Università di Genova

Metal Hydrides for hydrogen storage

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Agenda of Today

- **Personal and UNIGE TPG Introduction**
- **How to Store Hydrogen and Metal Hydrides**
- **Conclusions**

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- **Conclusions**

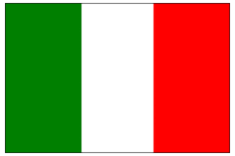
Stefano Barberis

Professional Experience

- *Mechanical Engineer*
- *PhD In Advanced Energy Systems*
- *Researcher and Assistant Professor at TPG UNIGE*
- *Founder and member of BluEnergyRevolution*
- *Horizon Europe JUST GREEN AFRH2ICA Project coordinator*
- *+5 years of experience in RINA Consulting managing and coordinating different EU Funded projects and leading proposal writing activities*
- ***R&D interests:** energy storage (thermal, power-to-X, CBs…), sCO2 energy systems, high temperature HPs*

Genova: where is it?

600,000 inhabitants
(6th city in Italy)



Italy

UniGe TPG

University of Genoa – established in 1481

- General purpose University (Engineering and Architecture, Human Sciences, Medicine, Sciences, Social Sciences)
- About 33,000 students
- About 7,000 graduations per year
- About 2,750 personnel units
- 5 Schools
- 23 Departments
- 127 courses
- 4 different locations (Genoa, Savona, La Spezia and Imperia)
- 110 International agreements for student mobility

Polytechnic School – established in 1870

- **Engineering** and **Architecture** Faculties
- About 6,000 students
- 5 Departments
- No.1 in Italy for International cooperation and exchange

EDUCATION

BIOMEDICAL
CHEMICAL
CIVIL
ELECTRICAL
ELECTRONIC
ENVIRONMENTAL
MANAGEMENT
MECHANICAL
NAVAL
SOFTWARE
TELECOMMUNICATION

Università di Genova | Centro del Mare

RESEARCH

BASED ON 4+1
RESEARCH DEPARTMENTS

STUDENTS

STUDENTS: 6000
5 YEARS CURRICULUM
3 YEARS CURRICULUM

Thermochemical Power Group – established in 1998

Thermochemical Power Group

- Professors (5)
- Lecturers (3)
- Researchers (9)
- PhD Students (10)
- Technicians (1)

Scientific activities

Publications, Awards, Patents, Spin-off

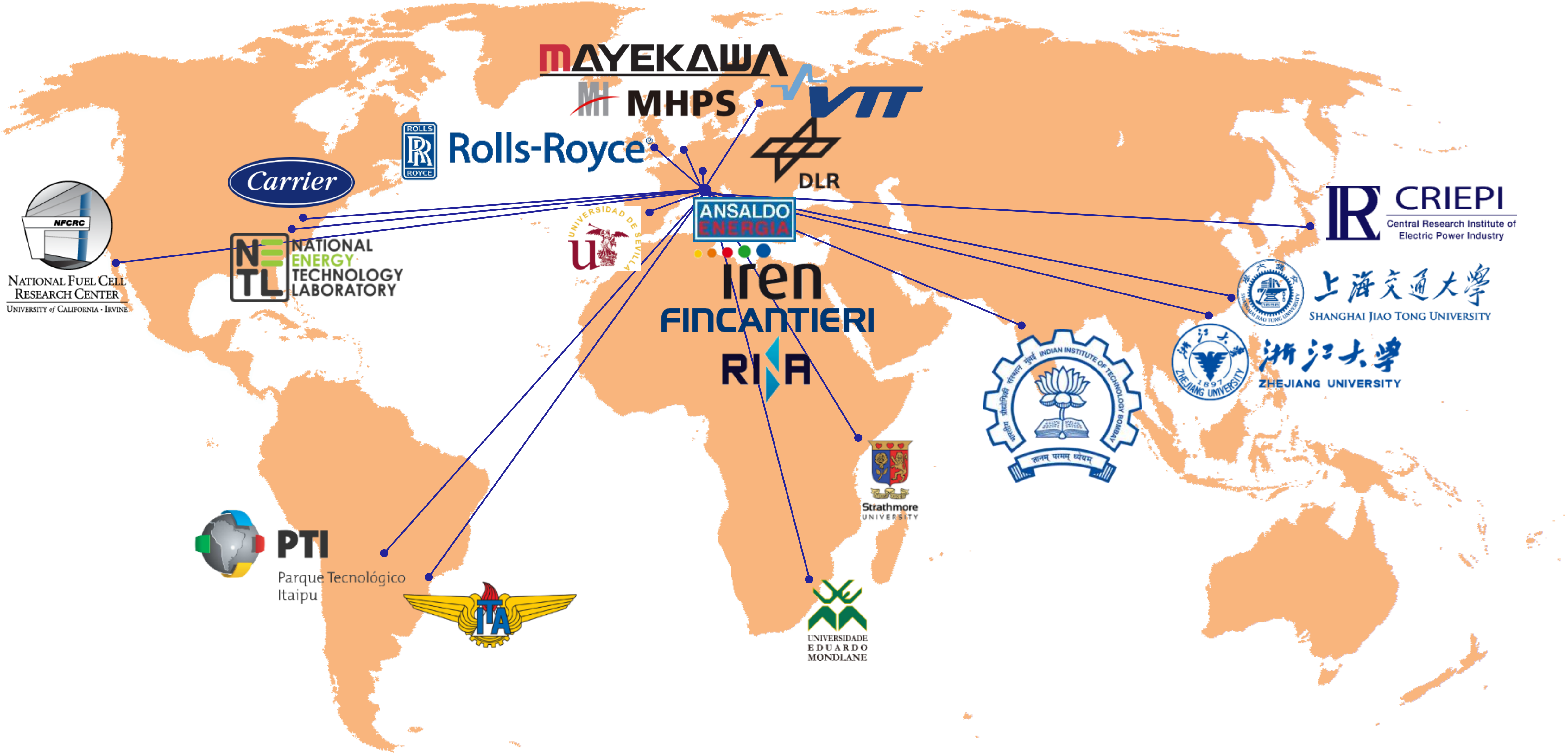
- >300 Papers, >200 Journals (1998-2020)
- 16 International Awards (1998-2020)
- 19 patents (1998-2020)
- 2 spin off companies (BluEnergyRevolution, SIT Technologies)

Funding

International 65% (35% EU)

National 35%

TPG major International links



TPG milestones

45M€ contracts

2021

2020

UNESCO Chair

250 journal arts

2019

30M€ contracts

2018

2016

FINCANTIERI lab

20M€ contracts

2015

SIT Technologies spin-off

2012

Innovative Energy Systems lab

CRADA contract with US research centre (NETL)

2009

H2boat spin-off

First H2020 project – MefCO2

Energy-Hub lab (Savona)

2006

10M€ contracts

100 journal publications

2005

Savona UTC lab

2004

3 Professor chairs sponsored by Rolls-Royce

2000

Rolls-Royce University Technology Centre

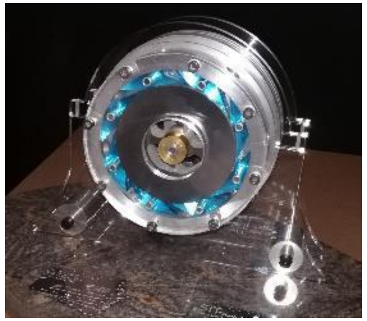
First international patent

1998

First European project (FP V) - GTPOM

TPG foundation

First ASME Best Paper Award



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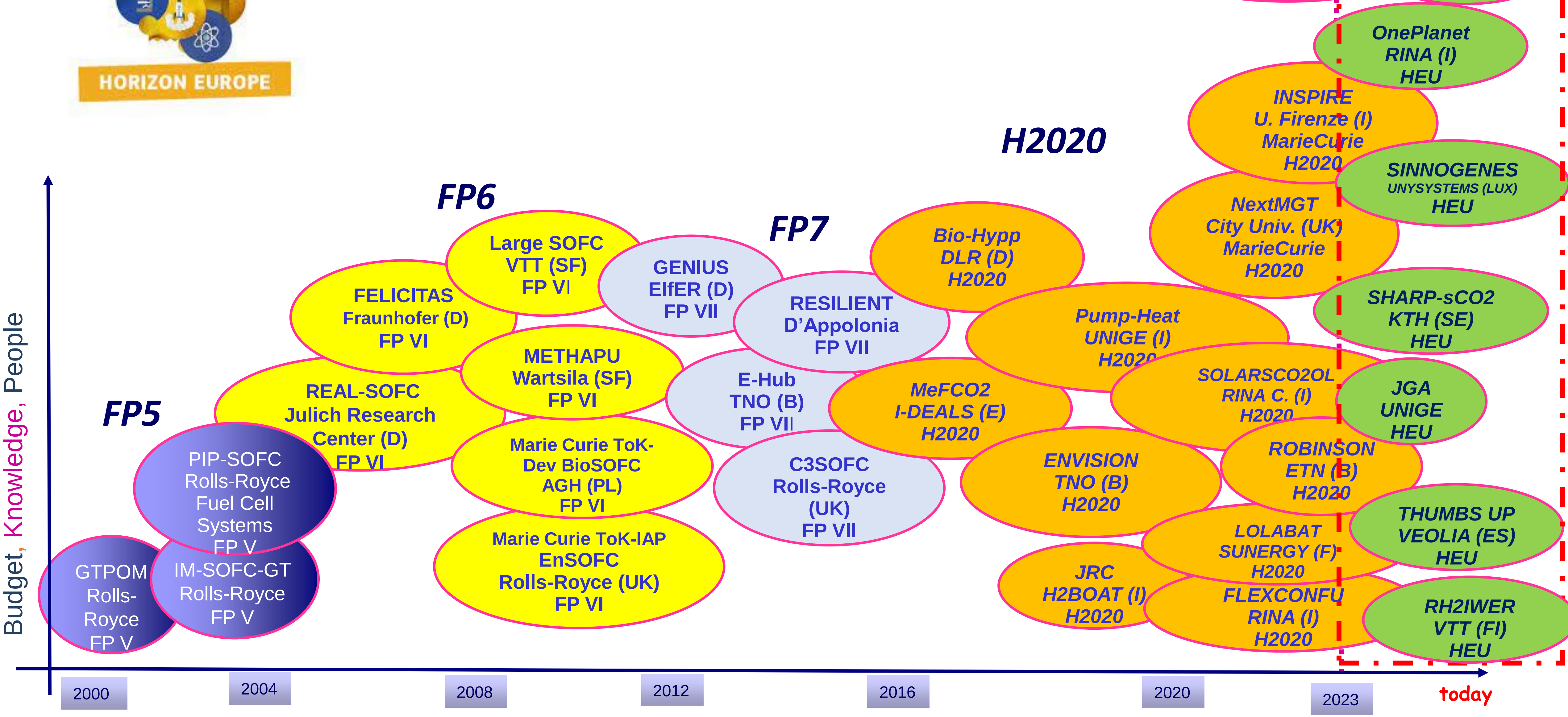
TPG European Research Projects
From FP5 to HORIZON EUROPE

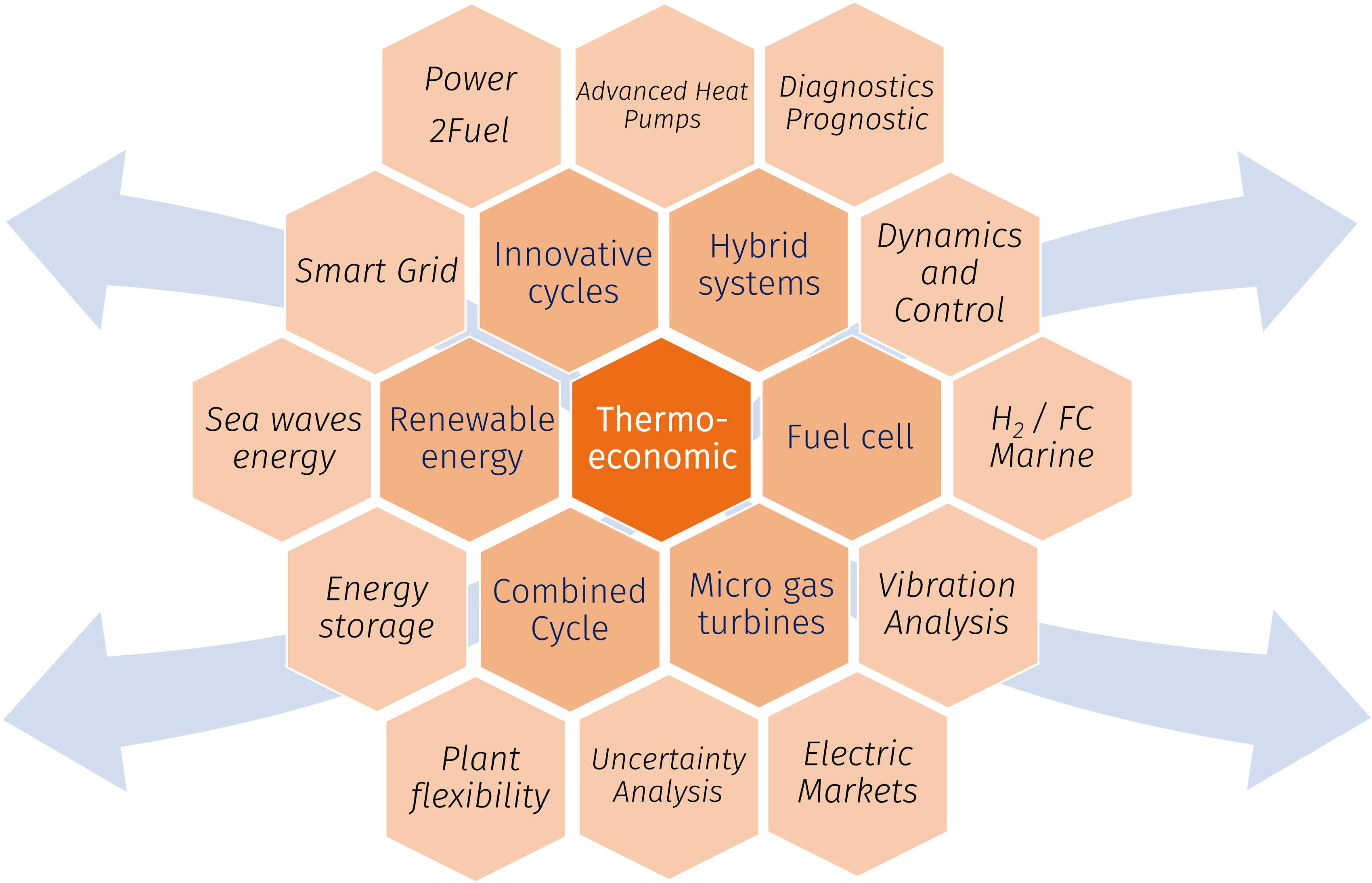


TPG milestones

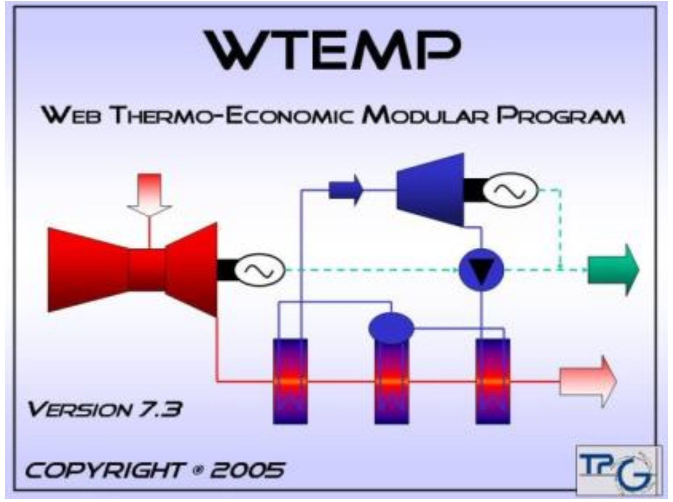
A long R&D story on hydrogen and FC (and international Collaborations)

- **1995:** first prof. A.F. Massardo on hydrogen at ASME TurboExpo – *"Combined Helium and Combustion Gas Turbine Plant Exploiting Liquid Hydrogen (LH2) Physical Exergy"*
- **2000:** first activities on SOFC-GT on hybrids – "*Internal reforming solid oxide fuel cell-gas turbine combined cycles (IRSOFC-GT): Part A—Cell model and cycle thermodynamic analysis*" - AF Massardo, F Lubelli- J. Eng. Gas Turbines Power 122 (1), 27-35
- **2001**: Starting activities on FC Modeling and testing: initially SOFC and MCFC
- **2003:** PIP-SOFC – First EU Funded Project on FCH Technologies – FP5
- **2004:** Rolls Royce UTC Technology Centre – First FP6 EU Funded Project on FCH Technologies (5 more FP6 will follow)
- **2010:** GENIUS – First FP7 EU Funded Project on FCH Technologies - First Metal Hydrides R&D activities
- **2011:** starting International collaboration activities with Paraguay – ITAIPU for a local National Hydrogen Strategy – Starting to study E-Fuels and thermoeconomics of FCH technologies
- **2012:** Starting Collaboration with FINCANTIERI for the Promotion of Hydrogen as key fuel for Maritime Sector – Start of PEMFC activities
- **2015:** MefCO2 – First H2020 EU Funded Project on E-FUELS
- **2016:** Opening of the new H2LAB in Savona
- **2019:** Opening of the new FINCANTIERI Lab
- **2020:** Power-to-Hydrogen H2020 Projects: FLEXNCONFU – ROBINSON – Starting of Ammonia Investigations (ENGIMMONIA H2020 project and AMMONIA Fuel Cell activities)

TPG cloud competences



TPG Tools for Energy Systems Modeling

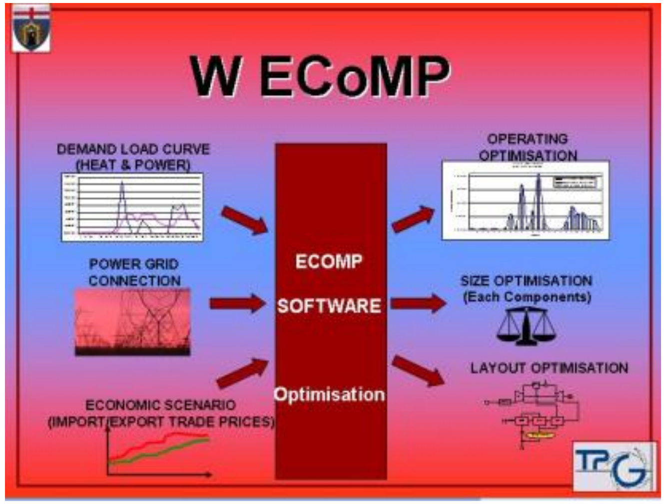


WTEMP

Optimization of the design of energy systems and power plants

HELM

Optimization of energy systems design on board of vessels and utilization of alternative fuels

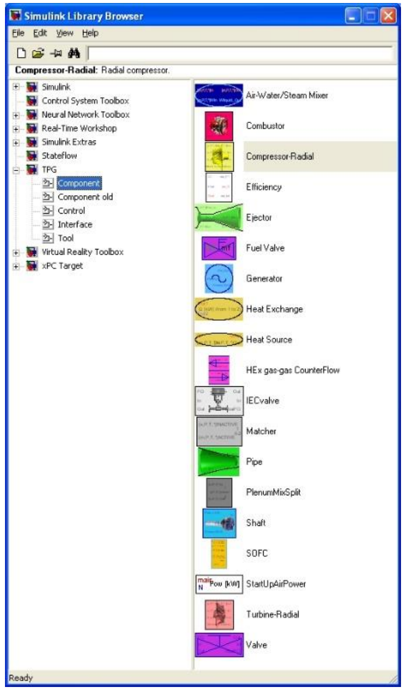


WECOMP

Time dependent optimization of the design and management of polygenerative energy districts

TRANSEO

Dynamic simulation of energy systems



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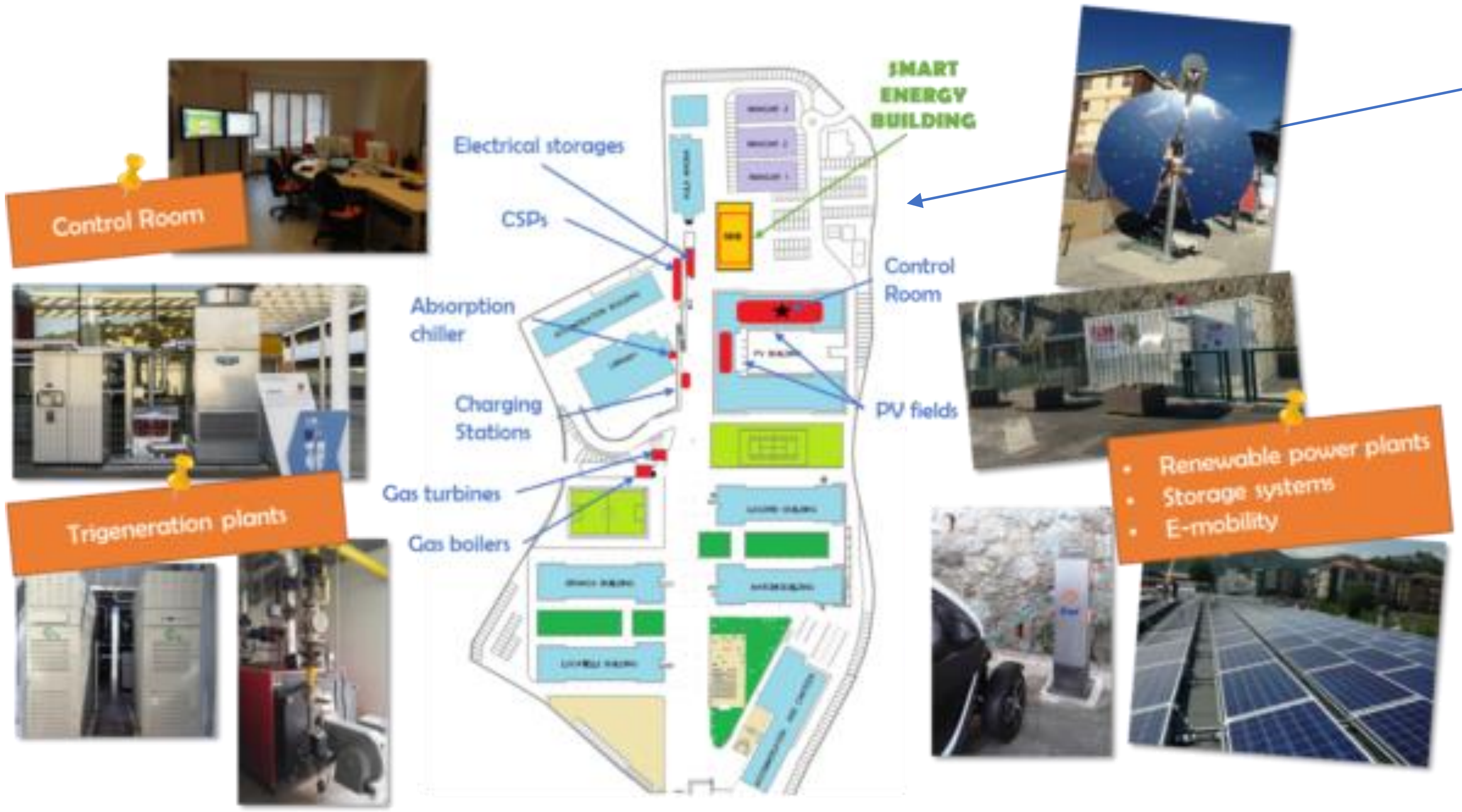
TPG laboratories

...the first Mediterranean Smart Grid

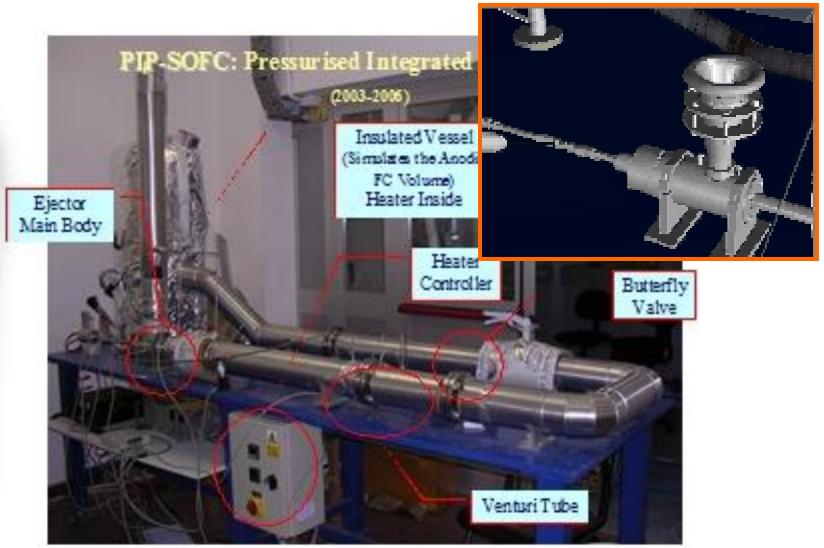


Innovative Energy Systems Laboratory

A Polygenerative Energy Hub (composed by different prime movers and storage, both electric and thermal) where to test new energy solutions and controllers coupled to local DHN and smart grid

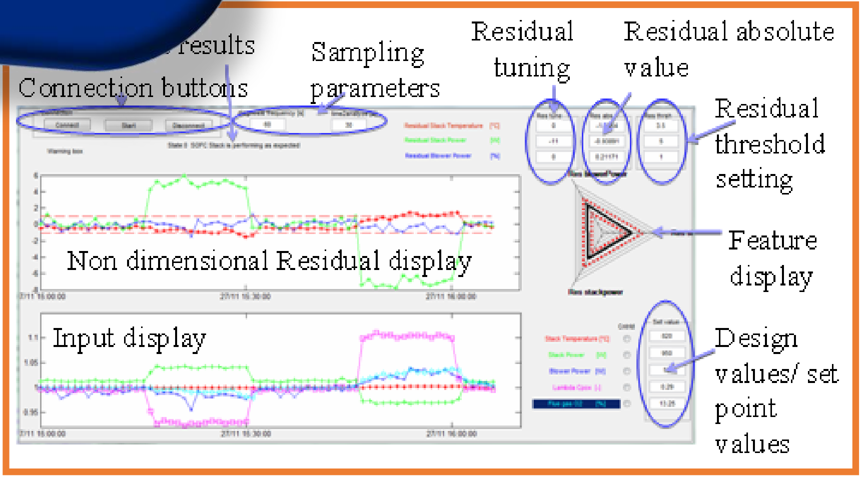
The Rolls-Royce University Technology Centre @ TPG …since 2004

Component and system modelling and validation



Test rigs

Performance modelling, Dynamics and controls

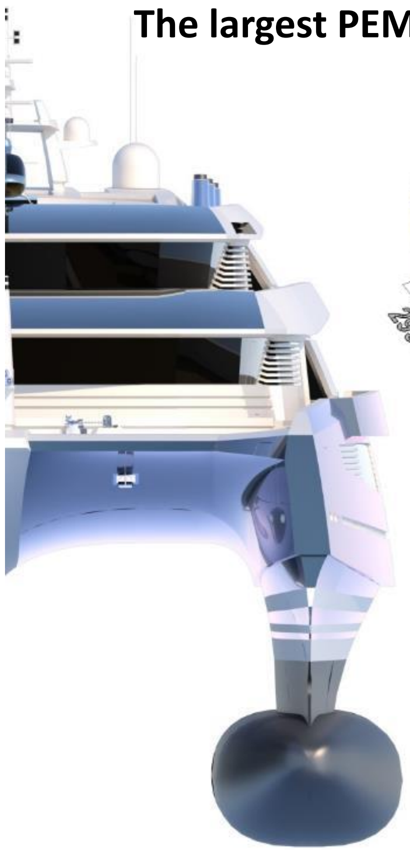


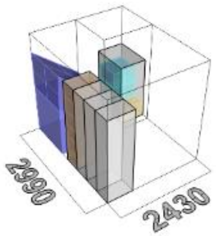
Real time diagnostics algorithms

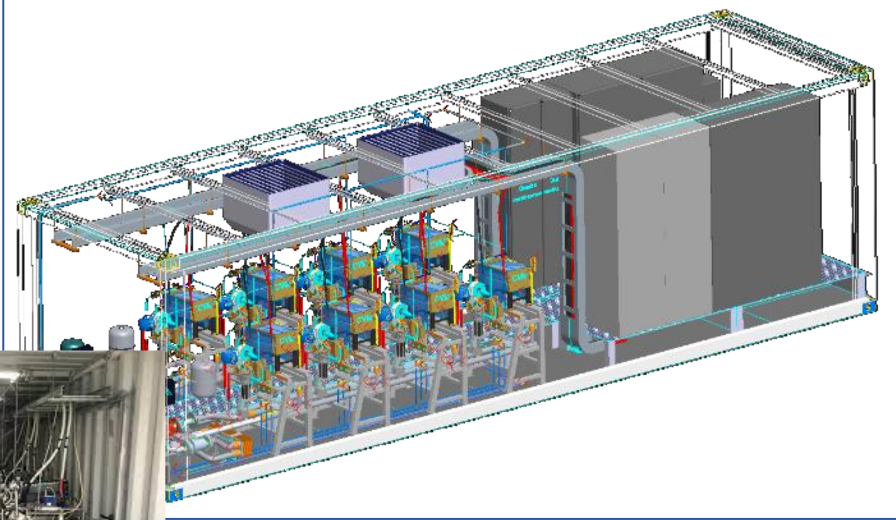
The FINCANTIERI Hi-Sea lab @ TPG

...since 2018

The largest PEM fuel cell laboratory systems of the world specifically designed for marine applications assessment







Numbers

Fuel Cell Power 130kW + 130kW
Two DC/DC converter 350-600 V
One AC/DC 60kW

Current operational achievements

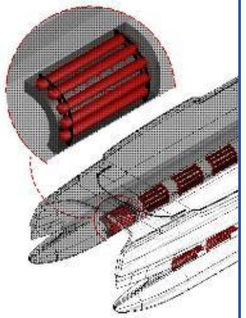
fuel cell H_2/Air 30 kW
fuel cell system H_2/AIR of 130 kW
fuel cell system H_2/AIR of 130+130 kW
operating series-parallel
battery physical simulation
fault simulation

Basic Design

Assessment of Fuel Cell Systems for marine applications: Mega Yacht, Navy, Passenger Ships, Ferries

System Sizing

Dynamic simulations of Fuel Cells and Metal Hydrides Storage systems coupling



***Genova* HI-SEA**

Hydrogen Initiative for Sustainable Energy Applications

University of Genova

Thermochemical Power Group

FINCANTIERI
The sea ahead

UniGe

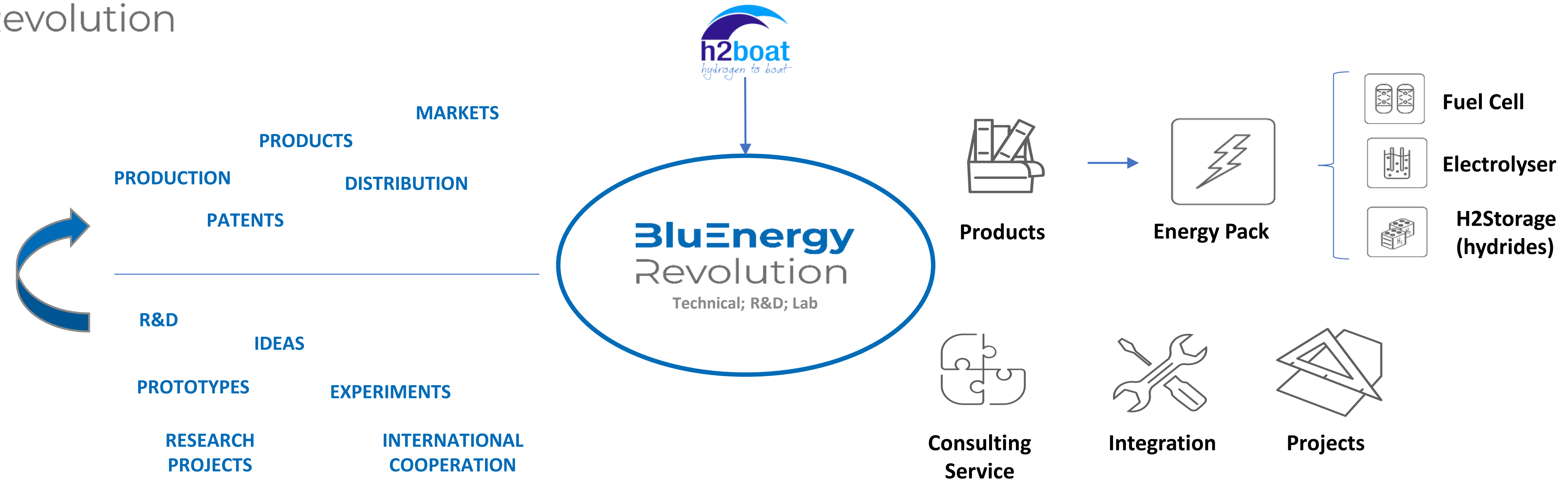
H2 for Shipping but...not only! Ammonia, methanol etc.

TPG spinoff company – H2Boat and BluEnergyRevolution

Spin off
Università degli Studi di Genova

BluEnergy Revolution

Over the years BluEnergy Revolution has built a technical team specializing in hydrogen technology, developing dedicated technical solutions, patents, research projects, consultancy.
The strong growth of the «Hydrogen» sector pushes us to grow further!



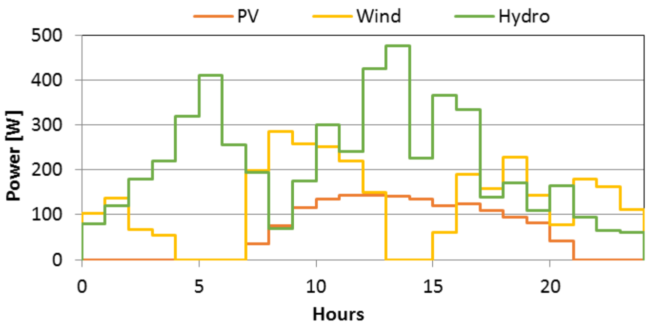
African Hydrogen Partnership

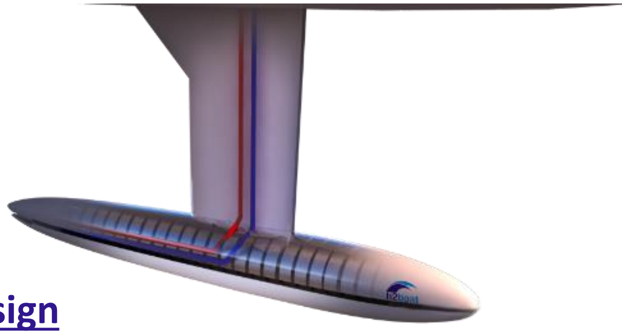
Together with UNIGE – BER is member of AHP and in contact with relevant EU (Hydrogen Europe) and Italian (H2IT) associations also thanks to our link with University of Genova

TPG spinoff company – H2Boat and BluEnergyRevolution

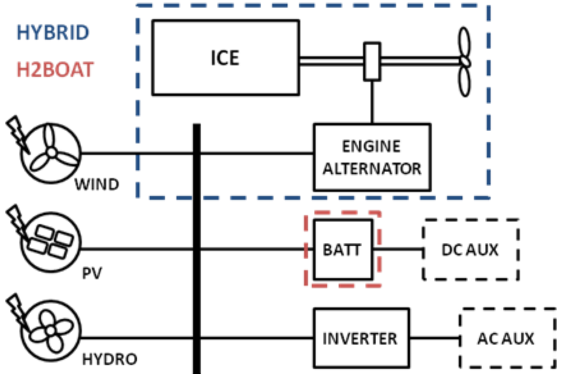
h2boat
hydrogen to boat

Hydrogen to Boat
is an innovative system designed to provide electrical energy for auxiliary systems and also for the propulsion of sailboat up to 40 ft (12 m).

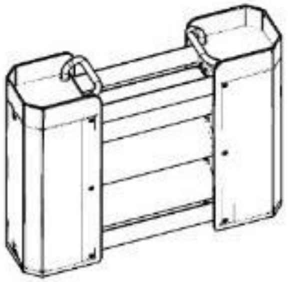




Patented Design
Special Metal Hydride hydrogen storage system integrated inside the keel for sailboats



RES
Dynamic analysis of RES production onboard boats



H2Boat solution
Design and analysis of electric systems for sailboats through dynamic simulations, laboratory test campaign and prototypes construction

TPG CARE: human & professional development

CARE: **Co**operative **A**ctions by **R**esearch and **E**ducation

SUSTAINABLE DEVELOPMENT GOALS

7 AFFORDABLE AND CLEAN ENERGY

'Sustainable Energy for all' panel session @ASME Turbo Expo 2018,19, 20

Activities:

- **Academic course** on International Cooperation for Development
- **Thesis projects** in low-income countries
- **Dissemination** in technical conferences
- **Financed projects:**


Small Smart Grid development with ICU @Burundi, Africa


Small biodigester installation with APURIMAC Onlus @Peru, S.America


Poultry Value & Energy chain optimization with CNFA Europe @Zimbabwe, Africa

PROMOTING A JUST TRANSITION TO GREEN HYDROGEN IN AFRICA

PROMOTING A JUST TRANSITION TO GREEN HYDROGEN IN AFRICA

HORIZON-JTI-CLEANH2-2022-05-05
HORIZON JU Coordination and Support Actions

Coordinator: Università degli Studi di Genova
11 Partners from 8 different EU-AU countries

Starting Date: 1st February 2023
Project Duration: 24 months

Total grant: 1M€

JUST-GREEN AFRH2ICA

PROJECT MOTIVATION AND OBJECTIVES

OVERALL OBJECTIVE

Develop mutual benefit joint green hydrogen roadmaps

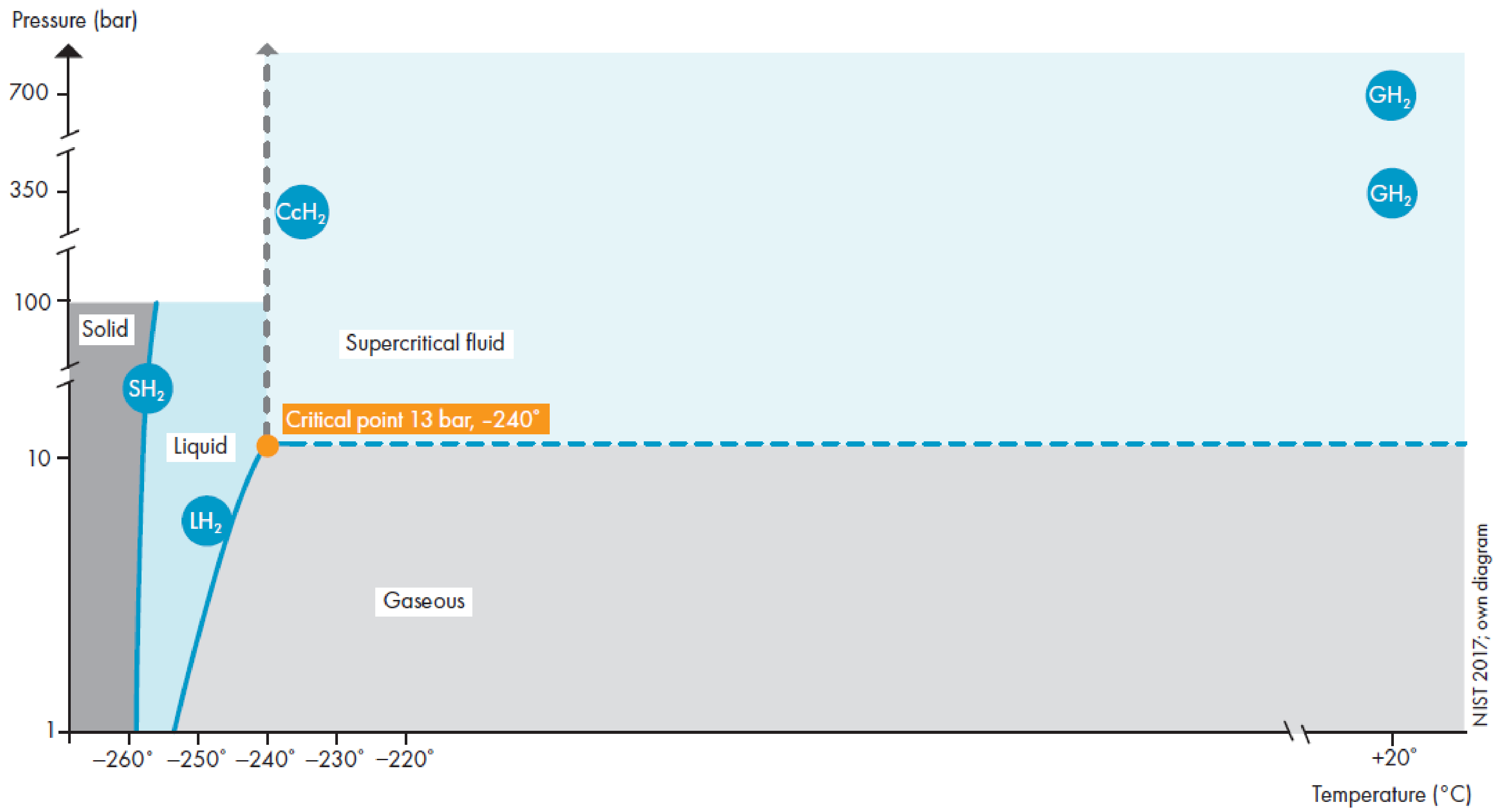
Agenda of Today

- **Personal and UNIGE TPG Introduction**
- **How to Store Hydrogen and Metal Hydrides**
- **Conclusions**

Goal of Today

….understanding what I was doing with these kids @OCEAN RACE INNOVATION VILLAGE Last year!

Hydrogen Properties – just to recap and introduce the topic…



At environmental conditions hydrogen is in gaseous phase

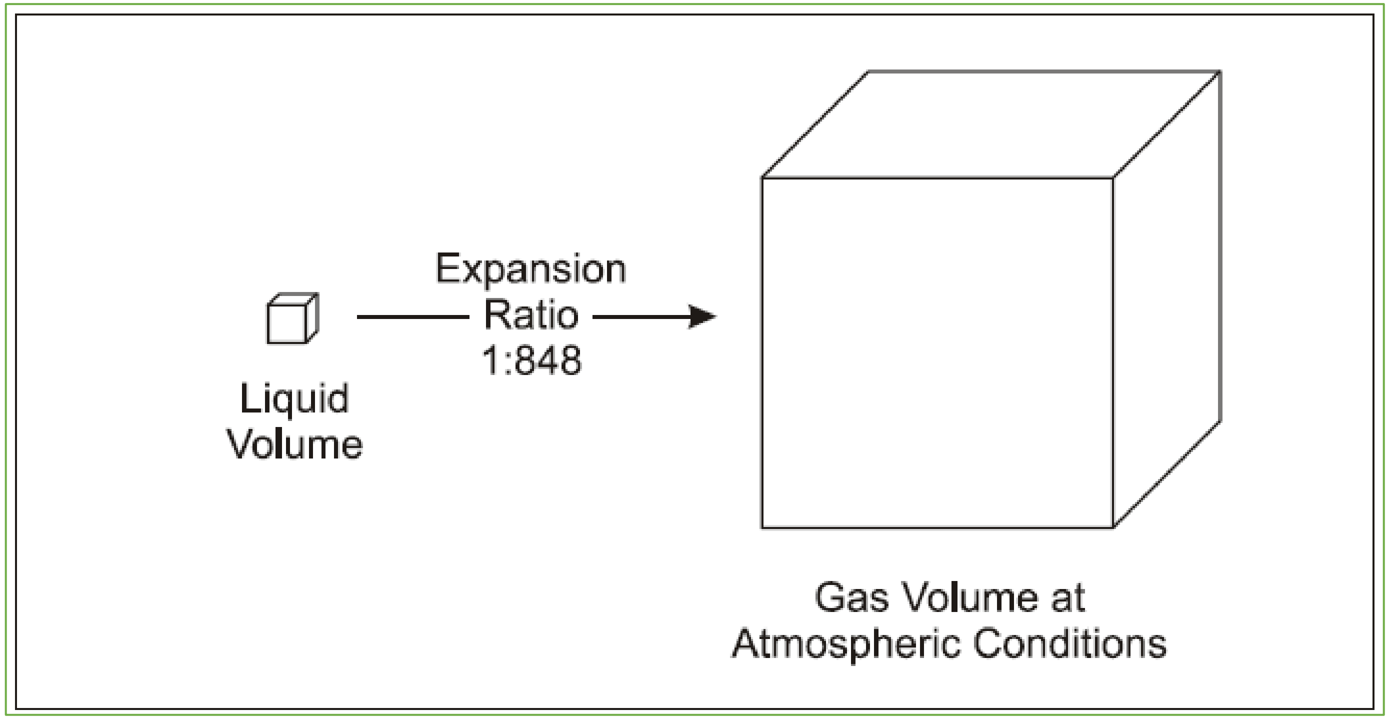
Liquefaction: T= -253°C @ 1 atm, -240°C @ 14 atm

Hydrogen Properties – just to recap and introduce the topic…

Hydrogen is very light and at environmental conditions density is very low!

1,22 kg/m³ air(15 °C, 1 atm)

0,085 kg/m³ H_2 (15 °C, 1 atm)



Volumetric expansion ratios are significant

1:240 H_2 gaseous at 250 atm vs H_2 gaseous at 1 atm

1:848 H2 liquid vs H2 gaseous at 1 atm

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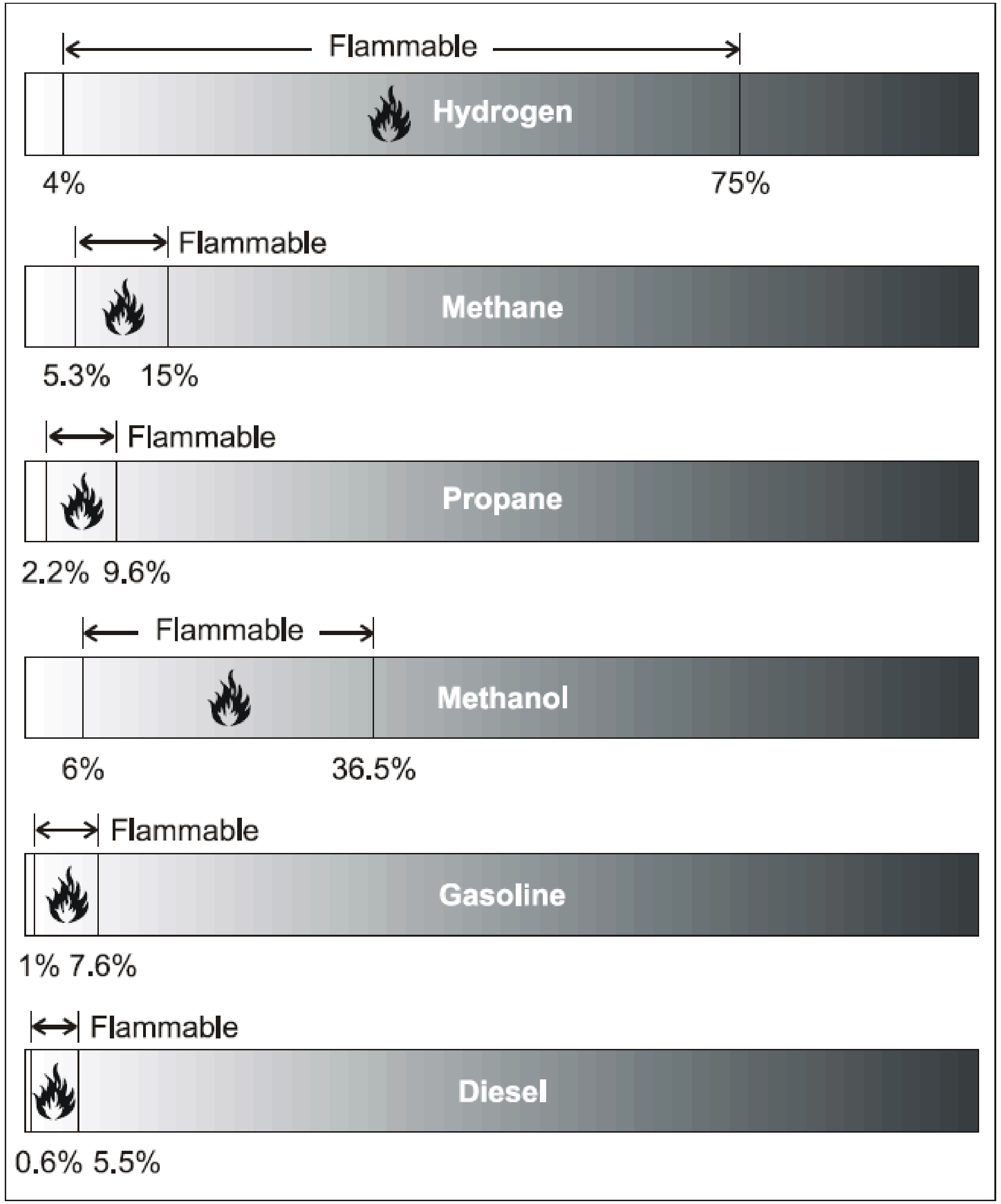
Hydrogen Properties – just to recap and introduce the topic…



LOW IGNITION ENERGY

SICUREZZA	H_2	Metano	Benzina
Limite di infiammabilità, aria (%vol)	4.0 - 75.0	5.3 – 15.0	1.0 – 7.6
Limite di detonabilità, aria (%vol)	18.3 – 59.0	6.3 – 13.5	1.1 – 3.3

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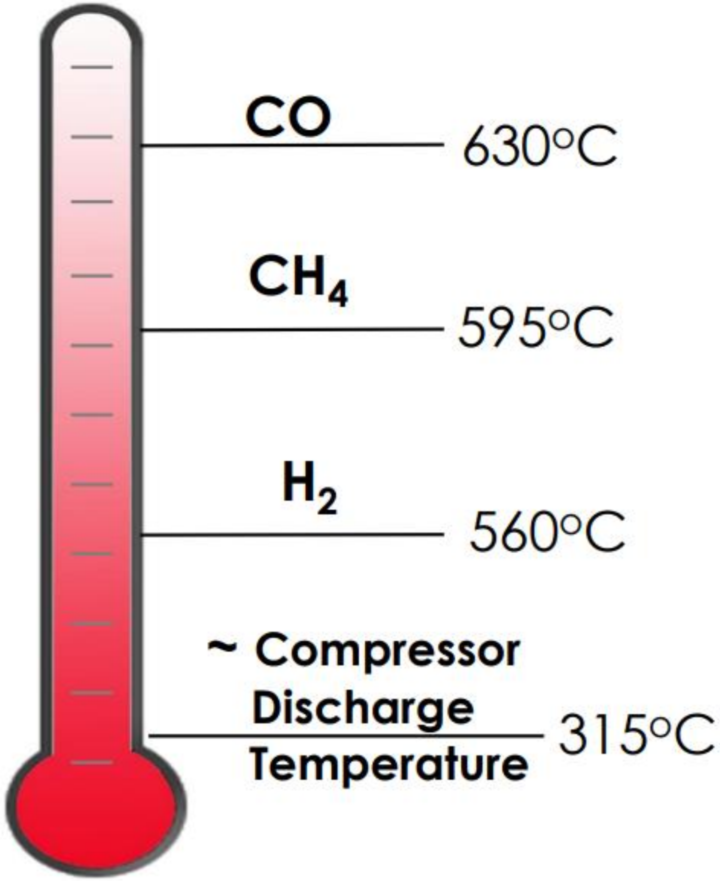
Hydrogen Properties – just to recap and introduce the topic…

Auto Ignition Temperature & Minimum Ignition Energy

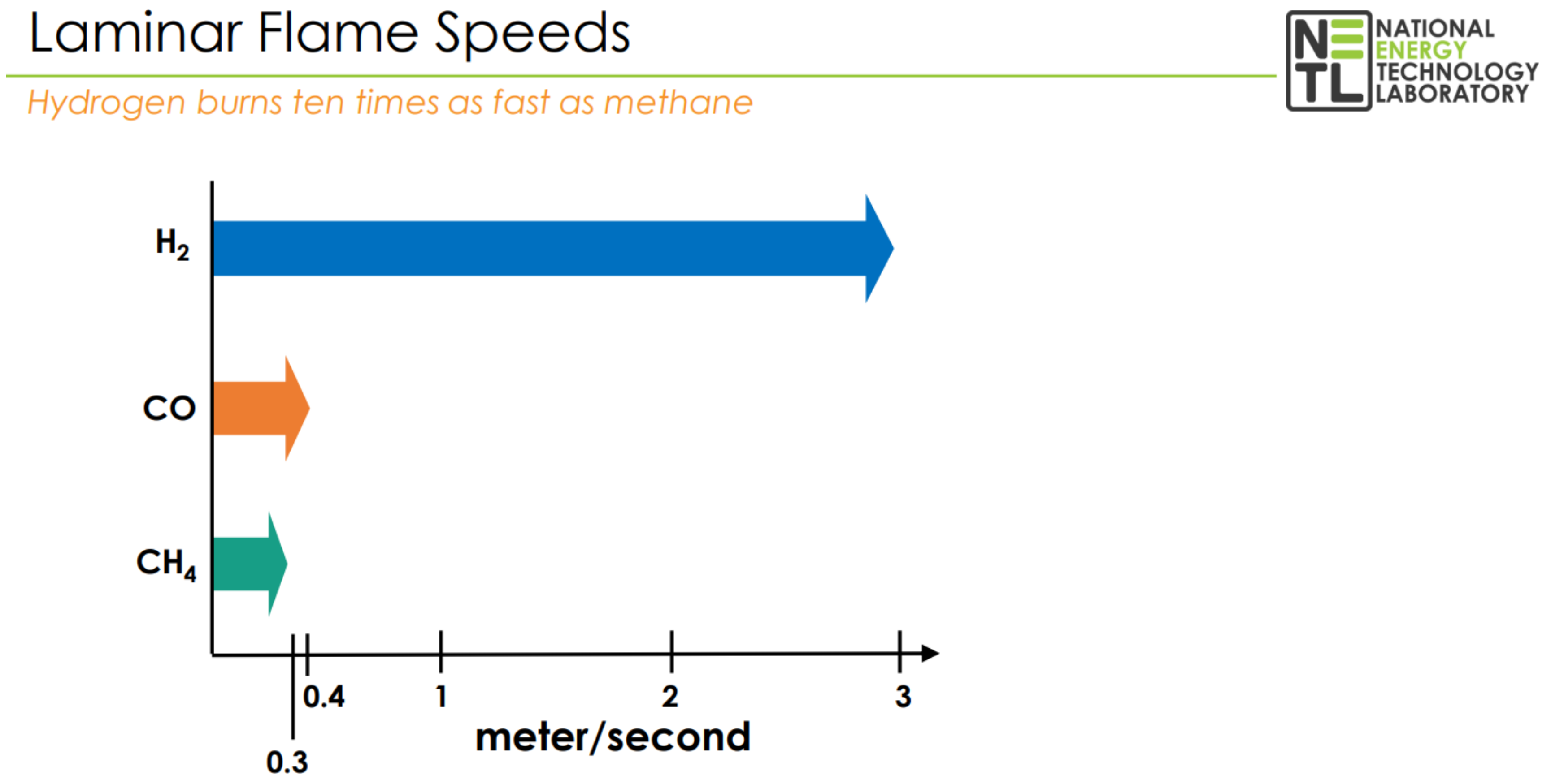
H_2 auto ignition temp. safely higher than compressor exit temperatures



Minimum Ignition Energy (mJ)

CO	0.3 (2)
CH_4............	0.3 (1)
H_2...............	0.017 (1)
Coffee.........	160 (1)

Hydrogen Properties – just to recap and introduce the topic…



Hydrogen Properties – just to recap and introduce the topic…

Table 2. Physical properties of hydrogen

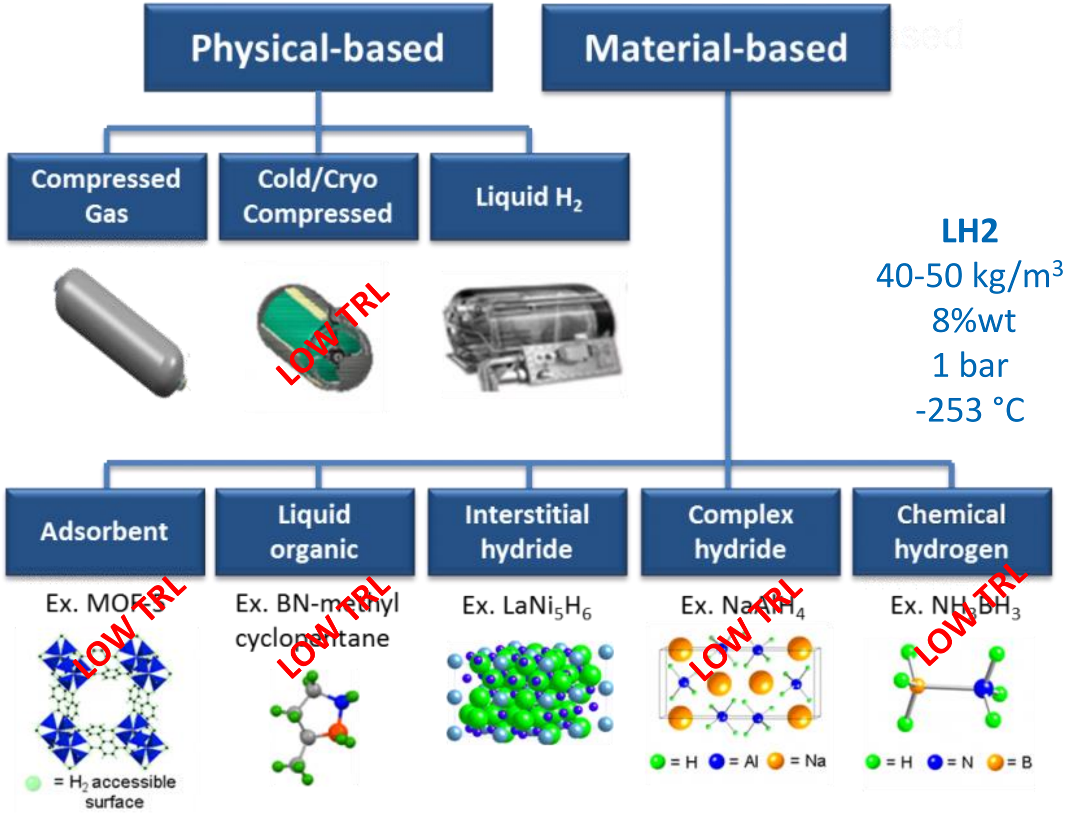
Property	Hydrogen	Comparison
Density (gaseous)	0.089 kg/m^3 (0°C, 1 bar)	1/10 of natural gas
Density (liquid)	70.79 kg/m^3 (-253°C, 1 bar)	1/6 of natural gas
Boiling point	-252.76°C (1 bar)	90°C below LNG
Energy per unit of mass (LHV)	120.1 MJ/kg	3x that of gasoline
Energy density (ambient cond., LHV)	0.01 MJ/L	1/3 of natural gas
Specific energy (liquefied, LHV)	8.5 MJ/L	1/3 of LNG
Flame velocity	346 cm/s	8x methane
Ignition range	4–77% in air by volume	6x wider than methane
Autoignition temperature	585°C	220°C for gasoline
Ignition energy	0.02 MJ	1/10 of methane

Notes: cm/s = centimetre per second; kg/m^3 = kilograms per cubic metre; LHV = lower heating value; MJ = megajoule; MJ/kg = megajoules per kilogram; MJ/L = megajoules per litre.

All these aspects have an impact on Hydrogen Storage Methods

There's **NO silver bullet solution**

CH2
24-40 kg/m^3
3-6 %wt
350-700 bar
Ambient T



LH2
40-50 kg/m^3
8%wt
1 bar
-253 °C

Today, we can consider only three H2 storage solutions:

- CH2
- LH2
- MH2

MH2
25-60 kg/m^3
2 %wt
1 bar
Ambient T

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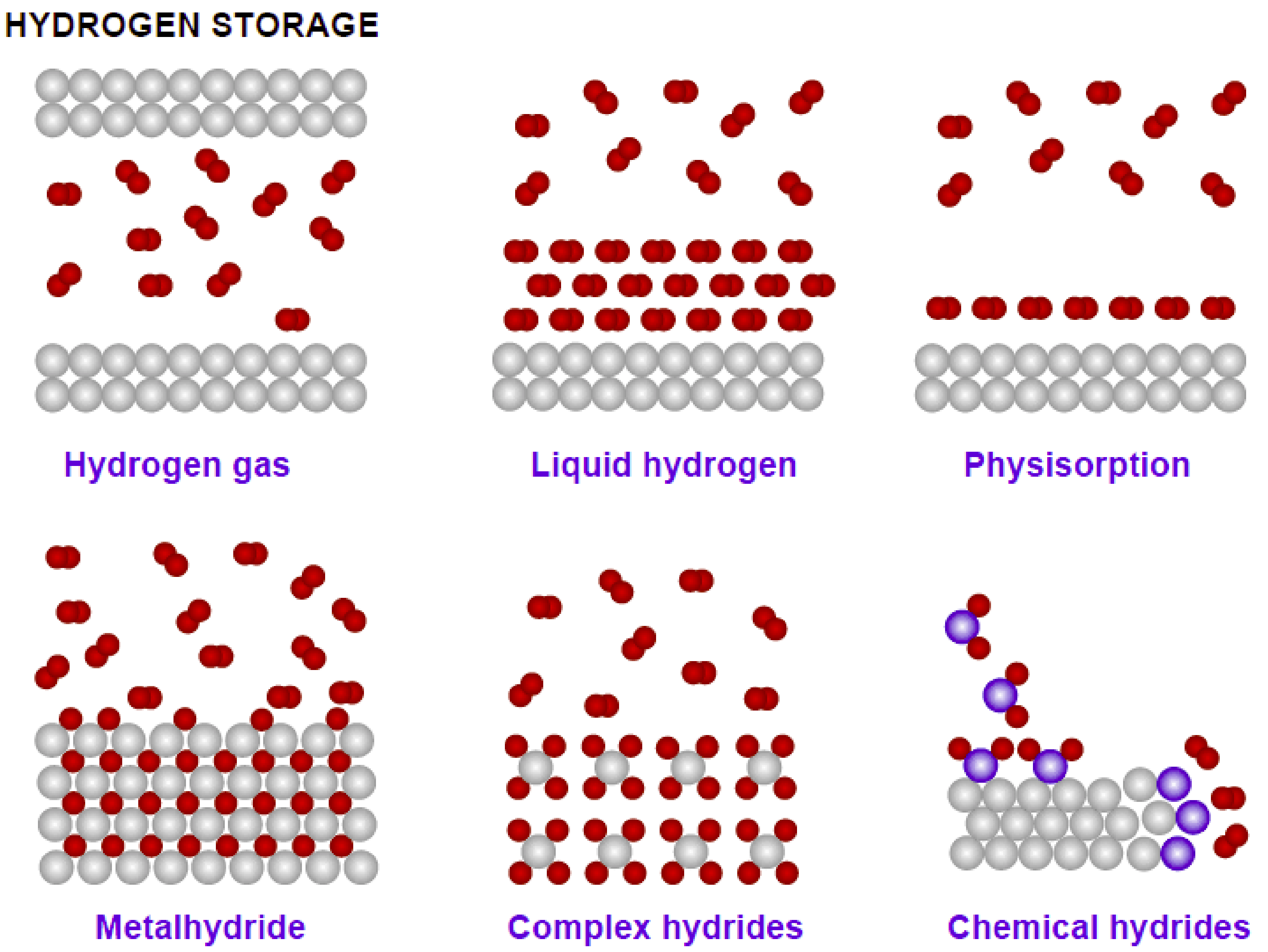
All these aspects have an impact on Hydrogen Storage Methods



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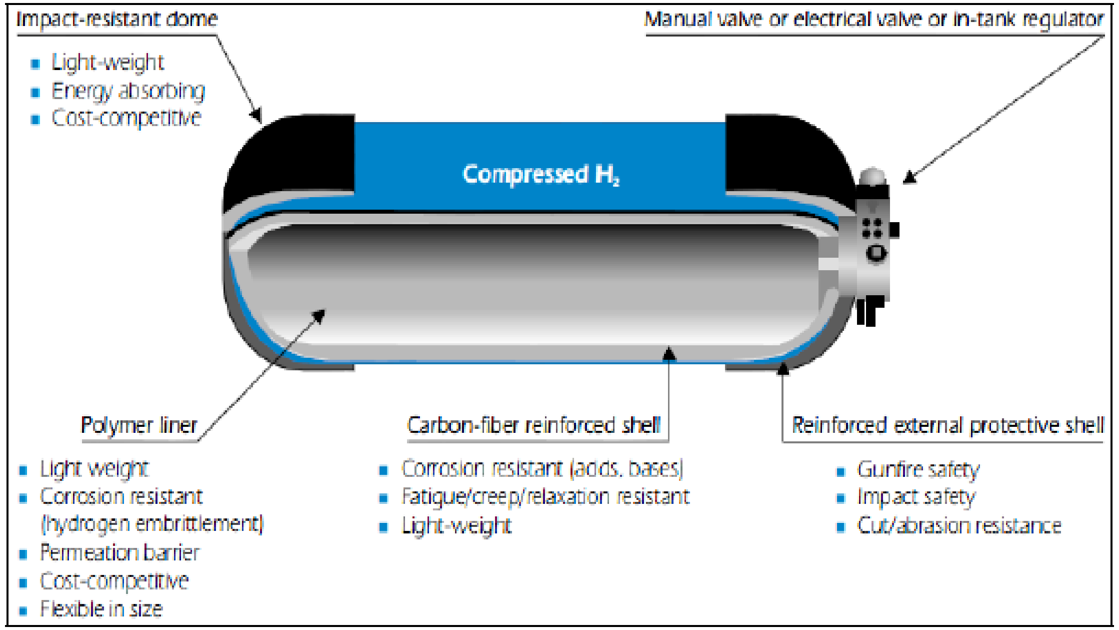
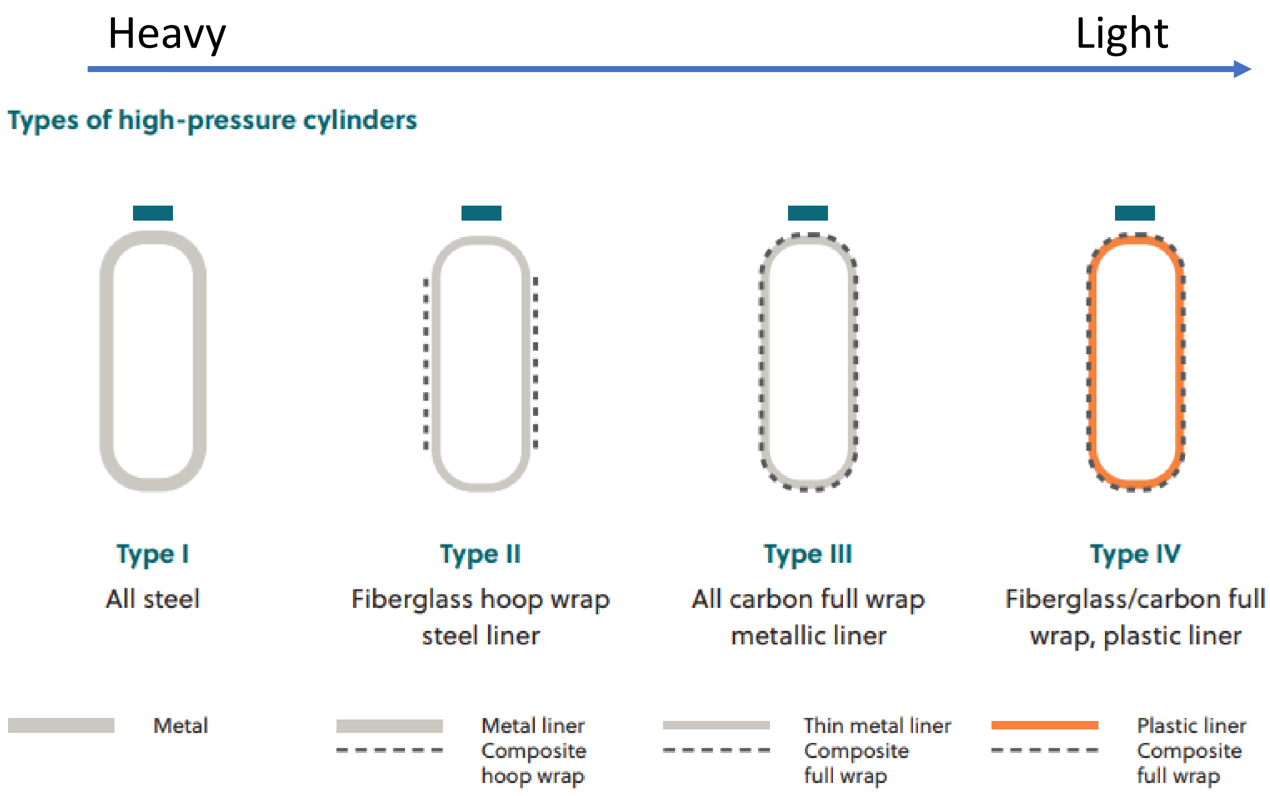
Compressed Hydrogen





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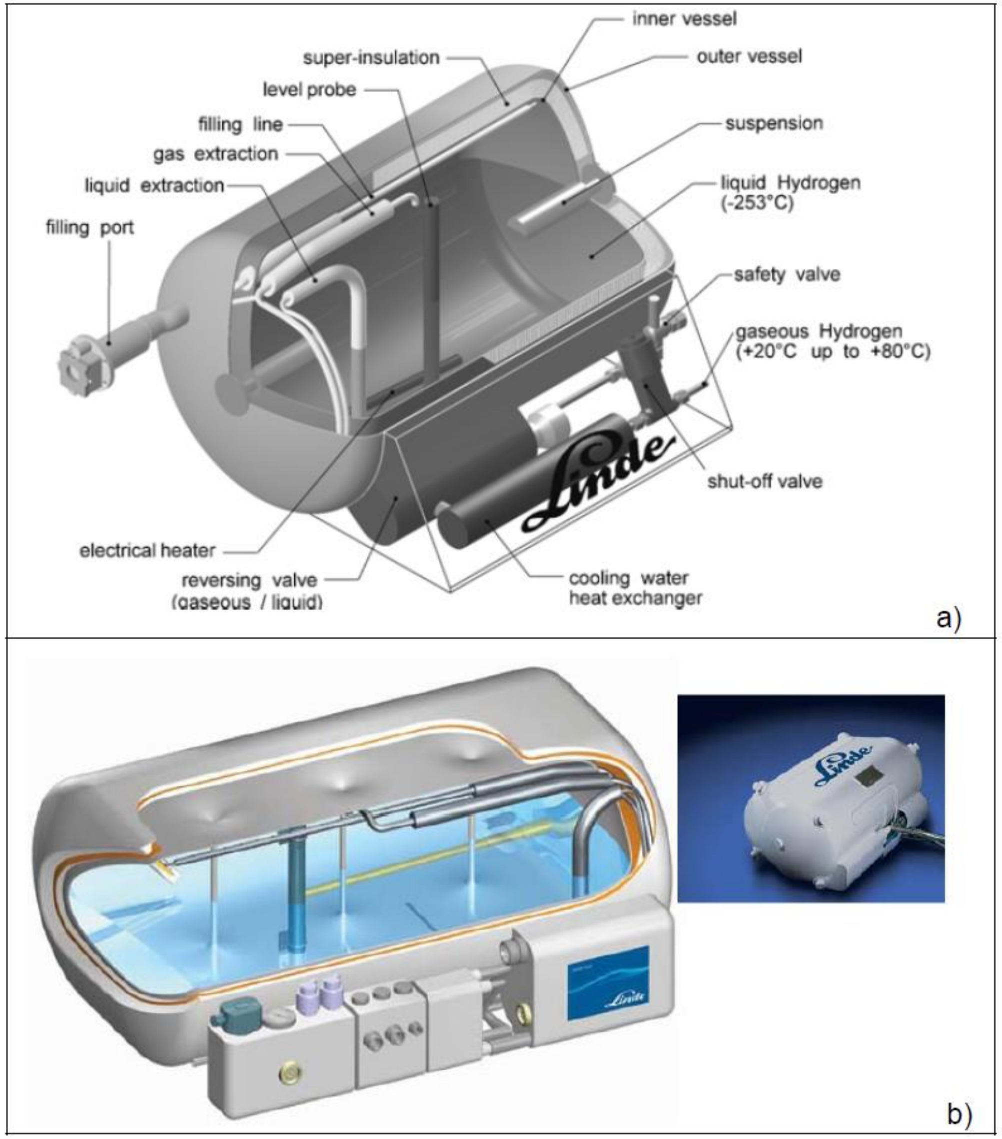
Liquid Hydrogen

- **Issues in liquefaction**
- **Issues in thermal insulation**
- **Issues in Boil-off management**



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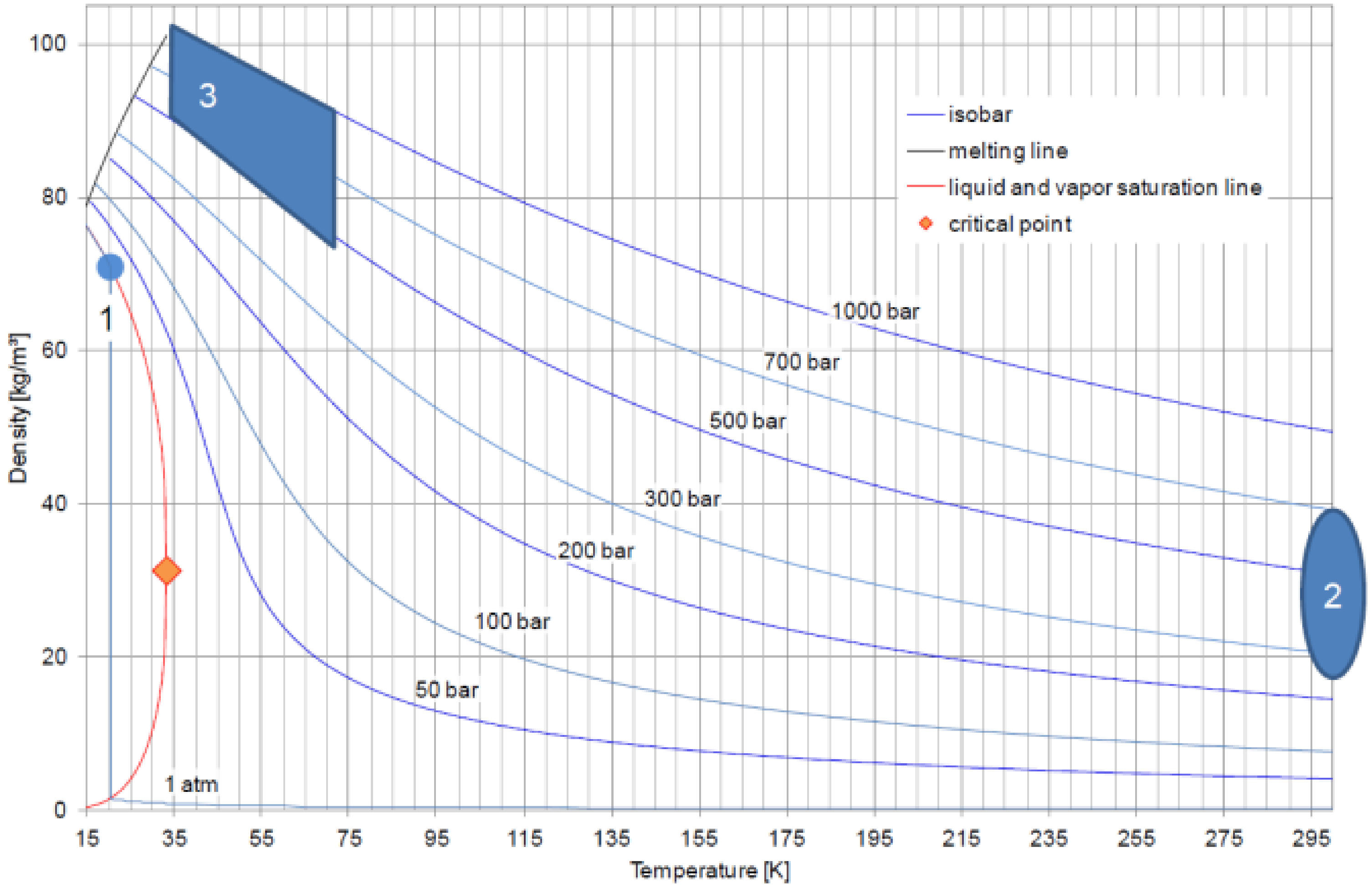
LH2 and pressure level/temperature level



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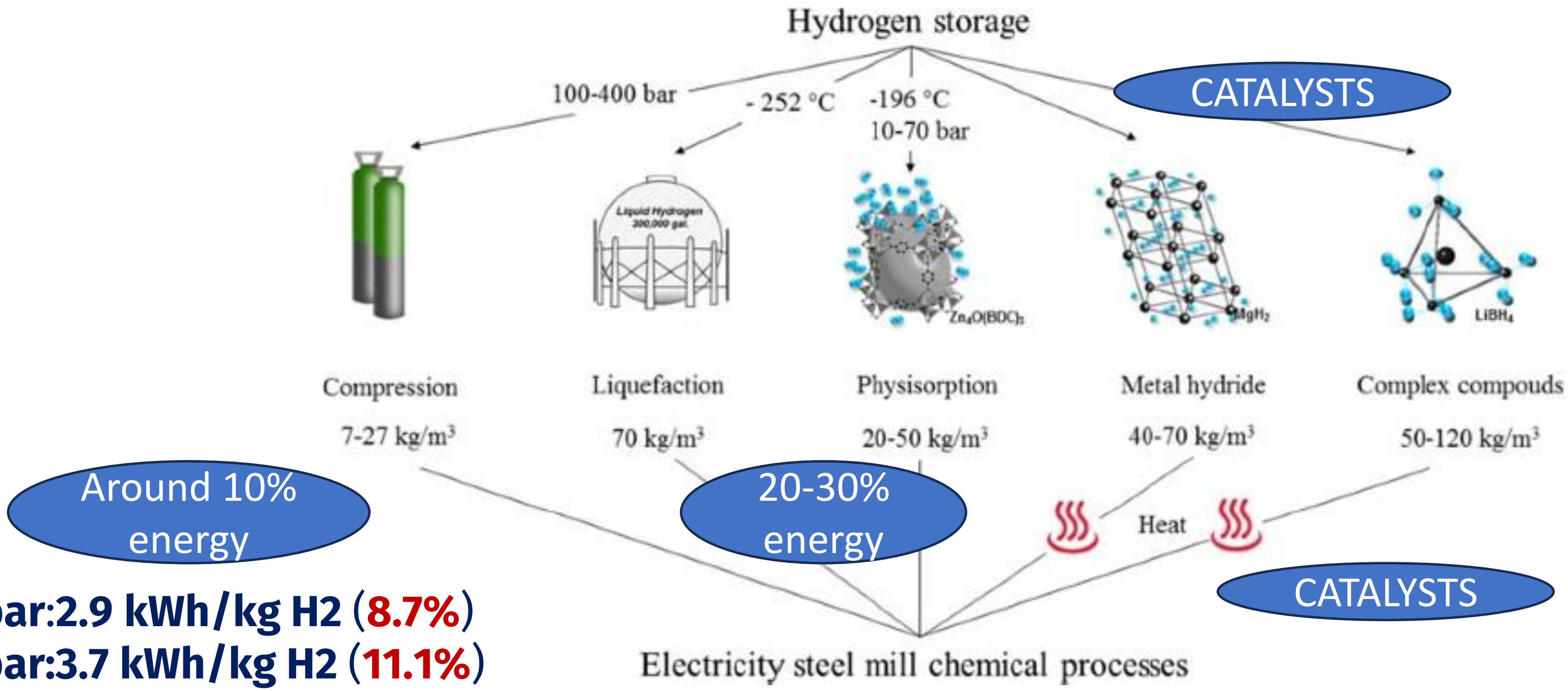
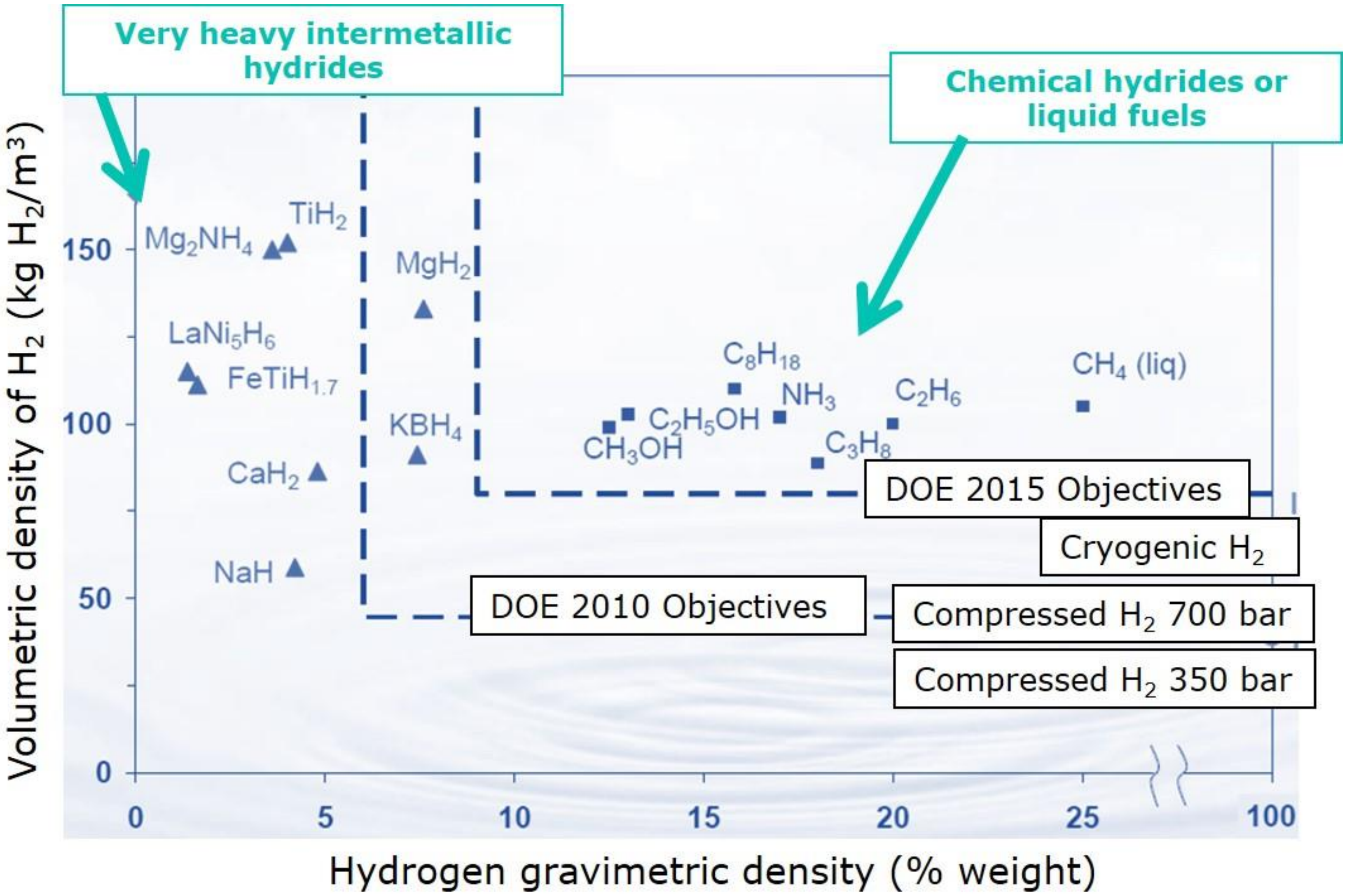
Hydrogen Storage Methods - let's benchmark them



At **350 bar:2.9 kWh/kg H2** (**8.7%**)
At **700 bar:3.7 kWh/kg H2** (**11.1%**)

Hydrogen Storage Methods - let's benchmark them



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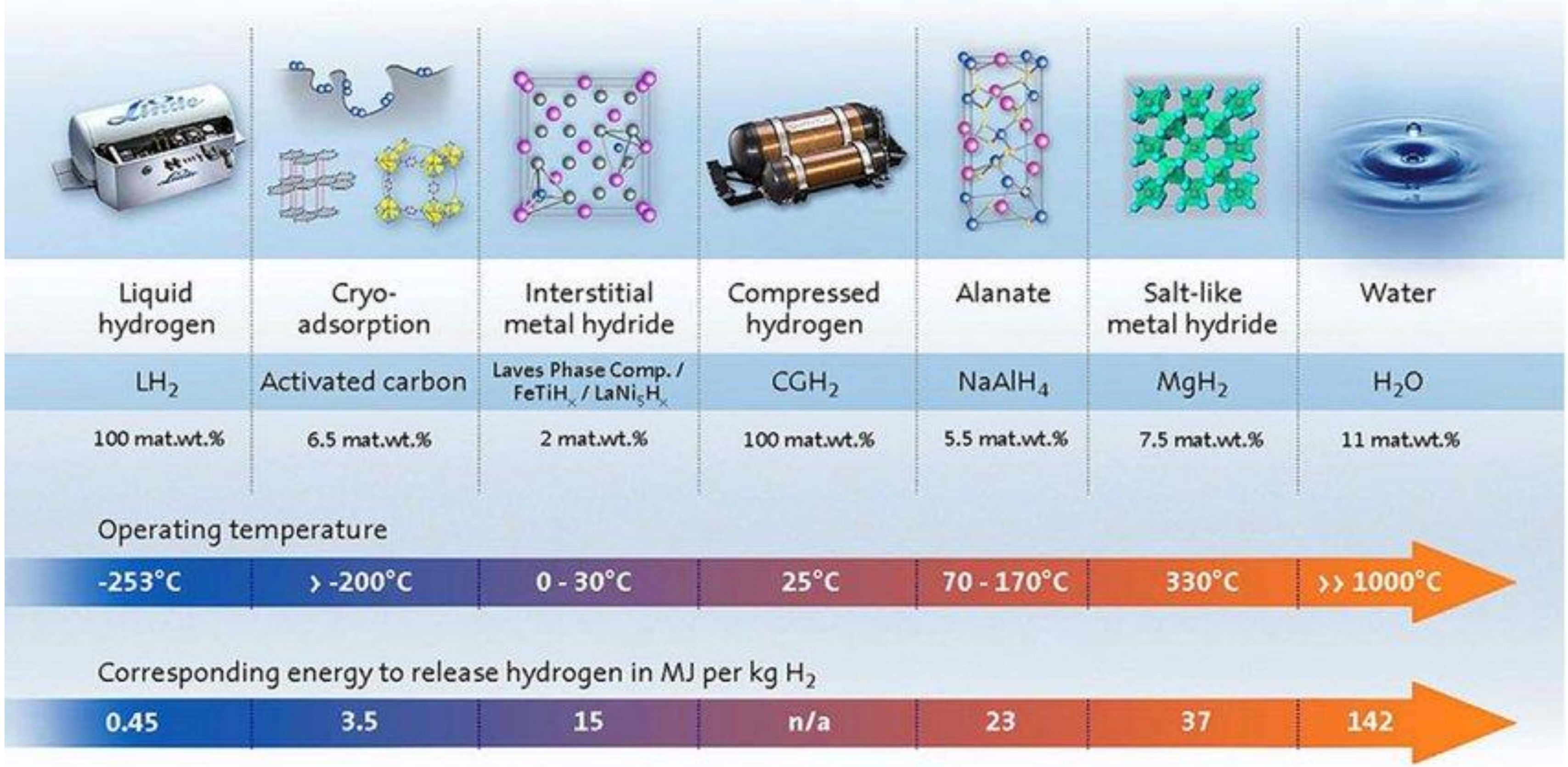
Hydrogen Storage Methods - let's benchmark them

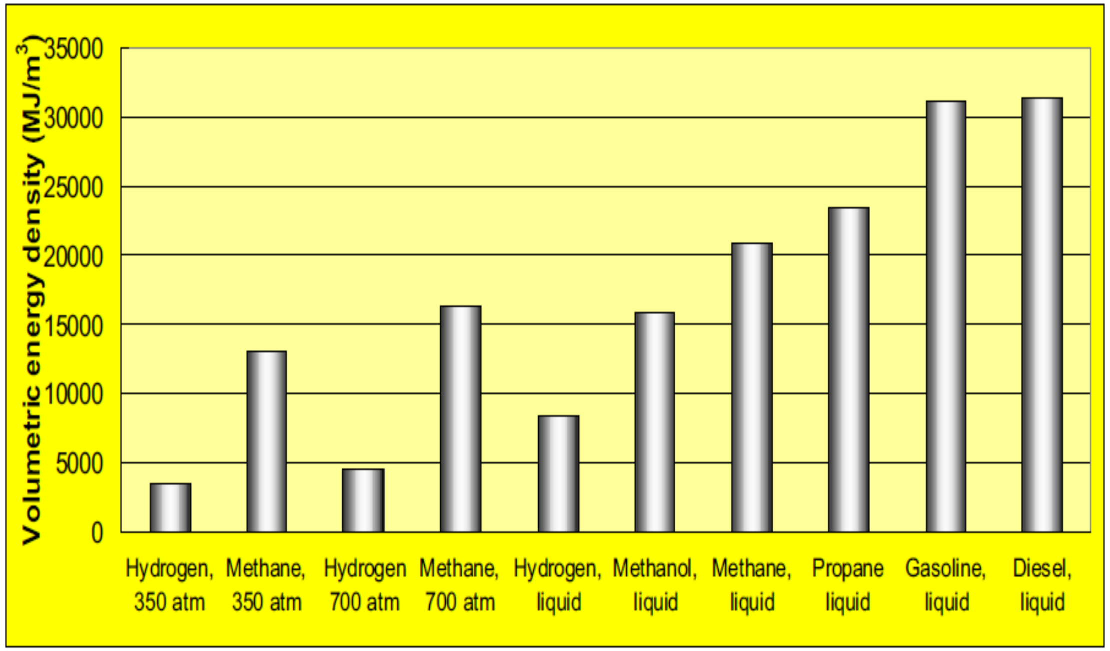


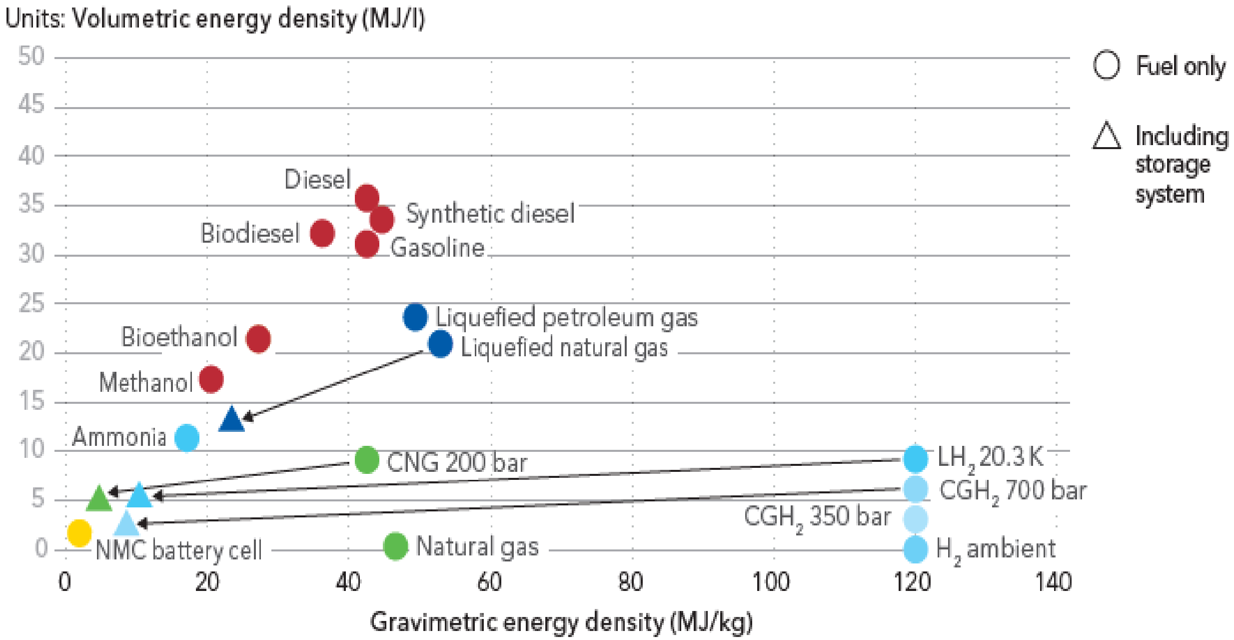
Hydrogen Storage Methods - let's benchmark them

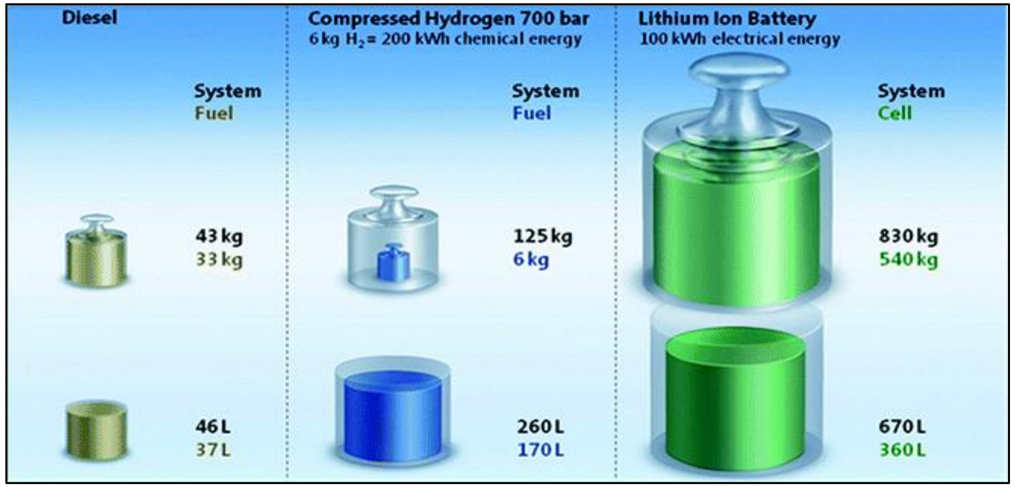
	Storage Process				Release Process	
Storage Technology	Heat (kWh/kg H_2)	Temp (°C)	Pressure (bar)	Electricity (kWh/kg H_2)	Heat (kWh/kg H_2)	Temp (°C)
Gas 100 bar	-	-	100	1	-	-
Gas 200 bar	-	-	200	1.2	-	-
Gas 700 bar	-	-	700	1.6	-	-
Liquid Hydrogen	-	-253	-	6	-	-
Adsorption	-	-176	40	6.7	-	-
AlH_3	54	<70	-	10	1	100
MgH_2	-	300	30	0.7	10.3	350
Intermetallic Hydride	-	<80	50	0.8	~2-6	<80
Formic Acid	64	100-180	105	6.7	4.3	<100
Ammonia	-	400	250	2-4	4.2	>425
Methanol	-	250	50	1.3-1.8	6.7	250

Numbers to be checked

Hydrogen Storage properties…
Always better than batteries, always worse than liquid fuels!







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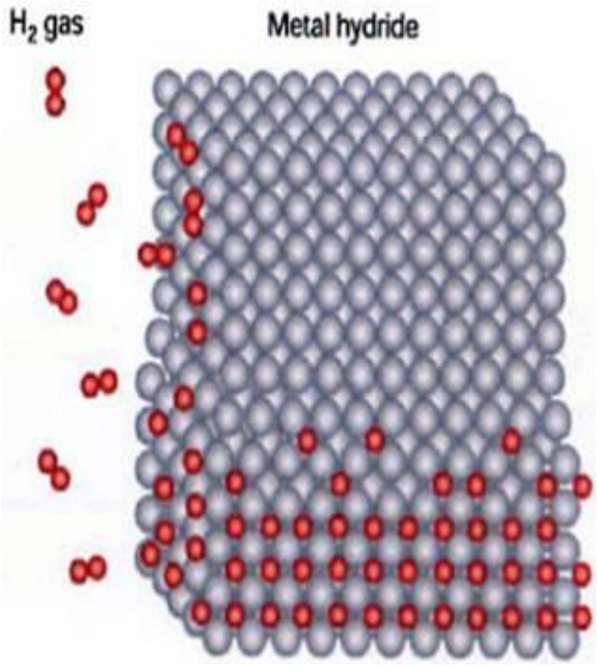
WHAT ARE METAL HYDRIDES?

Metal hydrides are metallic compounds that are formed (if a certain activation energy is provided at a certain pressure - ***HEAT***) once H2 in a gaseous phase reacts with a metal.

It's a reversible hydrogen storage technology (potentially with no losses).

The technology is very mature and different metallic alloys are investigated: different hydrides are able to react and operate with pressures and temperatures close to environmental ones or closer to electrolyser production pressure rates (e.g. 10-50 bar)



First MH: 1866 - Thomas Graham (1805-1869) who obtained Palladium Hydride

$$Pd + 1/2\ H2 \rightarrow PdH2$$

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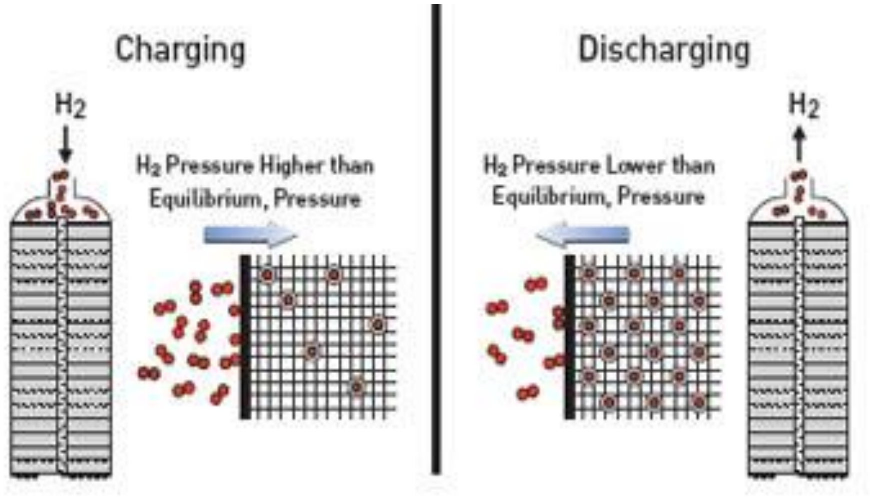
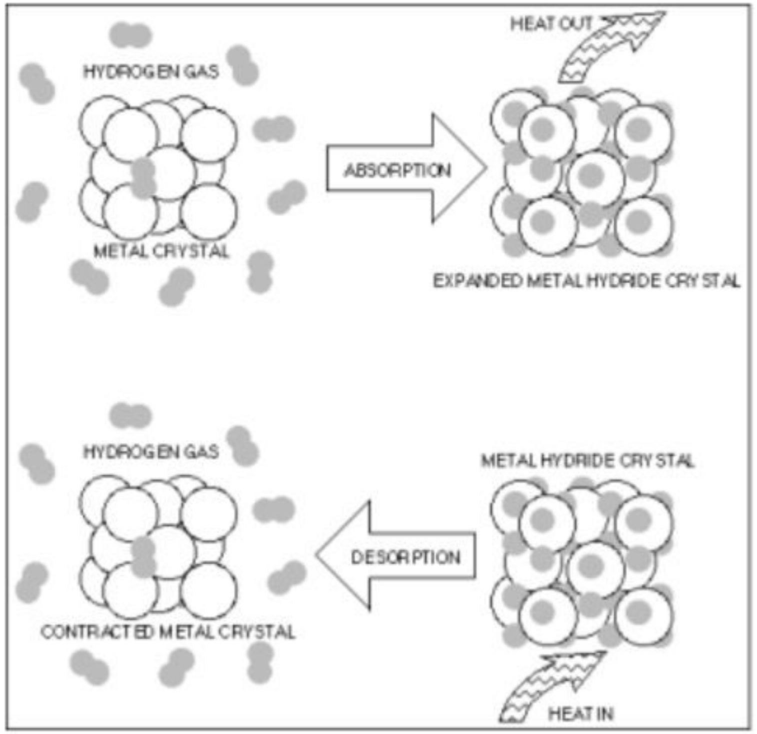
HOW DO METAL HYDRIDES WORK?

$2M + xH_2 \rightarrow 2MH_2 + \Delta H$ (EXOTHERMIC – CHARGING)

$2M + xH_2 \leftarrow 2MH_2 + \Delta H$ (ENDOTHERMIC – DISCHARGING)

- Changing pressure and temperature will cause the hydrogen to either be adsorbed (CHARGING) or desorbed (DISCHARGING)
- Under low temperature or high pressure the hydrogen atoms can enter the gaps in the parent metal, forming a solid solution
- When **I charge the Hydrides heat is produced**, when I have to **discharge the hydrides heat is needed.**





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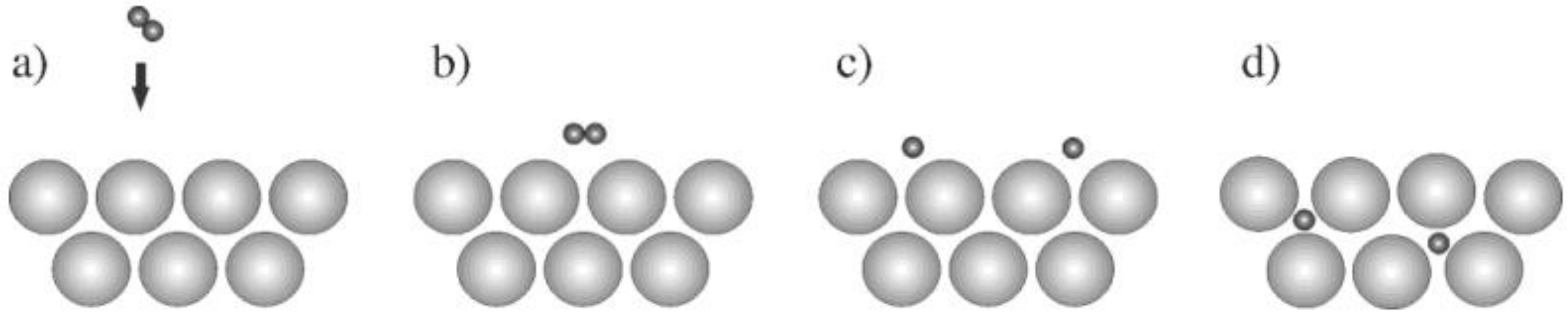
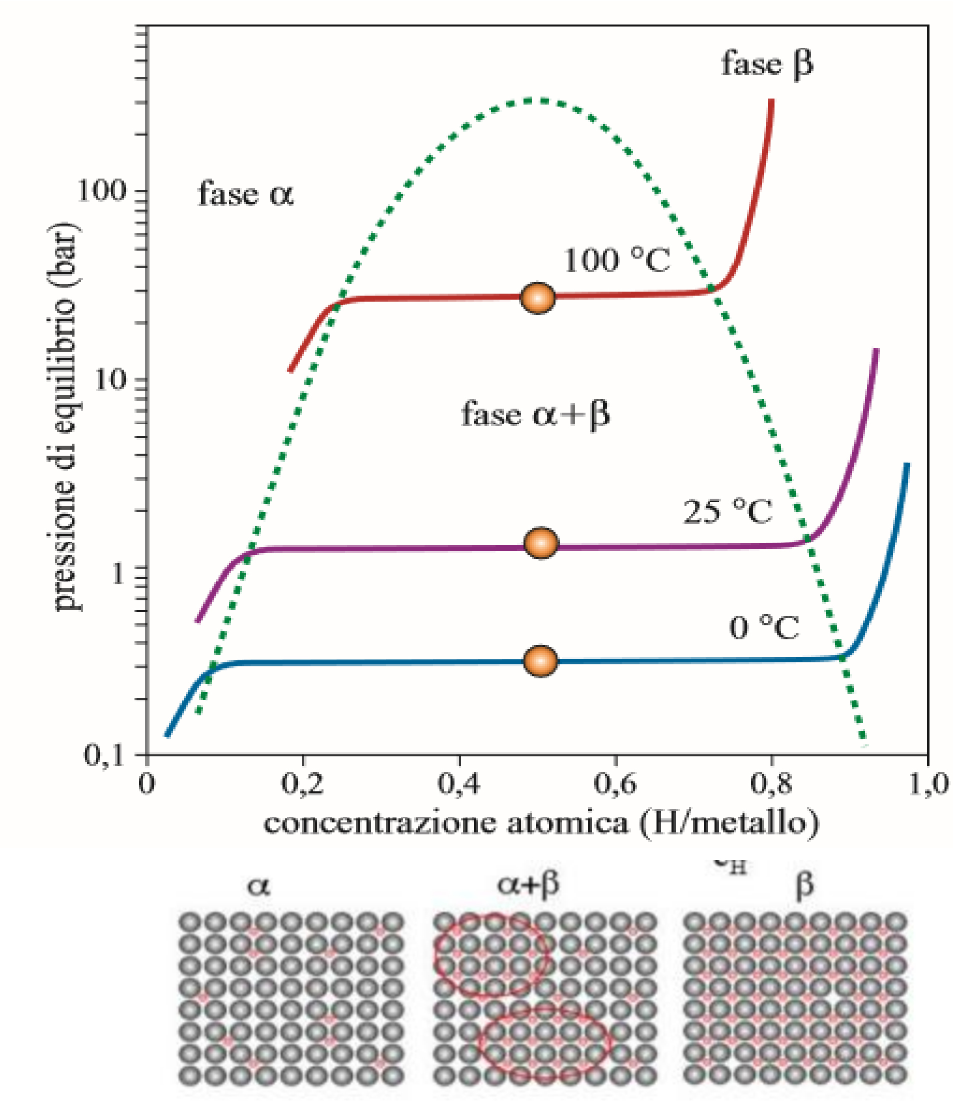
HOW DO METAL HYDRIDES WORK?



H2 Molecula is dissociated on the surface of H2 and atoms of hydrogen start to diffuse themselves in the metal in a solid solution (PHASE α – scattered interstitial atoms of H).

HOW DO METAL HYDRIDES WORK?



To start the real absorption I have to provide a pressure higher than equilibrium pressure, which is function of T and activation reaction enthalpy/entropy (Van't Hoff Eq.)

$$\ln\left(\frac{p_{eq}}{p_0}\right) = \frac{\Delta H_R}{RT} - \frac{\Delta S_R}{R}$$

Absorption and desorption processes are described by **these curves (named P-C-T) change with the MH**

Once H2 increases its concentration and/or pressure increases (thus increasing H2 partial pressure), the metal enters in full MH phase (phase β): once in this phase, the further injection of H2 increases the pressure of the MH.

At different temperatures we are able to store different amount of H2 (proportional to phase α+β plateau length).

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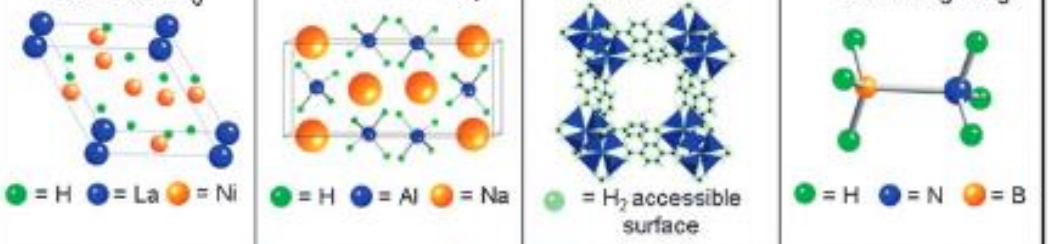
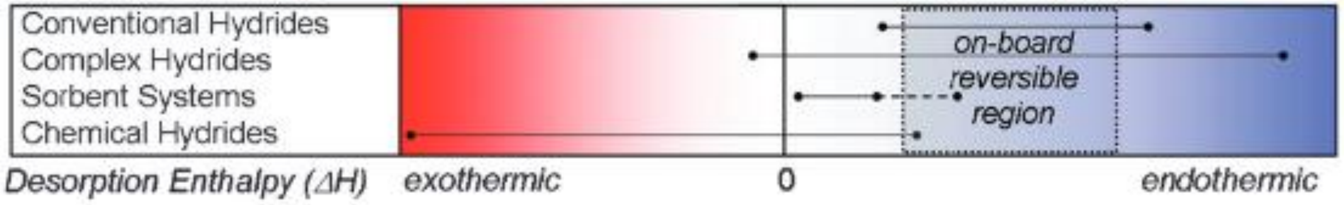
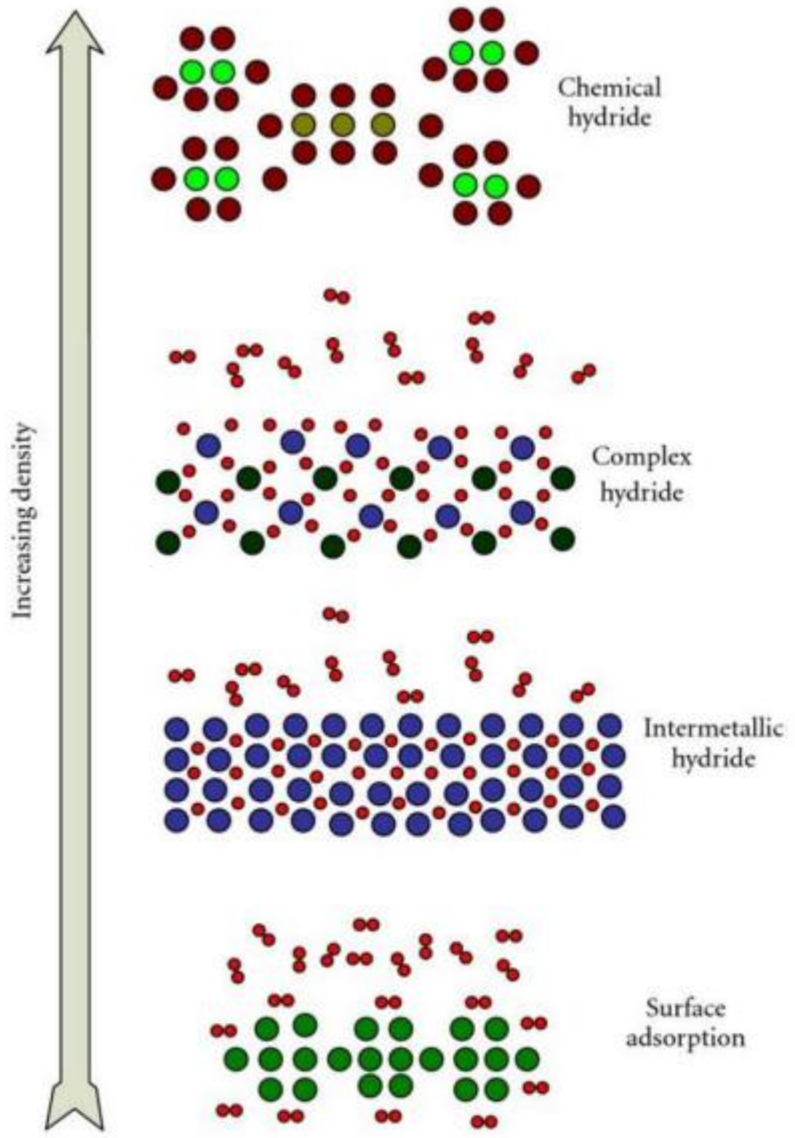
HOW ARE THEY DIFFERENT THAN OTHER HYDRIDES?

	Conventional Hydrides	Complex Hydrides	Sorbent Systems	Chemical Hydrides
	Ex. $LaNiH_6$	Ex. $NaAlH_4$	Ex. MOF-5	Ex. NH_3BH_3



General Trends	Hydrogen forms a metallic bond with the host metal atoms	Hydrogen covalently bonded as stable "complex" anions	Physisorption of molecular hydrogen to high surface area sorbent	Hydrogen covalently bonded in material & utilized as single use 'fuel'
Vol. Capacity	*G*	*G*	*Y*	*G*
Grav. Capacity	*R*	*G*	*G*	*G*
Reversibility	*G*	*G*	*G*	*R*
Thermodynamics	*G*	*G*	*R*	*Y*
Kinetics	*G*	*R*	*G*	*Y*
Efficiency	*G*	*G*	*G*	*R*

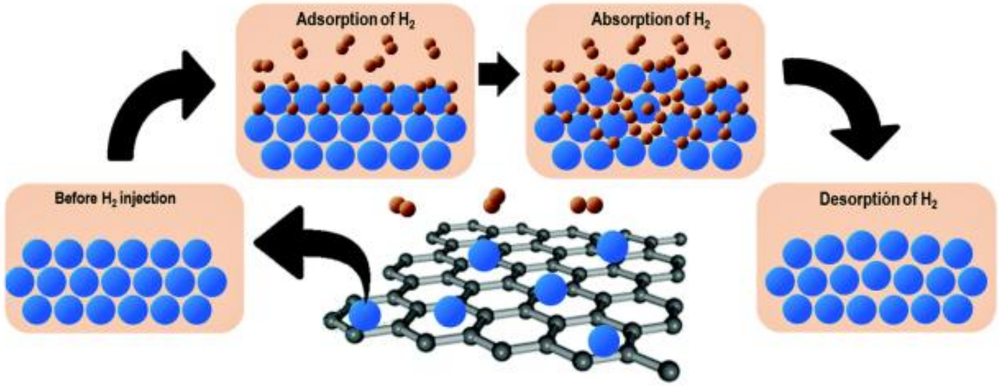




HOW ARE THEY DIFFERENT THAN OTHER HYDRIDES?

MOF and ADSORBENT SYSTEMS

- Van der Waals forces bond H_2 to materials with large specific surface area
- Adsorbents
  - Porous carbon-based materials
  - Metal-organic frameworks
  - Porous polymeric materials
  - Zeolites



- Low temperatures and elevated pressures are typically required to promote VWF
- Exothermic process, heat management necessary
- Lab-scale only, low TRL
- Storage capacity likely limited to 40 – 50 kg/m^3 at – 196 °C

HOW ARE THEY DIFFERENT THAN OTHER HYDRIDES?

COMPLEX METAL HYDRIDES

Liquid Hydrogen	Compress Hydrogen	MOF	Nanostru-cture	Metal Hydride	Complex Metal Hydride
-253°C	25 °C	-200 °C	25°C	330°C	>185°C

Table 1. Available hydrogen storage technologies and corresponding operating temperatures.

- Typical metal hydrides are a lattice of metal ions which form ionic bonds with hydrogen
- Complex metal hydrides contain additional compounds and cause the hydrogen form covalent bonds with molecular anions containing the hydride
- Complex metal hydrides provide additional options for metal hydride storage
  - $LiBH_4$
  - $NaAlH_4$
- Excellent gravimetric storage capacity, but the kinetics of hydrogen release are too slow for practical applications

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HOW ARE THEY DIFFERENT THAN OTHER HYDRIDES?

CHEMICAL HYDRIDES

- Highest energy density of all chemical storage methods
- Formic acid (53 kg/m^3)
  - Low hydrogen storage density
  - Easily dehydrogenated
- Methanol (99 kg/m^3)
  - Can be dehydrogenated with steam reforming
  - Synthesized from CO_2 and hydrogen, (also stores CO_2)
- Ammonia(123 kg/m^3 at 10 bar)
  - High hydrogen storage density
  - Requires high heat to completely dehydrogenate
- Liquid organic hydrogen carriers
  - Remain liquid at ambient conditions in both hydrogenated and dehydrogenated states

Always requiring hydrogenation and de-hydrogenation reactions

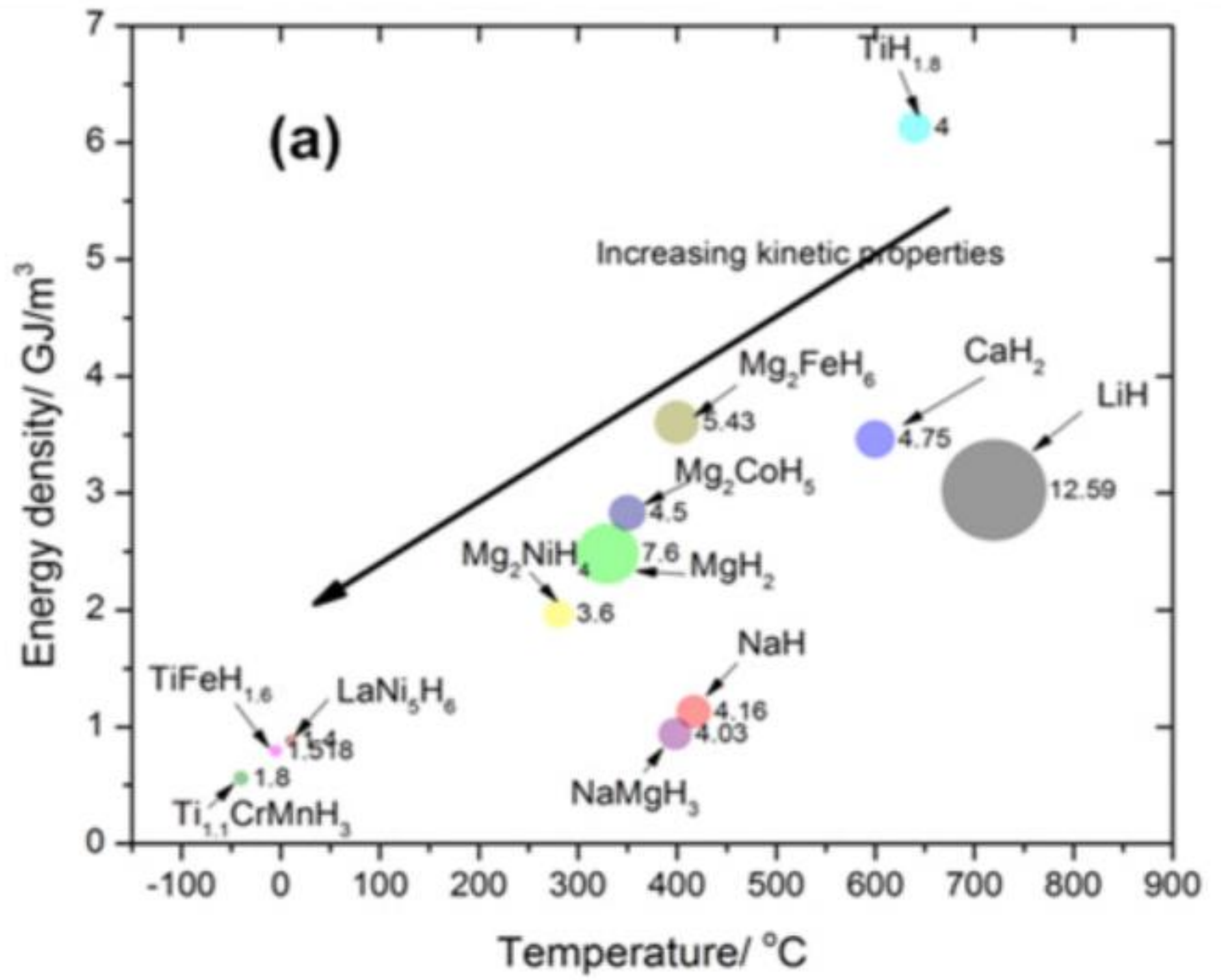
BUT WHAT ARE METAL HYDRIDES?

Composizione	A	B	Composti
A_2B	Mg, Zr	Ni, Fe, Co	Mg_2Ni, Mg_2Co, Zr_2Fe
AB	Ti, Zr	Ni, Fe	TiNi, TiFe, ZrNi
AB_2	Zr, Ti, Y, La	V, Cr, Mn, Fe, Ni	$LaNi_2$, YNi_2, YMn_2, $ZrCr_2$, $ZrMn_2$, ZrV_2, $TiMn_2$
AB_3	La, Y, Mg	Ni, Co	$LaCo_3$, YNi_3, $LaMg_2Ni_9$
AB_5	Ca, La, Terre rare	Ni, Cu, Co, Pt, Fe	$CaNi_5$, $LaNi_5$, $CeNi_5$, $LaCu_5$, $LaPt_5$, $LaFe_5$

Metal A: forms hydrides

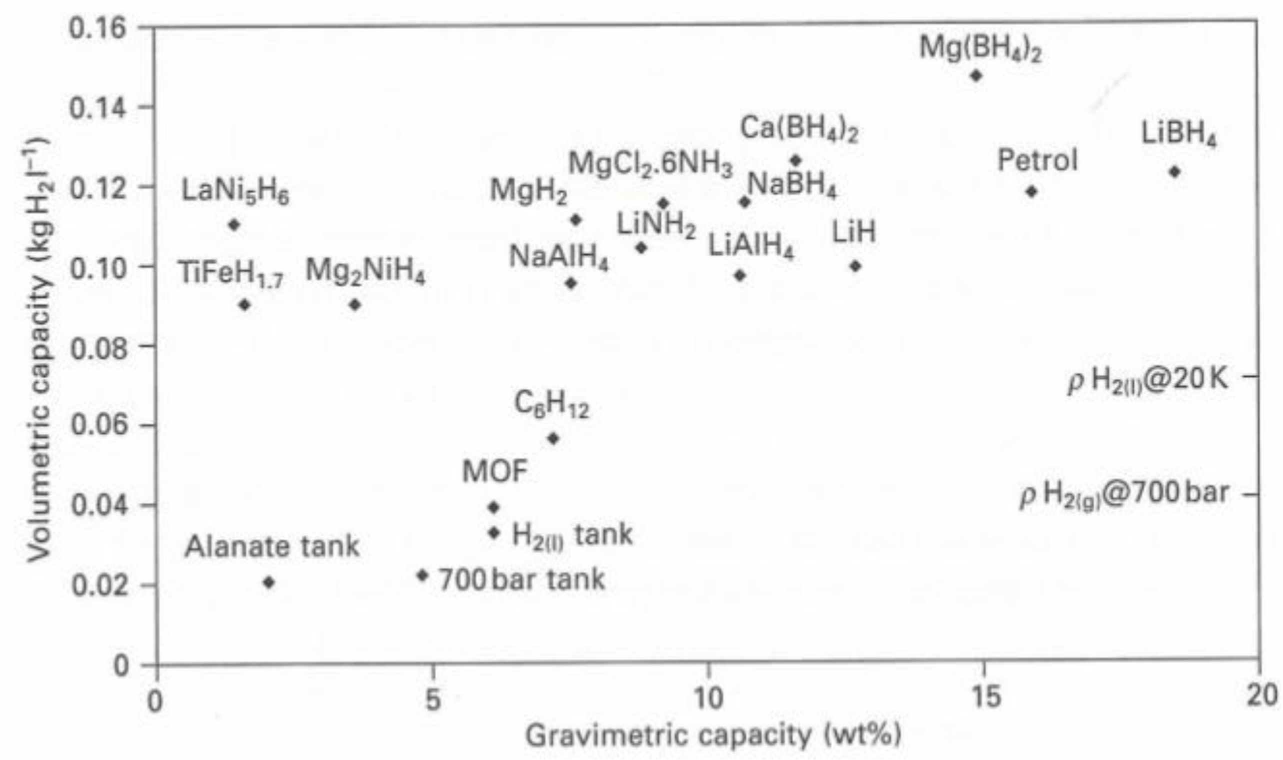
Metal B: does not form hydrides

BUT WHAT ARE METAL HYDRIDES?



How to identify the best MH

Few MH-alloys are able to operate at low T (within 100 °C) and moderate pressures (withing 50 bar) - LaNi and TiFe are the best in this sense, but they have low gravimetric capacity



How to identify the best MH

- high hydrogen content in mass and in volume
- low reaction Temperature
- moderate pressure of reaction
- low energy losses while charging and discharging (irreversibilities)
- good kinetics
- no major issues of oxidation with humidity and Oxygen
- good cycling
- low costs
- safety (low equilibrium pressure)

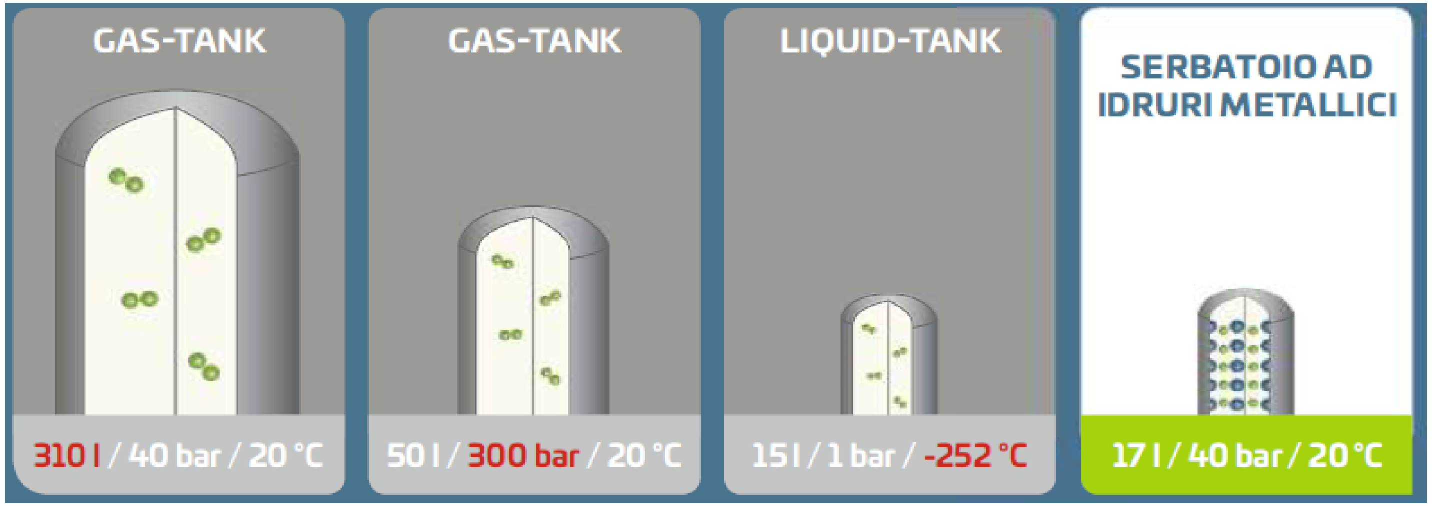
BUT WHAT ARE METAL HYDRIDES?

MH	MH [kg]	H_2 stoccato [kg]
$LaNi_5$	4,4	0,046
$LaNi_5$	7	0,089
$LaNi_5$	30,5	0,305
$LaNi_5$	16,8	0,252
$LaNi_{4,8}Al_{0,2}$	28,9 8	0,279
$LaNi_{4,78}Sn_{0,22}$	2,48	0,025
$Fe_{0,9}Mn_{0,1}Ti$	224	2
AB_2 (A = Ti+Zr , B=Mn+Fe)	213	2,98
AB_2 (A = Ti+Zr , B=Mn+Fe+V)	26	0,179
AB_2 (A = Ti+Zr , B=Mn+Fe+Cr+Ni)	64	0,9
$Ti_{0,95}Zr_{0,05}Mn_{1,4}Cr_{0,1}V_{0,2}$	6	0,082
$Ti_{0,95}Zr_{0,15}Mn_{1,6}Cr_{0,2}V_{0,2}$	2,9	0,038
$Ti_{0,98}Zr_{0,02}Fe_{0,09}Cr_{0,05}V_{0,43}$	4,4	0,044

HOW TO CHOOSE THE BEST MH?

- Weight
- Cyclability and H2 charging-discharging rate
- Availability of Heat
- Cost

WHY THEN METAL HYDRIDES?



	Compresso (CH2)	Liquido (LH2)	Idruri Metallici (MH)
Pressione	200 – 700 bar	Ambiente	1 – 30 bar
Temperatura	Ambiente	-253 °C	Ambiente
Densità volumetrica	≤ 40 kg/m^3	70 kg/m^3	40 – 80 kg/m^3
Peso contenitore	Ridotto	Ridotto	Elevato
Sicurezza	Gas a elevate pressioni	Serbatoi criogenici	-
Costo energetico	Elevato	Molto elevato	Ridotto

MAIN PRO

- Safety
- Volume
- Low Energy cost
- Recyclability

MAIN CONS

- Costs
- Weight
- Heat Management

WHY THEN METAL HYDRIDES?

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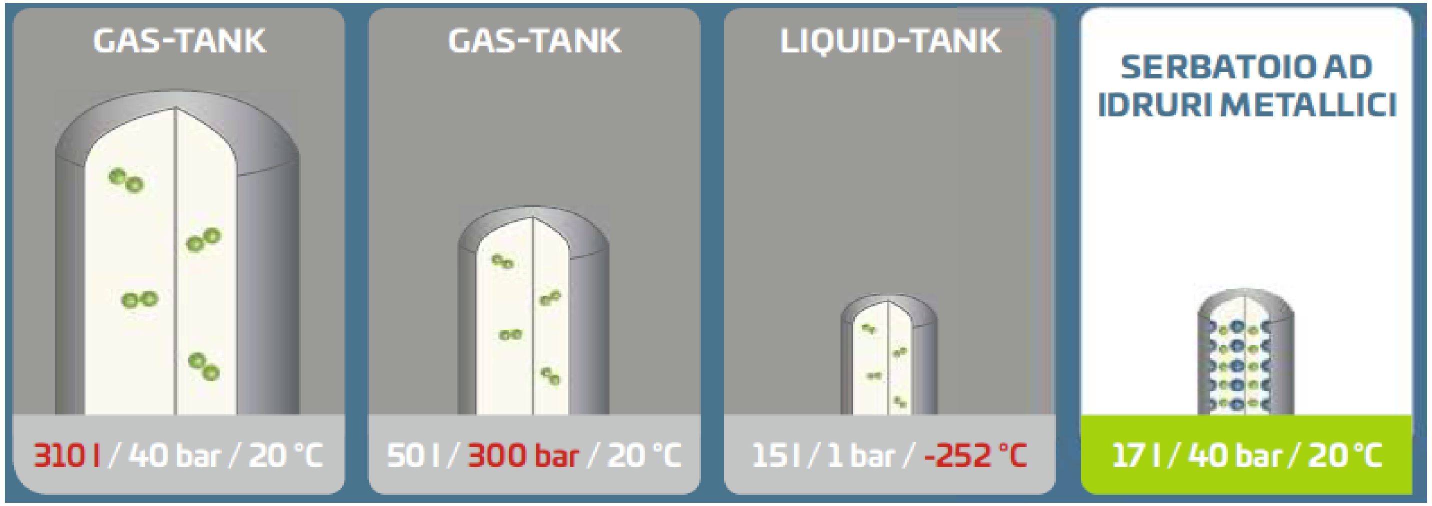
WHY THEN METAL HYDRIDES?



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MAIN PRO

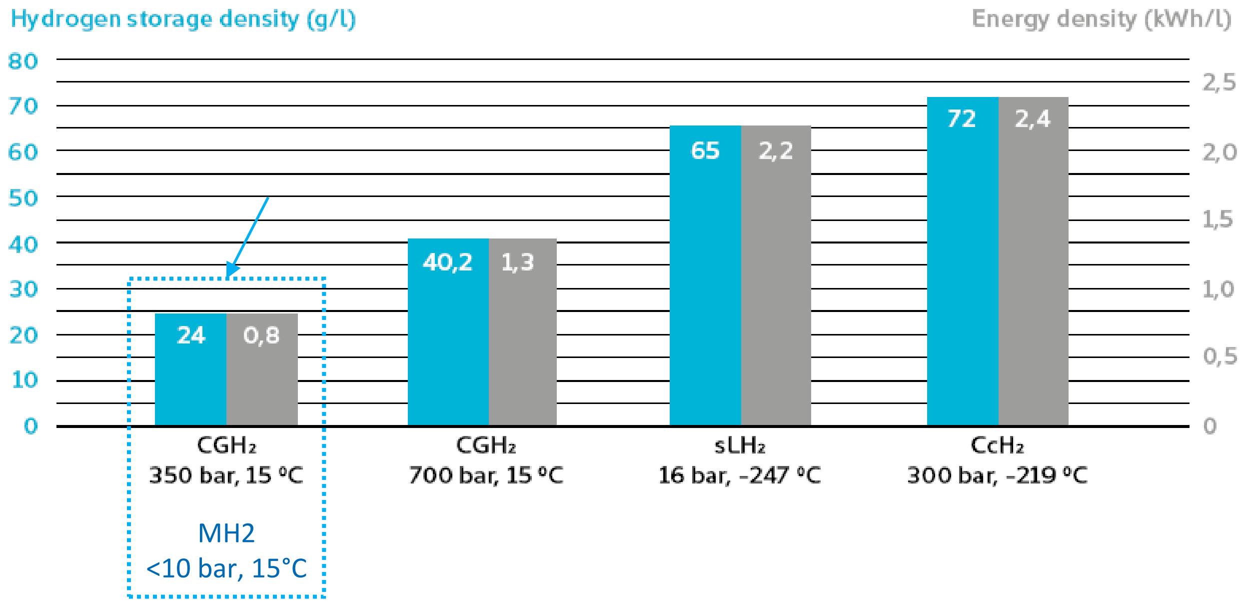
- Safety
- Volume
- Low Energy cost
- Recyclability

MAIN CONS

- Costs
- Weight
- Heat Management

OPPORTUNITY

WHY THEN METAL HYDRIDES?



CH2

CH2 350bar Tank
0.74 kWh/l
3%wt

CH2 350bar Rack
0.15 kWh/l
2.3%wt

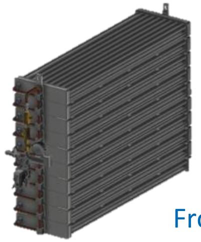
CH2 budget:
From 4 to 2 k€/kgH2

2.4 times
Lighter than MH2

MH2

MH2 10bar Module
0.73 kWh/l
1%wt

MH2 10bar Rack
0.50 kWh/l
0.9%wt



3.4 times
Compact than CH2

MH2 budget:
From 8 to 4 k€/kgH2

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HOW A MH TANK LOOKS LIKE?

VISUAL COMPARISON

- Compressed hydrogen in bottles (CH2), 200 bar
- 0,65 kg H2 per bottle
- 10,5 kg H2 per rack
- Total weight of a rack ~ 1800 kg

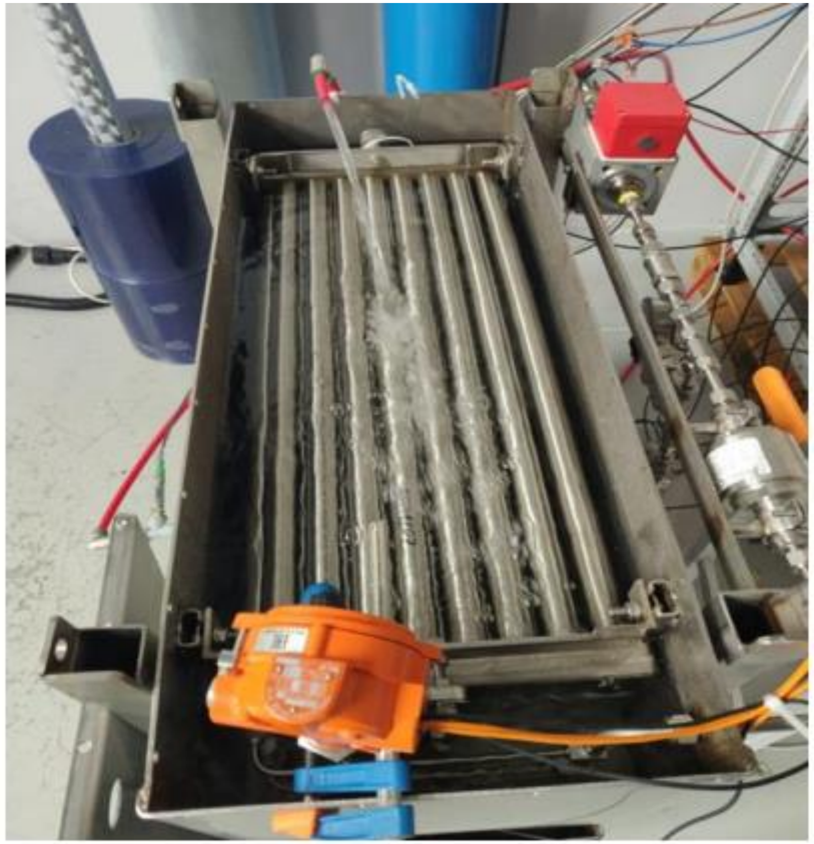
- MH pressure 30 bar
- Bottle weight ~ 7 kg
- 50g H2 per bottle
- Total weight of a rack ~ 1500 kg

In the end…neither weight seems a problem!

HOW A MH TANK LOOKS LIKE?

Dimensions:	Ø145 x L284 mm
Weight:	12 kg
Storage capacity:	1500NL (standard litre)
Vessel material:	Stainless steel
Type of connectors:	Swagelok Quick coupling
Charging pressure:	2 MPa
Discharge pressure:	0.2 to 0.5 MPa (H) 0.2 to 1 MPa (L)
Flow rate:	4 NL/min (@25°C air convection)
Heat supply:	air convection
Recharge time	≤ 45 min (20°C water bath)

HOW A MH RACK LOOKS LIKE?



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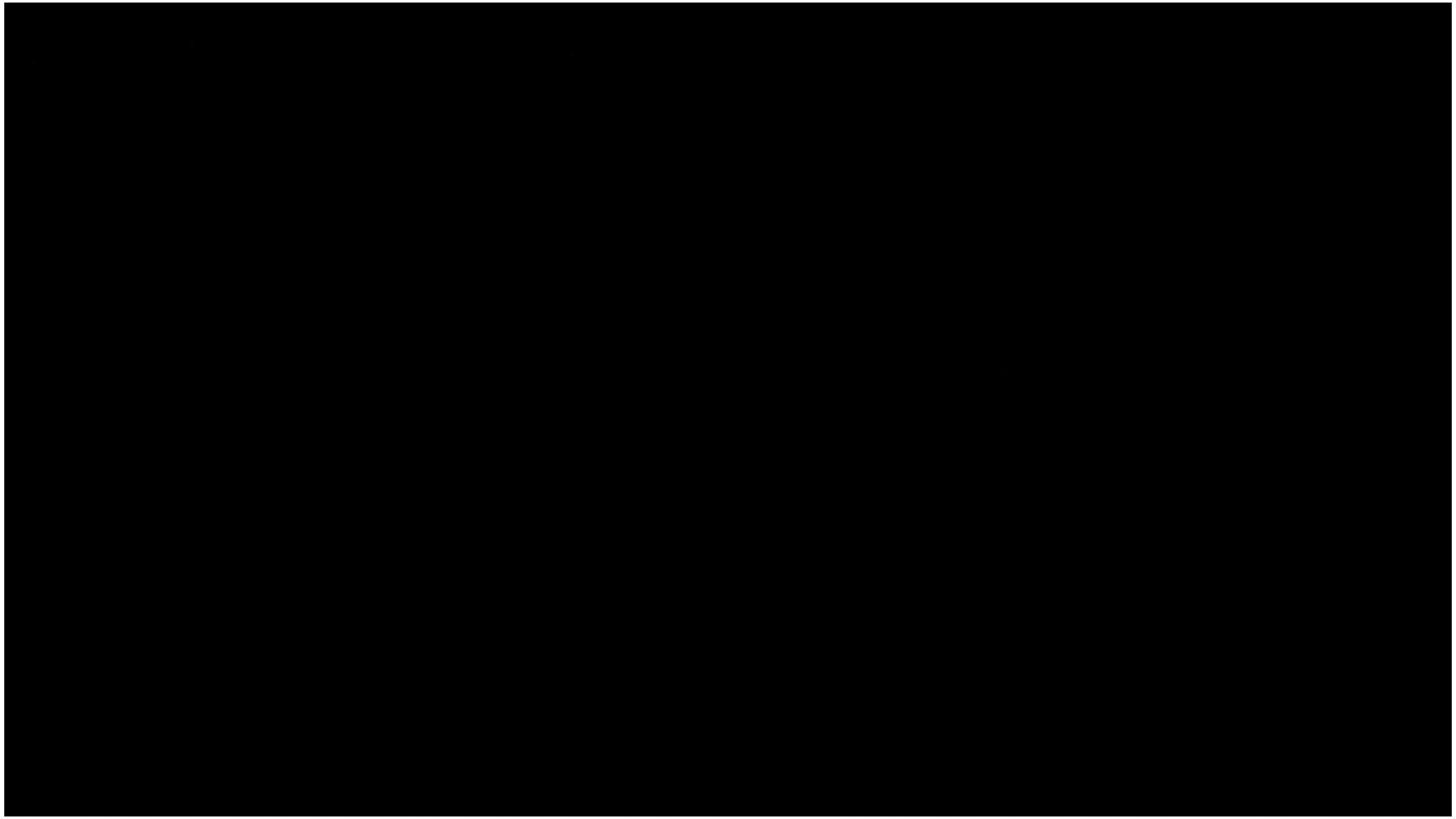
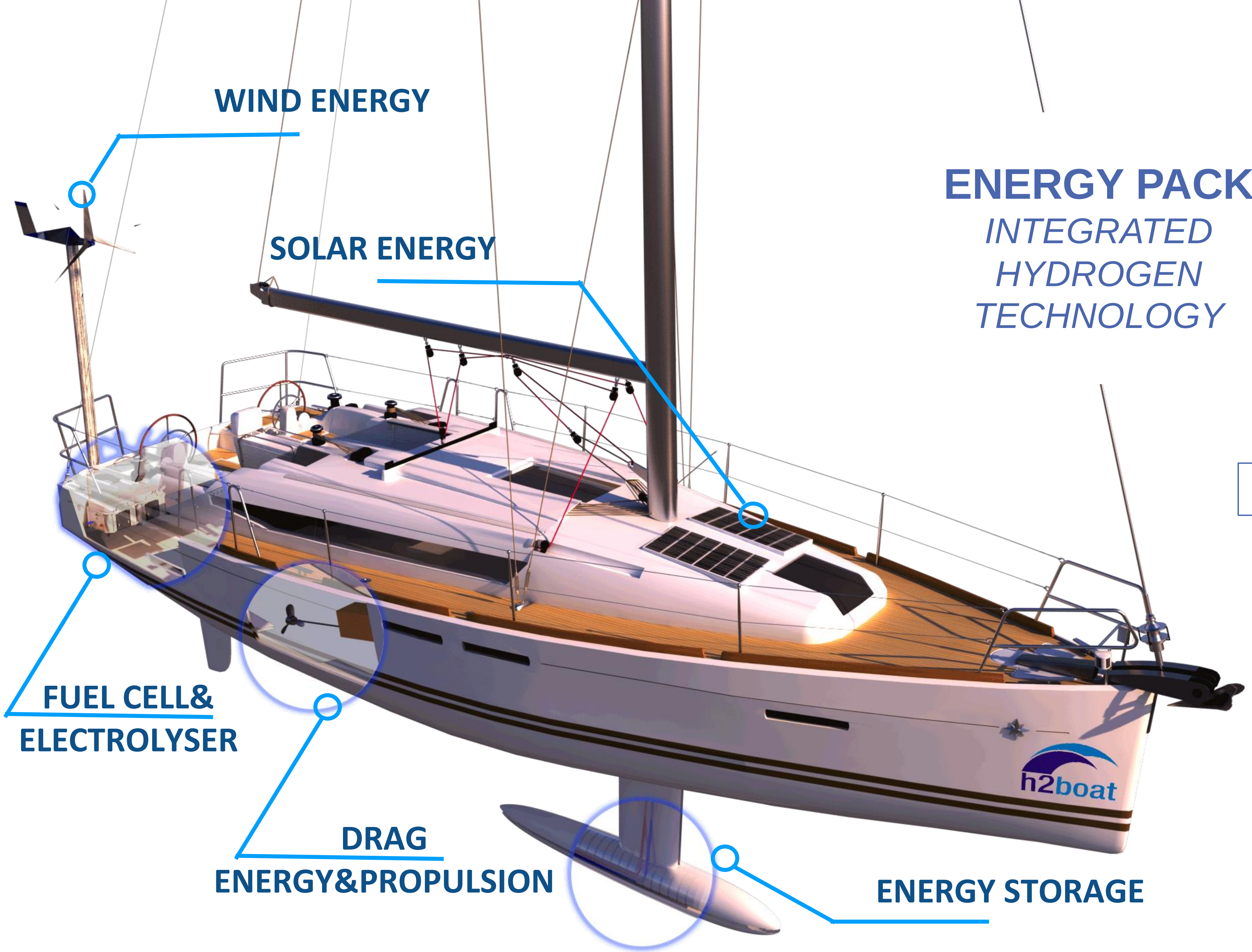


WEIGHT COULD BE AN OPPORTUNITY



ENERGY PACK

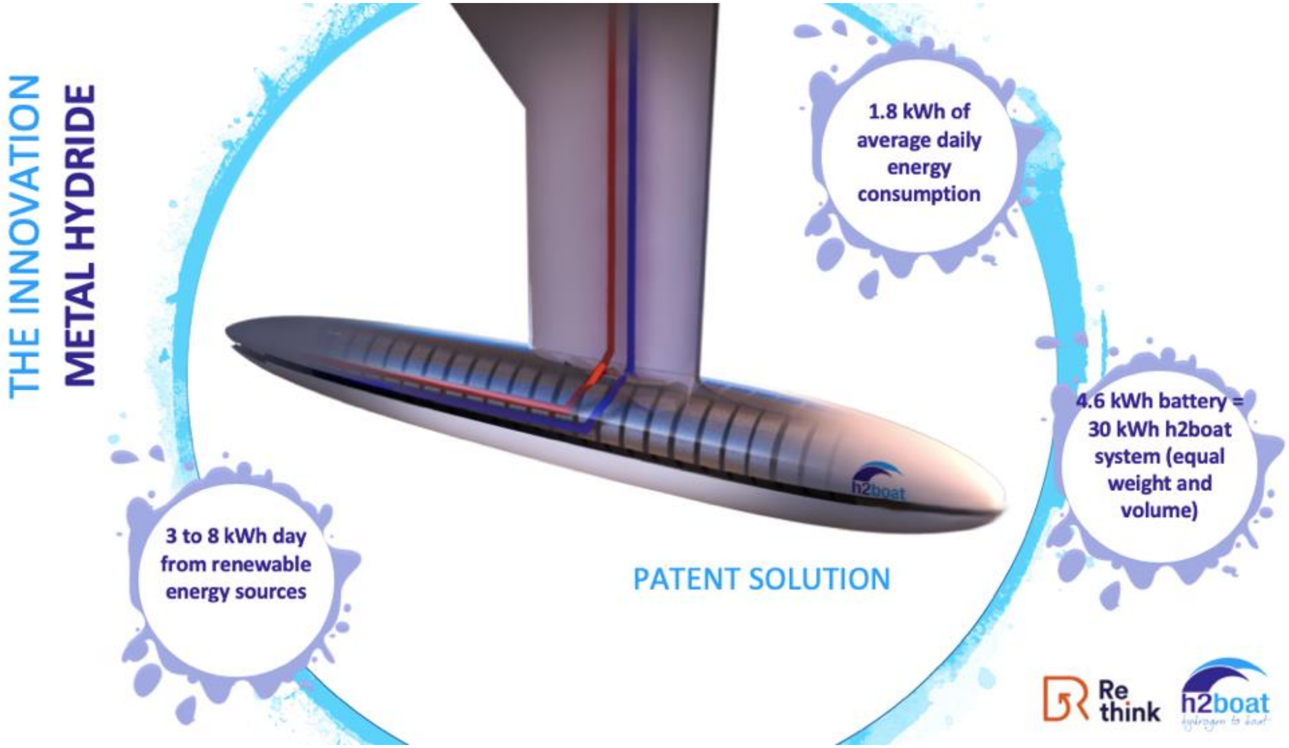
INTEGRATED HYDROGEN TECHNOLOGY

VIDEO

h2boat
hydrogen to boat

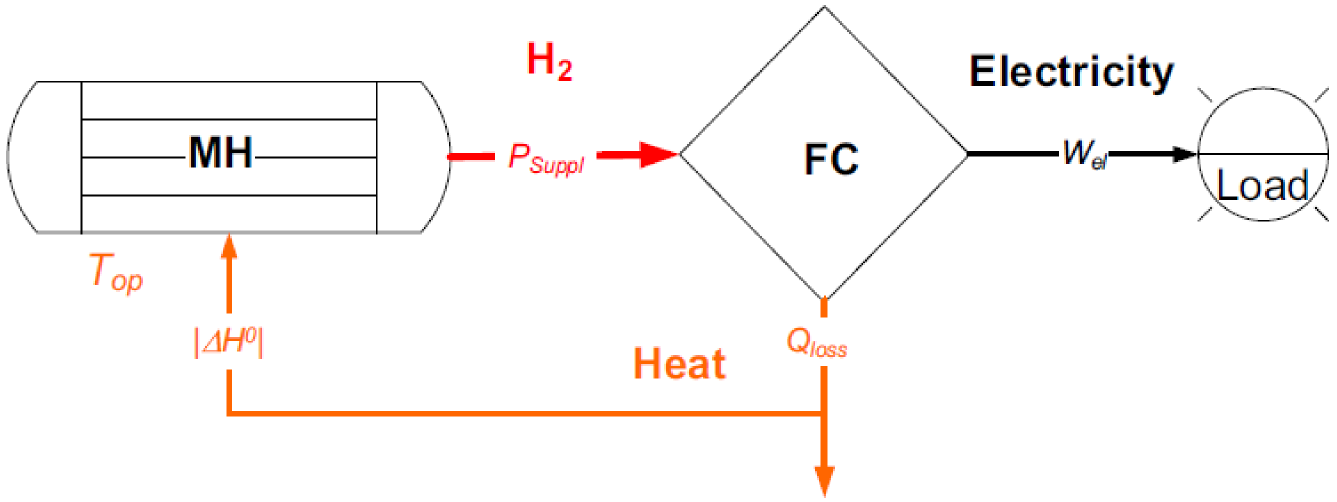
WEIGHT COULD BE AN OPPORTUNITY

Metal hydride tanks

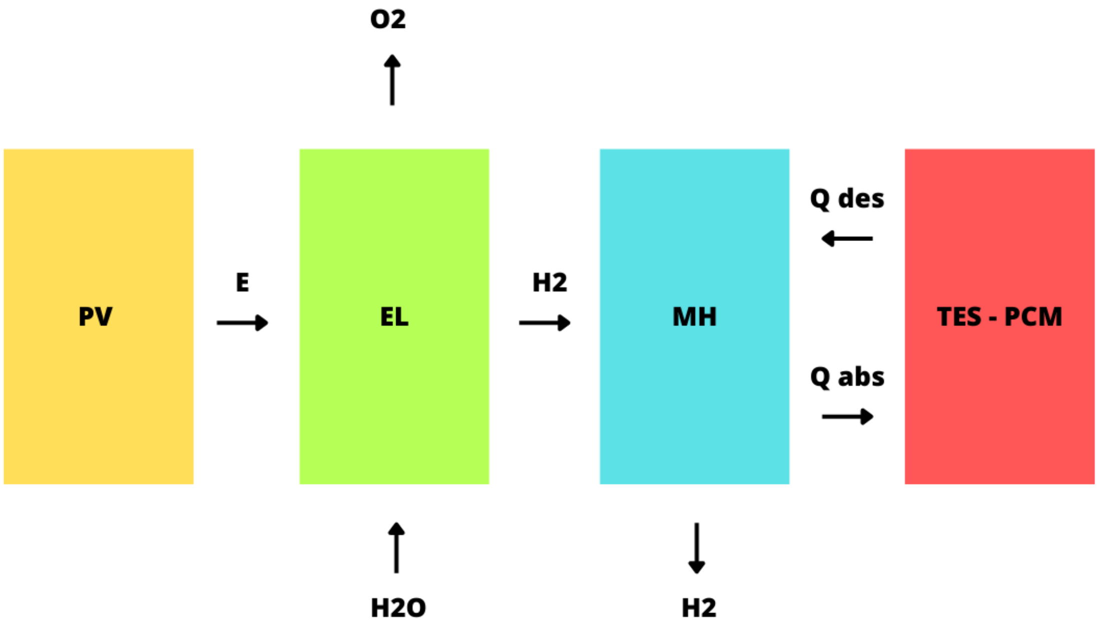


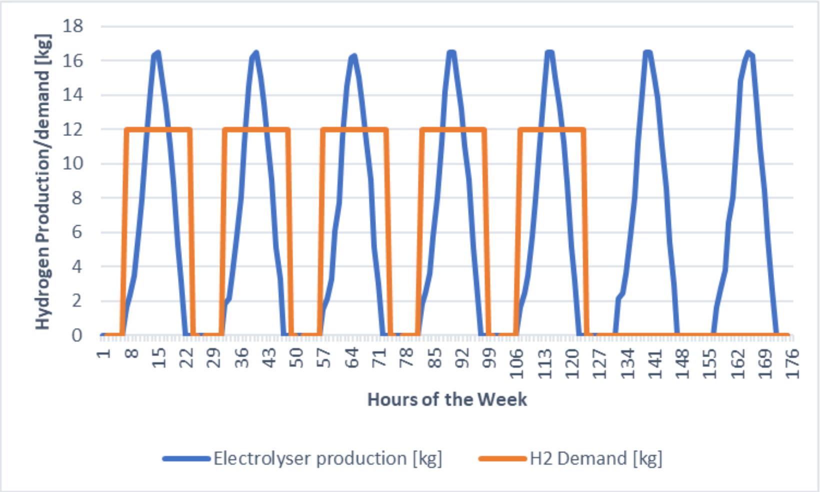
COUPLING FC AND METAL HYDRIDES

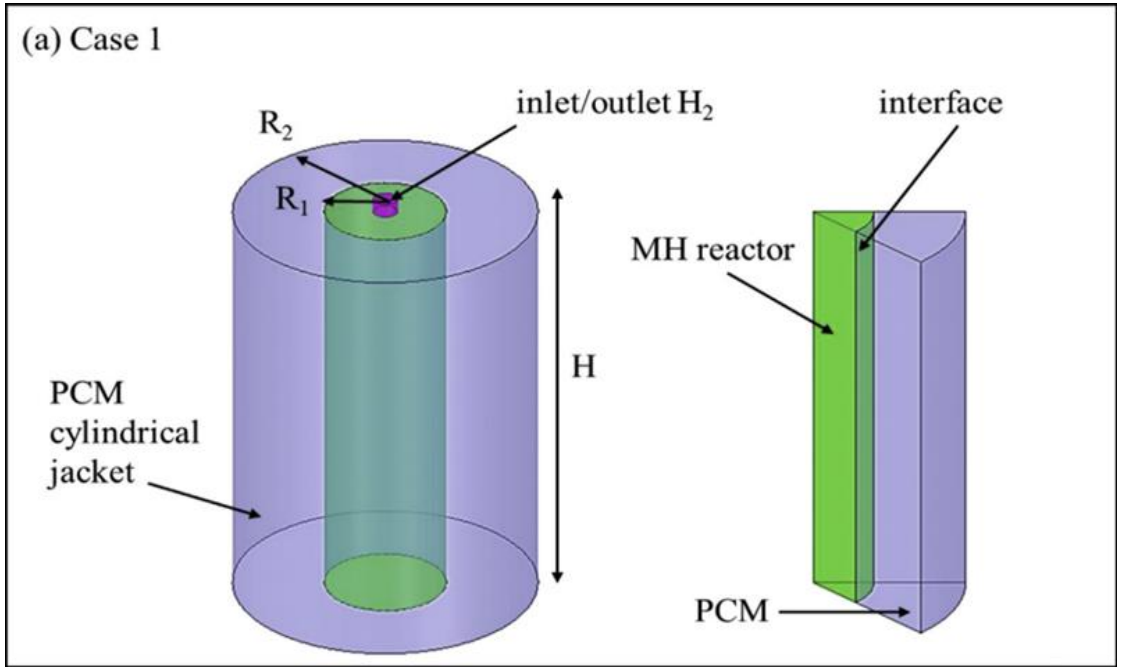
- While we discharge the MH tank, the heat produced by the PEMFC could be used to drive the MH storage discharging and FC ramp up in parallel → initially with low T we'll have a small flow rate from the MH storage to drive the ramp up, then once the PEMFC heat up and we have it we're able to elaborate larger mass flow rates



COUPLING MH AND PCM TES







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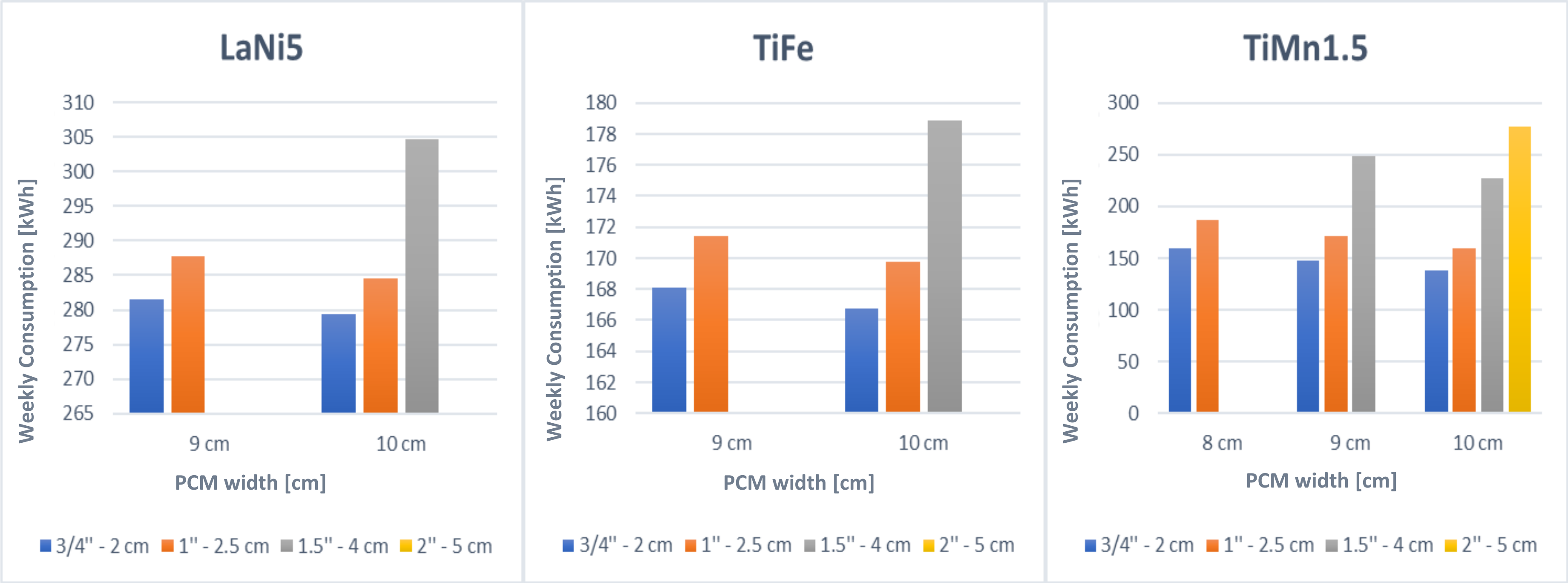
COUPLING MH AND PCM TES

MH material	Family	ΔH_R – Formation Enthalpy [J/mol]	ΔS_R – Entropy change during hydrogenation reaction [J/(mol·K)]	T_{abs} - Temperature of equilibrium at 40 bar [°C]	Thermal Conductivity [W/mK]	Cost of the MH [$/kg]
TiFe	AB	-28100	-106	100	1,49	4,68
$TiMn_{1.5}$	AB_2	-28700	-114	71,4	0,4	4,99
$LaNi_5$	AB_5	-30800	-108	125,3	1,32	9,87

PCM Name	RT111HC	RT90HC	RT62HC
Coupled MH	$LaNi_5$	TiFe	$TiMn_{1.5}$
Phase Change Temperature [°C]	110 – 112	91 - 92	62 - 63
λ_{PCM} – Latent heat [kJ/kg]	190 ± 7,5%	170 ± 7,5%	230 ± 7,5%
ρ_{PCM} – Density [kg/l]	ρ_s = 0,9 ρ_l =0,8	ρ_s = 0,95 ρ_l = 0,85	ρ_s = 0,85 ρ_l = 0,84
k_{PCM} – Thermal Conductivity [W/(m·K)]	~ 0,2	~ 0,2	0,2
Cost of the material [€/kg]	24,03	13,63	7,65

COUPLING MH AND PCM TES



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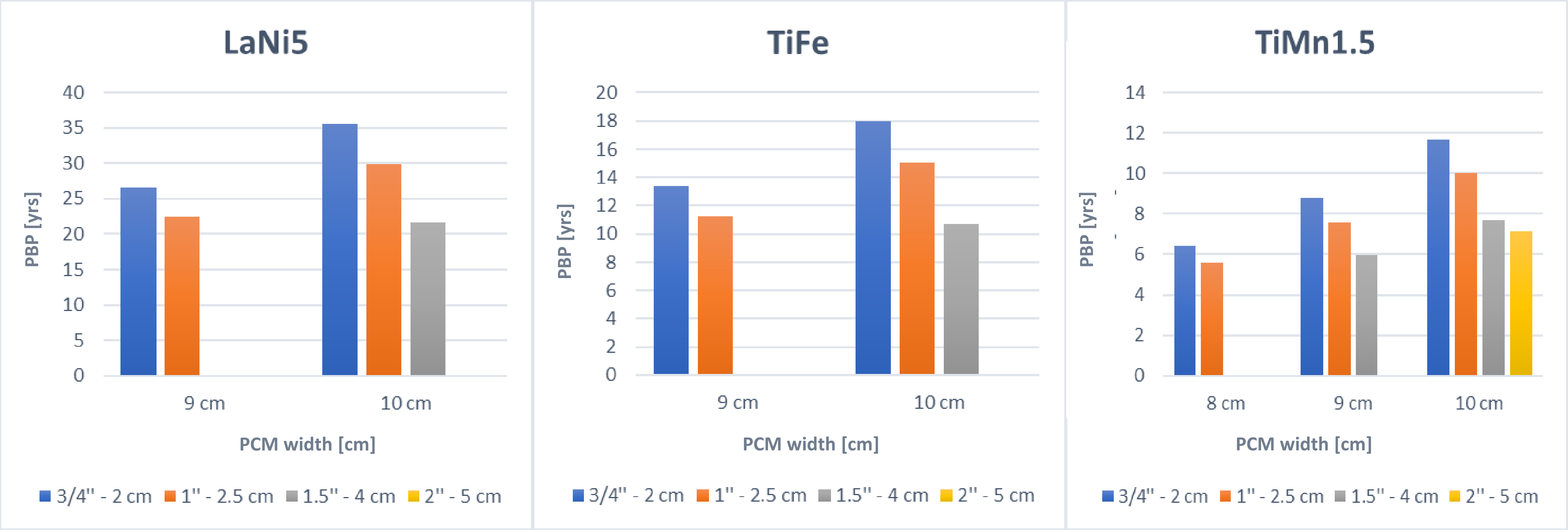
COUPLING MH AND PCM TES



PCM Cost is still the main barrier (PBP Above are already with «more convenient CAPEX)

MH APPLICATIONS – SOME EXAMPLES

MARITIME

STATIONARY
(less risk, less permitting)

DISCARDED FOR TRANSPORT

Project	Proposed Concept	Energy System	Storage System	Type of application
Submarines classe 212 -214	Propulsione ibrida con fuel cell e motore diesel	PEMFC (300 kW)	AB MH	**Submarines**
Protium, River Boat. BZERO…	River and small maritime vessels	PEMFC+Battery	Up to 6-10 kg (or propulsion or on-board service) TiFe – LaNi5…	**Small boats**
Eden	High density Hydrides	-	«doped» Mg Hydrides	Stationary
HyCARE	MH+PCM (TCM) TES	PEMFC	AB5 MH (optimized also for thermal applications) Up to 10 kg of H2	Stationary
Hy2Green	TES+MH for coupling with PEMFC	PEMFC	AB5 MH (optimized also for thermal applications) Up to 10 kg of H2	Stationary
Ingrid	Large scale H2 storage	-	Mg Hydrides up to 50 kg of H2	Stationary

CONCLUSIONS

- There’s no optimal option for storing hydrogen: your choice is very dependent on the application!
- Nevertheless: now that FCH Industry is more «Stationary sector» driven than mobility sector driven MH could have a new boost on R&D and application
- MH are the safest (and probably less annoying…) way to store Hydrogen
- MH Cons (Weight and Heat Management) can become an opportunity: Industrial – Maritime applications
- We should push again R&D on MH materials particularly looking at: 1) recyclability and recycled powders, 2) Hystheresis reduction, 3) thermal management and control
- Hydrogen Carriers/E-Fuels: perfect if we directly use them! Otherwise, using some of them just as carriers, could solve some issues, but pose other ones…

Goal of Today

METAL HYDRIDES

LIQUID HYDROGEN

Interesting Links

https://www.youtube.com/@fch2edu659/videos - FCH EDU Videos – Special section on Solid State Hydrogen Storage technologies

https://www.youtube.com/watch?v=VsQi0jHQ3to – MIT Course – Lesson on Solid State Hydrogen Storage technologies

https://www.youtube.com/watch?v=QiD7thxC9UQ&t=129s – The «GUN SHOT» video ☺

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