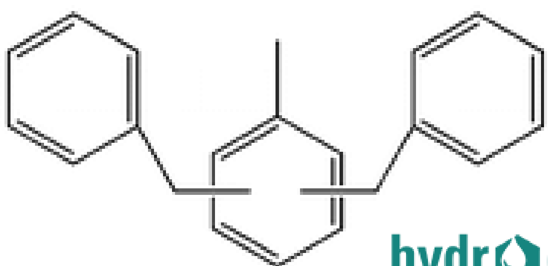
Energy density [MJ/kg]:

- Hydrogen 140
- Ammonia 19
- Methanol 20
- Formic acid 5

Liquid Organic Hydrogen Carriers - LOHC



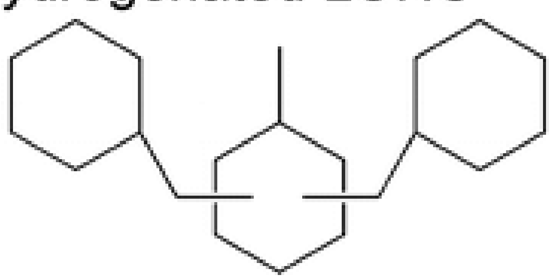
Non-Hydrogenated LOHC



Dibenzyltoluene

hydrogenious
LOHC TECHNOLOGIES

Hydrogenated LOHC

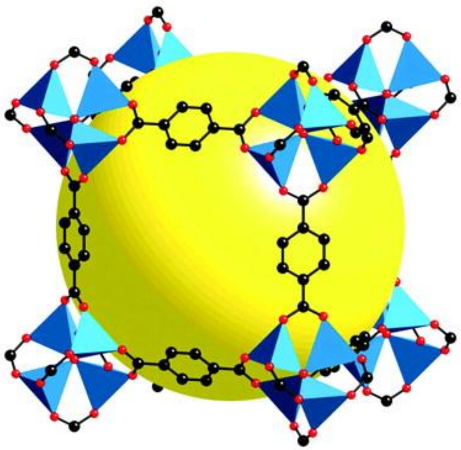


Perhydrodibenzyltoluene

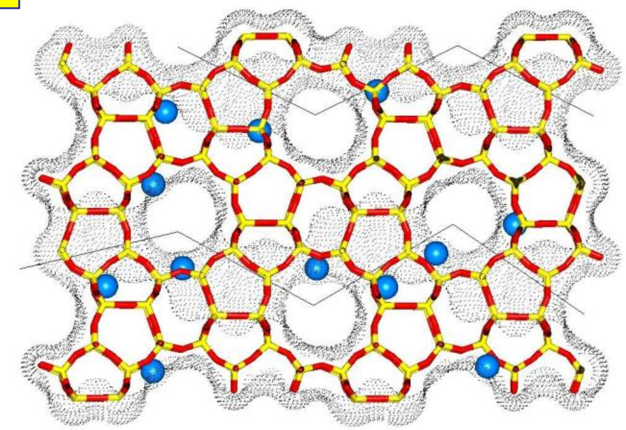
- **Liquid phase**
- **Different temperature ranges (150-350 °C)**
- **High gravimetric density (up to 6 wt%)**
- **Catalysts and purification are necessary**
- **Eventually 2nd store for dehydrogenated fluid necessary**
- **Commercially available**

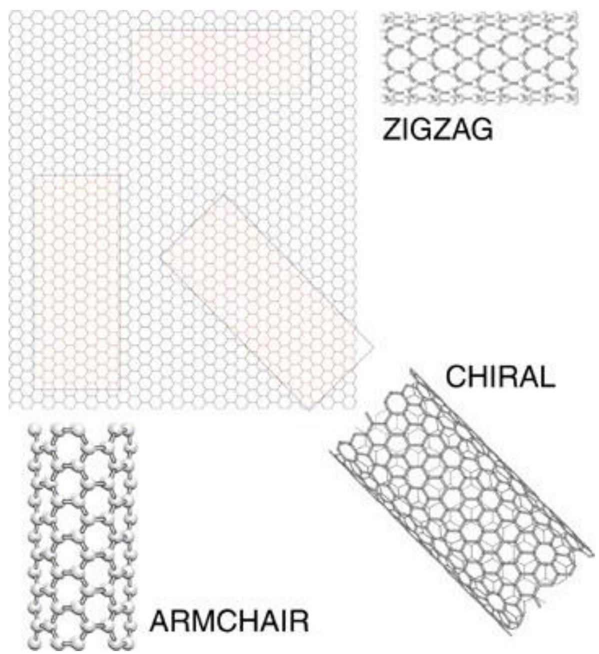
Adsorption

MOF



ZEOLITES

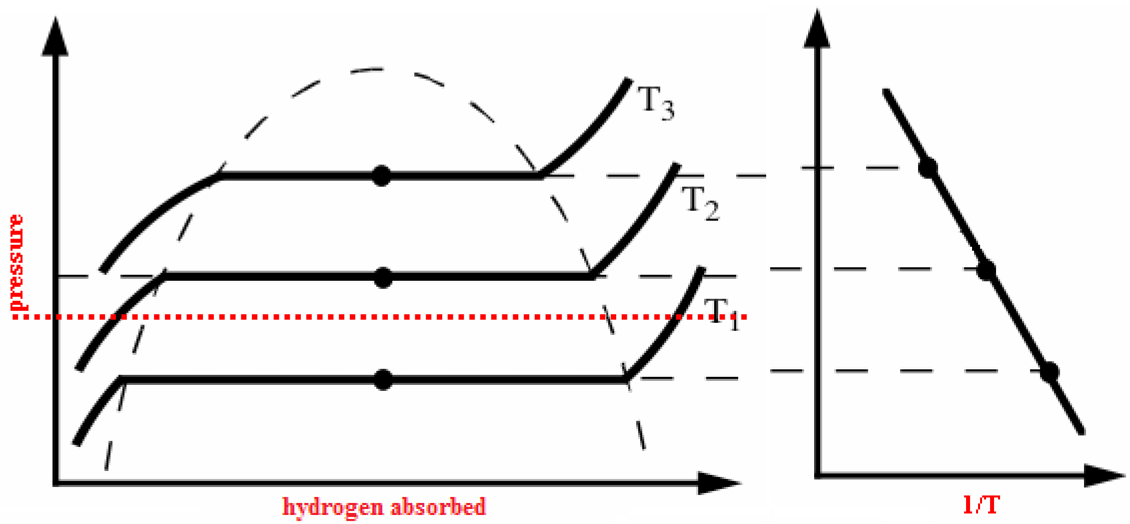


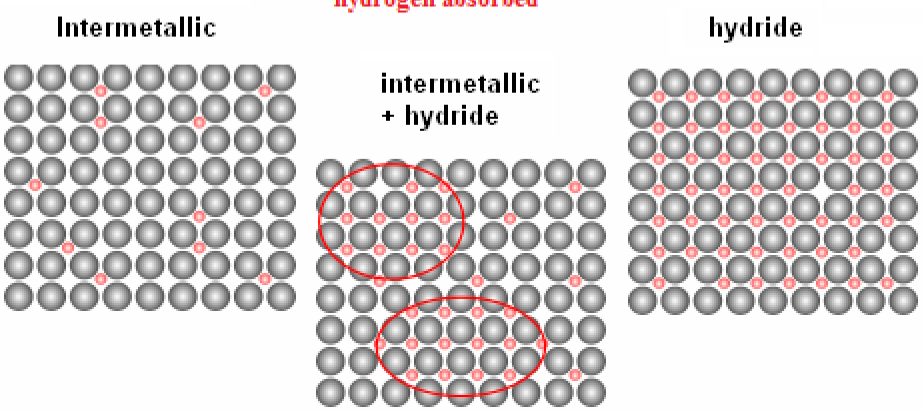


CARBON NANOTUBES

- **Low temperature**
- **Small volumetric density**

Hydrides for hydrogen storage





Van't Hoff equation

$$\ln\left(\frac{P}{P_0}\right) = \frac{\Delta S}{R} - \frac{\Delta H}{RT}$$

$\Delta S \approx 120\ \mathrm{J\ mol_{H2}^{-1}\ K^{-1}}$

Reversible in ambient conditions

$\Delta H \approx 30\text{-}40\ \mathrm{kJ\ mol_{H2}^{-1}}$

No one among light hydrides shows this ideal ΔH

Strategies to tailor ΔH

Multicomponent mixtures

FUEL CELLS AND HYDROGEN
JOINT UNDERTAKING

HORIZON 2020

The HyCARE Project

UNIVERSITÀ DEGLI STUDI DI TORINO

ENGIE

GKN

TECNO DELTA

Stühff GmbH

HyCARE

Helmholtz-Zentrum Geesthacht
Zentrum für Material- und Küstenforschung

FONDAZIONE BRUNO KESSLER

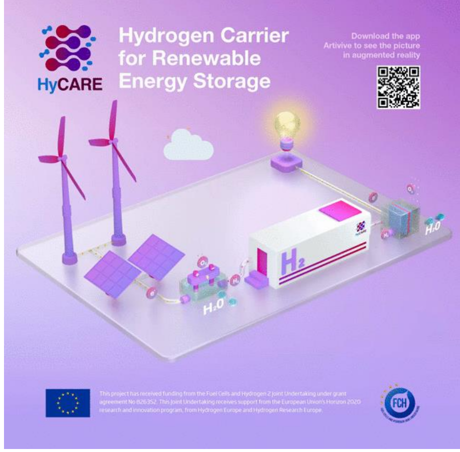
cnrs

2019-2021

IFE

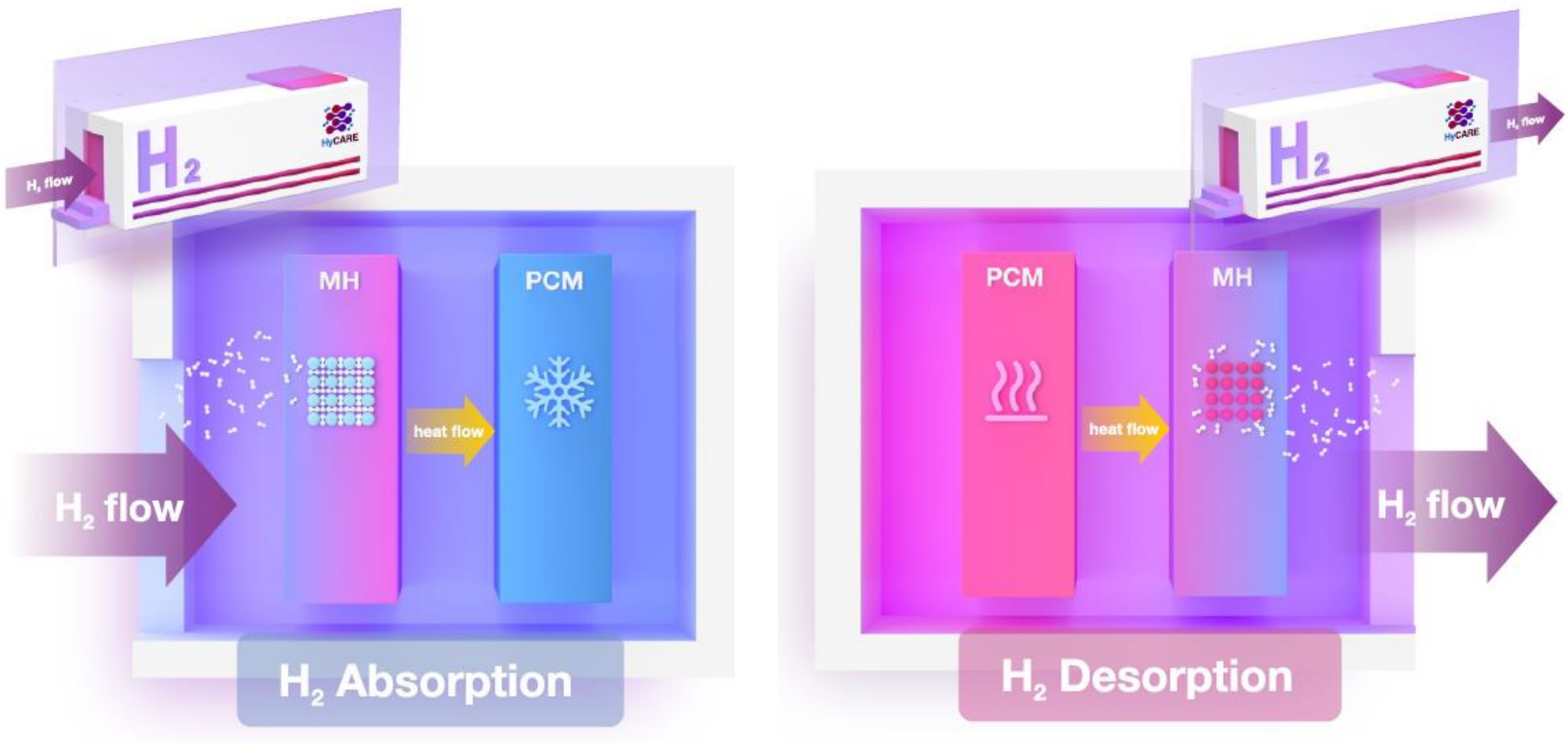
ENVIRONMENT PARK Parco Scientifico Tecnologico per l'Ambiente

The goals



- **High quantity of stored hydrogen** >= 50 kg
- **Low pressure** < 50 bar and **low temperature** < 100°C
- **Low foot print**, comparable to liquid hydrogen storage
- **Innovative design**
- **Hydrogen storage** coupled with **thermal energy storage**
- Improved **energy efficiency**
- **Integration** with an **electrolyser** (EL) and a **fuel cell** (FC)
- Demonstration in **real application**
- Improved **safety**
- **Techno-economical evaluation** of the innovative solution
- Analysis of the environmental impact via **Life Cycle Analysis** (LCA)
- Exploitation of **possible industrial applications**
- **Dissemination** of results at various levels
- **Engagement** of local people and institution in the demonstration site

The concept


H2 flow
H2
HyCARE
MH
PCM
heat flow
H2 flow
H2 Absorption
H2
HyCARE
H2 flow
PCM
MH
heat flow
H2 flow
H2 Desorption

System design & prototype test

System design

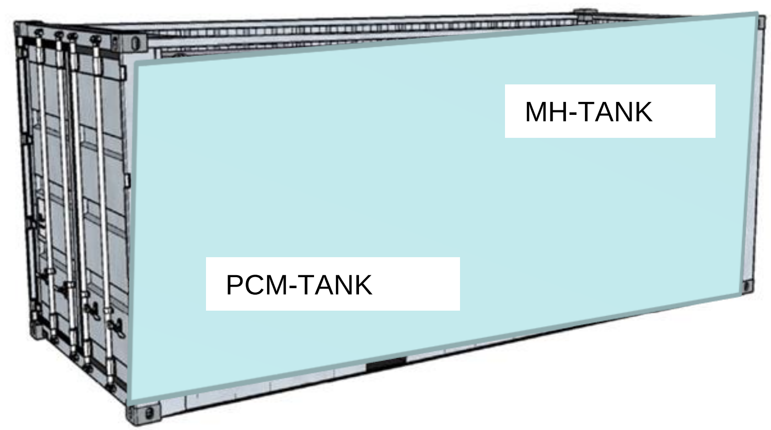
Metal hydride

- ≈ 4 ton of TiFe-alloy - ≈ 40-44 kg of H_2
- xx tanks

PCM

- ≈ 2.7 ton of PCM - CRODA
- yy tanks

Std. ISO Container



Prototype design

Metal hydride module

- 60 kg of TiFe-alloy
- pellets

PCM module

- 30 kg of PCM

Prototype test

- Models validation
- Optimization of the final design

Challenges for hydrogen handling

- LP-GAS
- HP-GAS
- LIQ
- CHEMICALS
- LOHC
- ADSORPTION
- MET HYDR

1. Quantity
2. Gravimetric density
3. Volumetric density
4. Energy efficiency
5. Charging time
6. Reversibility
7. Sensitivity to H_2 quality

9. Thermal management
10. Life cycle
11. Materials for tank
12. Stability on time
13. Availability
14. Safety
15. Cost
16. Acceptance

KPI
KEY PERFORMANCE INDICATOR

FCH FUEL CELLS AND HYDROGEN JOINT UNDERTAKING

Hydrogen Europe Research

EERA European Energy Research Alliance

Projects on hydrogen handling in Europe

FUEL CELLS AND HYDROGEN
JOINT UNDERTAKING

European Commission

BOR4STORE

HyTEC

COPERNIC

ECOSTORE

FIRECOMP

EDEN

TAHYA

COSMHYC XL

HyCARE

HyCOMP

COSMHYC

HySTOC

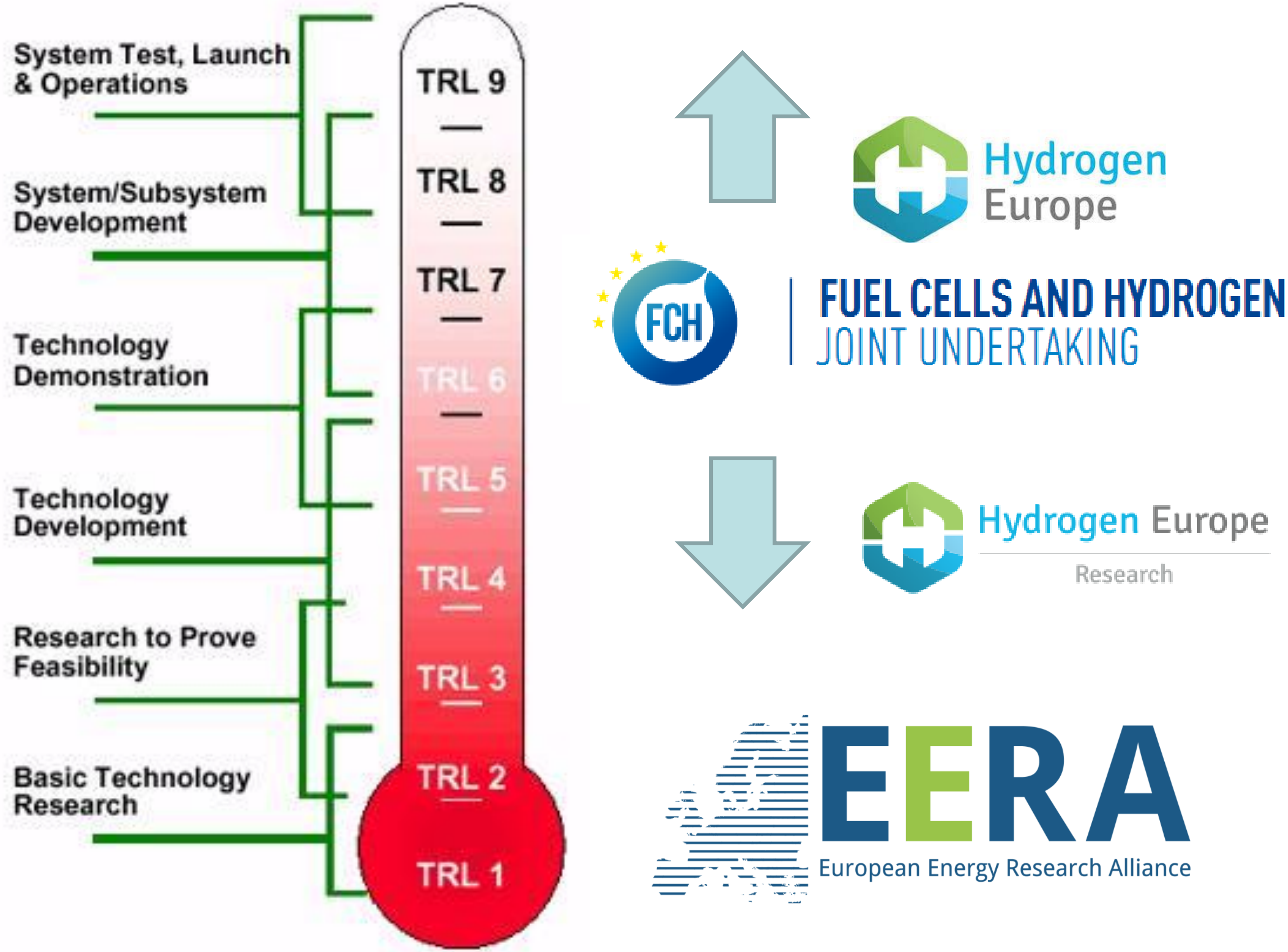
DeliverHy

IDEALHY

Hydride4Mobility

HyUnder

SSH2S



System Test, Launch & Operations
System/Subsystem Development
Technology Demonstration
Technology Development
Research to Prove Feasibility
Basic Technology Research
TRL 9
TRL 8
TRL 7
TRL 6
TRL 5
TRL 4
TRL 3
TRL 2
TRL 1
Hydrogen Europe
FCH
FUEL CELLS AND HYDROGEN
JOINT UNDERTAKING
Hydrogen Europe
Research
EERA
European Energy Research Alliance

Clean Hydrogen

Specific Objective 3: Delivering Hydrogen at low cost

Roadmaps:

- large scale hydrogen storage
- hydrogen in the gas grid
- hydrogen carriers
- developing existing hydrogen transport means
- key technologies for hydrogen distribution (H_2 compression, metering, purification and separation)

Open points for the discussion

What are optimal (energy, cost, footprint) hydrogen storage and transport options for:

- **On-shore storage and transport**
  - **Truck**
  - **Train**
  - **In the gas grid**

- **Large scale off-shore power production and hydrogen generation (i.e. electrolysers directly in the wind farms)**
  - **Underground**
  - **Ship**
  - **Pipeline**

- **National, international and Intercontinental hydrogen transport for supply of Europe**
  - **Ship**
  - **Pipeline**

Open points for the discussion

Transport and storage options – where to use which in relation to amount of H_2 to be stored and transported

- **Gaseous**
- **Liquid hydrogen**
- **Chemicals**
  - **Ammonia**
  - **Formic acid**
  - **Other**
- **LOHC**
  - **Toluene**
  - **Dibenzyltoluene/Marlotherm®**
  - **Others**
- **Solid carriers**
  - **Metal hydrides**
  - **Porous materials**