HYDROGEN STORAGE IN VEHICLES

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Outline

- Energy density basics
- Compressed hydrogen
- Other hydrogen storage options
- Discussion: Life time and costs
- Concluding summary

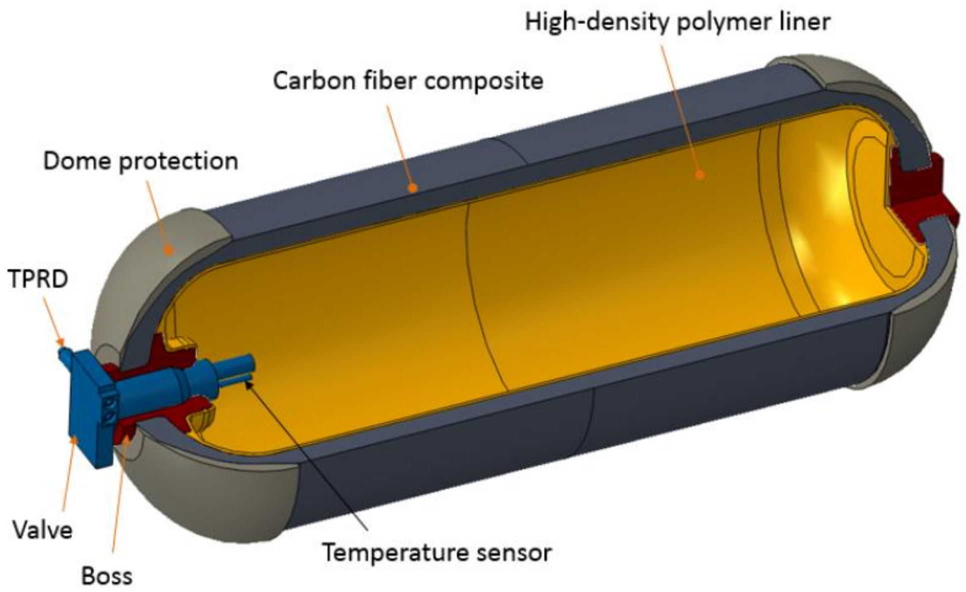
Density comparisons

Energy carrier	Energy density		Comments/ references
	Volume kWh/l	Weight kWh/kg	
Petrol	9,5	12,9	
Diesel	10,7	12,7	[1]
CNG 200 bar	2,50	14,9	[1]
Methane liquid (LNG)	6,17	14,9	[1]
Hydrogen 350 bar (20° C)	0,75	33,3	LHV, [2]
Hydrogen 700 bar (20° C)	1,3 - 3/Nm3	33,3	LHV, [1]
Hydrogen liquid	2,36	33,3	LHV, [1]
Batteries lithium-ion (anode NMC (6:2:2), cathode graphite)	0,120	0,155	[3]

[1] https://en.wikipedia.org/wiki/Energy_density
[2] http://www.h2data.de/
[3] Berkmans, G, Messagie, M, Smekens, J, Omar, N, Vanhaverbeke, L and Van Mierlo, J. (2017) Cost projection of state of the art lithium-ion batteries for electric vehicles up to 2030, *Energies*, 10, 1314. Dave Andre, Sung-Jin Kim, Peter Lamp, Simon Franz Lux, Filippo Maglia*, Odysseas Paschos and Barbara Stiaszny (forthcoming) Future generations of cathode materials: an automotive industry perspective, *Journal of Materials Chemistry A*.

Tank type classifications

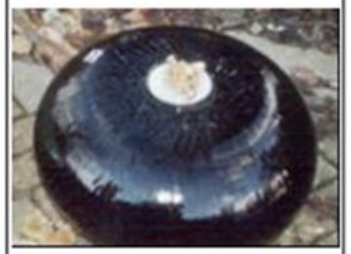
Type	Description
I	Metal tank up to 200 bar, stationary storage
II	Metal plus carbon fibre composite
III	Metal (aluminium) plus carbon fibre for storage up to 350 bar
IV	Polymer plus carbon fibre for storage up to 700 bar
V	Carbon fibre and no liner



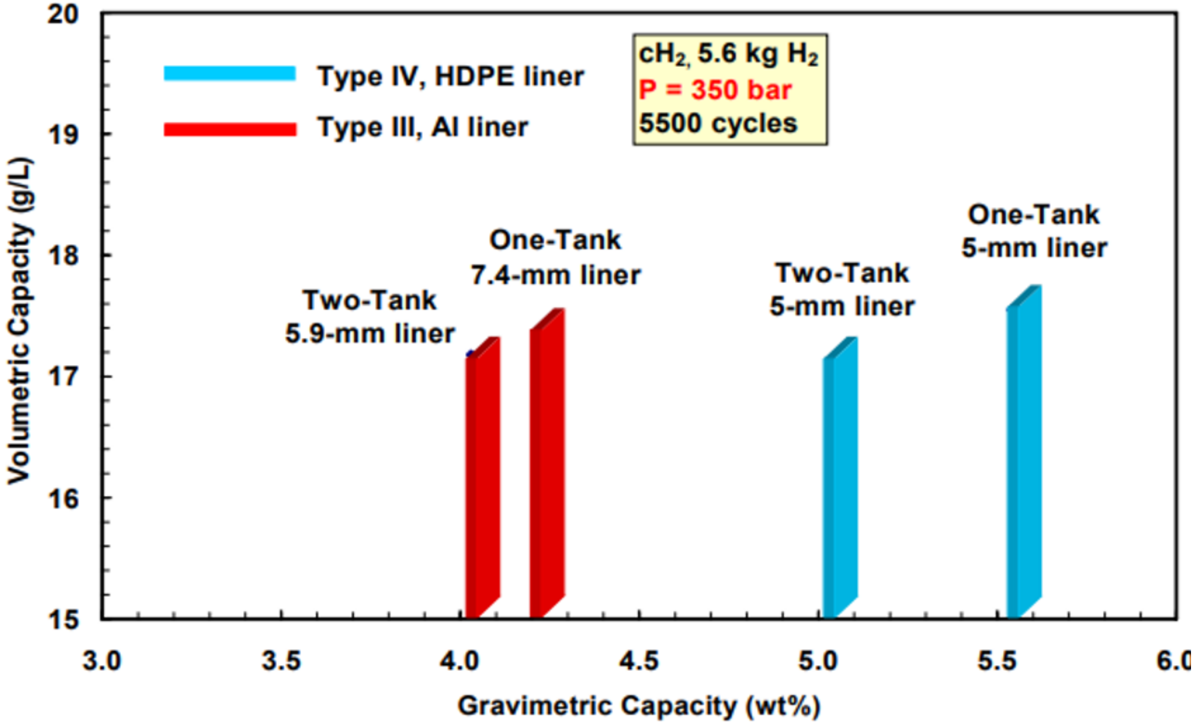

Type I cylinder

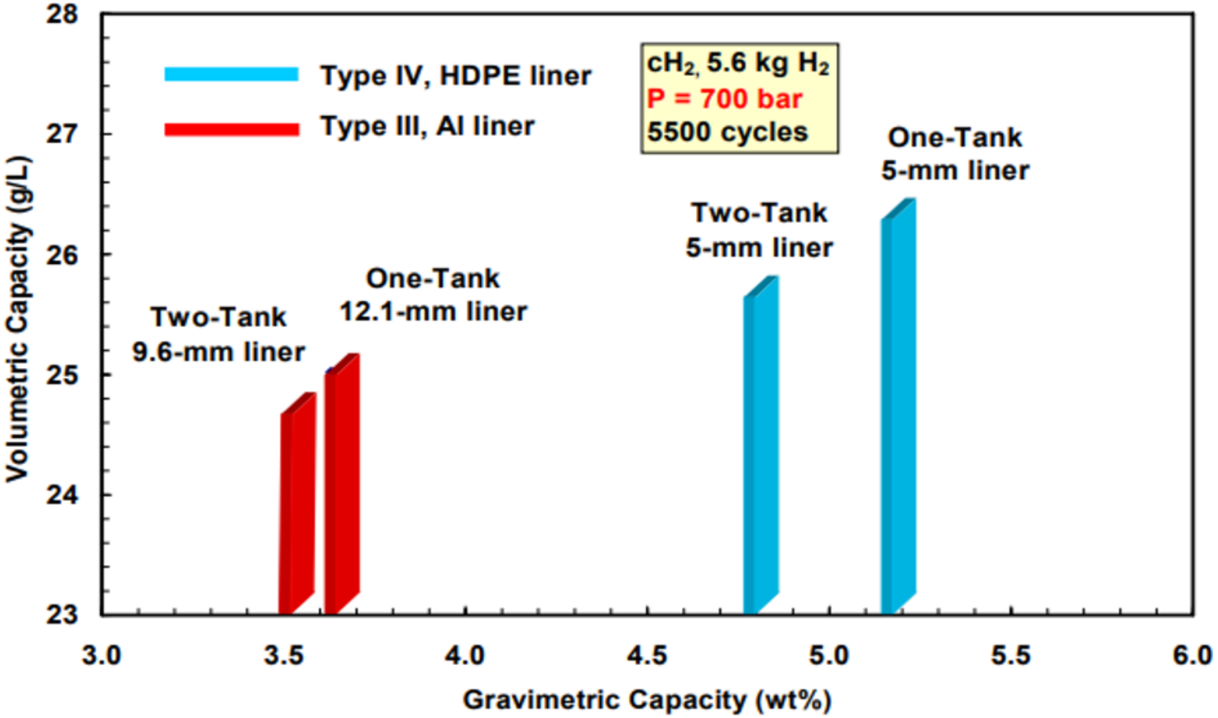

Type II vessel


Type III or IV vessel


Toroid composite vessel

Comparison type III and IV for vehicles





350 bar
Similar volymetric capacity
Type IV better gravimetric capacity
Type III lower cost

700 bar
Type IV better volymetric and gravimetric capacity

Lifetime of hydrogen tanks

700 bar

European Vehicle Type Approval: 5,000 cycles and up to 20 years

Lower pressures

Same rules as for natural gas tanks: If the tank is designed for 20 years in service, it must manage 20,000 cycles

"DO NOT REFUEL AFTER 2029/11" Warning On Fuel Door (Portion of Photo Via Car and Driver)

Hydrogen Storage

US DOE Target

Cost Status

(700-bar compressed system for onboard storage ǂ)

$21/kWh

$17/kWh
100K/yr

$15/kWh
500K/yr

$8/kWh

- Low-Volume Estimate
- High-Volume Projection
- Ultimate Target

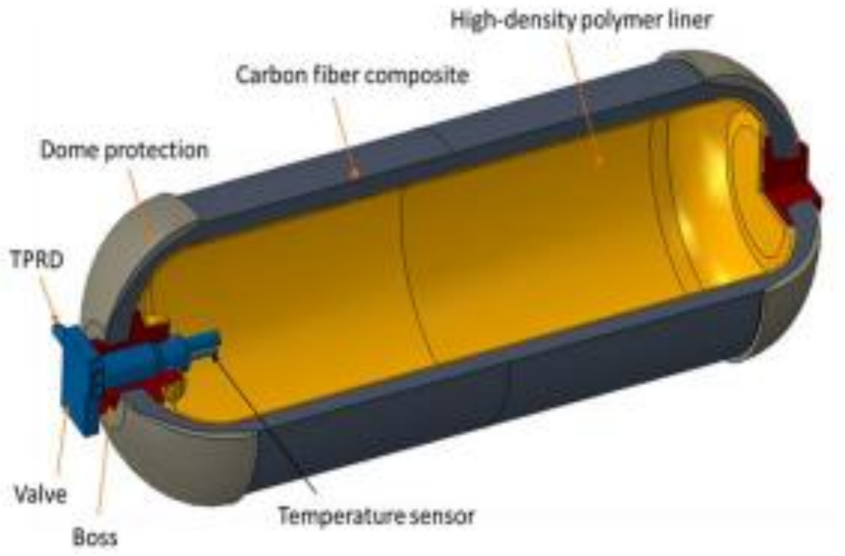
Overview: Strategy and Plans

HyMARC Hydrogen Materials Advanced Research Consortium

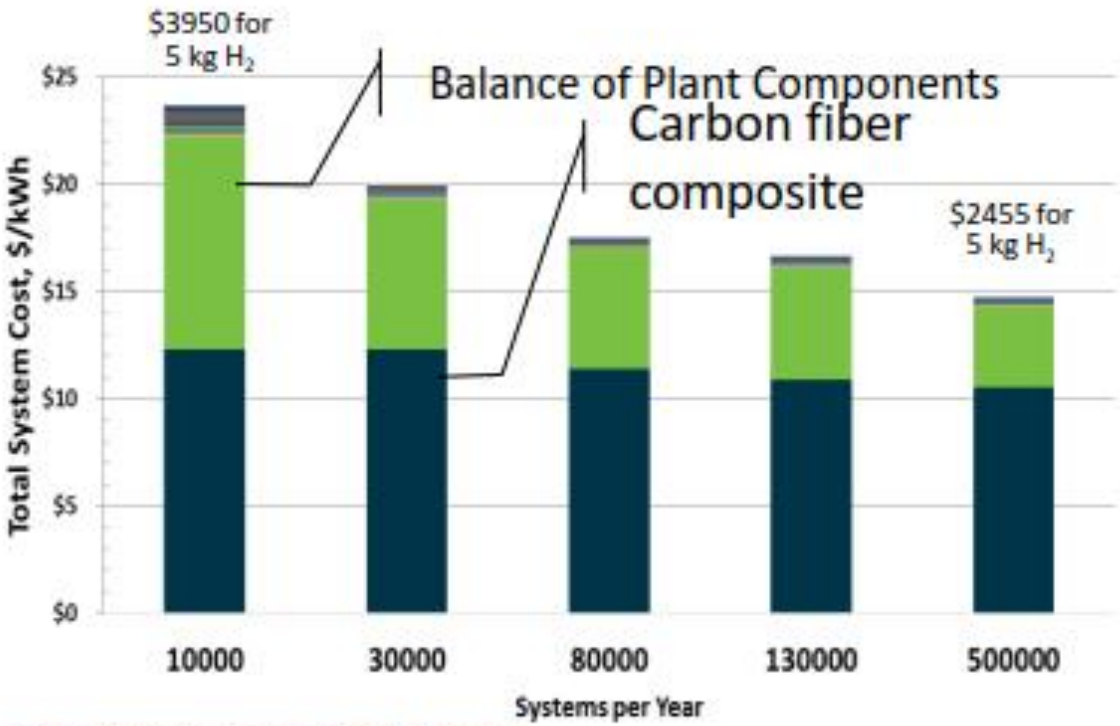
Enabling twice the energy density for onboard H_2 storage and $8/kWh

- **Expand beyond on-board LDVs**
  - Stationary, bulk storage
  - H_2 Carriers
- **Continue to increase collaborations**
  - Examples: H-Mat (cryogenic materials), VTO (NG storage), IACMI (C-fiber), NSF, DOD, others

ǂStorage costs based on preliminary 2019 storage cost record. Notes: Graphs not drawn to scale and are for illustration purposes only.



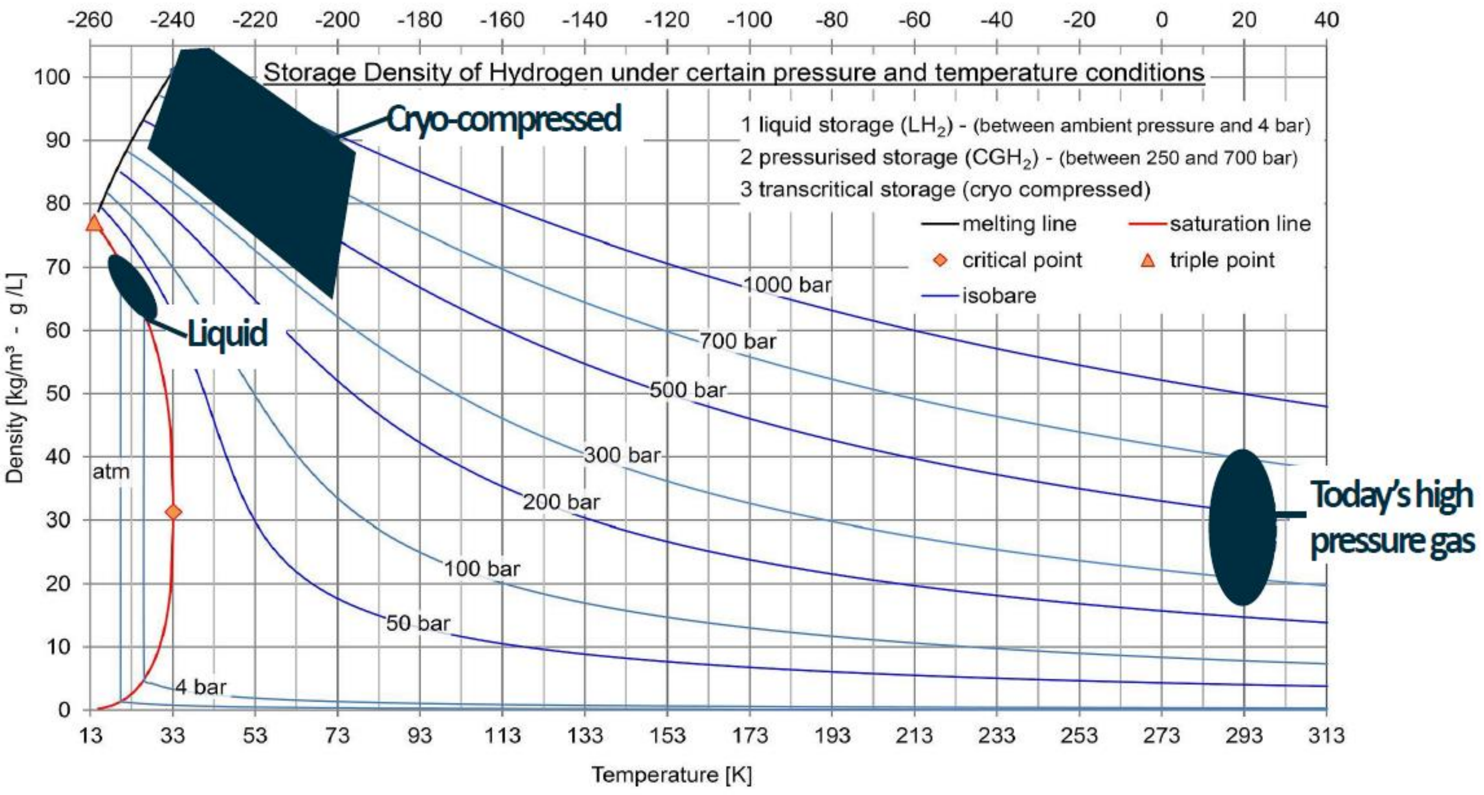
Carbon fibre is the dominating cost for Type IV hydrogen cylinders



Analysis for a single tank design

Cryocompressed hydrogen

- Storage of compressed and very cold hydrogen (<-200° C)
- Higher gravimetric energy density than 700 bar and liquid
- At least 7 days without boil-off
- US research indicates competitive:
  - gravimetric and volumetric densities
  - costs for such tanks for heavy and light vehicles
- Especially interesting when:
  - liquid hydrogen is used for the distribution to the refuelling station
  - vehicles are used frequently



ANL analysis (preliminary) shows potential for:

90-200% storage capacity increase	25% less cost (at 5,000 units/yr)	46% less carbon fiber composite

Hydrogen-rich liquids

- Easier to manage liquids than hydrogen
- The liquid is either reformed to hydrogen (plus by-products) or used directly in fuel cell system designed for such fuels
- Challenges:
  - Reformer – slow dynamics, H2 purity and cost
  - Direct methanol or ethanol fuel cell systems – low efficiency and durability t.b.c.
- If/when low-temperature SOFC become competitive, range extender solutions based on hydrogen-rich liquids are interesting

Other hydrogen storage alternatives

Hydrides

- Metal hydrides give high storage density but slow release/uptake of hydrogen
- Various types and combinations are investigated, borohydride is proposed by **Electriq** (formerly Terragenic)

Porous materials

- Zeolites, carbon structures and metal-organic frameworks (MOFs) may store hydrogen, preferably at low temperatures and high pressure.

	Terragenic	Compressed H_2	Li-Io
Bus range (km)	1,100	1,000	250
Re-charging (minutes)	5	5	300
Cost ($/KM)	0.25	0.55	0.35
Safety	Safe	Explosive	Flammable

Hydrogen infrastructure

- Refuelling stations exist in some areas
- The role of hydrogen depends on the energy system, pure renewable or fossil sources
- Convincing business models for hydrogen to vehicles are lacking
- Several pathway options discussed, among them:
  - Central production and transport by truck to station
  - Central production and pipeline transport
  - Local production near refuelling station
- Small stations give higher price per kilo hydrogen
- Time-consuming process to establish new stations
- Hydrogen production exists but **mainly not GHG neutral**

www.vatgas.se/tanka

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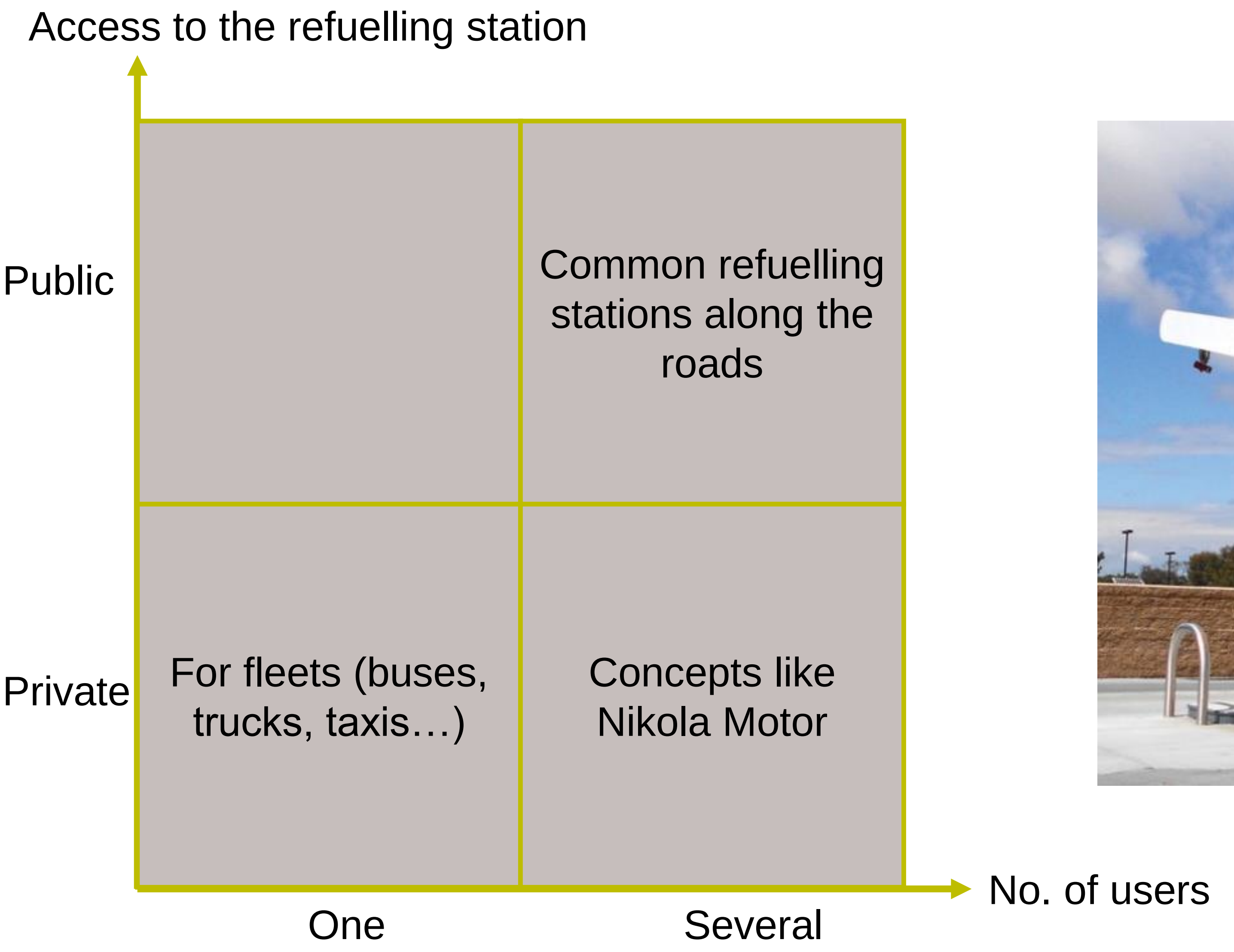
Hydrogen refuelling infrastructure



Lifetime of hydrogen tanks - revisited

700 bar

European Vehicle Type Approval: 5,000 cycles and up to 20 years

Lower pressures

Same rules as for natural gas tanks: If the tank is designed for 20 years in service, it must manage 20,000 cycles

700 bar

Cars. ~500 km range per fill. Assuming 300 km between refills, gives with 5,000 cycles a total distance of 1,500,000 km => tank lifetime in terms of cycles no problem!

Trucks and buses. Daily refuelling gives +13 years tank life.

Lower pressures

Tank life time no issue.

Hydrogen tanks and batteries

The cost logic differs:

Hydrogen tanks deliver the same capacity during its life. To maximize delivered energy, full refuelling cycles are preferable.

Batteries lose capacity over time, depending on usage. The use of a small state of charge window and frequent recharging extends life time and the total amount of delivered energy.

Fuel cells and batteries

The combination of hydrogen fuel cells and batteries might deliver ’the best of both worlds’:

- Low-cost electricity for most trips and a share of the total distance driven
- Sufficient range and quick refuelling
- Fuel flexibility (limited, but still valuable in an introduction phase)
- Enhanced life time of fuel cell and battery systems

Weight and cost might be among the disadvantages.

Concluding summary

- Compressed hydrogen at 700 bar dominates today
- The life time of tanks for 700 bar is sufficient for almost all car applications and several heavy vehicle applications
- Among the alternatives to compressed hydrogen, cryo-compressed hydrogen appears to be one of the main candidates, others are different kinds of liquid fuels
- Apart from the vehicle type and application, the surrounding energy system has implications on the choice of hydrogen storage

Cost of hydrogen tanks

- More expensive than petrol or diesel tanks
- Less expensive than batteries per stored kWh
- Given the durability, even more competitive per kWh delivered over the life time

But comparison is not fair, as fuel cells are needed to deliver electricity