UNIVERSITY OF PADOVA
ITALY

DEPARTMENT OF INDUSTRIAL ENGINEERING

TECNOLOGIE ENERGETICHE A BASE IDROGENO: PERCHÉ? QUANDO?

IL PROGRAMMA EUROPEO FCH2-JU

MASSIMO GUARNIERI

NOT AN APRIL FOOL!

CICLO SEMINARI LEDS 2014-15

PADOVA, 1 APRILE 2015

Horizon 2020 (FP8) - 2014-2020: 80 G€

- Ricerca di base
- Ricerca tecnologia
- Innovazione

- **24 G€ - Excellence science** – base research: scientific excellence, future and emerging technologies, research mobility, research infrastructures
- **14 G€ - Leadership in enabling and Industrial technologies** – ICT, Nanotech, Adv materials, Adv manufacturing and proc, Biotech, Space.
- **31 G€ - Social challenges** – health, food, **energy (5.9 G€)**, **transport (6.3 G€)**, environment, society, secutity, …

JOINT UNDERTAKING - 2014-2020: 17 G€

- Innovative Medicines Initiative (IMI)
- Aeronautics and Air Transport (Clean Sky)
- **Fuel Cells and Hydrogen (FCH) : 1.3 G€**
- Embedded Computing Systems (ARTEMIS)
- Nanoelectronics Technologies 2020 (ENIAC)

Fuel Cells and Hydrogen: to develop commercially viable, clean, solutions that use hydrogen as an energy carrier and of fuel cells as energy converters.

…

- Fusion for Energy …

Fuel Cells and Hydrogen

Transport pillar

Road vehicles (passenger cars, vans, buses, trucks and two-wheeled bikes)

- Non-road mobile vehicles and machinery
- **Refuelling infrastructure**
- Maritime, rail and aviation applications

Energy pillar

- H_2 production systems & integration in smart grids
- H_2 as a cost effective and safe storage medium
- H_2 conversion into electricity and heat
- Integrated demonstrative projects

Overarching and crosscutting

- Synergies, inter-operability, integrated technologies
- Safety, **regulations**, education, **social acceptance**, …

Stationary FC+H2

Main/RES-powered storage systems
Back-up services
EL-H2-FC
Independent energy/power sizing

PEMFC-PEMEL
High energy and power densities
Low temperature: 60–70°C (→ 150°C)
→ fast response
→ Pure hydrogen (≥5.0)

Electro Power System
6 kW – 12 kW unit

Autonomous generation systems
H2-FC
Independent energy/power sizing

SYNGAS-H2-SOFC→ CHP (power + heat)
High energy and power densities
High temperature: 400-600°C
→ Higher efficiency
→ 24% global energy saving
→ >70% electric efficency
→ Less H2 purity requirements

SOFCPower – EnGen 500
1-5 kW

Public urban electric mobility

H2-FC
→ PEMFC-PEMEL
Low temperature: 55-60°C (→ 150°C)
→ fast response
→ H2 purity requirements
High energy and power densities
Indep. energy (tanks) / power (FC) sizing
→ Large range

Typical spec.:
motors: 150 (300) kW
supply: 150 kW FC + 100 kW
energy: 1,640 L @ 35 MPa
+ 17.4 kWh Li-ion
8 Dynetek carbonfiber reinforced aluminum tanks (35 kg)

→ High V.LO City program – IFC program
City public transportation
- London, Hamburg, Aberdeen, Oslo
- Barcelona, Stuttgart, Amsterdam, Luxemburg, Madrid, Reykjavík, …
- Perth, …

Mercedes-Benz, MAN, Solaris, VanHool, VDL

Public transportation in non-metropolitan areas – HFC miniBus

Italian cases:

- Taggia-Ventimiglia: A330 Van Hool 120 kW + 35 MPa + 17.8 kWh: 450 km (refuel < 15 min) - High V.LO City program
- Val di Fiemme: Dolomitech (Daily) – 40 kW FC + 35 MPa + Li-ion: 300 km (refueling < 10 min)

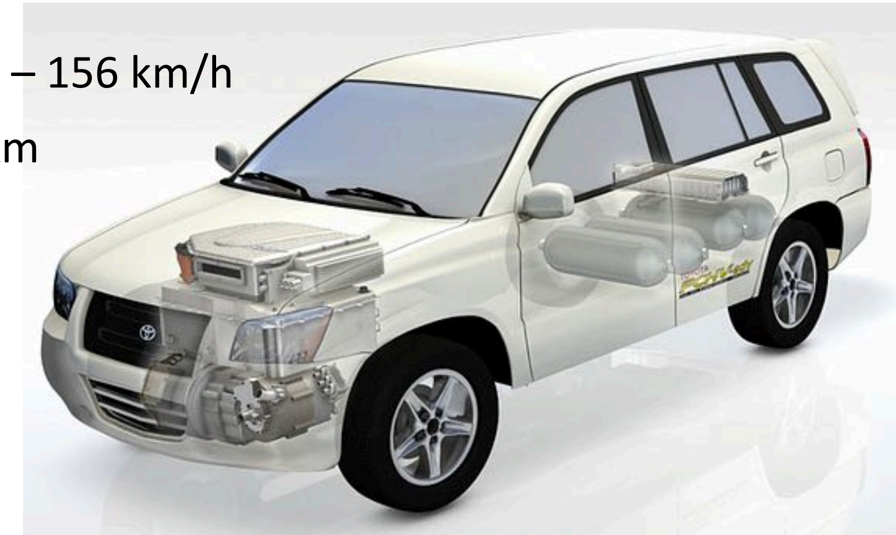
FCEV – HFCEV: Fuel-cell powered electric vehicles – now sold

Free Fuel

Better range and refueling time than batteries

Pre -series

- Toyota FCHV (2002, lim. prod.):
  - Power: 90 kW FC + 21 kW NiMH – 156 km/h
  - Energy: 156 L @ 70 MPa – 800 km



- Honda FCX Clarity (2008, lim. prod.): 100 kW FC + Li-ion – 380 km
- Daimler Mercedes F-Cell: (2010): 100 kW FC + 1.4 kWh Li-ion, 35 Mpa, 402 km

FCEV – HFCEV: Fuel-cell powered electric vehicles – now sold

Better range and refueling time than batteries

Mas production

- Hyundai ix35 (Tucson) Fuel Cell (2013)
  - Power: 100 kW FC + 24 kW Li-pol - 160 km/h
  - Energy: 5.64 kg @ 70 MPa + 0.95 kWh Li-pol - 594 km (3 min refueling time)

FCEV – HFCEV: (coming soon – 2015)

- Toyota Mirai FCV (J 2015): 100 kW FC + 21 kW NiMH - 70 MPa - 500 km
- Honda FCX Clarity II (J 2015): 100 kW FC + Li-ion – 3.9 kg @ 35 MPa - 240 km

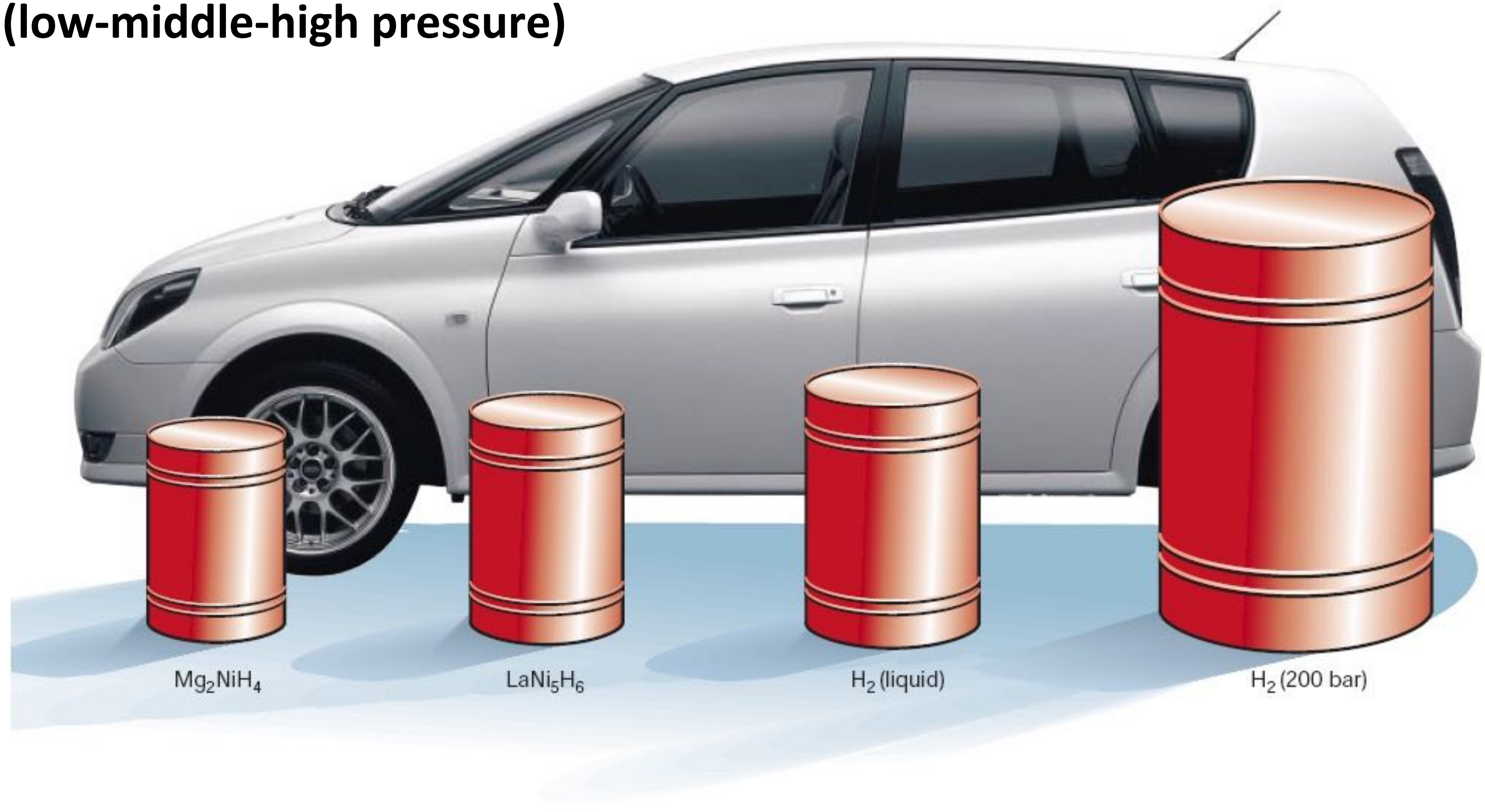
- Future producers:
  - Daimler
  - BMW
  - …

Storing strategies

Solid (hydrides)

Liquid (cryogenic cooling)

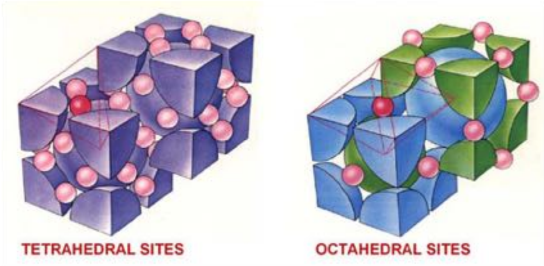
Gas (low-middle-high pressure)

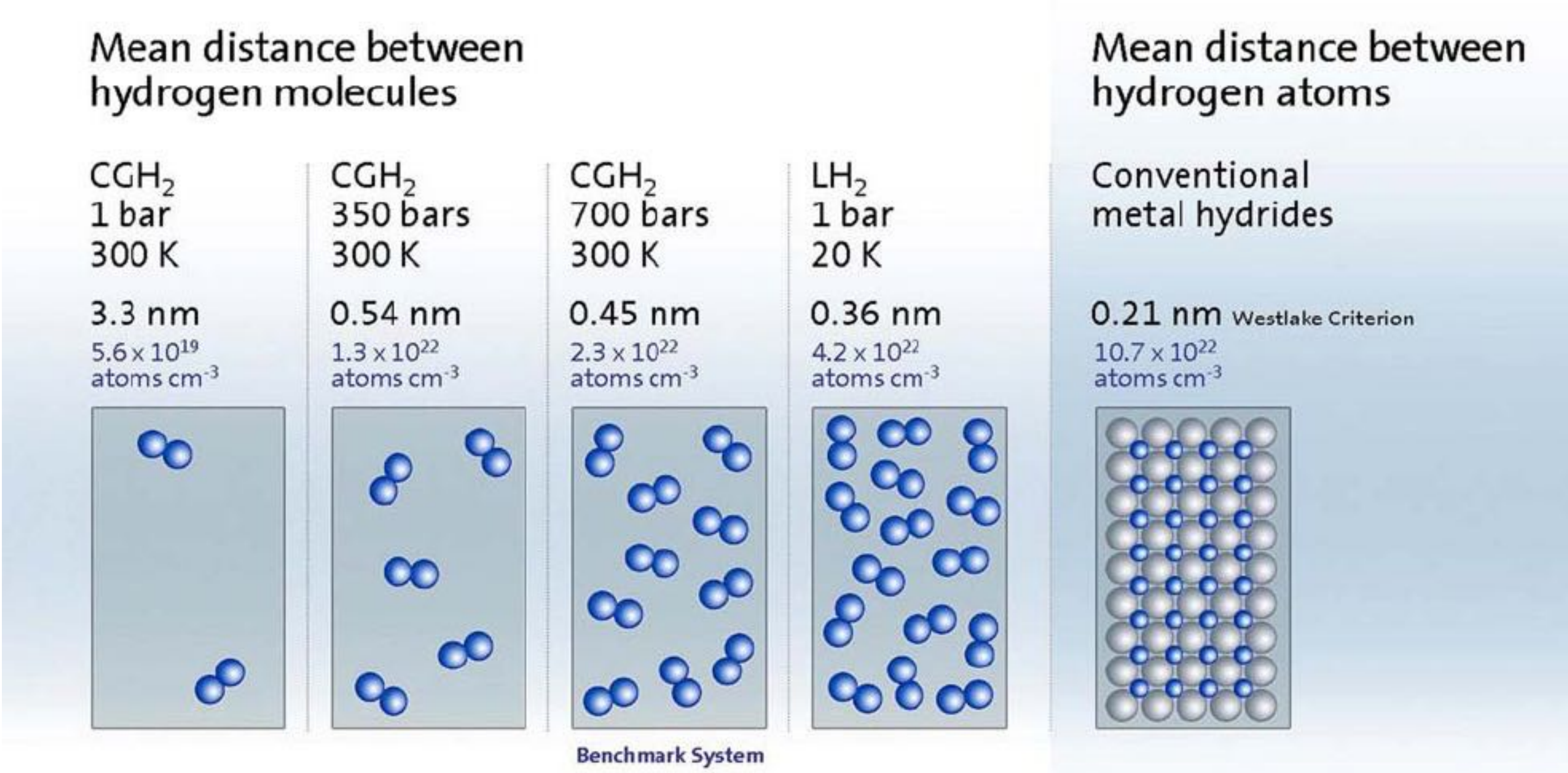


Solid (hydrides)

Liquid (cryogenic cooling)

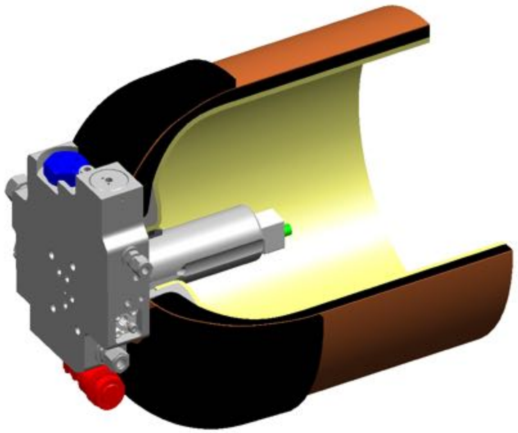
Gas (low-middle-high pressure)

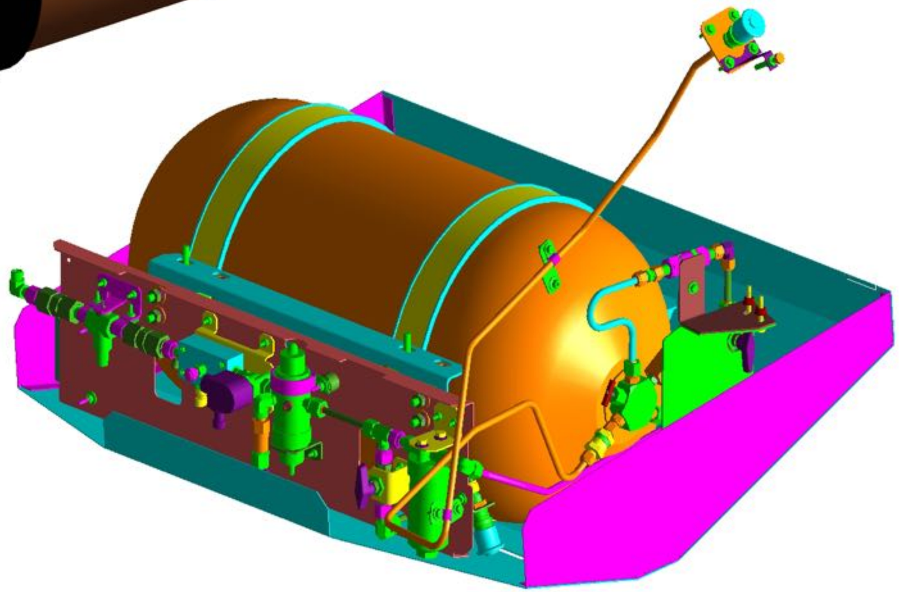




On board storing

- 70 (35) MPa – composite materials (Kevlar)





Validtion tests:
•Hydrostatic Burst
•Extreme Temperature Cycle
•Ambient Cycle
•Acid Environment
•Bonfire
•Gunfire Penetration
•Flaw Tolerance
•Accelerated Stress
•Drop Test
•Permeation
•Hydrogen Cycle
•Softening Temperature
•Tensile Properties
•Resin Shear
•Boss End Material

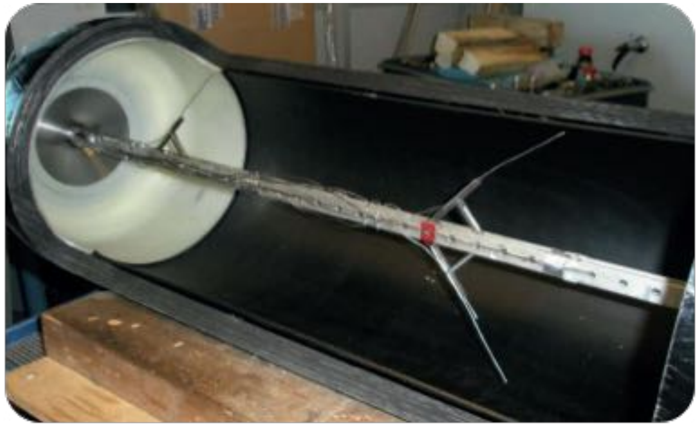
HP storage

EU-funded activities

Copernic project

- Increasing the maturity and competitiveness of innovative **CGH2** (compressed gaseous H2) manufacturing processes
- Evolving from classical automotive manufacturing technologies or concepts.
- Decreasing costs while improving composite quality and/or manufacturing productivity using optimised composite design, materials and components.
- All-in-one innovative high-pressure on-tank valve development and certification (benchmark, price and normative requirement analysis)

HP storage



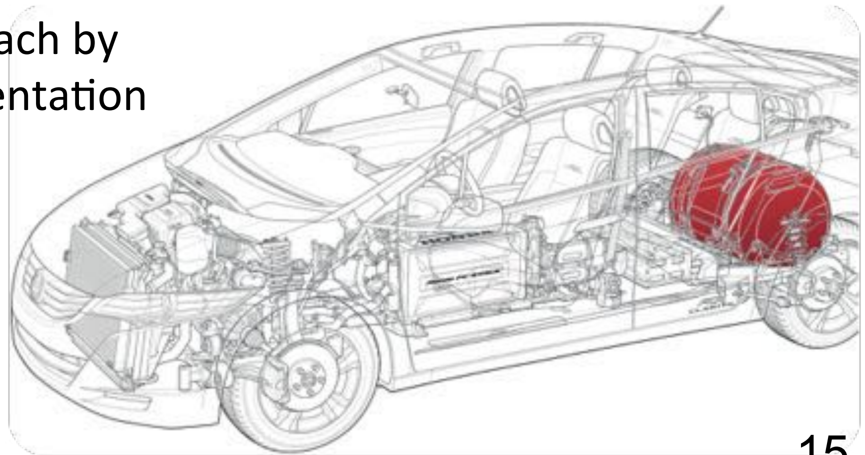
EU-funded activities

HyTransfer project

•Aims to develop and experimentally validate a practical approach for optimising means of temperature control during fast transfers of compressed hydrogen to meet the specified temperature limit (gas or material) taking into account the container and system's thermal behaviour.

•Creating conditions for an uptake of the approach by international standards, for wide-scale implementation

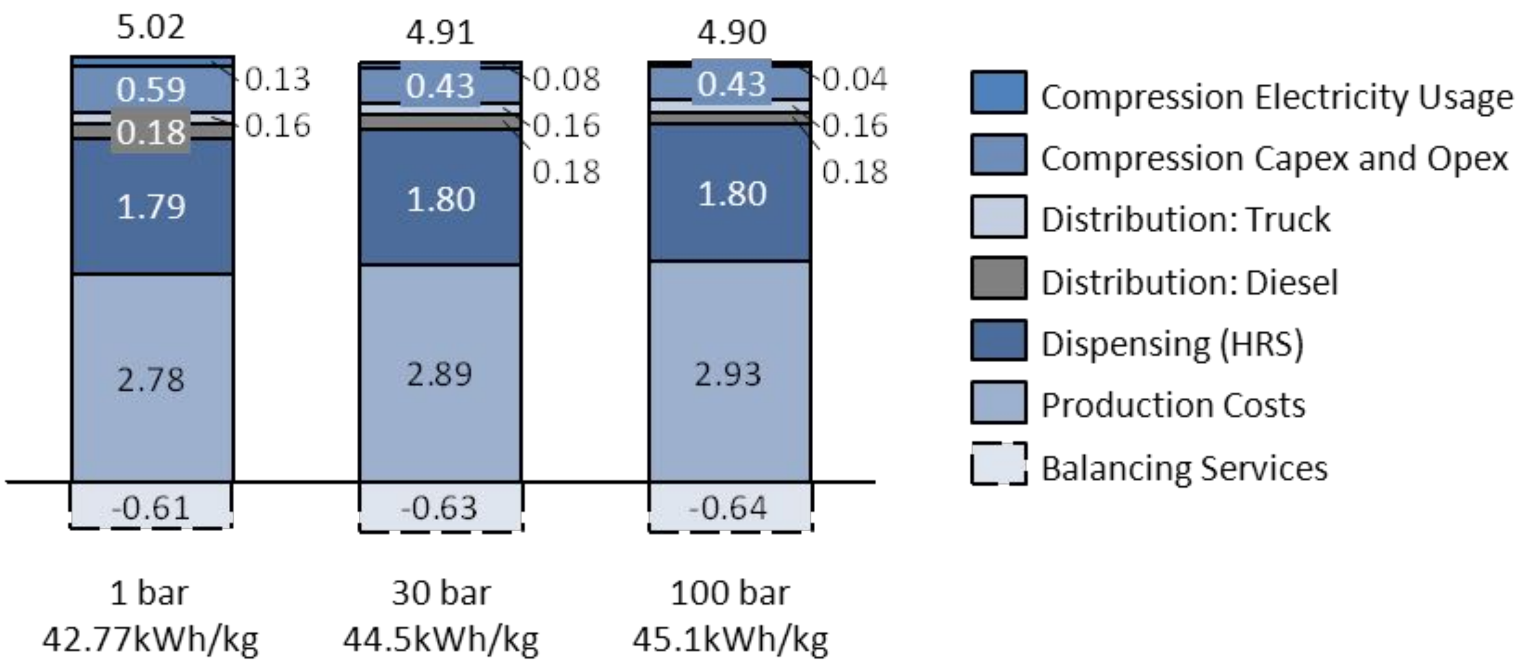
•into refuelling protocols



Refueling infrastructure - HRS

- mid pressure + compressor
- RES supply + electrolyzer
- 1 M€ each

PEM - Hydrogen cost at the nozzle, €/Kg



Refueling infrastructure - HRS

- mid pressure + compressor
- RES supply + electrolyzer
- 1 M€ each

Comparison H2 - Gasoline - Diesel fuel

		H2 (1 bar)	H2 (690 bar)	Gasoline	Gasoline DI	Diesel Fuel TDI
specific energy	MJ/kg	141,86	141,86	46,4	46,4	45,6
energy density	MJ/L	0,01005	4,5	34,2	34,2	38,6
density	kg/L	7,08E-05	3,17E-02	0,74	0,74	0,85
price	€/L			1,57	1,57	1,49
price	€/kg	4,95	4,95	2,13	2,13	1,76
fuel energy price	c€/MJ	3,49	3,49	4,59	4,59	3,86
powerdrive efficiency at the wheel	%	60%	60%	26%	34%	45%
wheel energy price	c€/MJ	5,82	5,82	17,66	13,50	8,58

HP storage

EU-funded activities

Phaedrus project

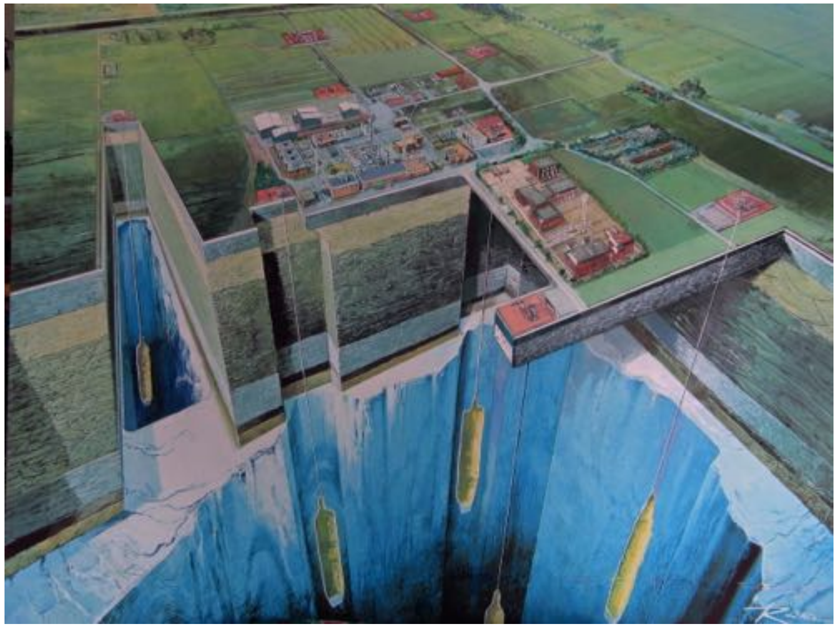
- Aims at developing and validating a new concept for 70 MPa **HRS** (H2 Refueling Station) infrastructure with a modular dispensing capacity in the range of 50-200 kg per day.
- An electrochemical hydrogen compression system consisting of parallel units for compression up to 100 MPa at a peak production of 10 to 50 kg/h;
- Storage tanks at low (10-20 MPa), or medium (50 MPa) and high pressure (100 MPa);
- A dispensing system equipped with a pre-cooling unit, with a capacity of 5 kg/3 min.

LP storage

EU-funded activities

HyUnder project

- Studies the deployment of hydrogen energy storage in underground storage caverns at large scale, benchmark their storage potential in relation to the energy market and competing storage technologies, and identify and assess application areas, stakeholders, safety, regulatory framework and public acceptance



Liquid storage

EU-funded activities

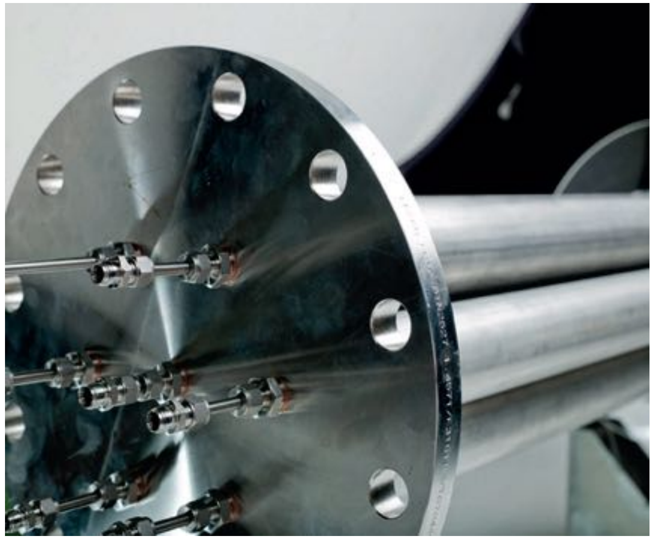
IdealHy project

- Aims to enable liquid hydrogen (LH2) as an efficient low-carbon energy carrier, by designing a process for efficient hydrogen liquefaction at a scale of up to 200 tonnes per day and developing plans for a demonstration plant.

- IDEALHY demonstrates that liquefaction energy requirement is no barrier to an efficient liquid hydrogen distribution chain, thus enabling transport in larger volumes and over longer distances. Life-cycle analysis shows that cost and overall greenhouse gas emissions can be competitive with compressed gaseous hydrogen.

Solid storage – Hydrides

EU-funded activities



Bor4store

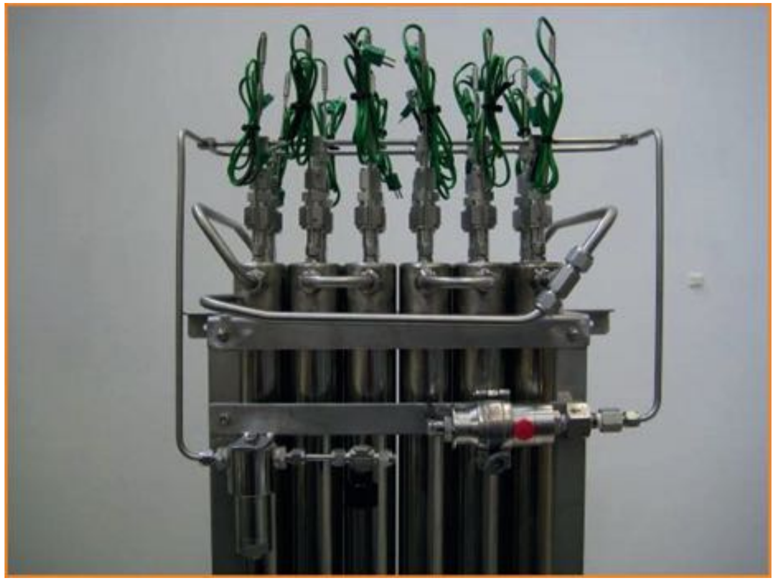
Integrated approach for development and testing of novel, optimised and cost-efficient boron hydride-based hydrogen storage materials with superior performance (materials capacity more than 8 wt.% and 80 kg H2/m3) for SOFC applications

Solid storage – Hydrides

EU-funded activities

SSH2S project

Development of a solid-state hydrogen storage tank fully integrated with a fuel cell.



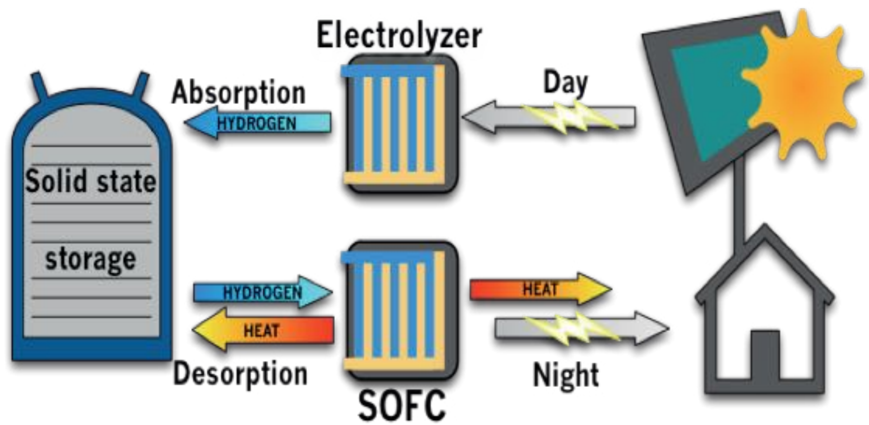
- Well assessed hydrogen storage material (i.e. a mixed lithium amide/magnesium hydride) considered as the active material for the tank.
- New materials (i.e. mixed borohydrides) also investigated.
- Application of the hydrogen tank on a real system investigated with a 1 kW prototype on a high-temperature polymer electrolyte membrane (HTPEM) fuel cell.
- Possible scale-up of the tank to a 5 kW APU.

Solid storage – Hydrides

EU-funded activities

Eden project

- Development of an integrated system for stationary solid state H2 storage realised through:
- 1) an optimised fast reacting Mg-based hydride,
- 2) a newly designed tank with
- 3) full thermal and hydrogen management in connection and integration with a SOFC



Waterborne FCEV

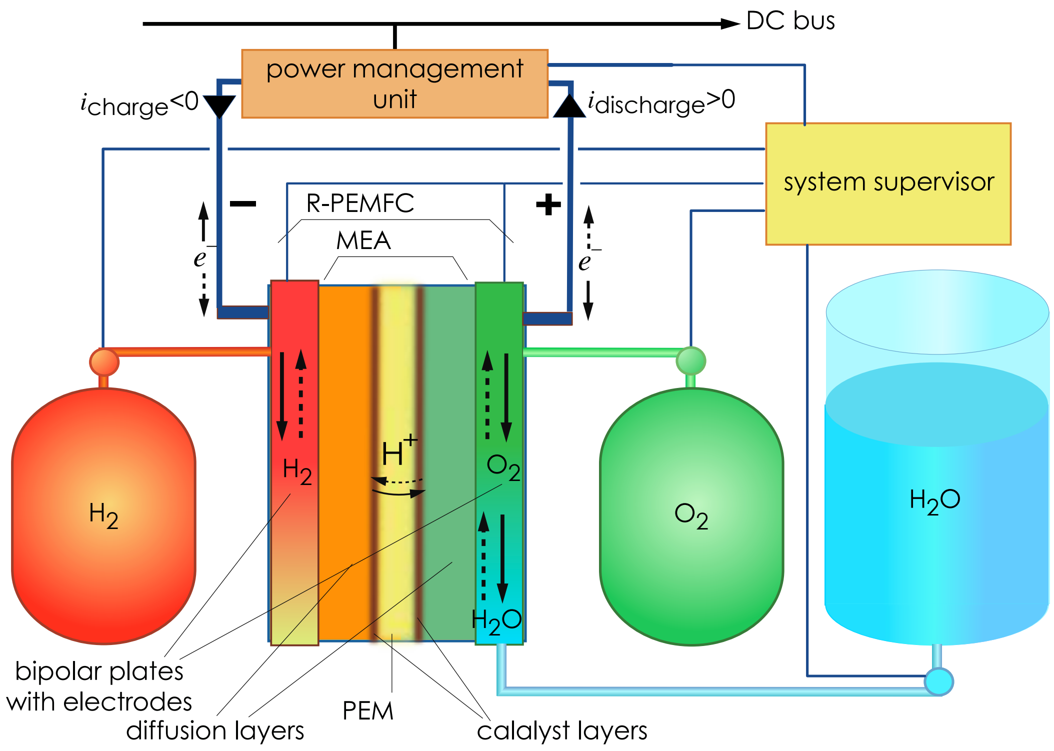
Prototype FC–H_2 boats

- Amsterdam 2009:
- H2 Nemo
- 22 m - 87 passengers
- “zero CO_2 canal cruise”
- 75+11 kW propulsion
- 70 kW FC – 50 kW battery
- 6 tanks – 24 kg @ 35 MPa
- 8.6-7 knots – 9 h

Similar FC boats:

- Alsterwasser (Hamburg), Berlin, Bristol, La Rochelle, Rotterdam, New York, Istanbul, …
- Venice … ?

RFC concept



RFC structure
unique power converter
gas and water storages
gas management units
dc/ac converter
supervisor

Development stage
under development
early market
needs for material and design optimization

Thank you

UNIVERSITÀ DEGLI STUDI DI PADOVA

Research groups FCH at UNIPD

- **ECES-MPS-Lab** *(Electrochemical Energy Storage and Multiphysics Simulation)* – Department of Industrial Engineering
  Experimental development, numerical analysis and optimization of Fuel Cells and electrochemical energy storage systems.

- **CheMaMSE** *(Chemistry of Materials for the Metamorphosis and the Storage of Energy)* – Department of Chemical Sciences
  Design, characterization and testing in prototype devices of advanced nanostructured functional materials for fuel cells and electrolysers.

- **Heterogeneous catalysis research group** – Department of Industrial Engineering
  Synthesis, characterization and activity measurement of solid catalysts and nanocatalysts.

- **SSL** *(Surface Science Lab)* / **ECG** *(Electrochemistry group)* – Department of Chemical Sciences
  Study of electrocatalysts for the oxidation of ethanol and the reduction of oxygen.

- **Hydrogen Storage interdepartmental group** – Department of Industrial Engineering, Department of Physics and Astronomy
  Materials for solid-state hydrogen storage.

- **Research Group of Environmental Engineering** – Department of Civil, Environmental and Architectural Engineering
  Biological hydrogen production by anaerobic processes from biodegradable residues and from the organic fraction of municipal solid waste.

Research groups FCH at UNIPD

Heterogeneous catalysis

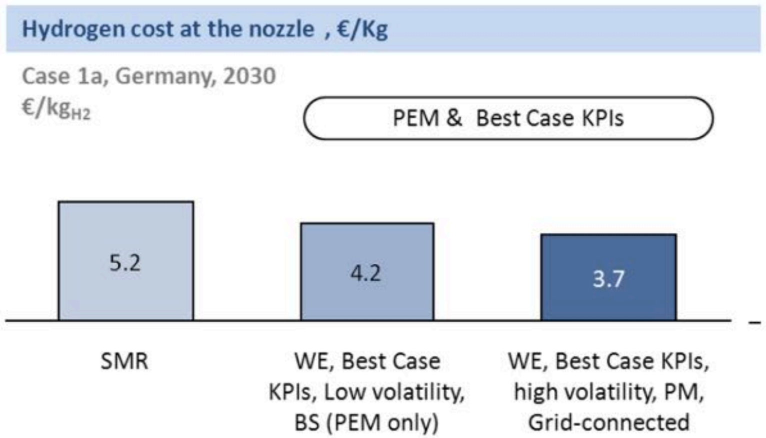
- development of novel catalysts for steam reforming, preferential CO oxidation of syngas mixtures, dry reforming and water-gas shift reactions and processes based on biogas and biofuels.
- characterization of existing catalysts for the above processes, including development of detailed surface kinetics.

Hydrogen Storage

- optimization of AB2 and AB5 alloy-based metal hydrides.
- optimization and pelletization of catalyzed Mg-based hydrides.
- fabrication of high specific surface area materials with tailored porosity.
- improvement of hydrogen storage properties of light hydrides

Refueling infrastructure - HRS

- mid pressure + compressor
- RES supply + electrolyzer
- 1 M€ each



		Alkaline	PEM	AEM
Development status		Commercial	Commercial medium and small scale applications (≤ 300 kW)	Commercial in limited applications
System size range	Nm^3_{H2}/h	0.25 – 760	0.01 – 240	0.1 – 1
	kW	1.8 – 5,300	0.2 - 1,150	0.7 – 4.5
Hydrogen purity [6]		99.5% – 99.9998%	99.9% – 99.9999%	99.4%
Indicative system cost	€/kW	1,000-1,200	1,900 – 2,300	N/A

Refueling infrastructure - HRS

- mid pressure + compressor
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Electricity input [1]			Today	2015	2020	2025	2030
kWh_{el}/kg_{H2}	Alkaline	Central	**54**	**53**	**52**	**51**	**50**
		Range [2]	50 - 78	50 - 73	49 - 67	48 - 65	48 - 63
	PEM	Central	**57**	**52**	**48**	**48**	**47**
		Range [2]	50 - 83	47 - 73	44 - 61	44 - 57	44 - 53

System cost [1]			Today	2015	2020	2025	2030
EUR/kW	Alkaline	Central	**1,100**	**930**	**630**	**610**	**580**
		Range	1,000 - 1,200	760 - 1,100	370 - 900	370 - 850	370 - 800
	PEM	Central	**2,090**	**1,570**	**1,000**	**870**	**760**
		Range	1,860 - 2,320	1,200 - 1,940	700 - 1,300	480 - 1,270	250 - 1,270

Refueling infrastructure - HRS

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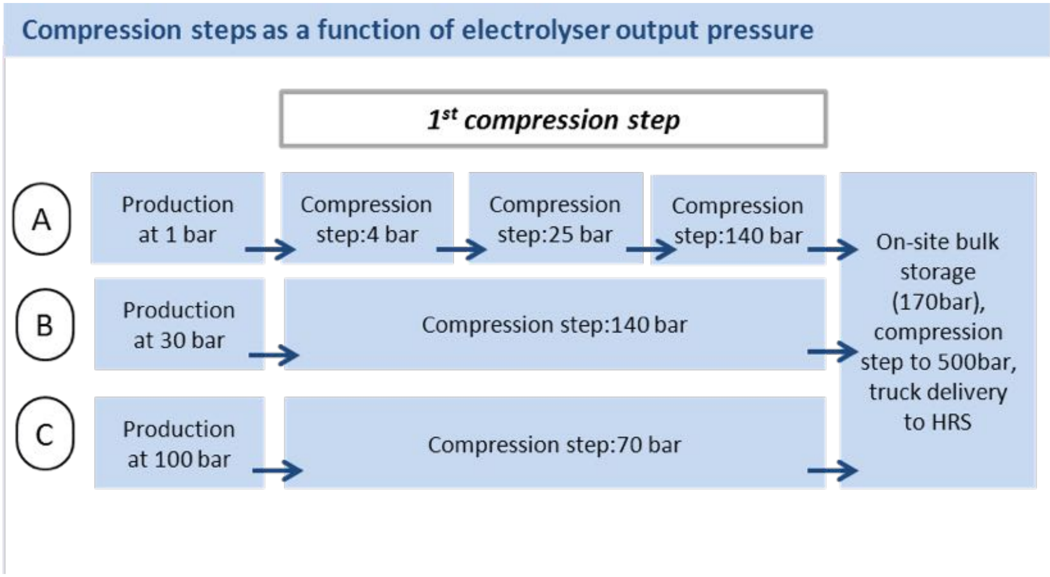
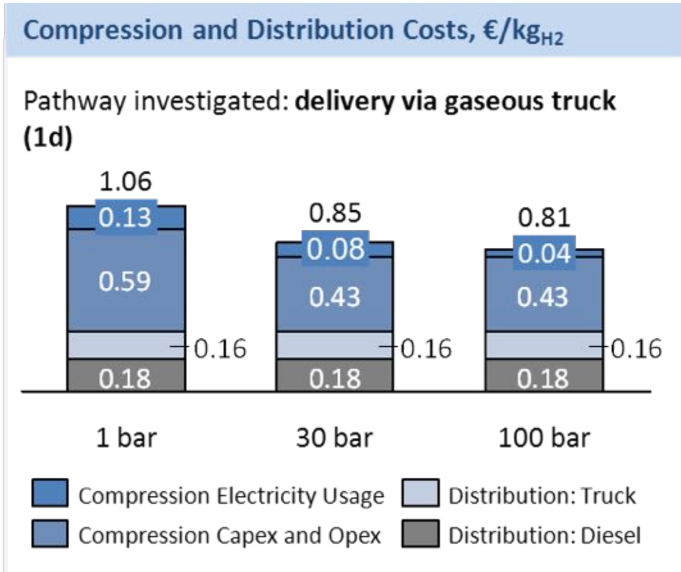
- RES supply + electrolyzer
- 1 M€ each





Refueling infrastructure - HRS

Free Fuel

- mid pressure + compressor
- RES supply + electrolyzer
- 1 M€ each

Medium use case 10 to 250 MW
System is not sized according to demand, but instead according to a range of possible electrolyser system sizes.

Use Case	Size	Pipeline Cost (€/kg)	Compression Cost (€/kg)	Storage Cost (€/kg)	Use Case Electricity Annual Demand (MWh)
2a	10 MW	1.33	0.14	0.27	1,414
2b	100 MW	0.44	0.09	0.27	14,143
2c	250 MW	0.19	0.06	0.27	35,358

Energy storage assumptions

Free Fuel

Medium use case 10 to 250 MW
System is not sized according to demand, but instead according to a range of possible electrolyser system sizes.

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