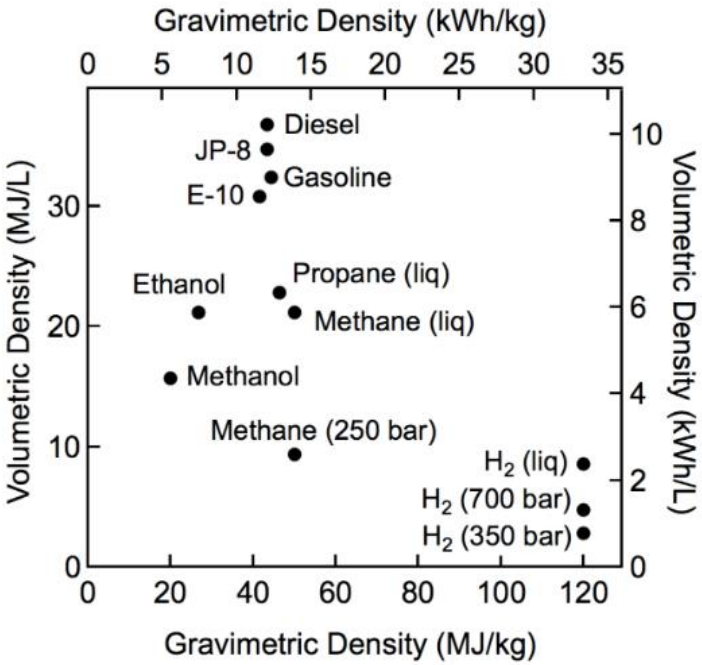
Hydrogen Storage
Introduction

Marco Azzolin
marco.azzolin@unipd.it

The Energy Density



- Hydrogen excels on a mass basis 120 MJ/kg
  methane 50 MJ/kg
  gasoline 44 MJ/kg

- Problem: under normal temperature and pressure, hydrogen's volumetric energy density is only 0.01 MJ/l (density=0.09 kg/m^3)

- Gasoline stores 3,200 times more energy per liter than hydrogen gas at standard conditions

Pressure	LHV	density
[bar]	[MJ/l]	[kg/m^3]
1	0.01	0.09
200	1.8	15
350	2.9	24
700	4.8	40

https://www.energy.gov/eere/fuelcells/hydrogen-storage

Real-World Example:
Storing Hydrogen for a 500 km Vehicle Range

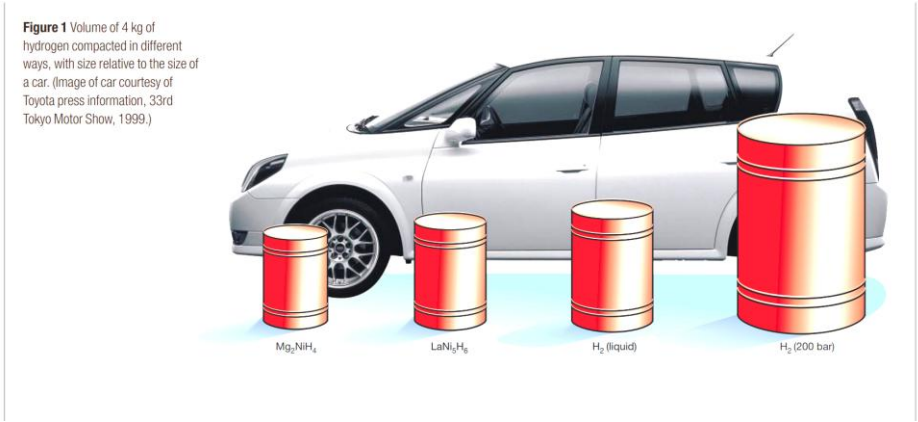
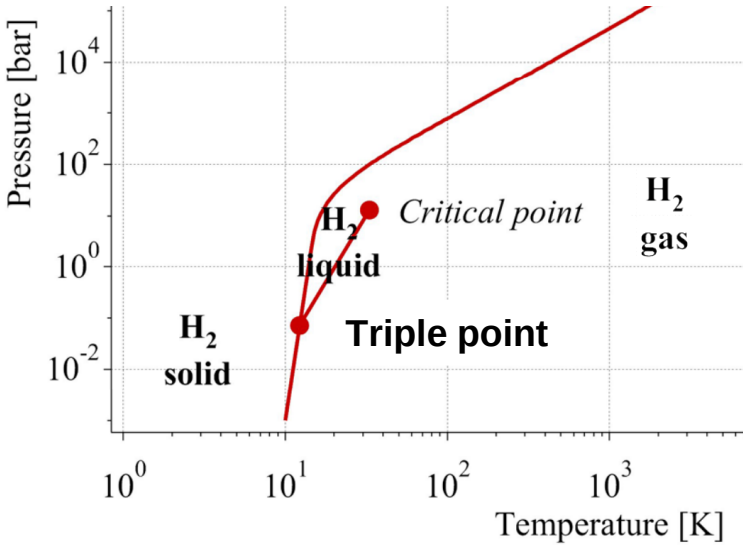


Figure 1 Volume of 4 kg of hydrogen compacted in different ways, with size relative to the size of a car. (Image of car courtesy of Toyota press information, 33rd Tokyo Motor Show, 1999.)

Louis Schlapbach, Andreas Züttel, Nature, 414, 2001

- A light vehicle needs approximately 5 kg of hydrogen to travel 500 km (equivalent to 1 kg per 100 km)
- Equivalent gasoline energy would require 30 liters; the same energy in hydrogen gas at standard conditions would need 11,940 liters
- Compressed to 300 bar: tank volume reduces to 212 liters
- At 700 bar: 125 liters
- At 850 bar: 111 liters
- Liquid hydrogen: 75 liters
- Solid-state hydrogen: 33.3 liters

Phase Diagram



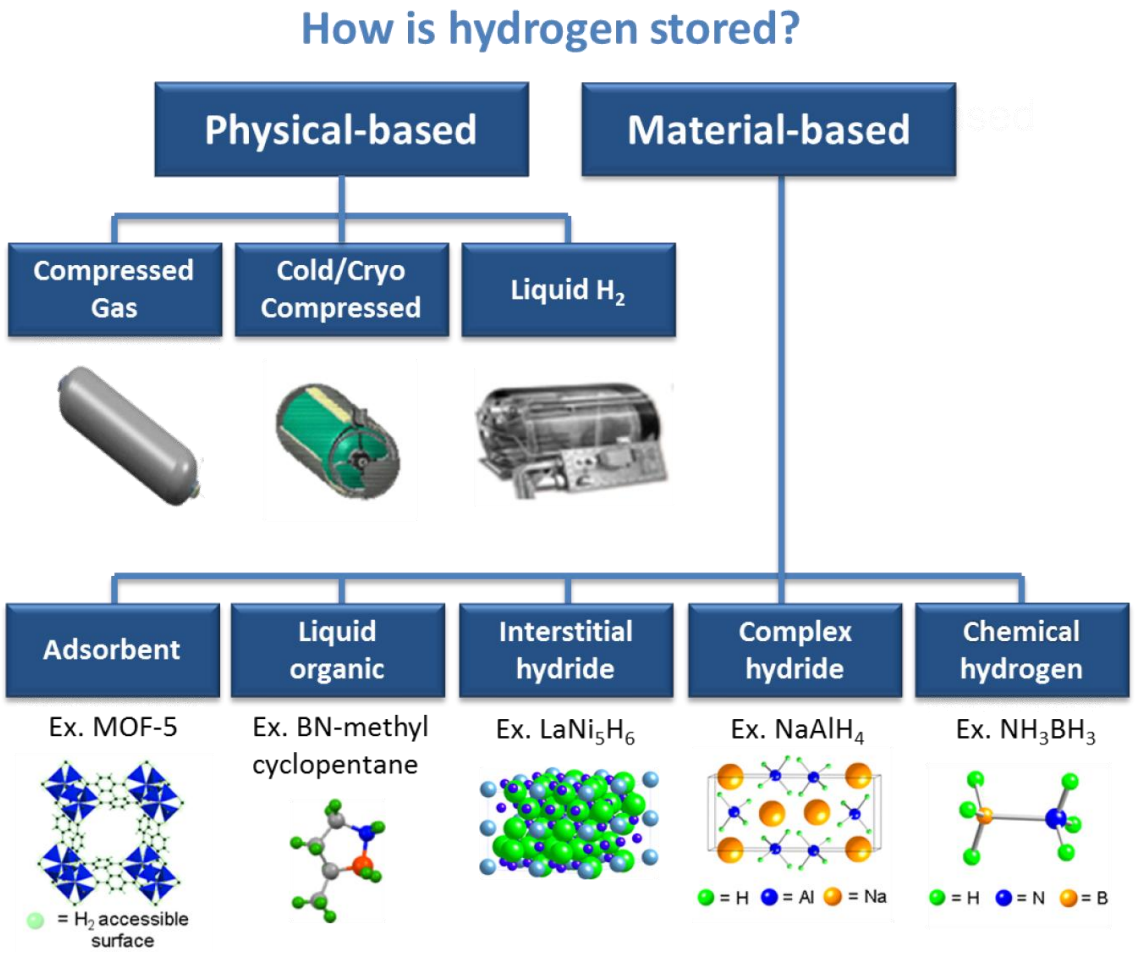
Triple point
at T = 13.8 K (−259 °C) and P = 7.2 kPa

Critical point
at T = 33.2 K (−240 °C) and P = 1.3 MPa

Melting point:
−259.2 °C (14 K) at atmospheric pressure

Boiling point:
−253 °C (20 K) at atmospheric pressure

Ref:: W. B. Leung, N. H. March and H. Motz, Physics Letters 56A (6) (1976), pp. 425-426



Hydrogen can be stored physically as either a gas or a liquid. Storage of hydrogen as a gas typically requires high-pressure tanks (350–700 bar).

Storage of hydrogen as a liquid requires cryogenic temperatures because the boiling point of hydrogen at one atmosphere pressure is −252.8°C.

Hydrogen can also be stored on the surfaces of solids (by adsorption) or within solids (by absorption).

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Ortho- and Para-hydrogen

- Normal hydrogen at room temperature is 75% ortho-hydrogen and 25% para-hydrogen
- When cooling hydrogen for liquefaction, orthohydrogen must convert to parahydrogen (the lower energy state)
- This conversion is exothermic, releasing 670 kJ/kg — even more energy than the latent heat of vaporization (446 kJ/kg)