GKN HYDROGEN

Hydrogen Solid State Storage

Ivan Gruber
Rome, November 2022

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Overview and market trends

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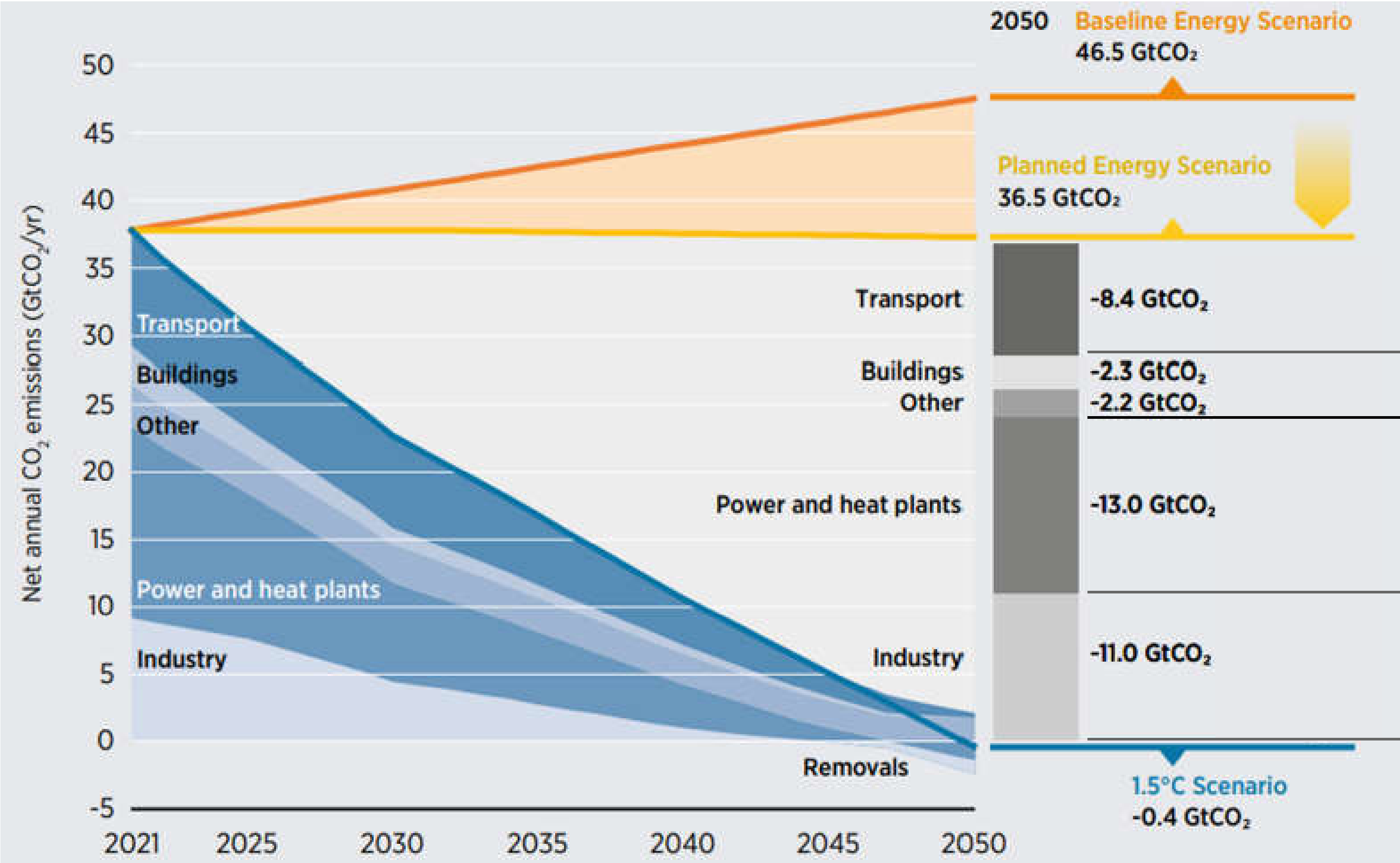
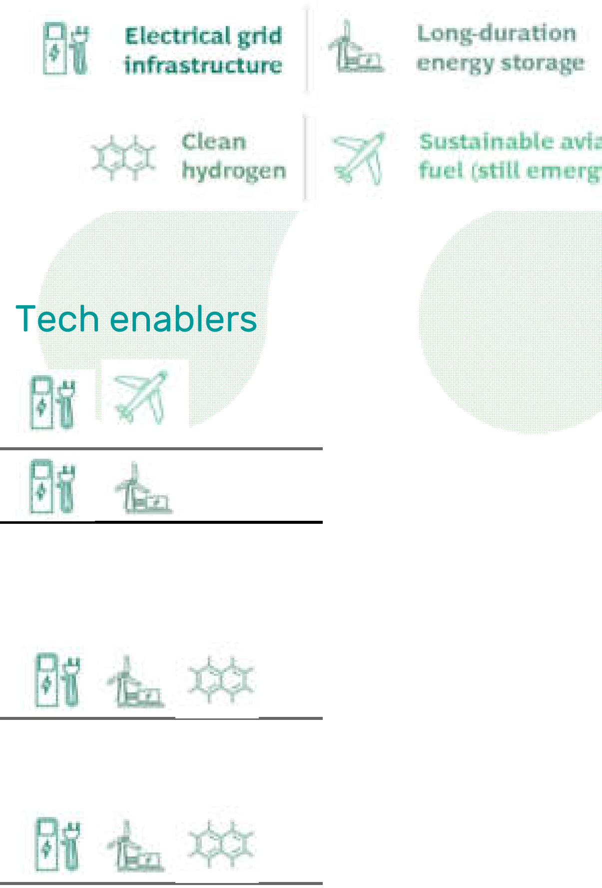
Climate change mitigation actions globally widely agreed

Negative emissions needed in 2050 to meet 1.5°C scenario





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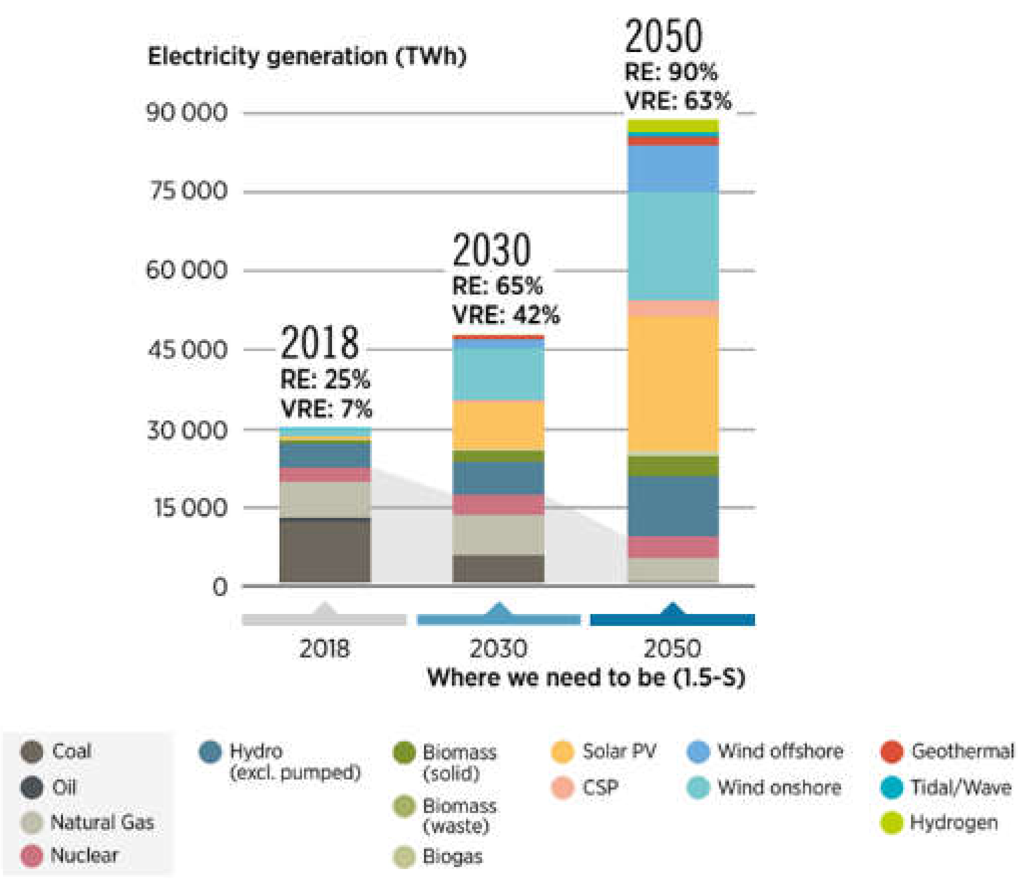
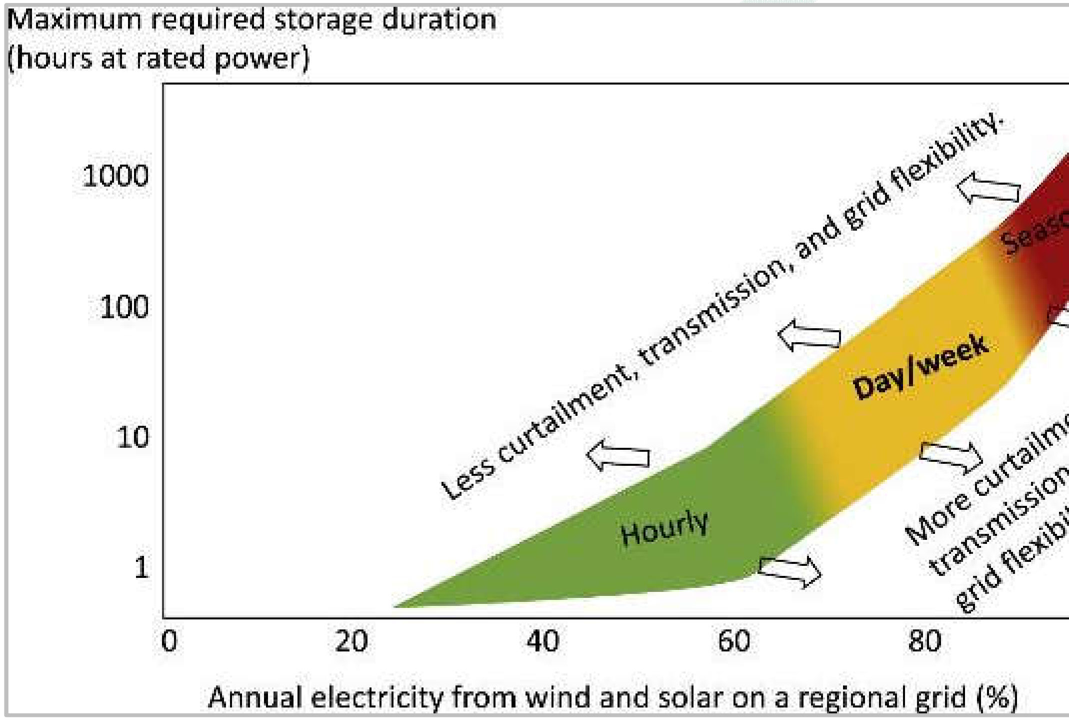
IRENA WETO 2021

Significant increase in electricity generation expected

63% of total electric energy will be not dispatchable



Source: IRENA WETO 2022

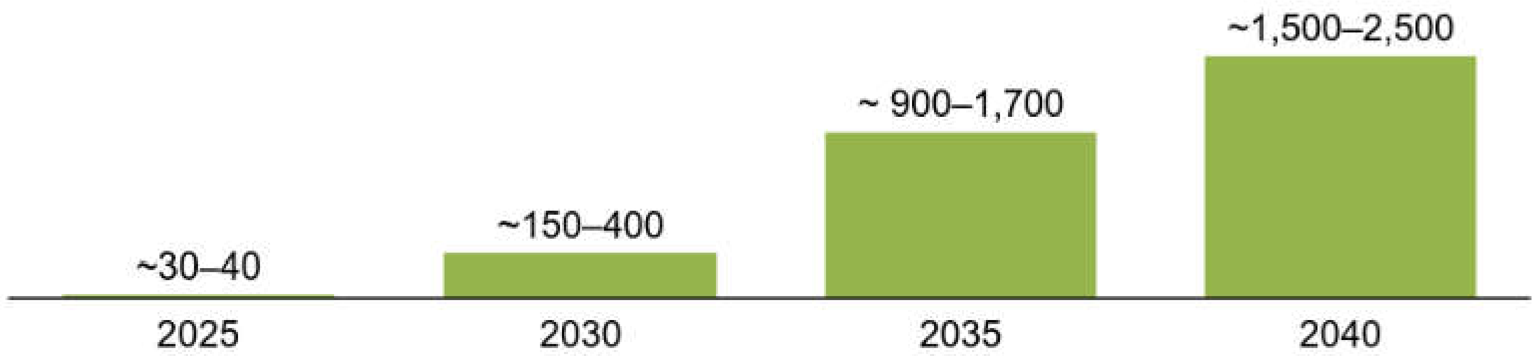


Source: Joule, 15 January 2020

Exponential growth of storage market over the next years

Long duration energy storage total addressable market

GW
Cumulative installed power capacity[1]



	2025	2030	2035	2040
TWh Cumulative installed energy capacity[1]	~1	~5–10	~35–70	~85–140
$ Cumulative capex investment[1], USD bn	~50	~200–500	~1,100–1,800	~1,500–3,000

Source: LDES council

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GKN Hydrogen Offering

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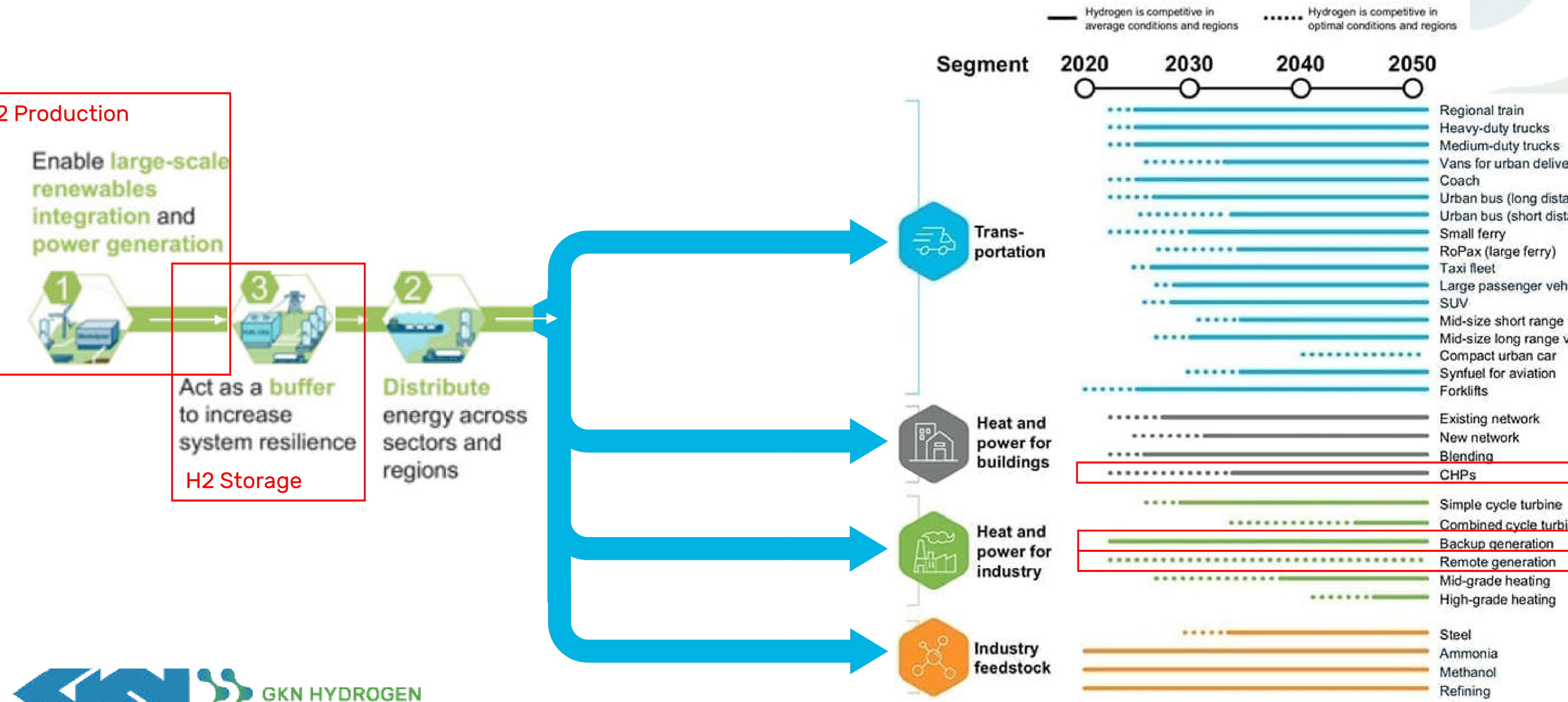
Hydrogen will help to decarbonize different segments

Our modular component portfolio built around our storage will target several applications alongside the H2 value chain



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HY2 Product Suite

HY2MINI

H_2 10-25 kg

170-425 kWh electrical

HY2MEDI

H_2 30-120 kg

0,5-2 MWh electrical

HY2MEGA

H_2 +250 kg

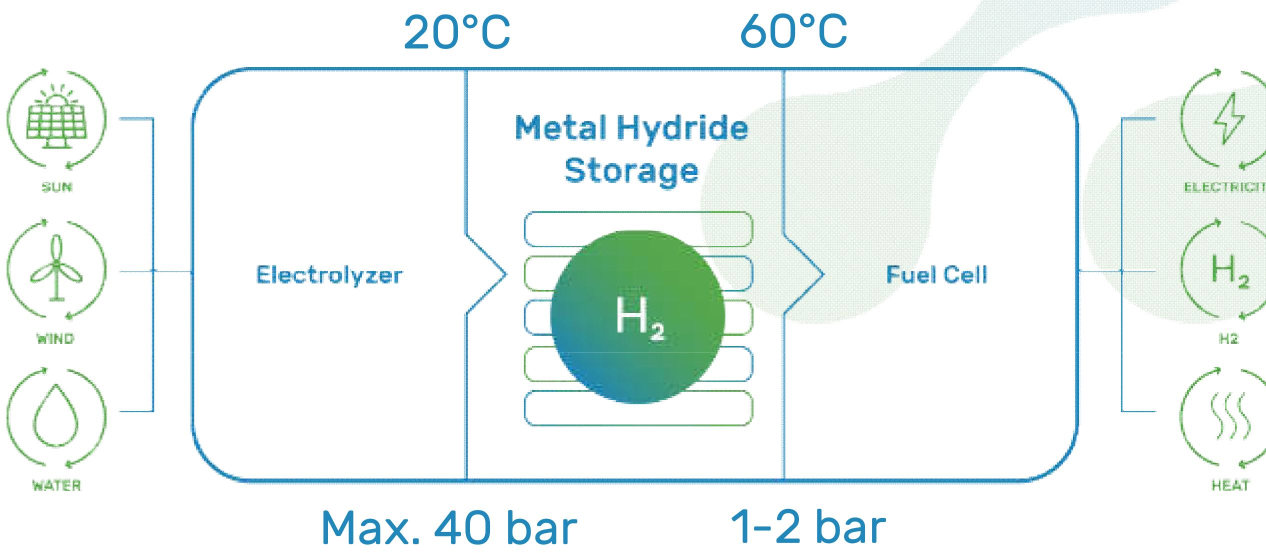
8,3 MWh Energy

SYSTEMS Plug and Play

STORAGE

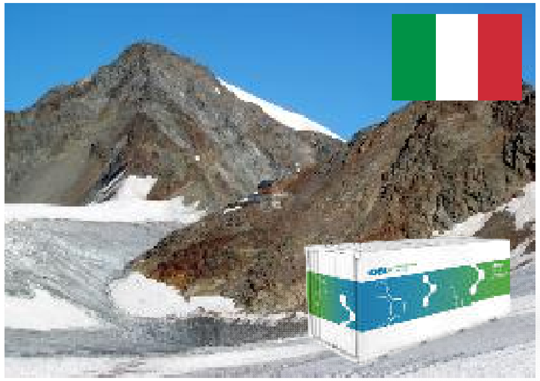
High efficiency operations mode

No need for compressor, fuel cell heat reused for hydrogen release



<u>no</u> compressor needed

Case Studies for Decentralized Solutions



Application: 100% Off-Grid
System: HY2MEDI

1MWh
Stored Energy

60kg
H2 Storage

16kW
Nominal Power

12kW
Electrolyzer

Application: E-Chargin
System: HY2MEDI

2MWh
Stored Energy

120kg
H2 Storage

16kW
Nominal Power

24kW
Electrolyzer

Application: Micro-Grid
Storage: HY2MEGA

17MWh
Stored Energy

500kg
H2 Storage

1MW
Nominal Power

1.5MW
Electrolyzer

Application: 100% Off-
System: HY2MINI

0,4MWh
Stored Energy

25kg
H2 Storage

8kW
Nominal Power

10kW
Electrolyzer

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Metal hydride storage technology

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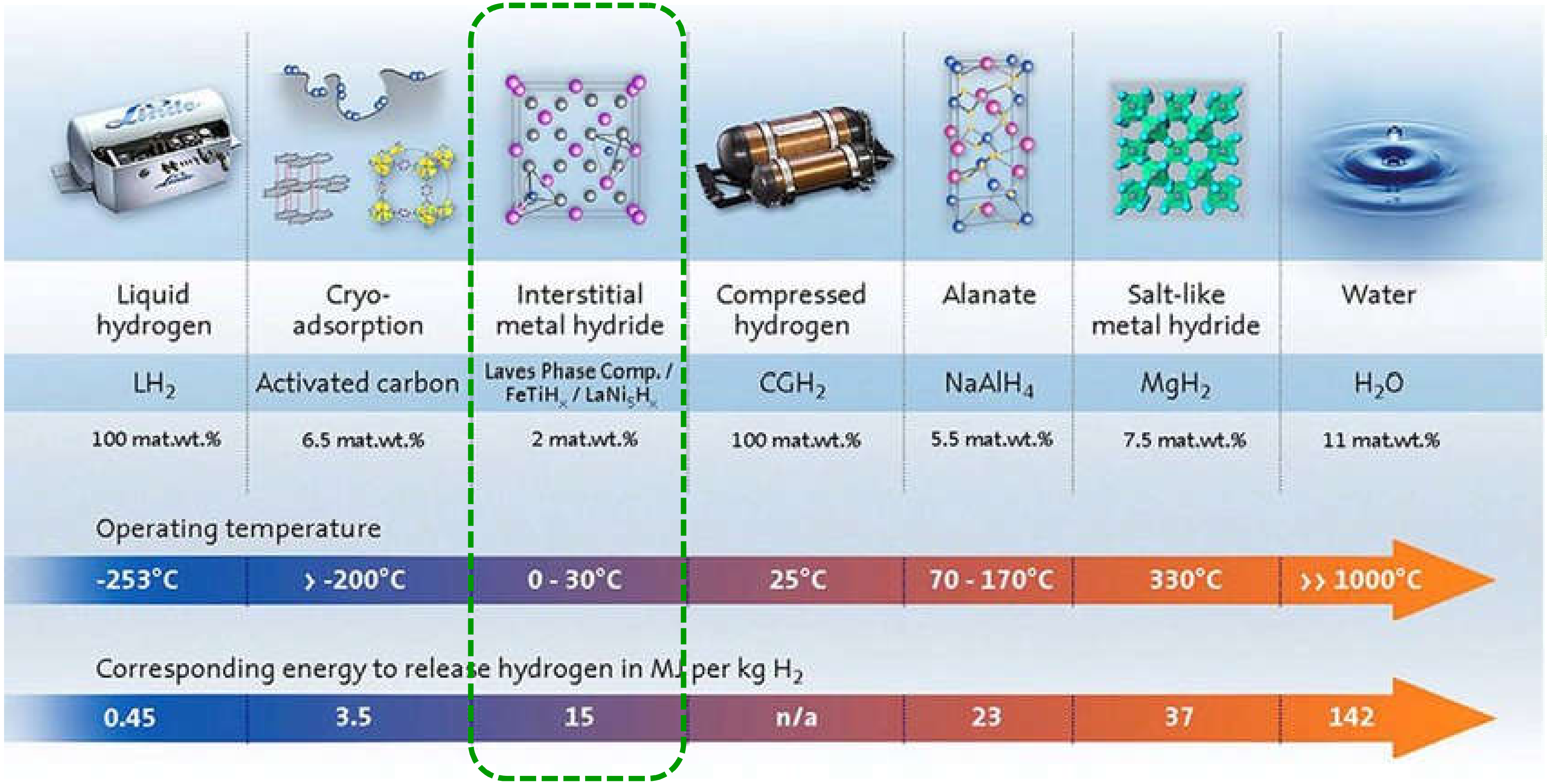
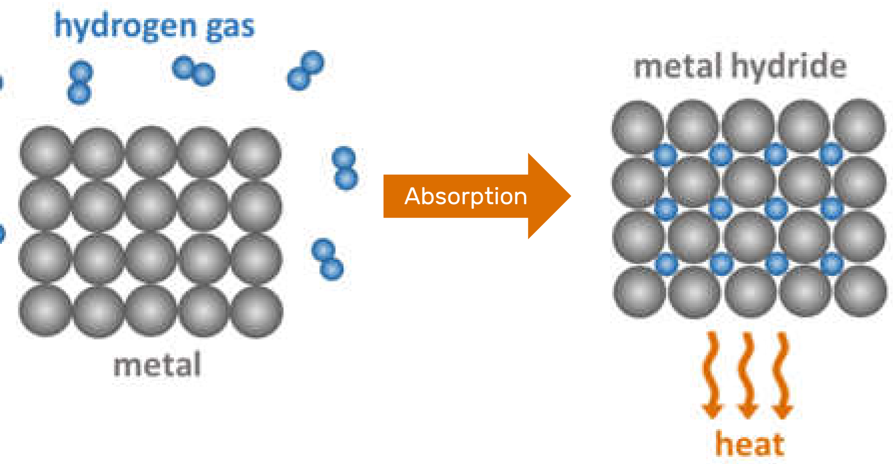
Working parameters of H2 storage systems



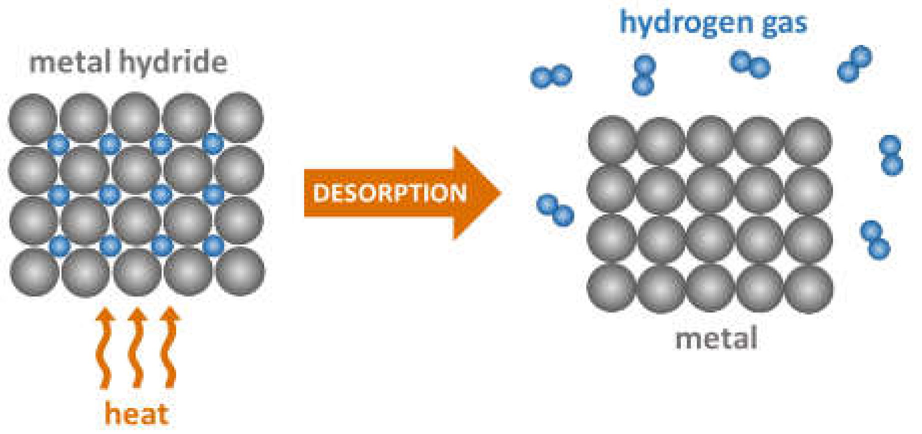
How do MH work

MH is a metal structure, that is able to integrate Hydrogen in its lattice

Loading the storage



Unloading the storage



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The GKN MH - properties

Intermetallic compound based on TiFe

No hazardous substances or mixtures according to EC No 1272/2008 (CLP)

- No health hazards
- No physical hazards

Can be handled in standard atmospheric conditions

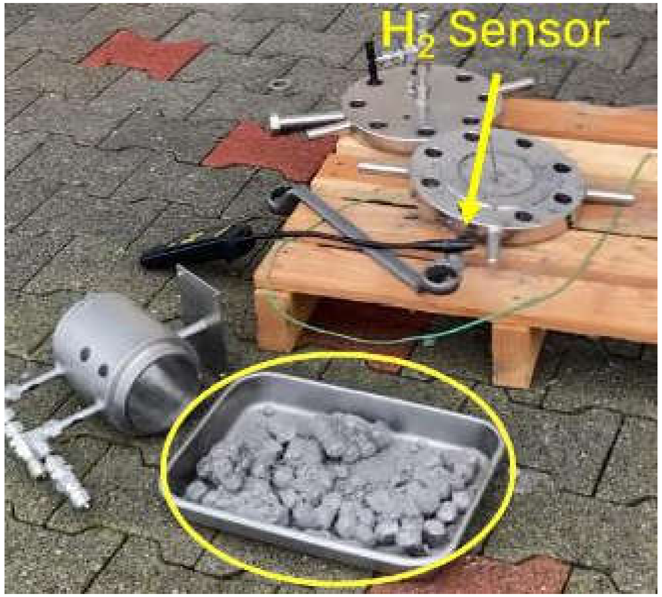
- While most MH-materials require protective atmosphere since they
  - Ignite spontaneously before and especially after activation
  - react heavily with oxygen heavily

The GKN MH - properties

GKN MH has almost now reactivity when exposed to different environments

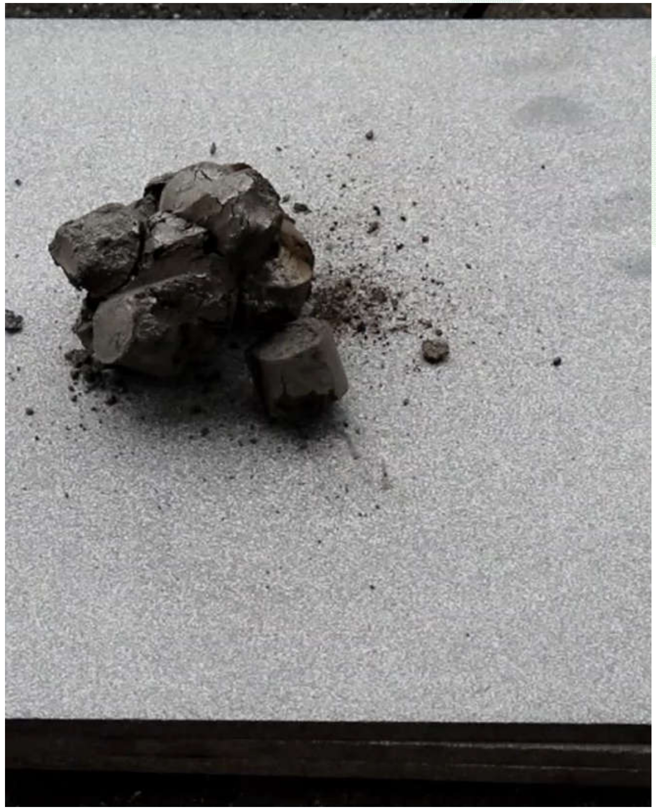
MH in Water

MH exposed to Air



H2 release and interting of MH when exposed to air and

MH exposed to fire



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Vessel damage scenario

Self locking H2 flow is a key safety driver

- **<u>H2 flow from MH is self locking</u>**
- H2 desorption is an endothermic process. The flow rate is continuously decreasing and finally stopping in case when no heat is added.
- Physically, there is no isothermal process. Therefore, H2 release will never stop totally but be much slower compared to other H2 storage technologies (H2 safety advantage)

Summary

MH is amongst the safest H2 storage options

- H2 is stored in solid state @ 35bar
  - H2 stored @35bar (!) in MH has the same energy content as H2 stored @700bar (!) in pressure vessel
- Gaseous H2 account for <5% of total H2 mass in the MH storage
- H2 release is endothermic therefore H2 flow is self-locking

MH has **significant safety advantages** compared to conventional H2 storage

BUT

This is not considered in Italian & EU regulations while it is in the US

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Appendix

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Proving of safety advantages of MH storages

Comparison of extreme behaviour of pressurized H2 vs. MH bases H2 storages

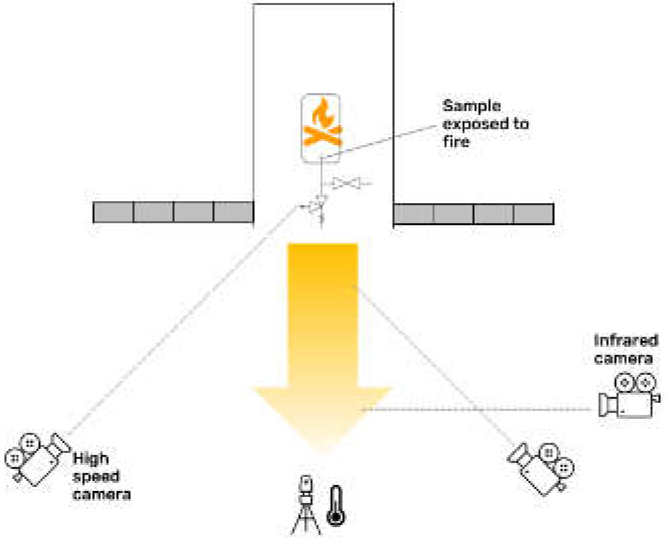
Bonfire testing

<u>Test decription</u>

H2 storages will be exposed to a defined temperature to simulate fire event

<u>Excpected results:</u>

Time period from start of fire exposure till burst will be much lower for pressurized H2 storage compared to MH H2 storage.



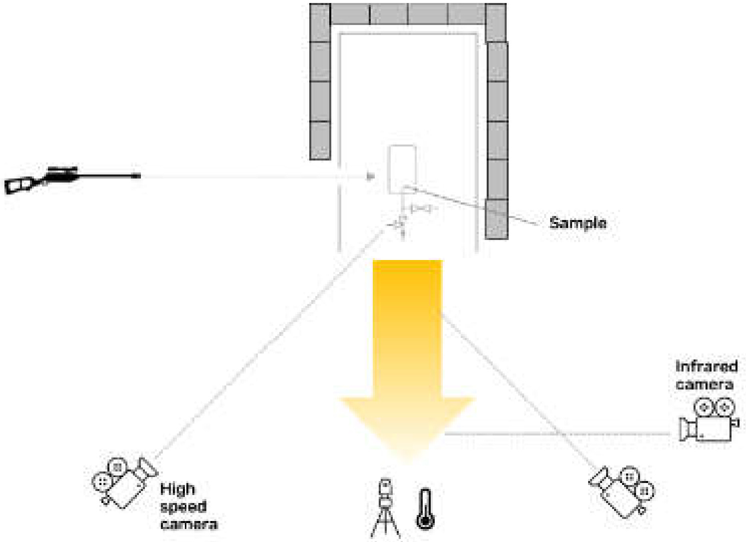
Penetration testing

<u>Test decription</u>

H2 storages will be penetrated with gun fire to simulate crash with shell breakage

<u>Excpected results:</u>

H2 outflow will be much slower for MH H2 storage compared to pressurized H2 storage → burning intensity



Images test site TestNet

Penetration/Gunfire test

Bonfire testing

H2 Explosion

ACT.

Overview of potential Hydrogen buffers

MH has significant advantages in some of the items

n characteristics		Ammonia	Liquefied hydrogen	LOHC (benzyltoluene)	Pressurized 700bar	MH FeTi Carrier
age density	Volum. [kg H_2/m³ of carrier] Gravim. [kg H_2/t of carrier]	121.2[1] 177.5[1]	70.8 1,000	55.2 62.7	57 1000	55.8 18
rgy needs	Conversion [MWh/t H_2] Reconversion [MWh/t H_2]	5.75 11.2	12.0 0.6	0.5 15.0	11.4 > 0.2	< -3.0[2] > 5.2
nological process urity	Conversion – Small scale	■■■	■■■	■■□	■■■	■■■
	Conversion – Large scale	■■■	■□□	■□□	■■■	■■□
	Storage	■■■	■■■	■■■	■■■	■■■
	Transportation – Ship	■■■	■□□	■■■	■■■	■□□
	Transportation – Rail	■■■	■□□	■■■	■■■	■□□
	Transportation – Truck	■■■	■■■	■■■	■■■	□□□
	Reconversion	■□□	■■■	■■□	■■■	■■■
rational e ositions	Advantages	• High storage capacity • Mature value chain, except for cracking process	• No reconversion required • High purity hydrogen	• Easy to store and transport (diesel-like liquid) • Use of existing infrastructure	• No reconversion needed • Pressure available for downstram processes	• High purity hydr • Low energy @ lo grade temperatu
	Disadvantages	• Additional purification step needed • High energy requirements for cracking process	• Boil-off losses along value chain • High energy requirements for liquefaction • Storage and transport complexity	• Number of cycles impact environmental footprint • High energy requirements for dehydrogenation	• Energy intensive compression • Complexity of storage (composite materials needed)	• High weight – su only if not weigh sensitive (e.g. tr mile transportat
	Safety	• Acute toxicity, flammable, explosive under heat, toxic to aquatic life	• Highly flammable with no visible flame, can form explosive mixtures with air	• Low toxicity, non-explosive, hazardous to aquatic environment	• Highest H2 release rate in case of storage damage	• Only small amou gaseus H2 - mos solid state • Self-inhibiting

urce: BCG (modified)

erties of liquid ammonia — ■■■ Proven & commercial — ■■□ Prototype demonstrated — ■□□ Technology validated or under development

gative, because heat energy is released

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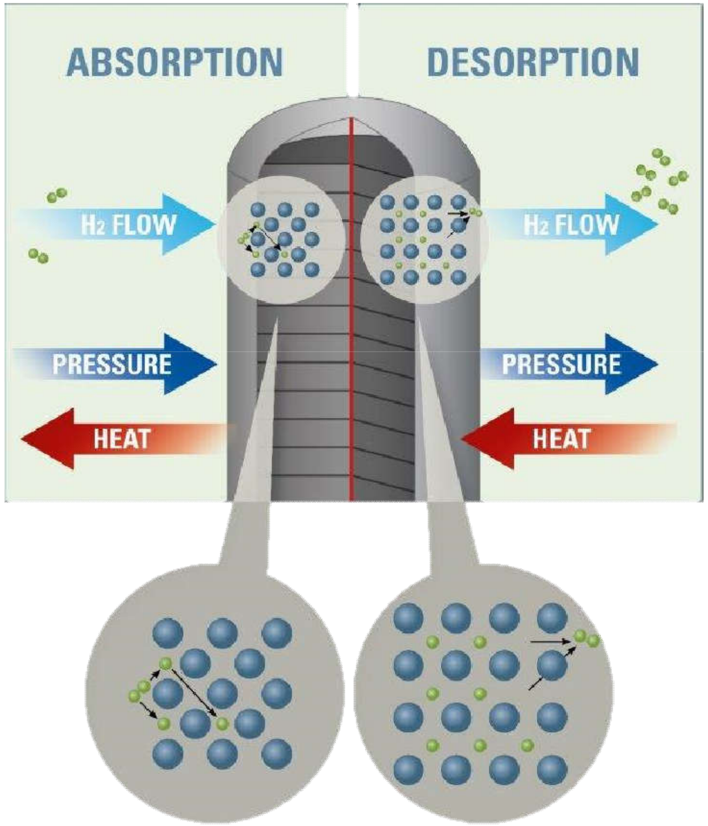
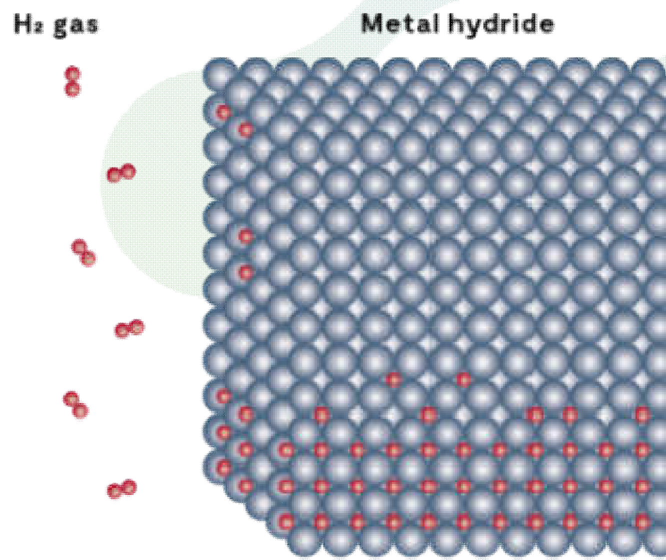
Solid storage hydrogen storage

MH able to store hydrogen in its lattices





- ✓ H2 is stored as metal hydrid / solid state
- ✓ Low pressure (<40 bar) - inherent
- ✓ Low temperature (<60°C)

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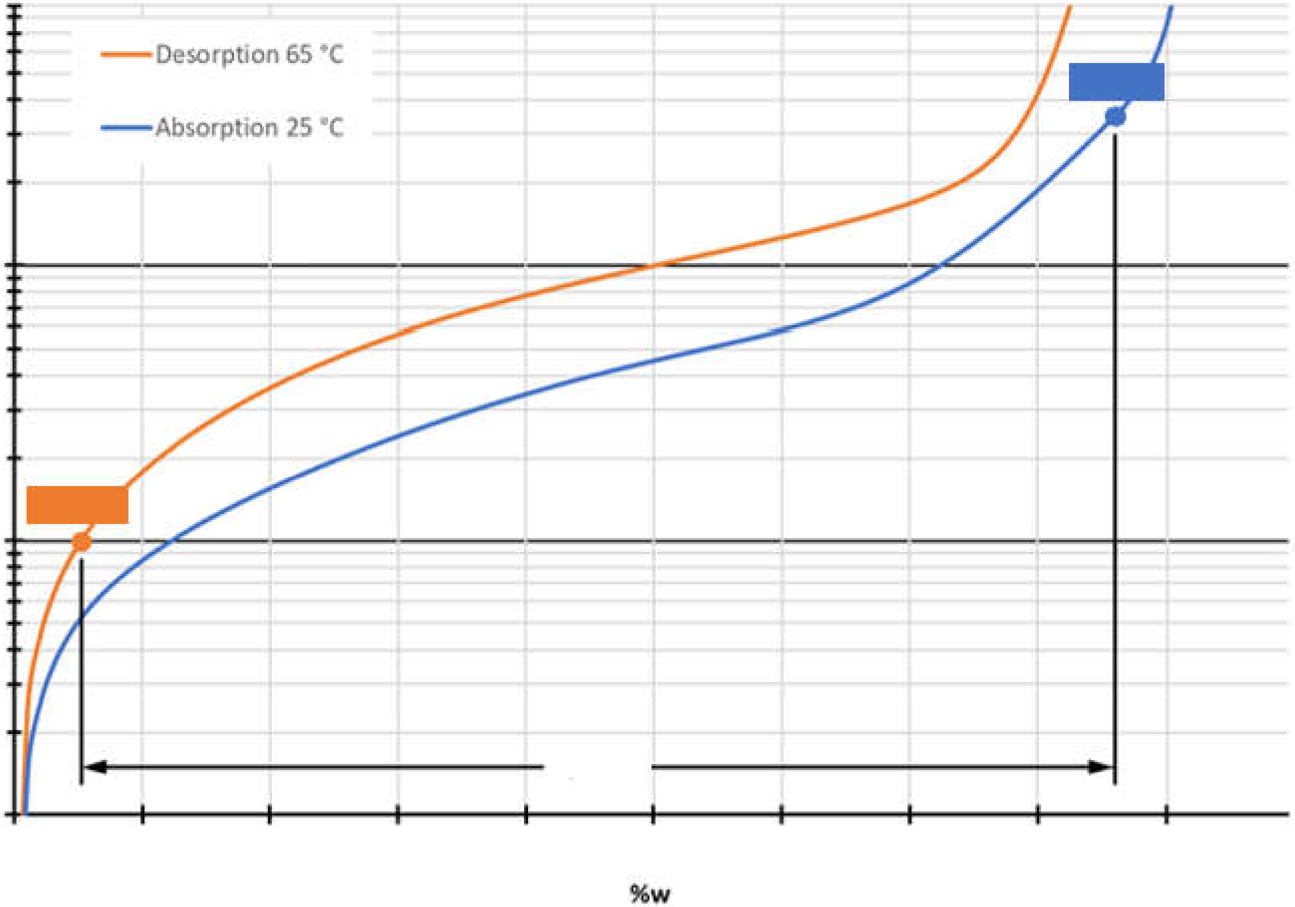
How do MH work

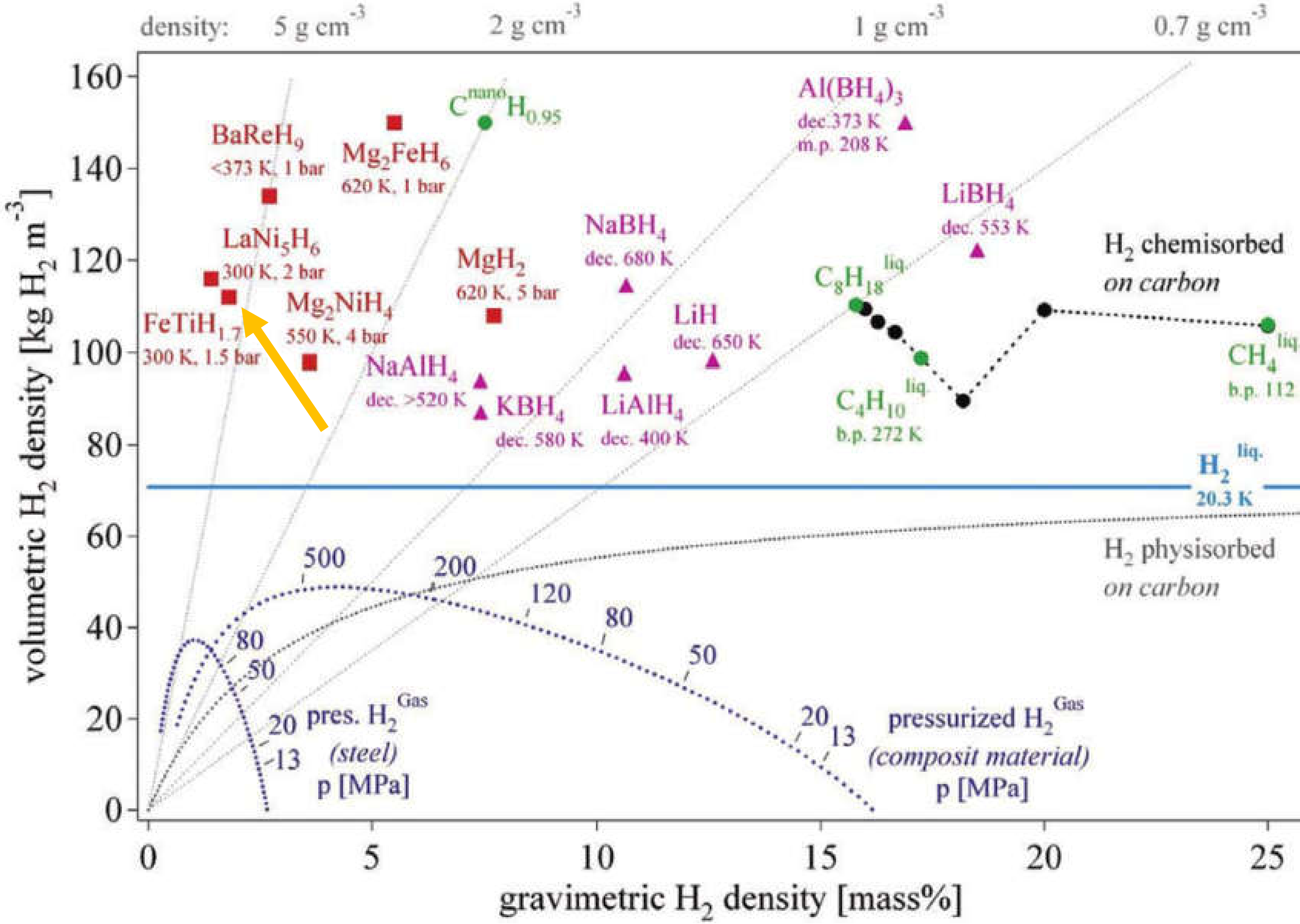
PCT (pressure concentration temperature)



- Non linear storage behaviour
- MH fully loaded @35bar
- 50% load @3bar

The GKN MH - selection

- Very competitive in terms of volumetric density
- Improvement potential in gravimetric density
- Ideal operating conditions (pressure, temperature)



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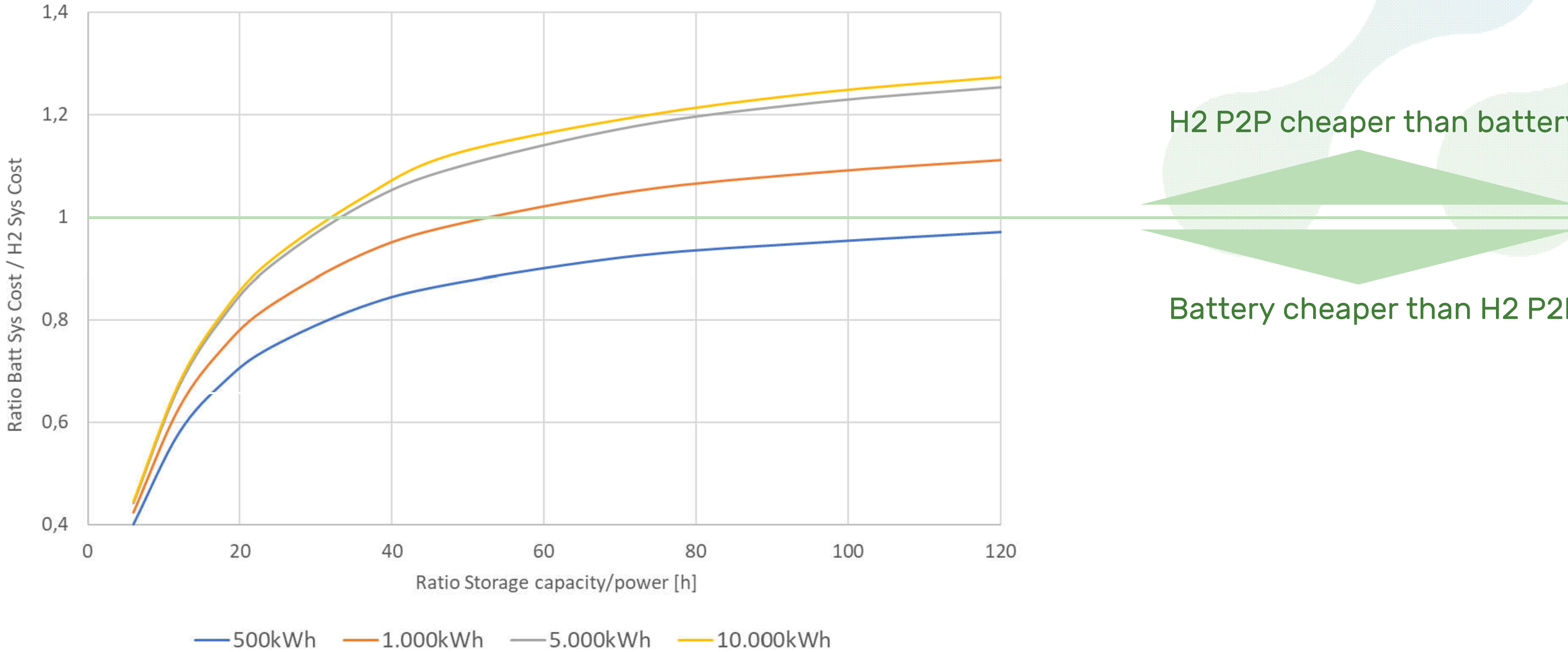
Cost analysis of P2P applications

H2's right to win strongly dependent on charging and discharging power



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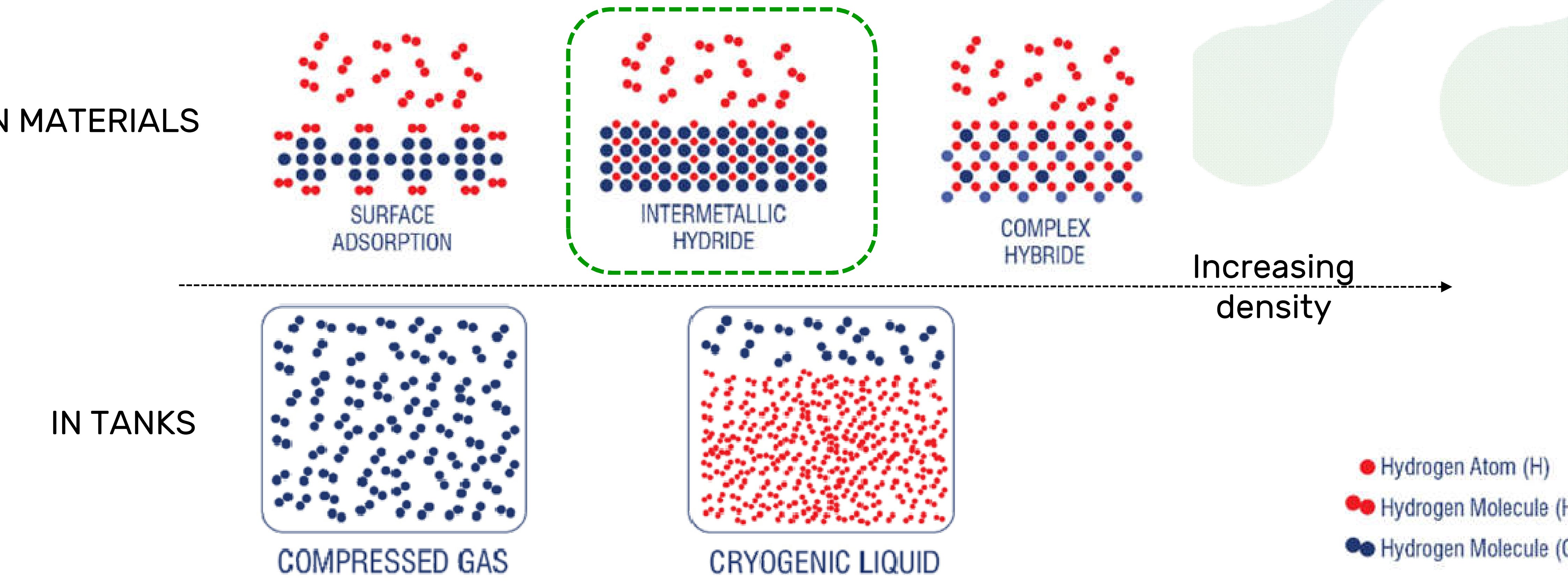
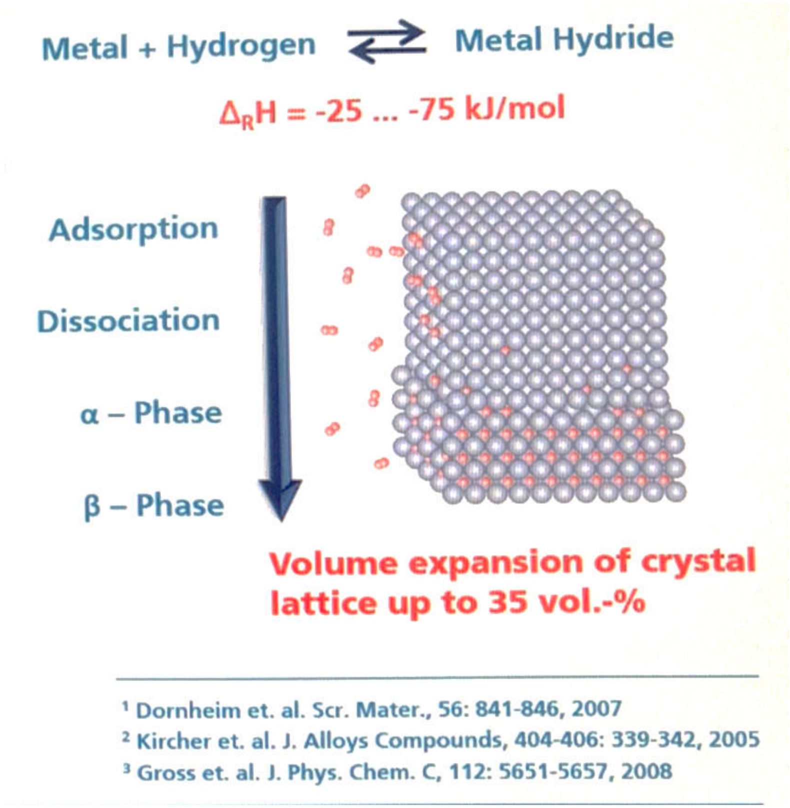
Overview of H2 storage options

MH is a metal structure, that is able to integrate Hydrogen in its lattice



Vessel design considerations – MH expansion

MH expanding during hydrogenation needs to be considered in pressure vessel design



The phase transformation from metal to the metal hydride results in a volume increase of the hydrogen storing materi

- The filling strategy includes the provision of spare volun for the material to expand (80% MH/Total volume)
- Spare volume needs to be as low as possible in order t keep heat transfer high
- Strain measurements have shown that metal hydride ap approximately 10bar of pressure on top of gas pressure

<u>50bar vessel design pressure</u>

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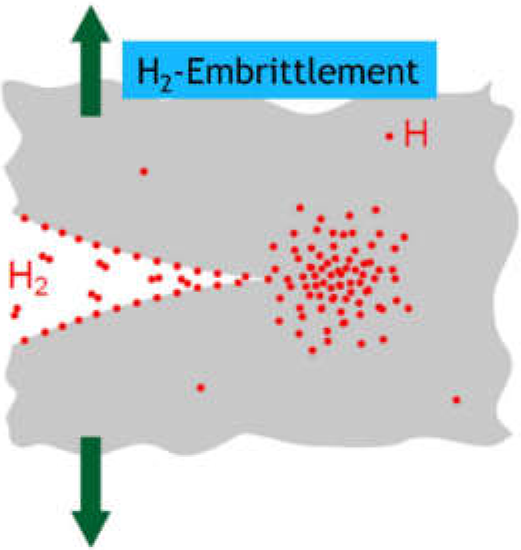
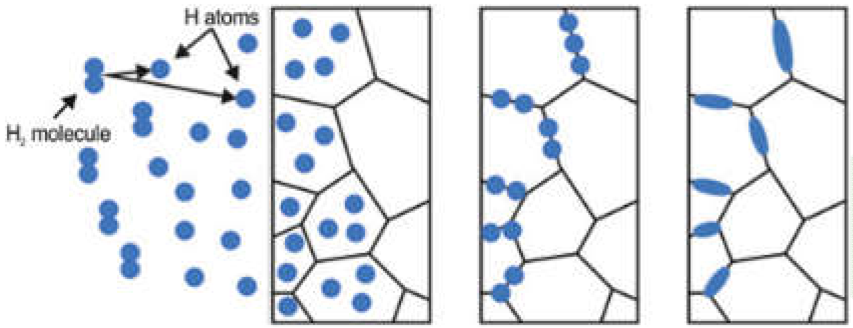
Vessel design considerations – H2 embrittlement

Hydrogen embrittlement impact on tensile strength



- Hydrogen diffuses to crack tip
- Hydrogen chemisorbs
- Moves to high stressed region



GKN HY testing

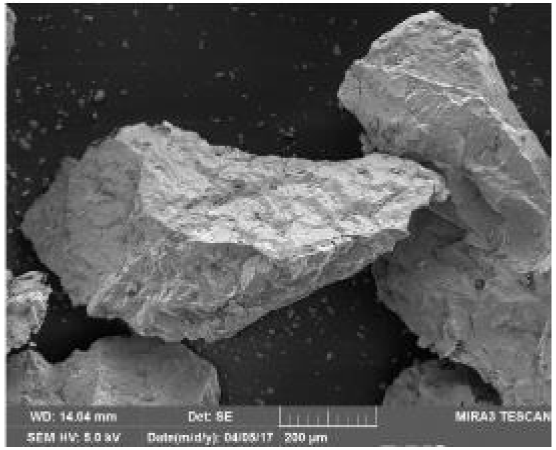
1. Overloading material with H2
2. Tensile strength measurement with overloaded

→ No impact on tensile strength in GKN applicatio
due to low pressure

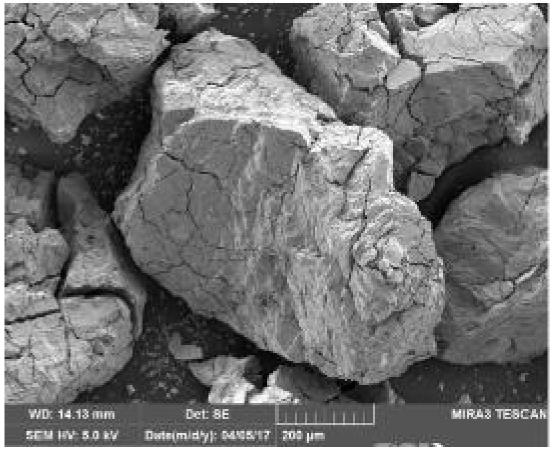
Vessel design considerations – powder segregation

Segregation of fines might lead to uneven MH filling distribution

FeTi-base particle (IP) - Not activated



FeTiMn particle – activated



Particle refinement (decrepitation)
Particle size < 5µm

Due to the volume increase during hydrogen uptake the powder particles decrepitate.

Fine particles can migrate to the bottor of the tank and can uneven volume distribution, which needs to be prevent

- To prevent the migration of fines a special binder was developed whicl prevents segregation

Vorking parameters of H2 storage systems

Method	ρ_m (wt%)[a]	ρ_v (kg m^{-3})[b]	T (K)[c]	p (bar)[d]	Description
Compressed gas	13	< 40	273	800	Compressed hydrogen gas; lightweight, high-pressure cylinder
Liquid	Varies	70.8	21.5	1	Liquid hydrogen, continuous loss of a few % per day at RT
Physisorption	≈ 2	20	77	100	Physical adsorption by porous materials, fully reversible
Interstitial metal hydrides	≈ 2	150	273	1	Atomic hydrogen occupies interstitial sites, fully reversible, metals are heavy
Complex hydrides	< 18	150	> 100	1	Complex compounds $[BH_4]^-$ or $[AlH_4]^-$, desorption at elevated temperature, adsorption at high pressure
Chemical hydrides	< 40	> 150	273	1	Thermal decomposition of chemical hydrides, not directly reversible

[a] Gravimetric storage density [b] Volumetry storage density [c] Operational temperatures for storage method
[d] Operational pressures for the storage method [e] Table adapted from Ref. [2]

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