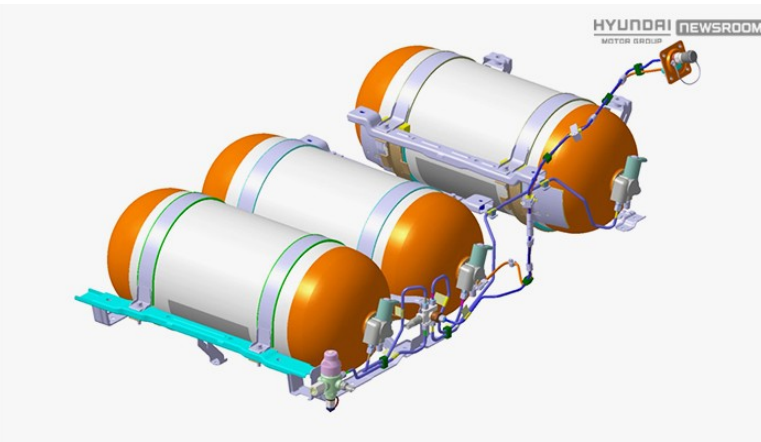


Hydrogen Storage Methods

From contemporary

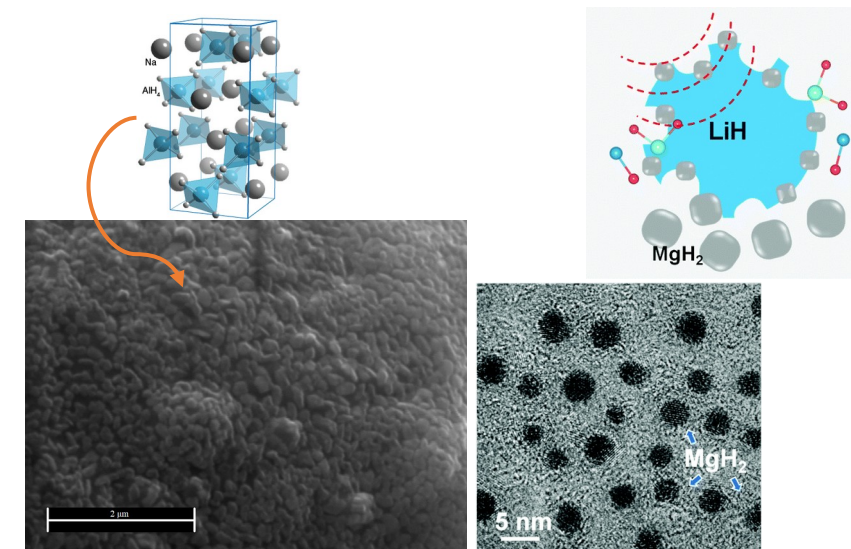


NASA/Kim Shiflett



Hyundai motor group

To under R&D



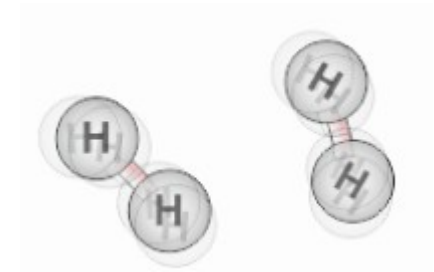
Energy Environ. Sci.,
2021,14, 2302-2313

Rasmus Palm

rasmus3@kth.se

Hydrogen as a fuel

- Low density at ambient conditions: $0.08988 \text{ g}_{\text{H}_2}/\text{L}$
- Low volumetric energy content: 3 Wh/L vs 9500 Wh/L (gasoline)
vs 11 Wh/L (methane)
- High gravimetric energy content: 33.3 kWh/kg vs 12.9 kWh/kg (gasoline)
vs 15.4 kWh/kg (methane)
- High diffusion coefficient in air: $0.61 \text{ cm}^2/\text{s}$ vs $0.16 \text{ cm}^2/\text{s}$ for methane
- Main problem of H_2 storage: Increasing density of H_2 at low cost, high energetical efficiency and over many use cycles in the same system

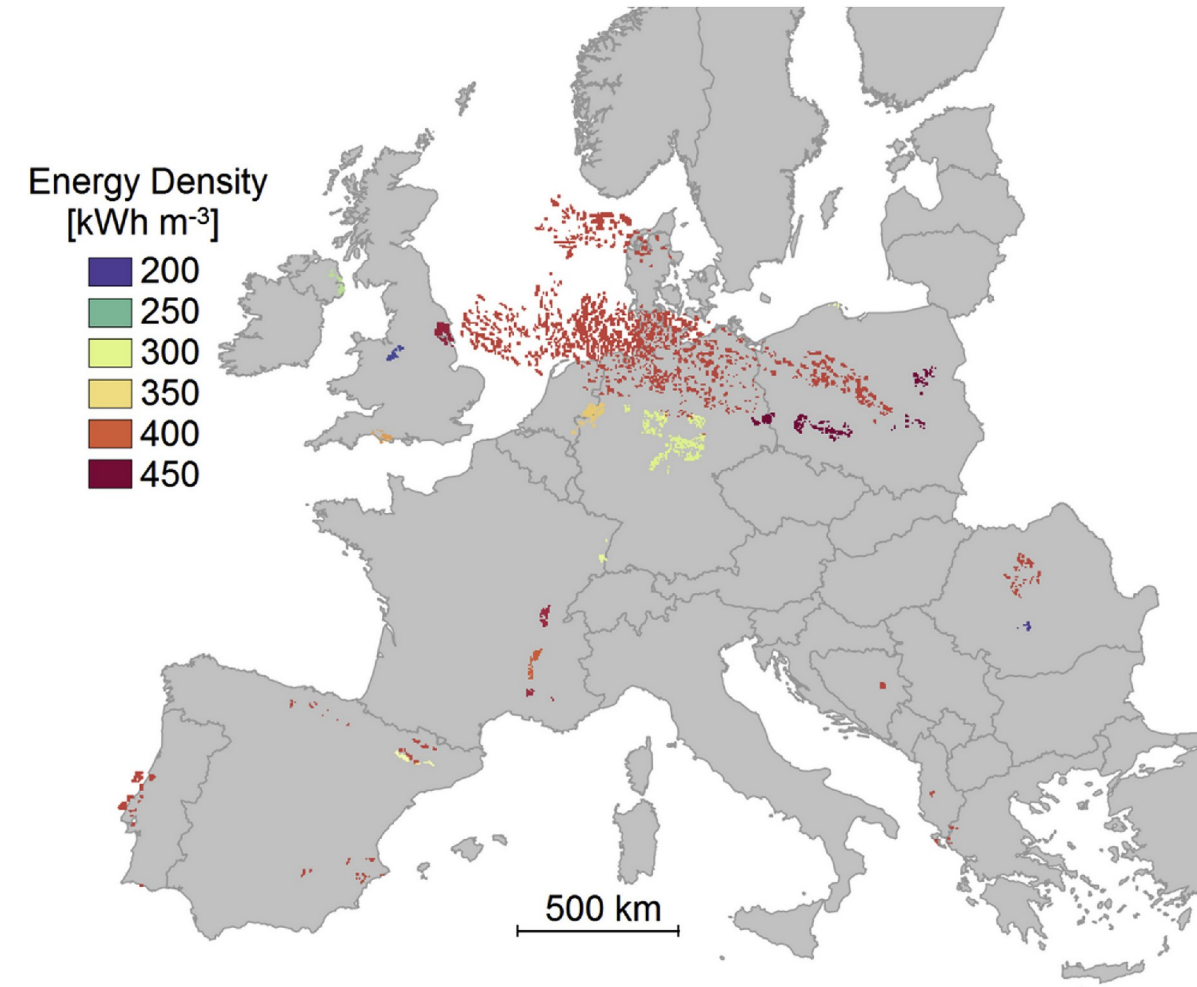


Contemporary hydrogen storage methods

- Contemporary:
 - Pressurized ($41 \text{ g}_{\text{H}_2}/\text{L}$ at 273.15 K and 700 bar)
 - Liquefied ($70 \text{ g}_{\text{H}_2}/\text{L}$ at 20 K)
- Likely to be applied in close future:
 - Low-pressurized (up to $14 \text{ g}_{\text{H}_2}/\text{L}$) in salt caverns
 - High-pressurized (up to $52 \text{ g}_{\text{H}_2}/\text{L}$ at 273.15 K and 1000 bar)



<https://www.fibatech.com/2014/11/24/type-2-hydrogen-vessel/>

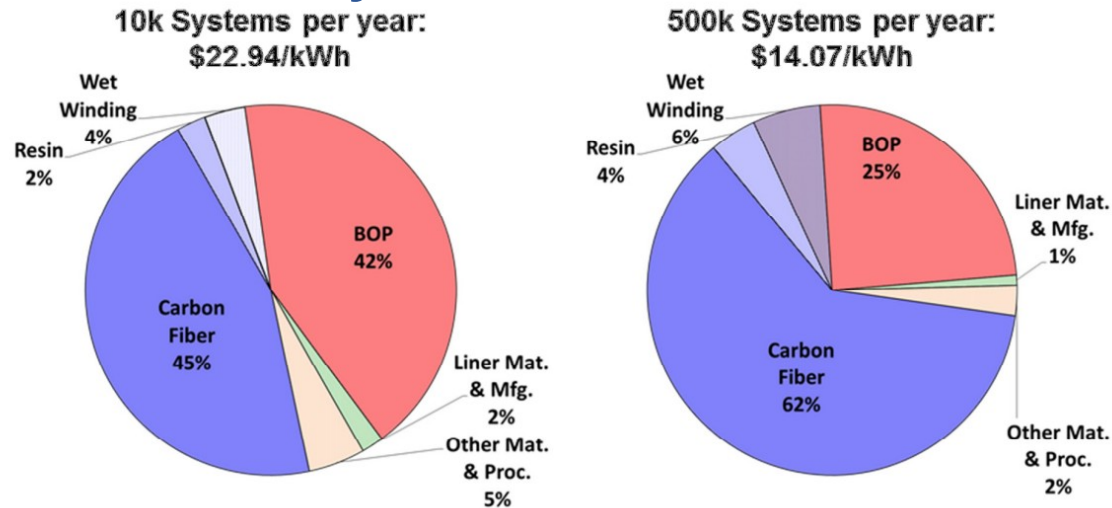


D. G. Caglayan, et al. Int. J. Hydrogen Energy 45, **11** (2020)

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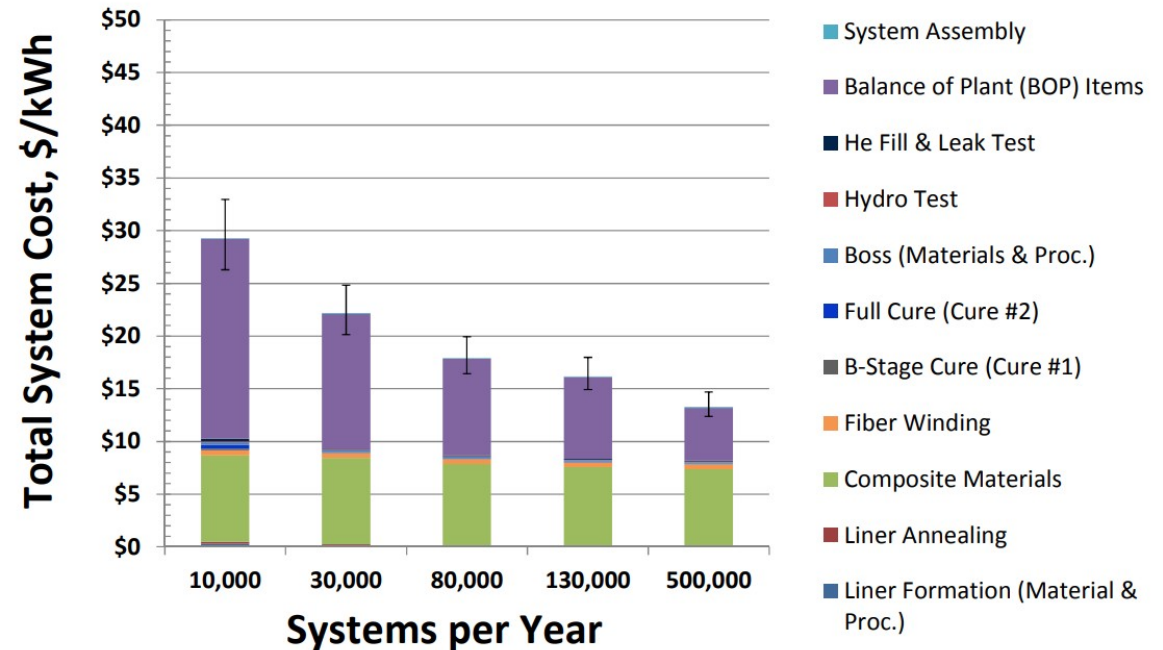
Production price of pressurised H₂ tank for mobile applications

- 700 bar H₂ (Toyota):
 - 147 L, 5.6 kgH₂
 - Considerable weight of carbon fibre (up to 107 kg)
 - From 4300 to 2650 USD/system



- 350 bar H₂:
 - 245 L, 5.6 kgH₂
 - Suppliers did not reflect economies of scale

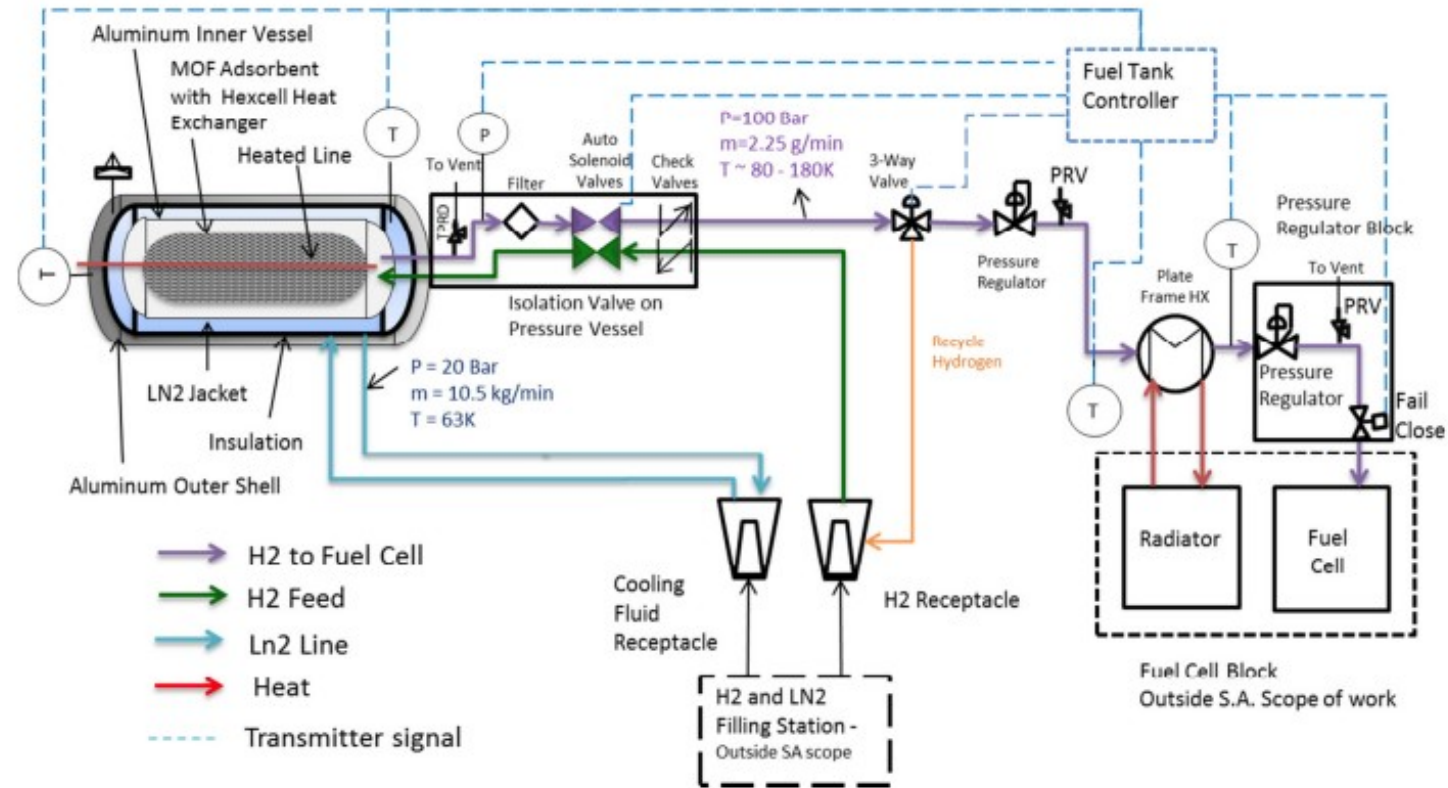
35MPa Compressed Gas Storage System
Single tank holding 5.6kgH₂ usable, cost in 2007\$



B. D. James et al., Final Report: Hydrogen Storage System Cost Analysis, 2016, Stratetic Analysis Inc.

Production price of cryosorption tank for mobile applications

- 5.6 kg of H₂ stored at 100 bar and 77 K
- Adsorbent (metal-organic framework):
 - From 15 to 25% of total cost
 - 32 kg
 - 165 L Al storage vessel
- From 33.5 to 16.2 USD/kWh

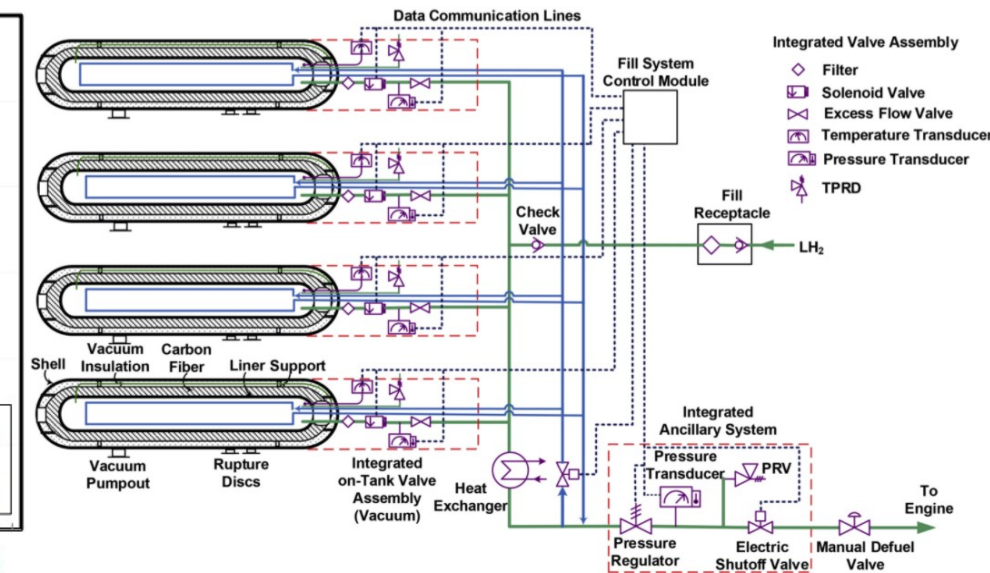
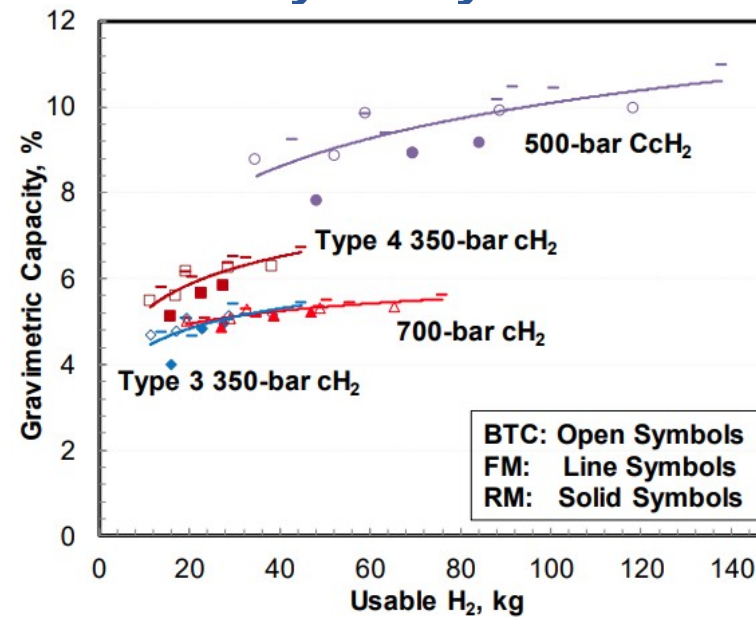
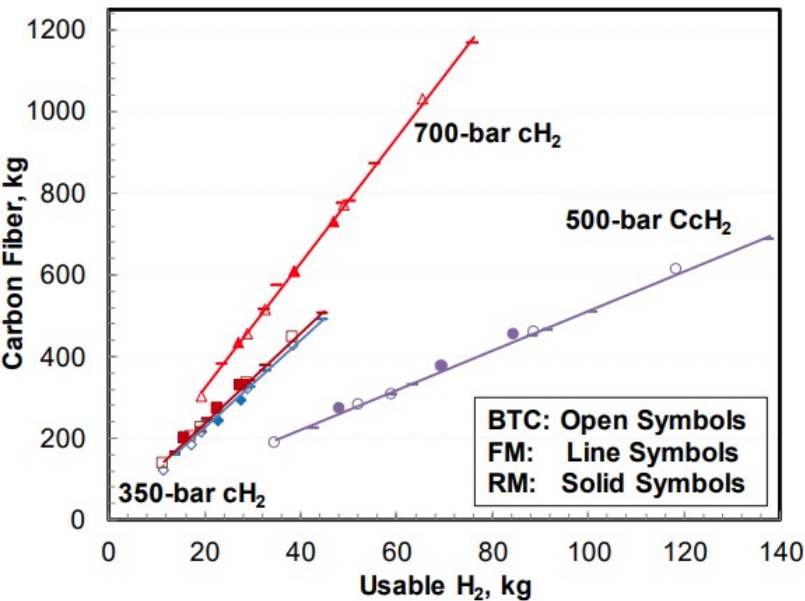
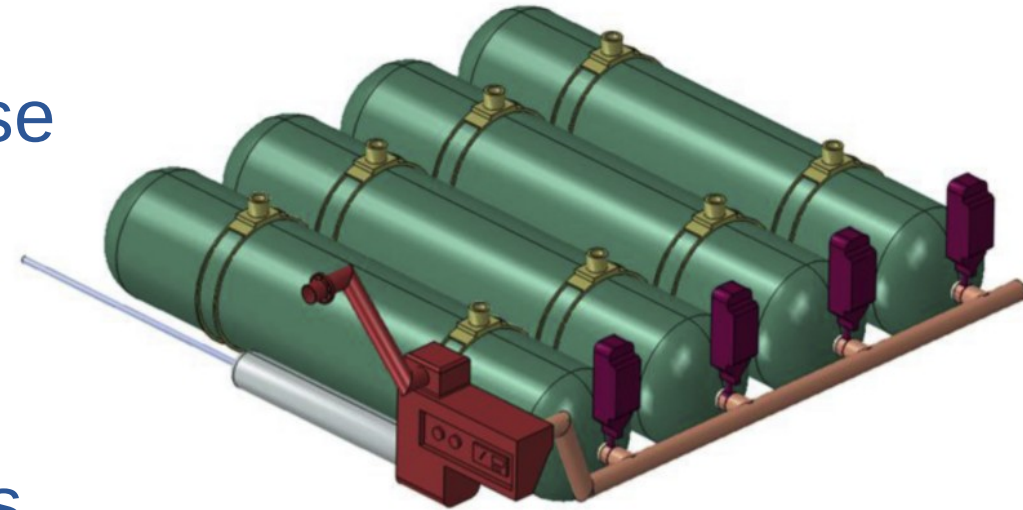


		Total Cost (2014 \$/system)				
Name	Quantity	10,000	30,000	80,000	100,000	500,000
TOTALS =		\$6,298.89	\$4,645.80	\$3,822.44	\$3,675.59	\$3,051.65

B. D. James et al., Final Report: Hydrogen Storage System Cost Analysis, 2016, Stratetic Analysis Inc.

Cryocompression of H₂

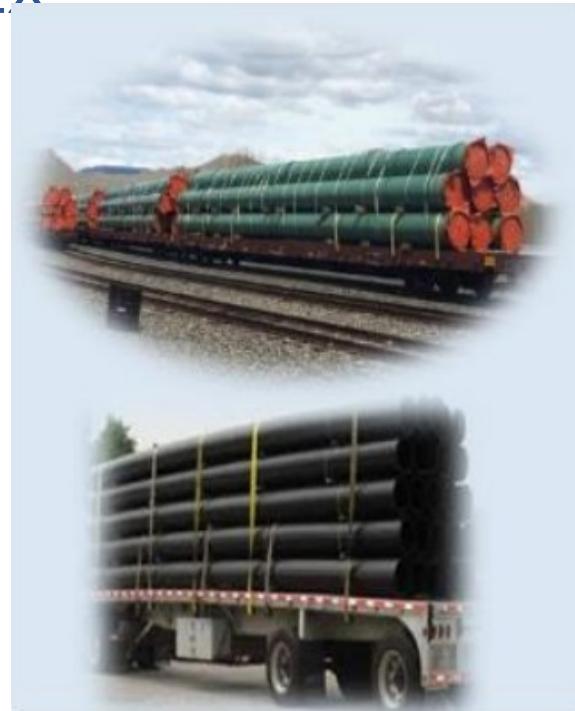
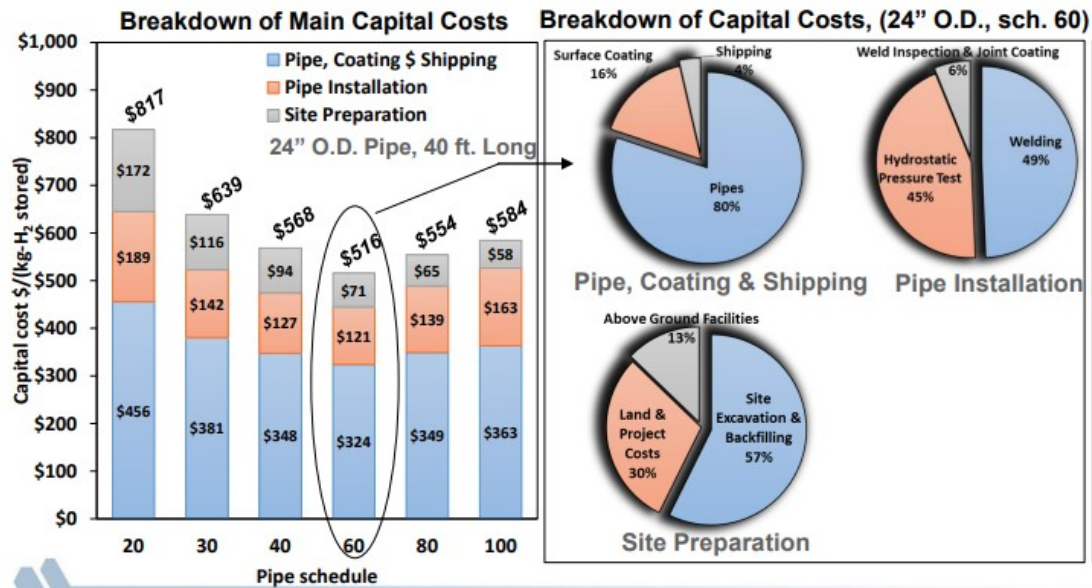
- Storage around 77 K and 500 bar to increase volumetric density
- Decreased need of carbon fibre for same amount of H₂
- Designed for medium and heavy-duty trucks



R. K. Ahluwalia et al., 2019, System Level Analysis of Hydrogen Storage Options, Argonne National Laboratory
R. K. Ahluwalia et al., Int. J. Hydrogen Energy 43 (2018) 10215

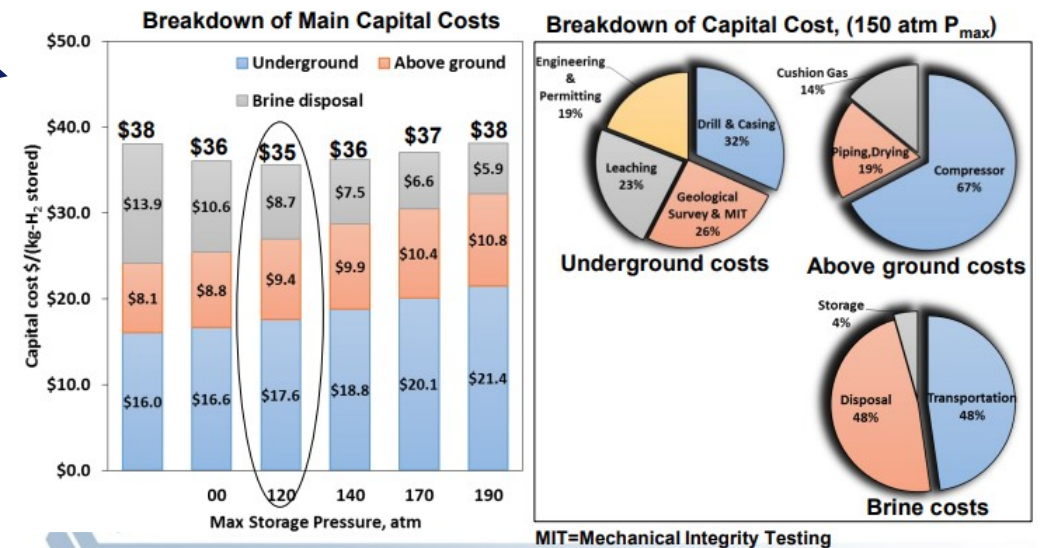
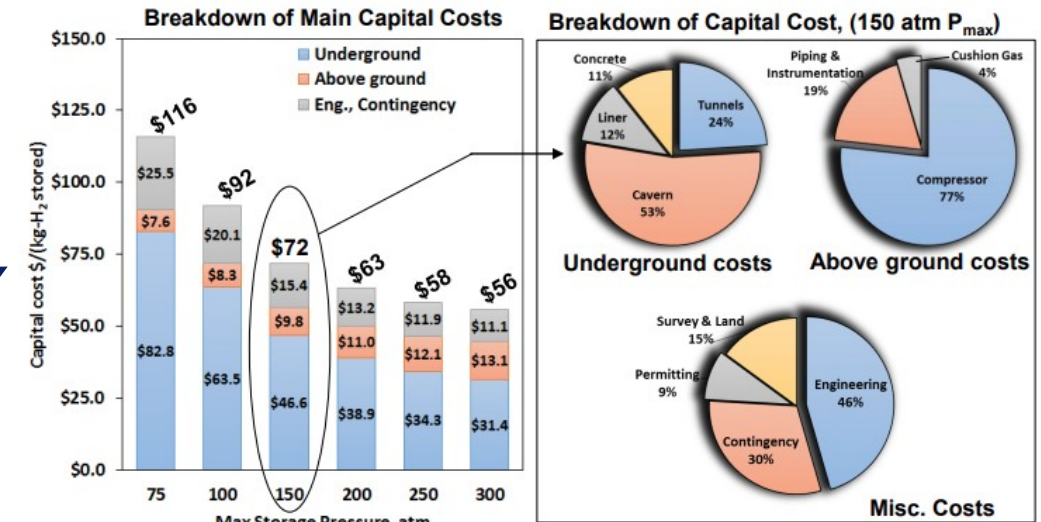
Price of underground H₂ storage

- Underground pipes:
 - 7 - 100 bar
 - 90% working capacity
 - 500 t-H₂ storage and 50 tpd usage
 - 2.17 USD/kgH₂, from which 95% CAPEX
 - Price based on ~6.5 years of operation

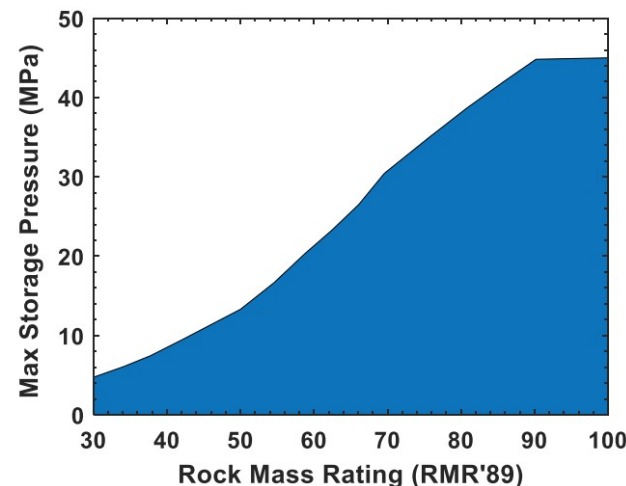


Price of underground H₂ storage

- Salt and lined rock caverns:
 - Geographically limited
 - 500 t-H₂ storage and 50 tpd
 - Lined rock:
 - 0.36 USD/kgH₂, 85% CAPEX
- Salt cavern:
 - 0.21 USD/kgH₂, 75% CAPEX



MIT=Mechanical Integrity Testing



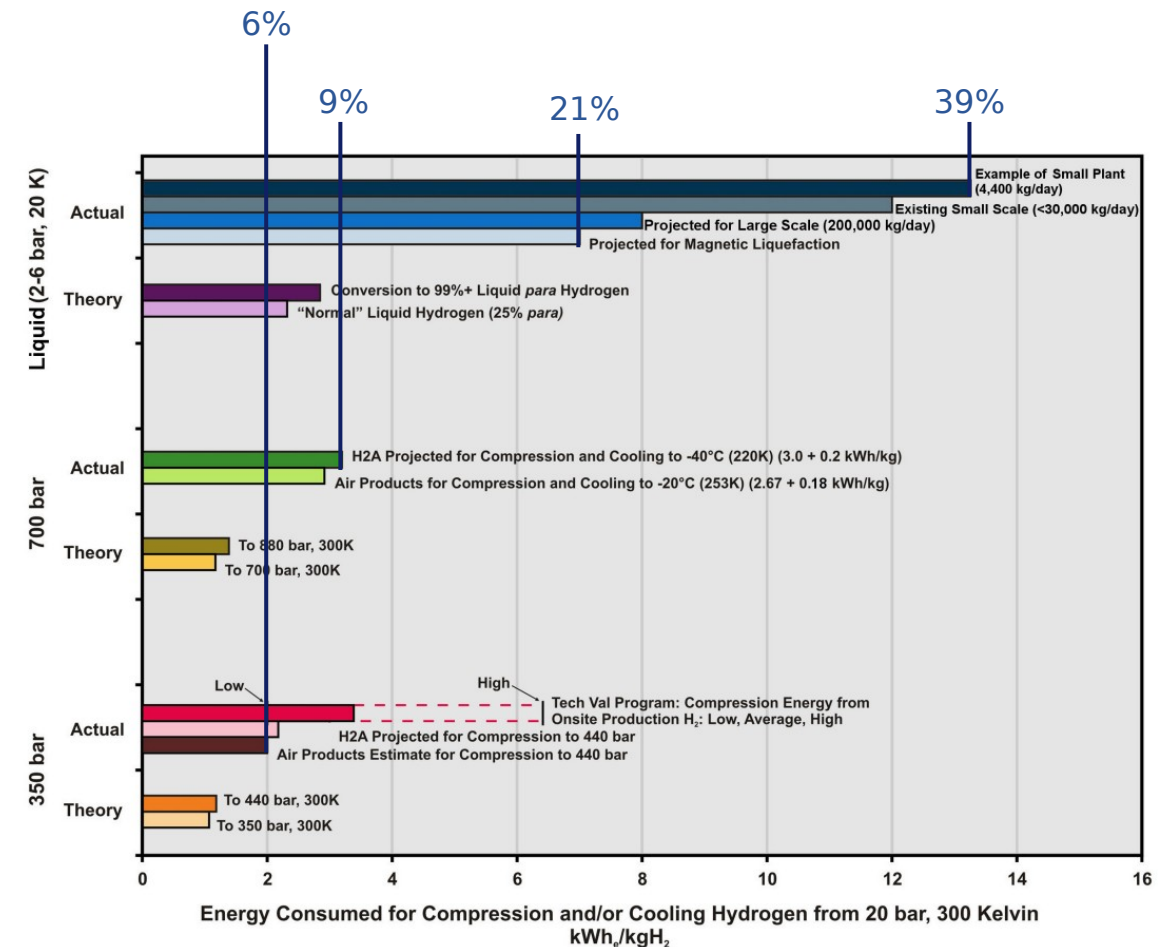
R.K. Ahluwalia et al., 2019, System Level Analysis of Hydrogen Storage Options, Argonne National Laboratory

H₂ storage and transport fuel efficiencies

- Converting H₂ to liquid or alternative fuels causes considerable efficiency losses
- Production involves converting H₂ to transport form

Storage method	Production	Transportation	Utilization	Total
Liquid H ₂ (direct comb.)	55% ^a	95% ^b	55% ^c	28%
Liquid H ₂ (fuel cell)	55%	95%	65% ^d	34%
Liquid H ₂ (fuel cell)	73% ^{5)e}	95%	65%	45%
MCH (dehydrogenation, direct comb.)	85% ^f	100%	26% ^g	25%
MCH (fuel cell)	85%	100%	45% ^h	38%
NH ₃ (direct combustion)	58% ⁱ	98% ^j	60% ^k	34%
NH ₃ (direct fuel cell)	58%	98%	65%	37%
NH ₃ (decomposition, fuel cell)	58%	98%	60% ^l	34%
NH ₃ (direct fuel cell)	67% ^m	98%	70% ⁿ	46%

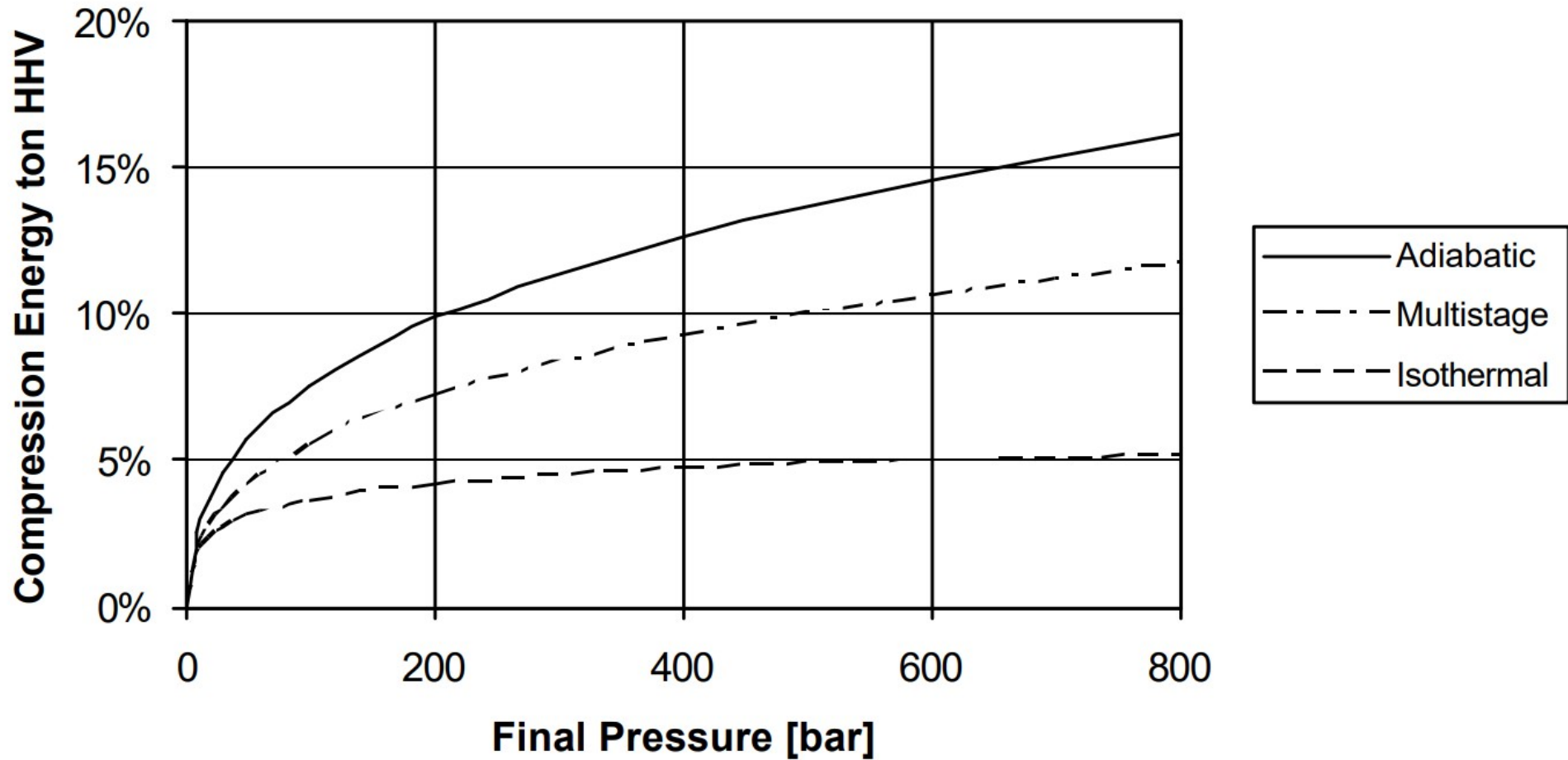
A. T. Wijayanta et al., Int. J. Hydrogen Energy 44 (2019) 15026



M. Gardiner, Energy requirements for hydrogen gas compression and liquefaction as related to vehicle storage needs, 2009, DOE Hydrogen and fuel Cells Program Record

Lower pressure, higher efficiency

- If H_2 is stored at low enough pressures (< 35 bar) no additional compression after production is required

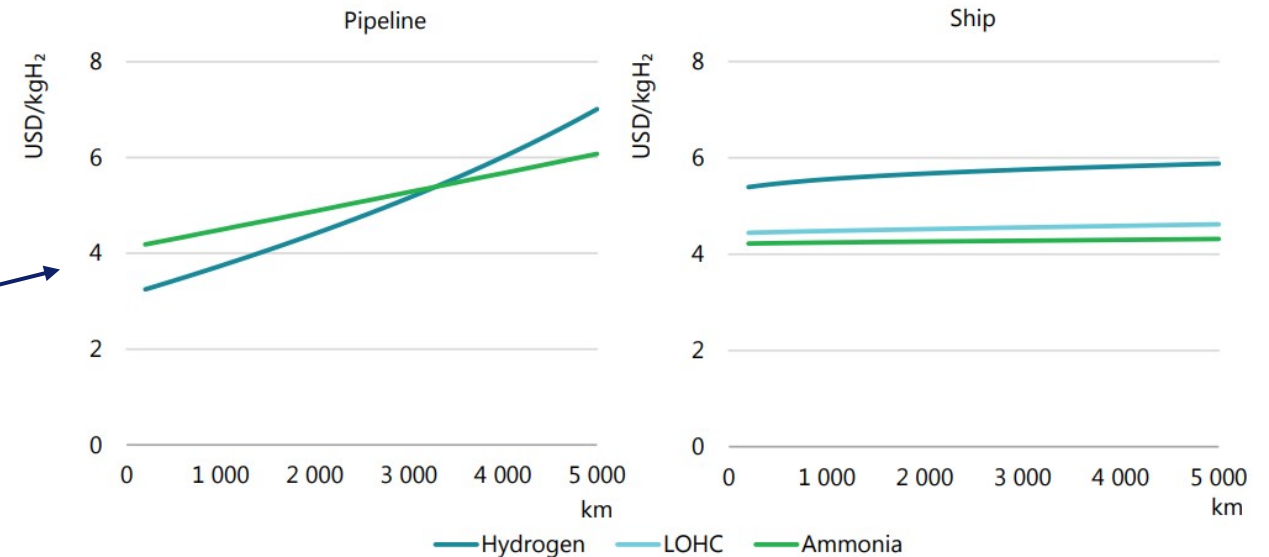


U. Bossel et al., Energy and the hydrogen economy, US DOE, EERE

H₂ based transport fuels

- Ammonia and LOHC potential alternatives to gaseous or liquid H₂
- Price increase with increased distance correlates with decrease in efficiency
- Inland pipelines < 3500 km with H₂ and ammonia on ships in case of > 1500 km cheaper
- Includes a 3 USD/kgH₂ production price

	Liquid hydrogen	Ammonia	LOHC (MCH)
Hazards**	Flammable; no smell or flame visibility	Flammable; acute toxicity; precursor to air pollution; corrosive	Toluene: flammable; moderate toxicity. Other LOHCs can be safer.
Conversion and reconversion energy required***	Current: 25–35% Potential: 18%	Conversion: 7–18% Reconversion: < 20%	Current: 35–40% Potential: 25%
Technology improvements and scale-up needs	Production plant efficiency; boil-off management	Integration with flexible electrolyzers; improved conversion efficiency; H ₂ purification	Utilisation of conversion heat; reconversion efficiency
Selected organisations developing supply chain	HySTRA; CSIRO; Fortescue Metals Group; Air Liquide	Green Ammonia consortium; IHI Corporation; US Department of Energy	AHEAD; Chiyoda; Hydrogenious; Framatome; Clariant



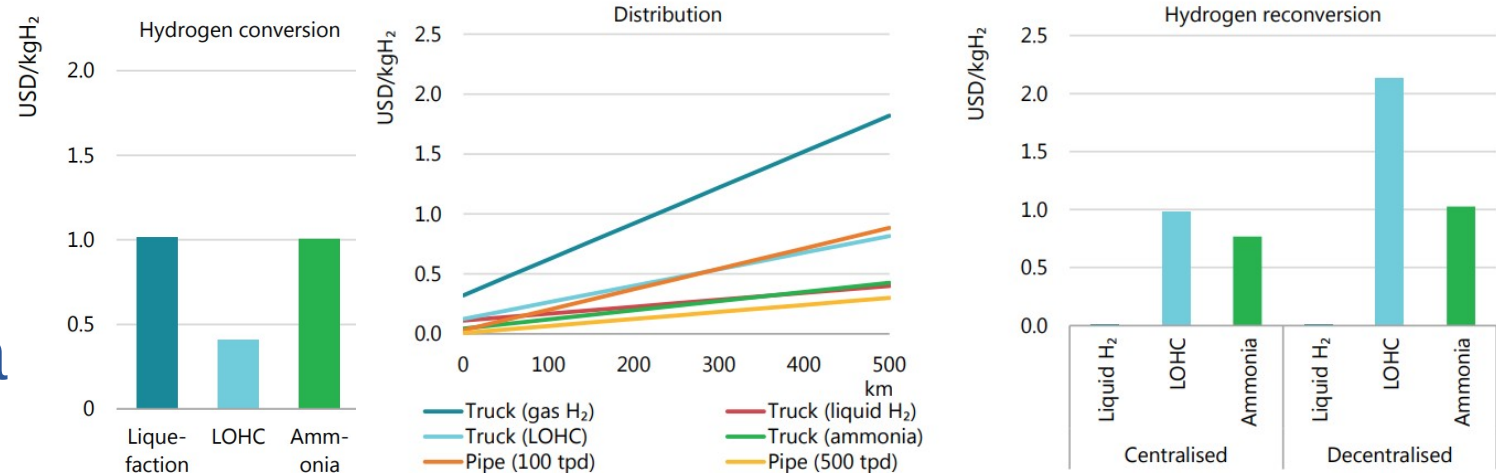
The Future of Hydrogen Seizing today's opportunities, IEA Technology report 2019

H₂ based transport fuels

- In case of liquid H₂, ammonia and liquid organic hydrogen carriers (LOHCs) high cost is associated with conversion and reconversion
- In case of ammonia and LOHCs, reconversion cost involves H₂ purification
- For short distances building H₂ pipelines or refitting natural gas pipelines for H₂ a viable solution
- Considerable CAPEX of pipelines

Technology	Parameter	Units	Hydrogen	LOHC	Ammonia
Pipelines ¹	Lifetime	years	40	-	40
	Distance	km	Function of supply route		
	Design throughput	ktH ₂ /y	GH ₂ : 340	800	240
	Gas density	kg/m ³	7.9	-	-
	Gas velocity	m/s	15	-	-
	CAPEX/km	USD million/km	1.21	2.32	0.55
	Utilisation	%	75%	75%	75%

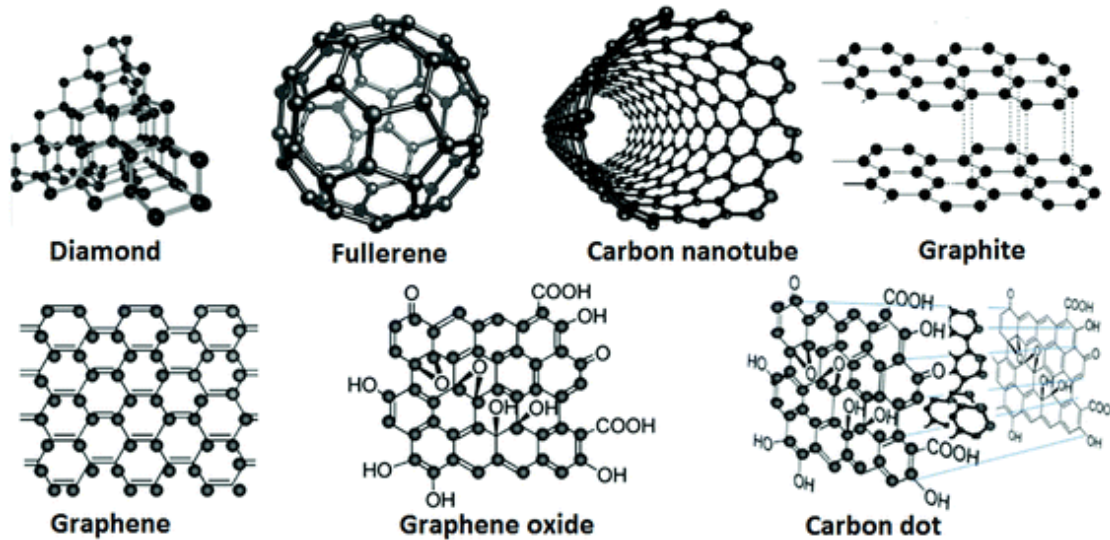
The Future of Hydrogen Seizing today's opportunities, IEA Technology report 2019, Assumptions annex
S. Baufumé et al., Int. J. Hydrogen Energy 38 (2013) 3813



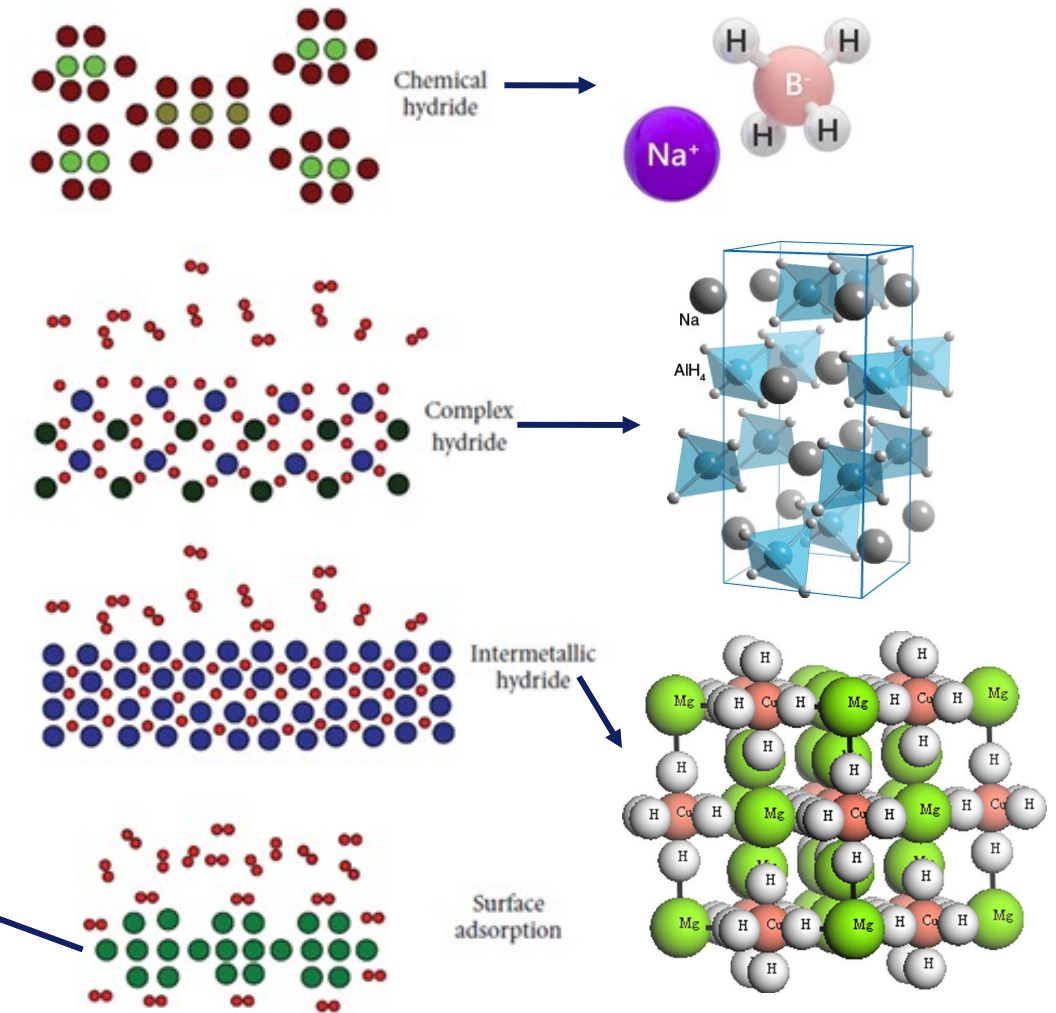
The Future of Hydrogen Seizing today's opportunities , IEA Technology report 2019

Hydrogen storage methods under development

- Under research:
 - Chemically bound (up to $150 \text{ g}_{\text{H}_2}/\text{L}$ reversibly)
 - Advanced adsorption systems:
 - Increase of volumetric H_2 density
 - Adsorption capability near-ambient temperatures
 - Optimised adsorption interactions and enthalpy of adsorption



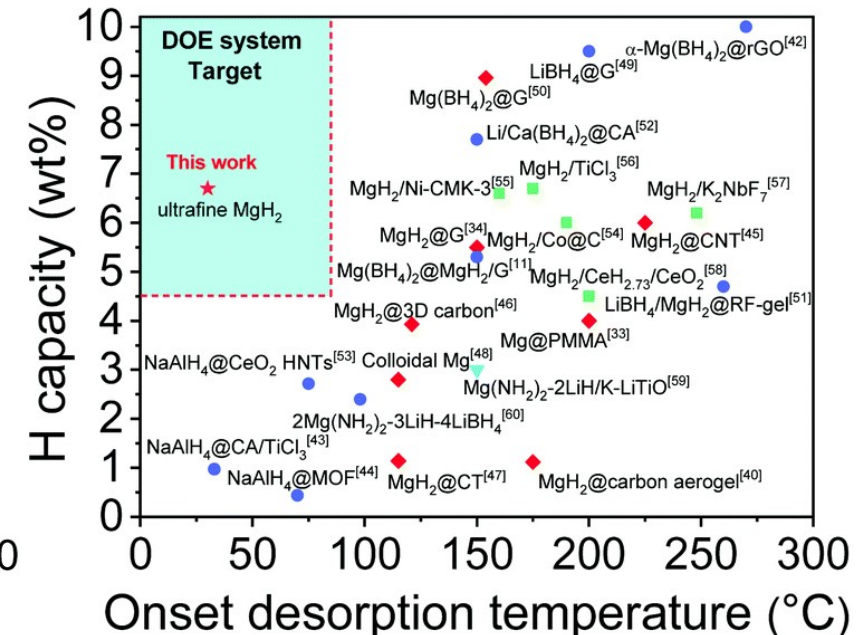
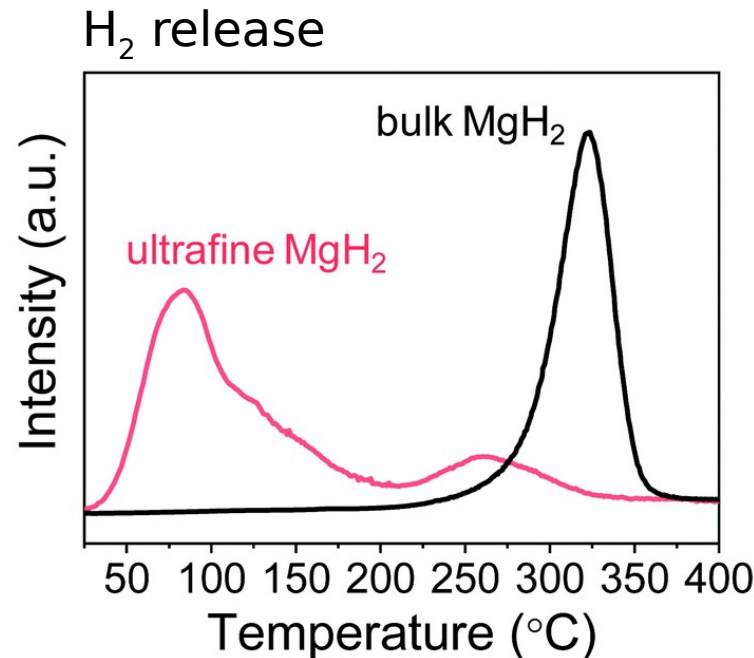
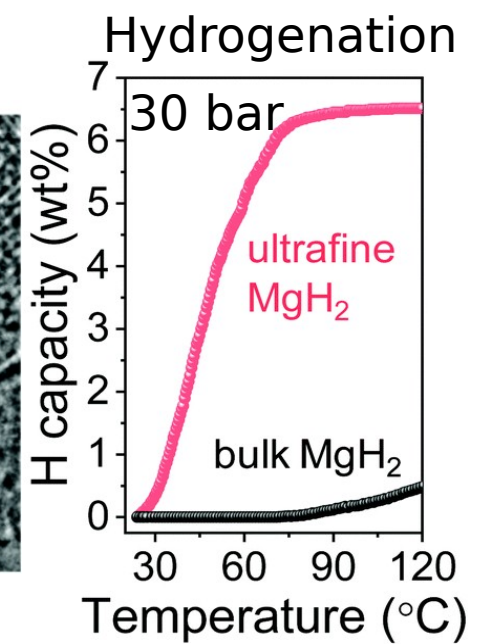
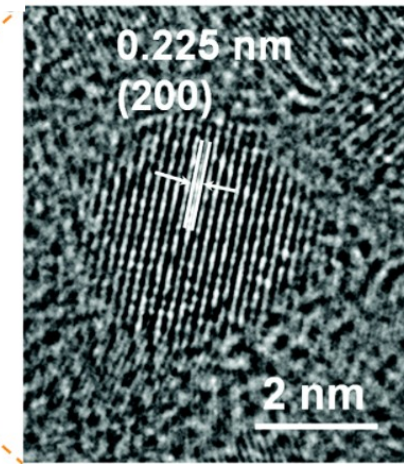
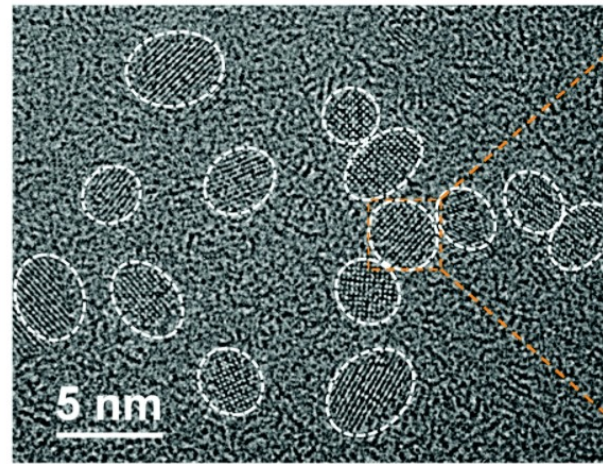
Q.-L. Yan et al. Nanoscale 8 (2016) 4799



M.U. Niemann et al. J. Nanomater. 2008, Article ID 950967

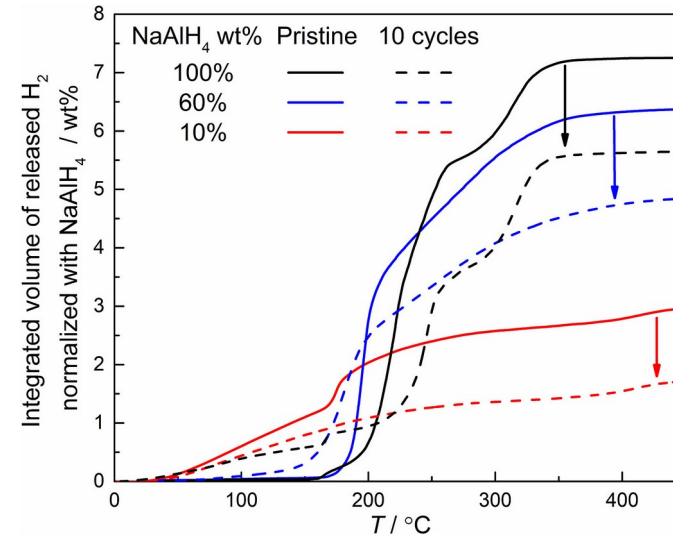
Ultrafine hydrides

- Nanoparticulate (4-5 nm) MgH_2 :
 - $\text{MgCl}_2 + 2\text{LiH} \rightarrow \text{MgH}_2 + 2\text{LiCl}$ (in THF)
 - Ultrasound for stimulation of formation
 - H_2 release and uptake at low T -s and pressures
 - 65.6 $\text{g}_{\text{H}_2}/\text{L}$ from pressed pellets
 - At 80 °C rehydrogenation within 20 min
 - Very low equilibrium pressures near ambient temperature

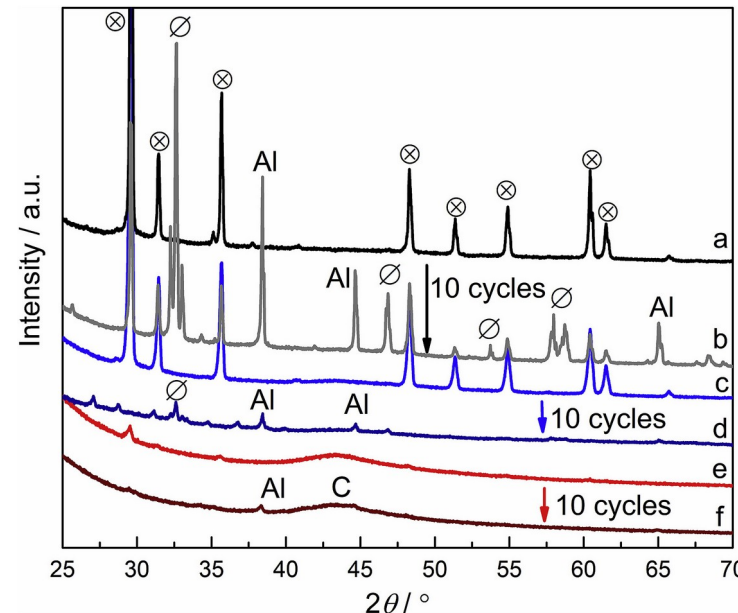


Nanoconfinement of hydrides at UT

- Bulk hydrides have various limitations application-wise
- Confinement of hydrides in the porous structure of carbons:
 - Considerably lowers the temperature of H_2 release
 - Supports the formation of amorphous/small particles during cycling
 - Inhibits the formation of crystalline Al phase



Degradation of material during de-/hydrogenation cycles a considerable problem



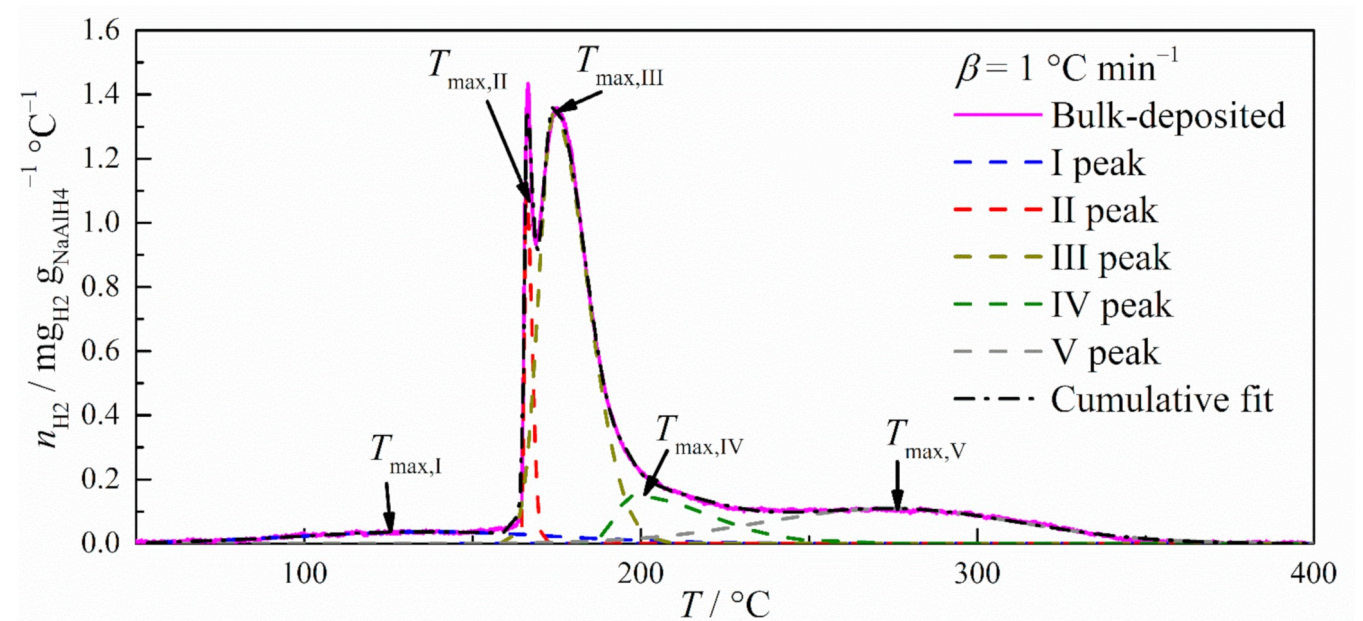
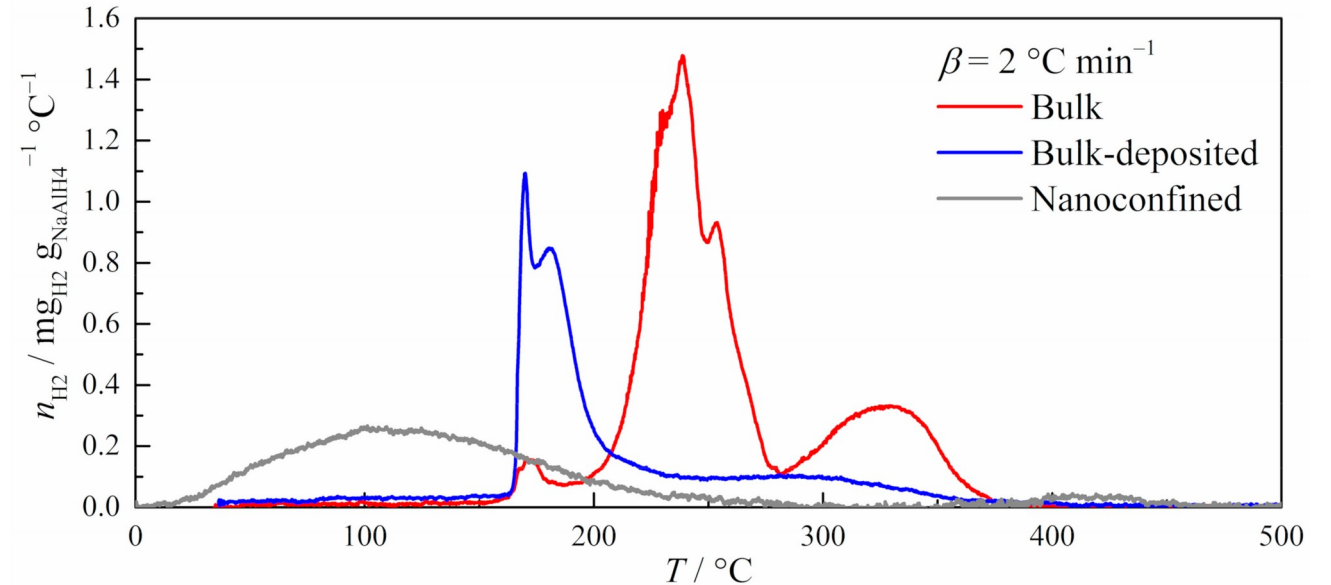
Bulk $NaAlH_4$

Bulk-deposited $NaAlH_4$

nanoconfined $NaAlH_4$

Nanoconfinement of hydrides at UT

- Multiple-step H_2 process
- H_2 release step from truly nanoconfined hydride:
 - Very quick H_2 release kinetics
 - H_2 release near ambient or at ambient conditions
 - H_2 release at suitable conditions for PEMFC applications





European Union
European Regional
Development Fund



Investing
in your future

Acknowledgments

ARCHIMEDES



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Department of Geology

- Jaan Aruväli

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Thank You! Questions?

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