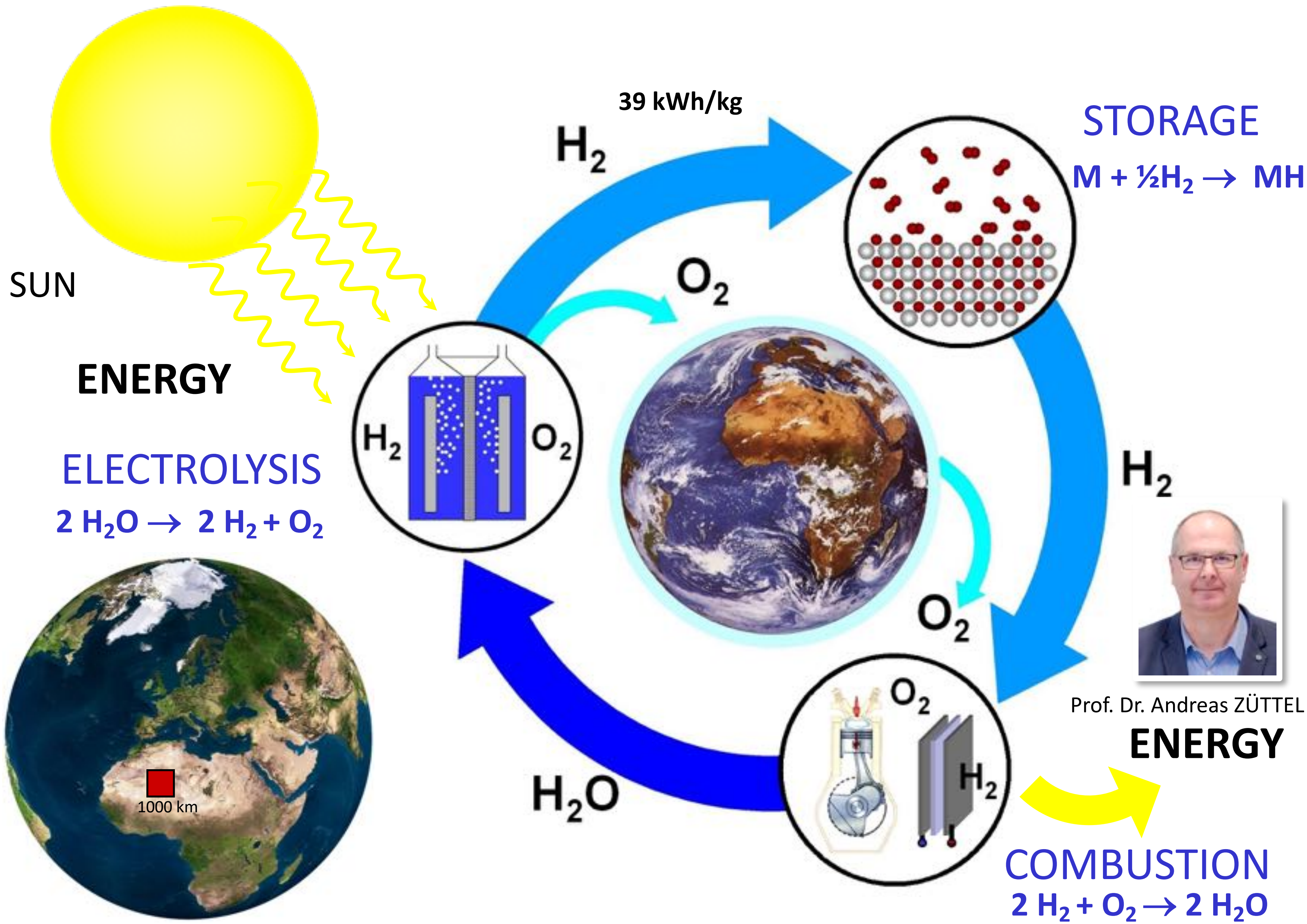
Hydrogen beyond production



Hydrogen beyond production

Hydrogen beyond production

10. Renewable Energy Storage

10.1. Energy Storage Density
10.2. Efficiency of energy conversion
10.3. Synthetic Hydrocarbons
10.4. Efficiency and storage density of renewable electricity
10.5. Seasonal Storage with Hydrogen
10.6. Import of liquid hydrogen
10.7. CO_2 reduction with green hydrogen
10.8. Electrochemical CO_2 reduction
10.9. Bio oil refining with hydrogen
10.10. Bio-SAF
10.11. Role of H_2 in Renewable Energy

11. Safety

11.1. Hindenburg accident Investigation
11.2. Hydrogen Accidents
11.3. Flammability & Explosion limits
11.4. Hydrogen & Elements
11.5. Swiss Hydrogen Developments

1. Hydrogen Properties

$Fe + H_2SO_4 \rightarrow FeSO_4 + H_2$ "Hydrogène"

Robert BOYLE
1670

Antoine LAVOISIER
1783

first H_2 balloon flight

Jacques Alexandre César CHARLES
1783

Metal hydride

Thomas GRAHAM
1868

liquid & solid H_2

James DEWAR
1889

Properties of H_2

H_2
T_c = 33 K
p_c = 13.3 bar

Zygmunt Florenty WRÓBLEWSKI
1885

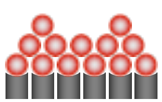
H_2 weather balloon

Leon Teisserenc DE BORT
1896

Zeppelin with H_2

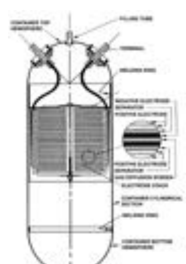
Graf Ferdinand VON ZEPPELIN
1900

Physisorption



Brunauer, Emmett, Teller
1938

Ni-Hydrogen Battery

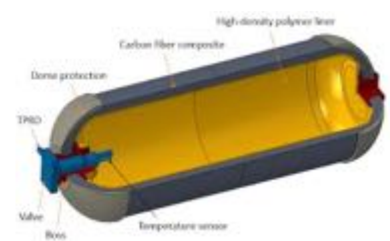


1971

Space Shuttle liq. H_2

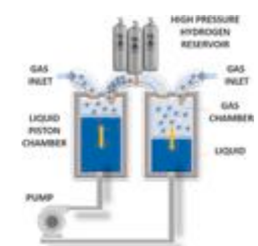
1981

Type IV H_2 tanks 700 bar



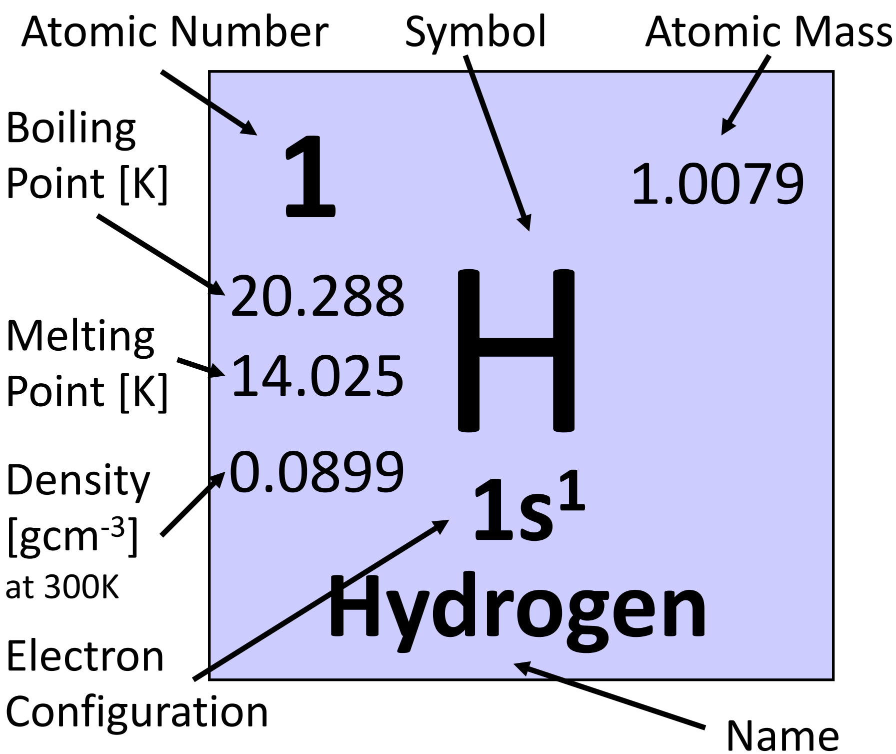
2001

Ionic liquid compressor

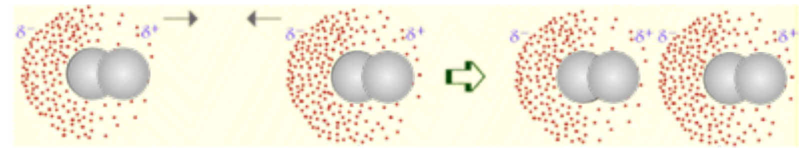


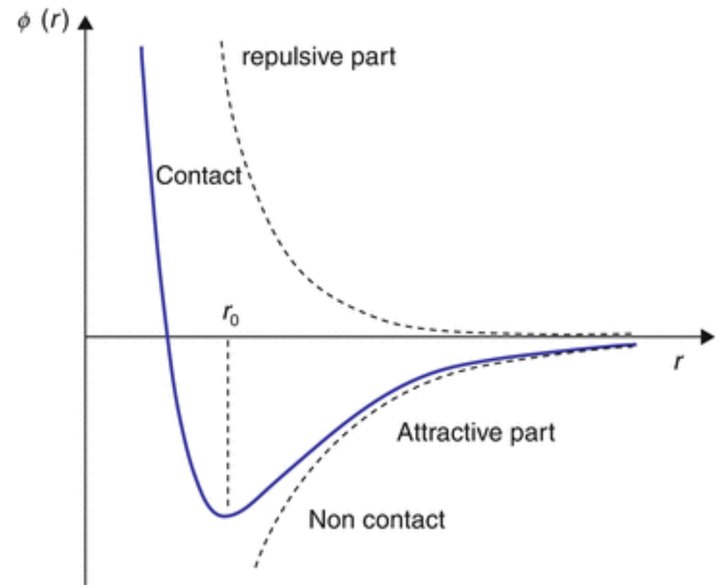
2005

1.1. Hydrogen Atom & Molecule

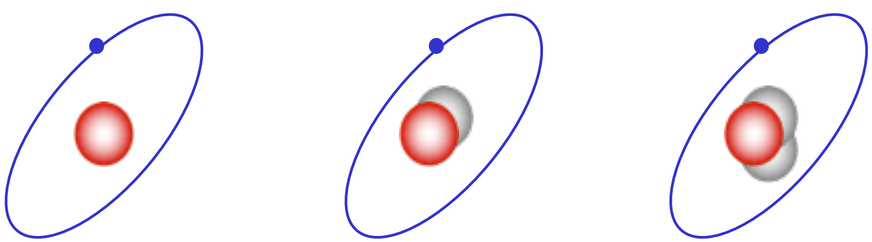


Van der Waals Forces





Isotopes



Hydrogen

Deuterium
$t_{1/2} = \infty$

Tritium
$t_{1/2} = 12.32y, \beta^-$

kin. Gas Theory

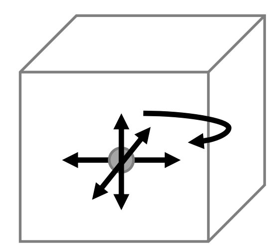
$$p = m\,n\left\langle v_x^2 \right\rangle$$

$$p = \frac{1}{3} m\,n\left\langle v^2 \right\rangle$$

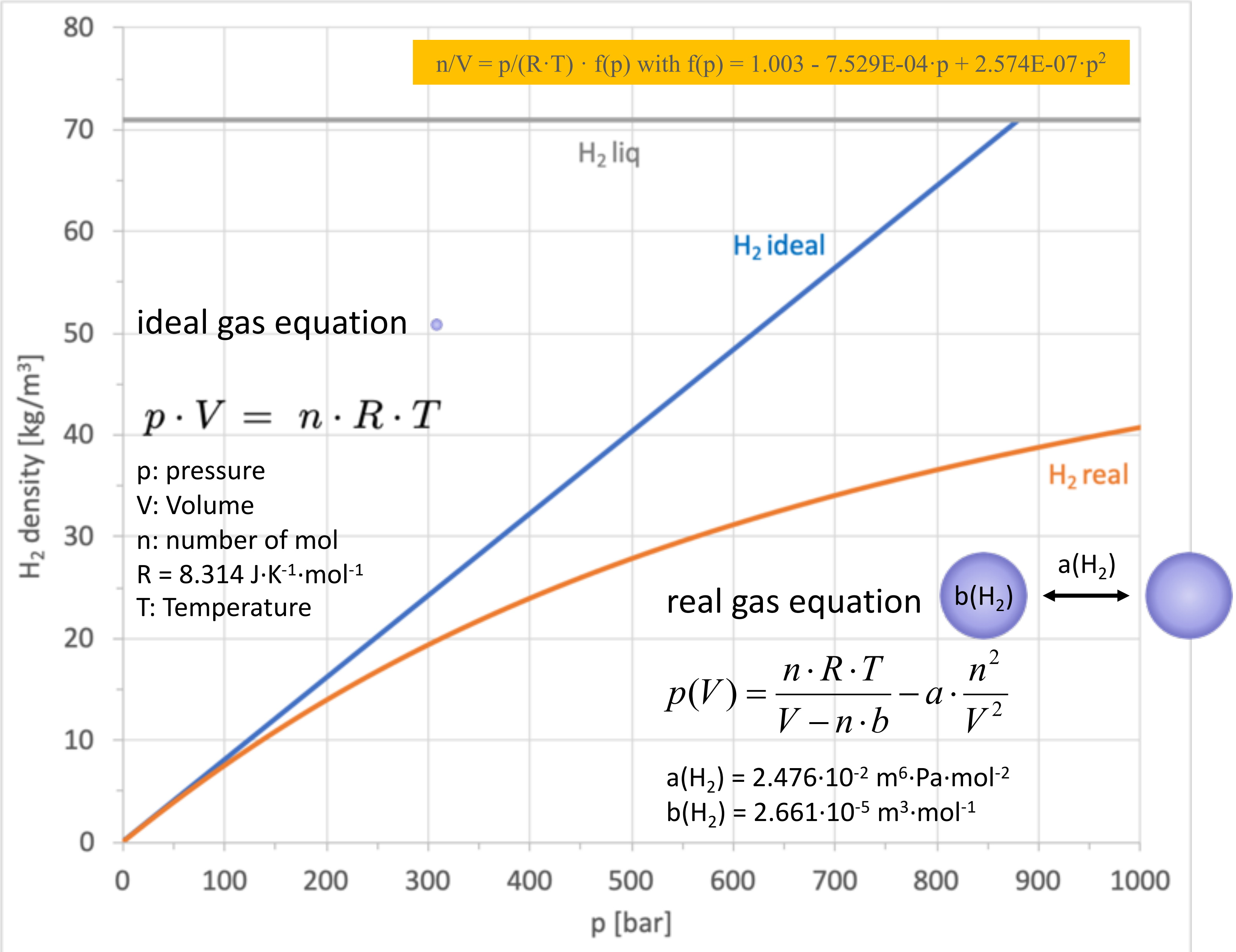
$$p \cdot V = n \cdot R \cdot T$$

H_2

$$c = dQ/dT = 5/2 \cdot R$$

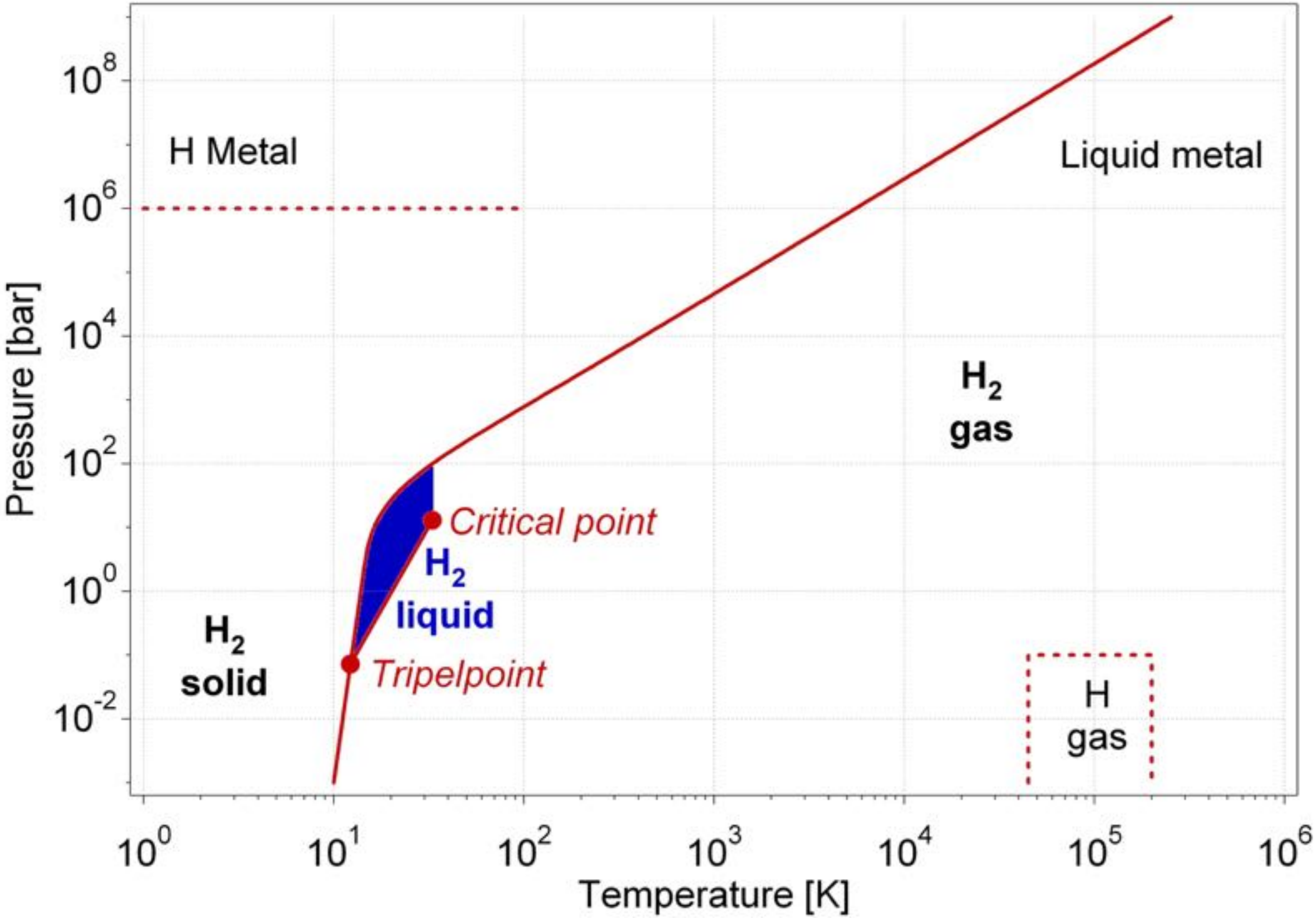


1.2. Pressurized Hydrogen



1.3. Hydrogen phases

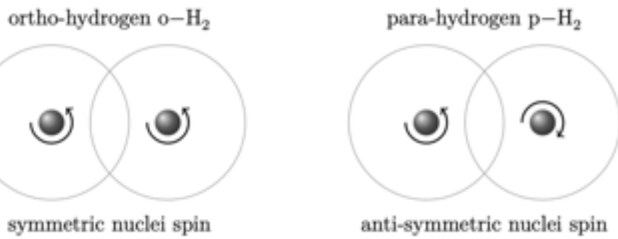
Primitive Phase diagram

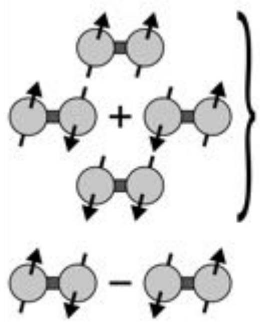


Ref: W. B. Leung, N. H. March and H. Motz, Physics Letters 56A (6) (1976), pp. 425-426

1.4. Nuclear Spin and Joule-Thomson Effect

Nuclear spin Isomer of H_2 molecules

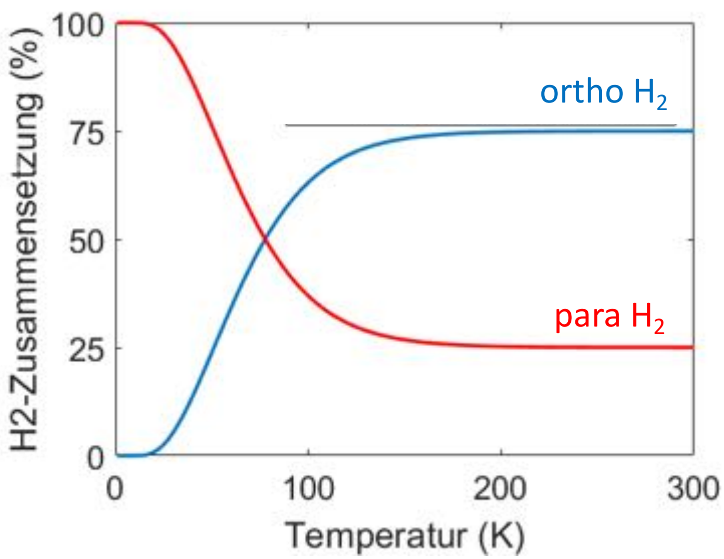




Triplet
I = 1
ortho hydrogen

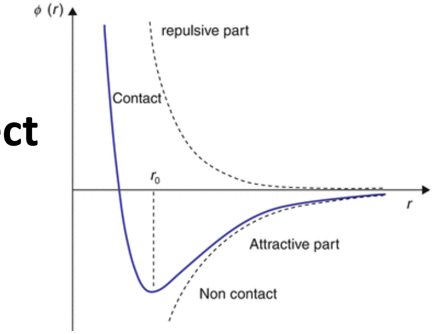
ΔH

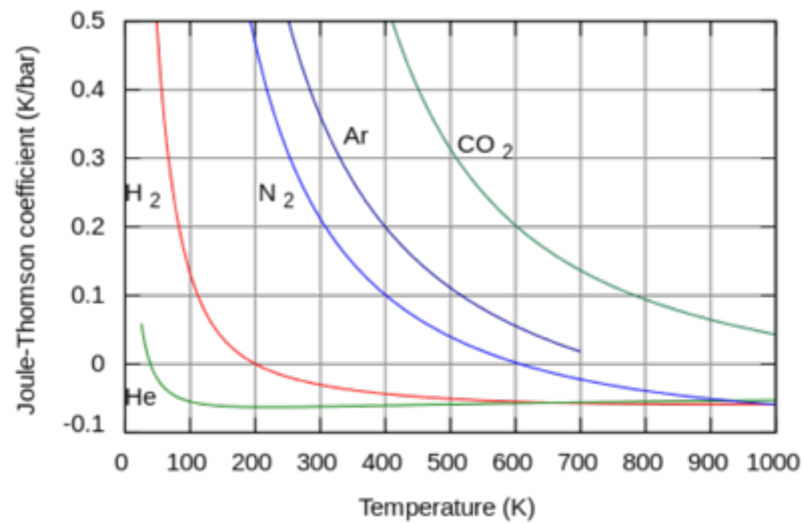
Singlet
I = 0
para hydrogen



Joule-Thomson-Effect

$$\mu_{JT} = \left(\frac{\partial T}{\partial p}\right)_H$$





Van der Waals

$$\Delta H = 0 \qquad \mu_{JT} = \frac{1}{C_p}\cdot\left(\frac{2a}{RT} - b\right)$$

$$T_{inv} = \frac{2a}{Rb}$$

$a(H_2) = 2.476\cdot10^{-2}\ m^6\cdot Pa\cdot mol^{-2}$
$b(H_2) = 2.661\cdot10^{-5}\ m^3\cdot mol^{-1}$
$R = 8.314\ J\cdot K^{-1}\cdot mol^{-1}$

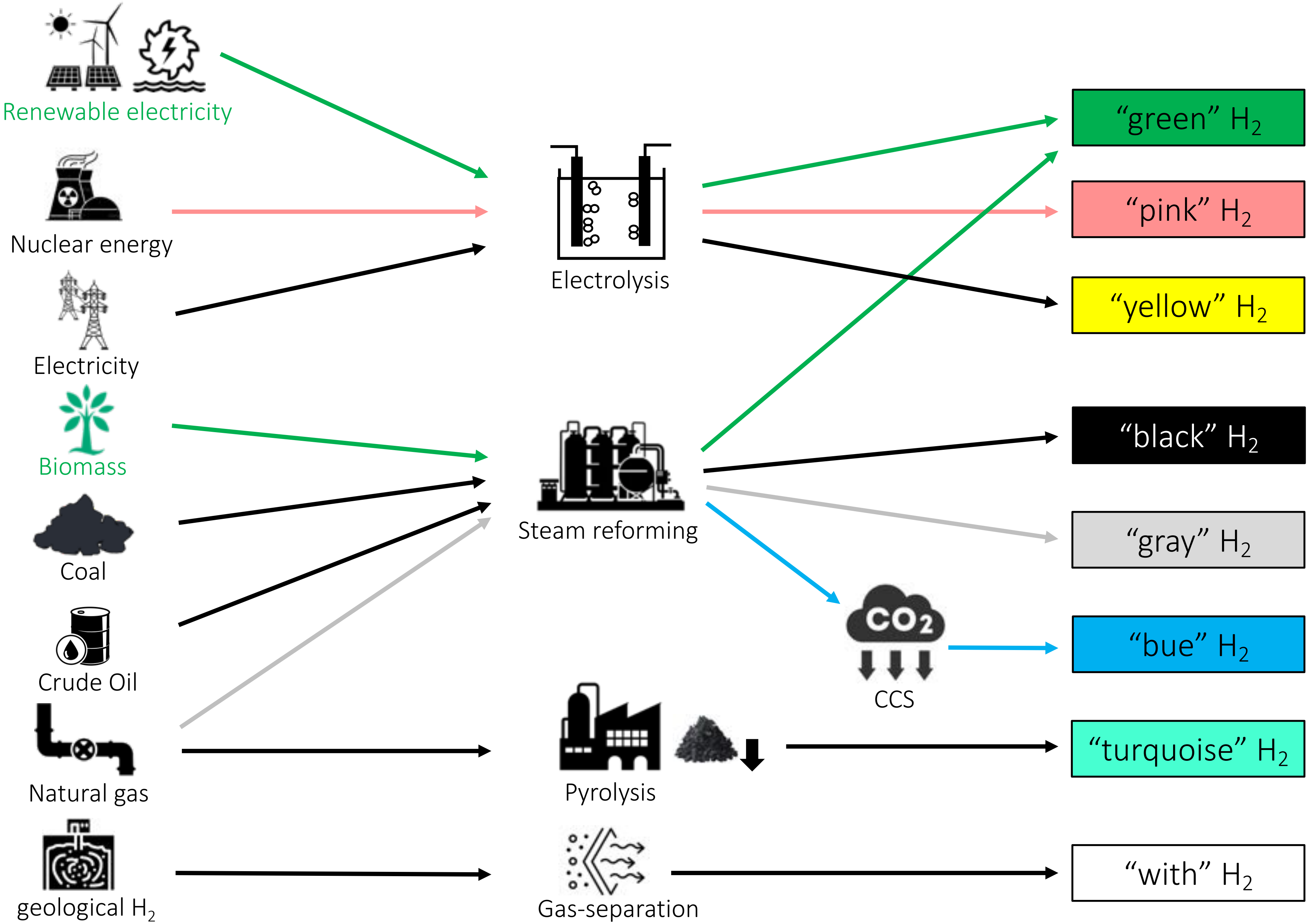
$$\Delta T = \mu_{JT}\cdot\Delta p$$

Temperature change in isenthalpic expansion

1.5. Properties of Hydrogen as Fuel

Properties		Hydrogen (H_2)	Methane (CH_4)	Gasoline ($-CH_2-$)
lower heating value	[kWh ·kg^{-1}]	33.33	13.9	12.4
self ignition temperature	[° C]	585	540	228-501
flame temperature	[° C]	2045	1875	2200
ignition limits in air	[Vol%]	4 - 75	5.3 - 15	1.0 - 7.6
minimal ignition energy	[mWs]	0.02	0.29	0.24
flame propagation in air	[m ·s^{-1}]	2.65	0.4	0.4
detonation limits	[Vol%]	13 - 65	6.3 - 13.5	1.1 - 3.3
detonation velocity	[km ·s^{-1}]	1.48 - 2.15	1.39 - 1.64	1.4 - 1.7
explosion energy	[kg TNT ·m^{-3}]	2.02	7.03	44.22
diffusion coefficient in air	[cm^2 ·s^{-1}]	0.61	0.16	0.05

1.6. Hydrogen and CO_2 emissions in colors



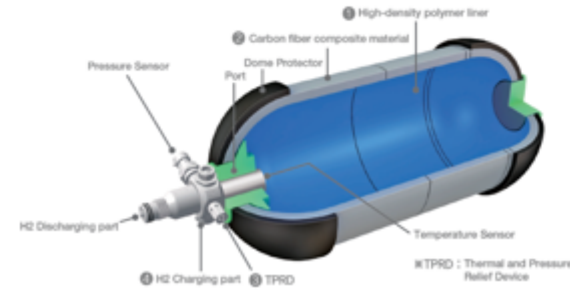
2. Compressed Hydrogen Storage

	V1	V2	V3	V4
composition	All Metal	Metal Liner + GFRP layer (hoop lap)	Metal Liner + CFRP layer (full lap)	Plastic Liner + CFRP layer (full lap)

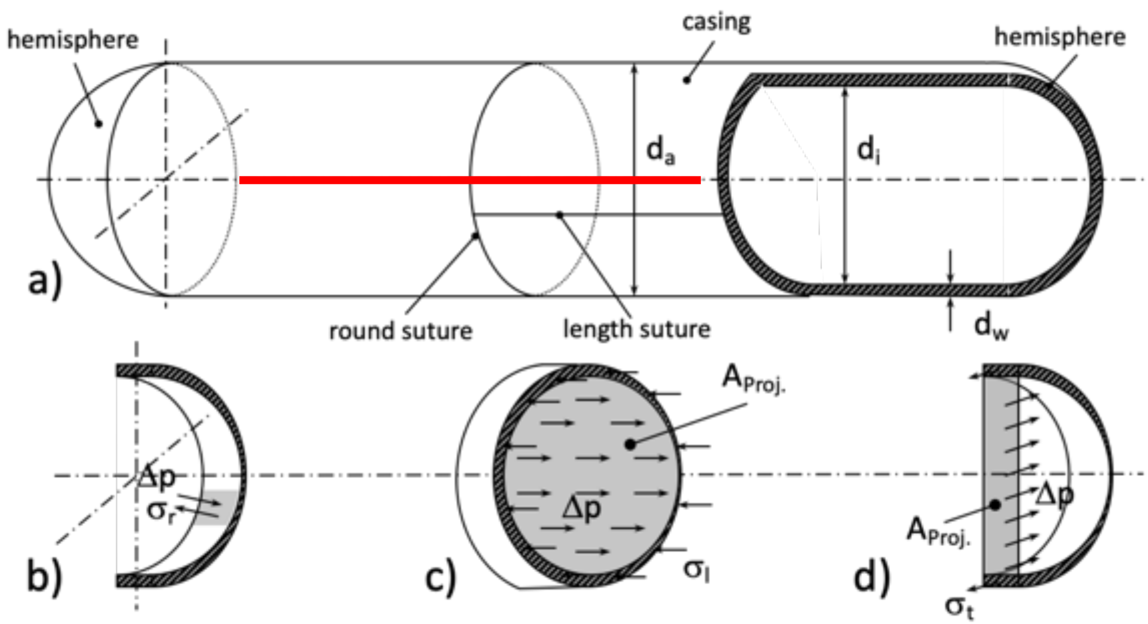
Aluminum
10 bar, 1l, ?kg

Steel
30 bar, ?l, ?kg

Steel, Type 1
200 bar, 50l, 70kg



Composite, Type 4
500 bar, 300l, 270kg



tensile breaking strength σ_v

$$\sigma_v = \sigma_{max} - \sigma_{min}$$

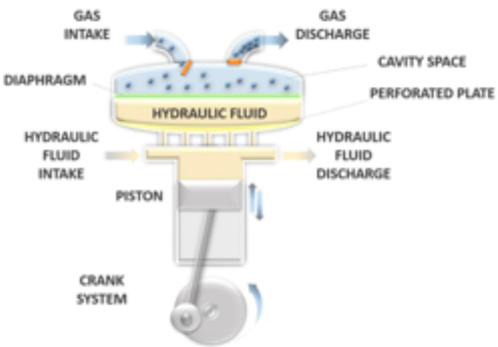
wall thickness d_w

$$d_w = \frac{\Delta p \cdot d_i}{2 \cdot \sigma_v + \Delta p}$$

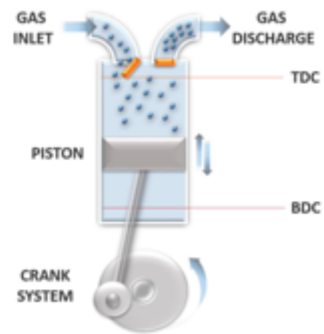
$$d_w = \frac{\Delta p \cdot d_a}{2 \cdot \sigma_v \cdot f_1 + \Delta p} + f_2$$

Ref.: Wilhelm Matek, Dieter Muhs, Herbert Wittel and Manfred Becker, "Roloff/Matek Maschinenelemente", Viewegs Fachbücher der Technik (1994), 690 pages, ISBN: 3-528-74028-0

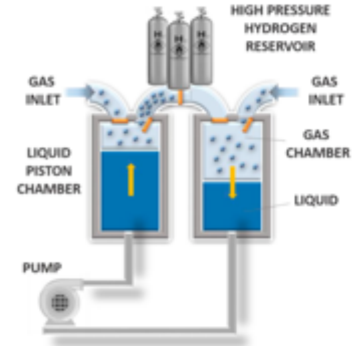
2.1. Hydrogen Compression Devices



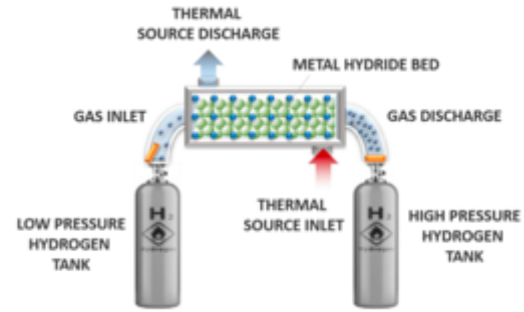
Diaphragm Compressors
10 bar, 1l, ?kg



Piston Compressors
30 bar, ?l, ?kg



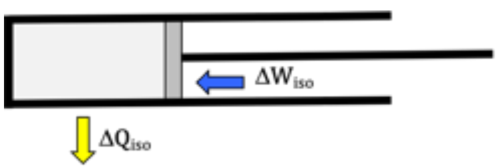
Ionic liquid
200 bar, 50l, 70kg



Metal hydride
500 bar, 300l, 270kg

Isothermal compression

T = const. → ΔQ = -ΔW



$$\Delta W = n \cdot R \cdot T \cdot ln\left(\frac{p_2}{p_1}\right)$$

Adiabatic compression

ΔQ = 0 → ΔU = ΔW

$$\Delta W = -n \cdot c_V \cdot (T_2 - T_1)$$

$$\frac{p_1}{p_2} = \left(\frac{T_1}{T_2}\right)^{\frac{c_V}{R}+1}$$

Thermal compression

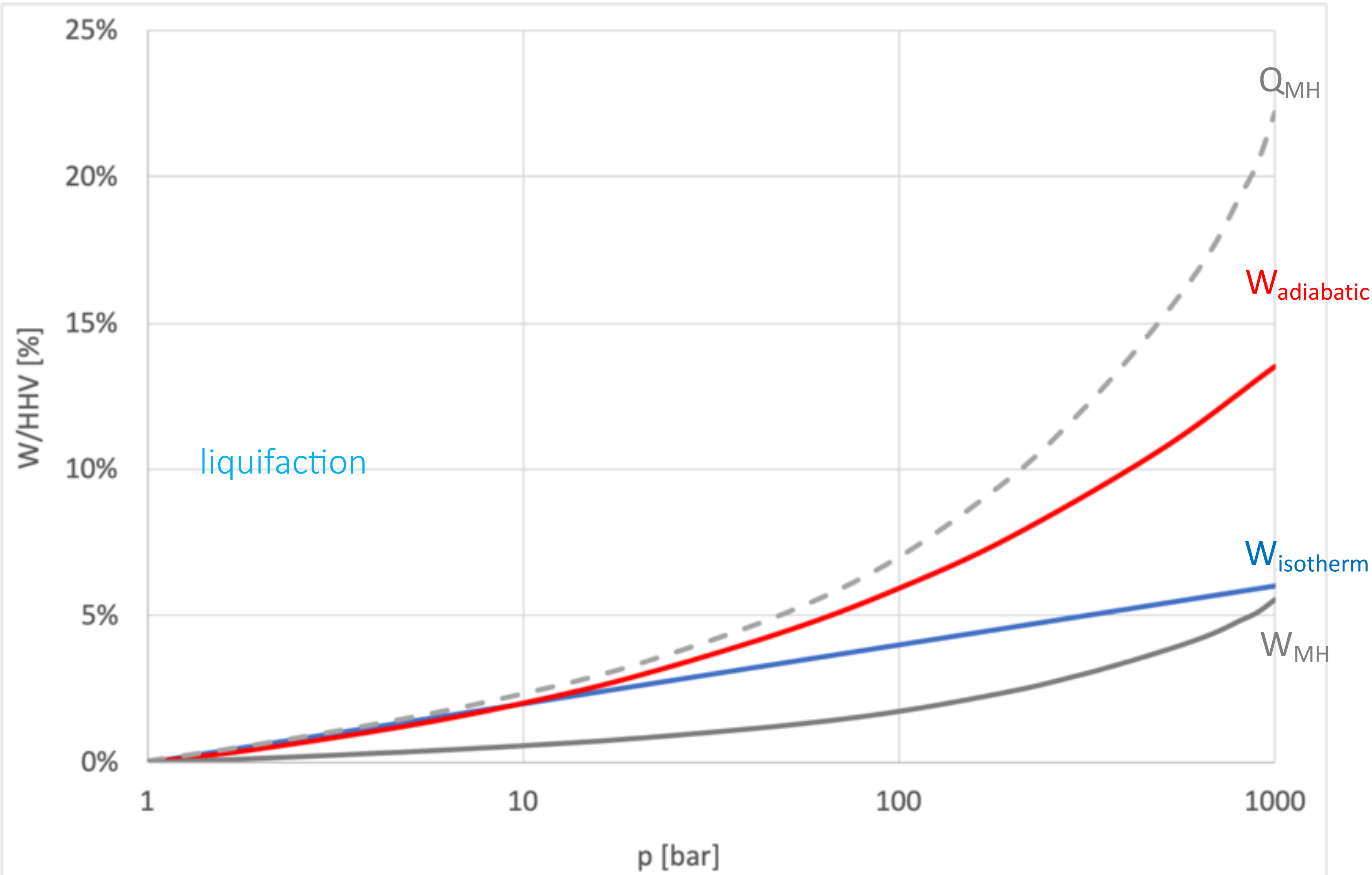
$$\Delta Q_S = m \cdot c_V \cdot (T_2 - T_1)$$

$$ln\left(\frac{p_2}{p_1}\right) = \frac{\Delta H(T)}{R \cdot T} - \frac{\Delta S}{R}$$

$$\Delta Q_L = \Delta H(T)$$

Ref.: G. Sdanghi, G. Maranzana, A. Celzard, V. Fierro, "Review of the current technologies and performances of hydrogen T compression for stationary and automotive applications", Renewable and Sustainable Energy Reviews 102 (2019), pp. 150 – 170

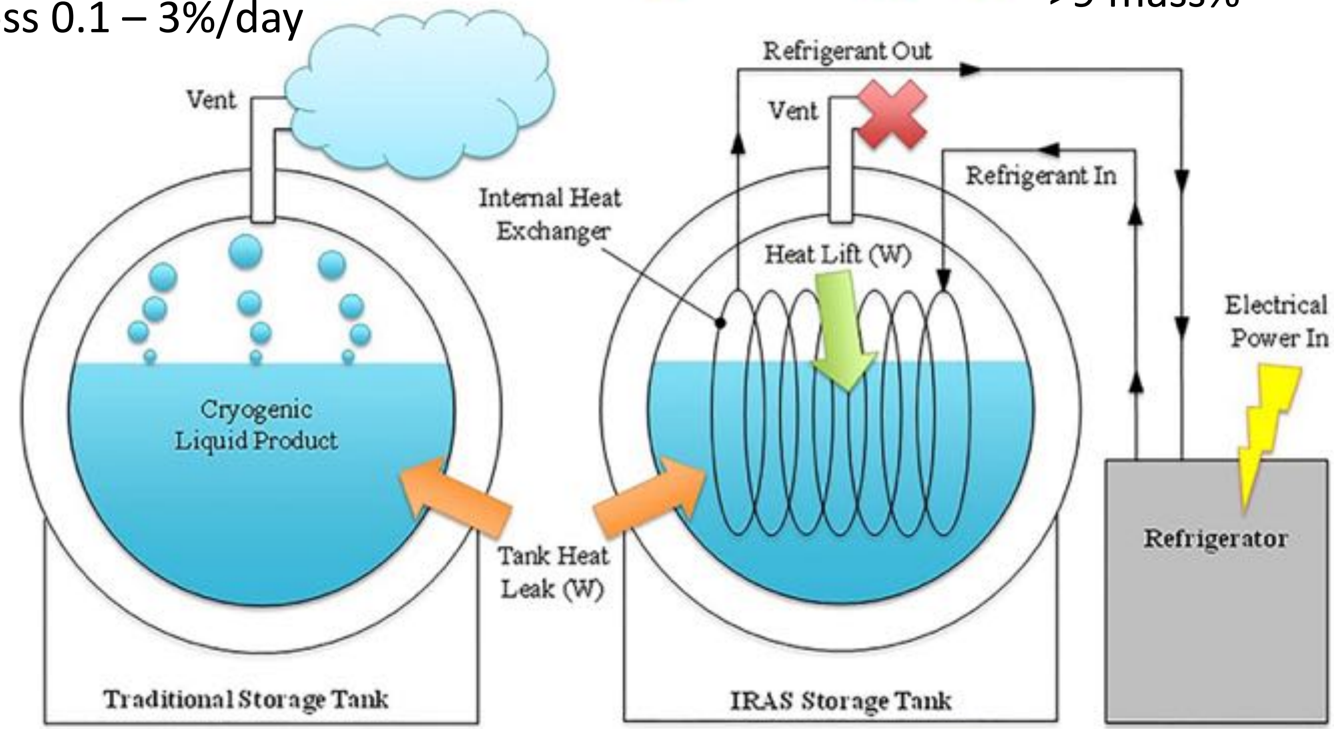
2.2. Hydrogen Compression Energy (Q: heat and W: work)



3. Liquid Hydrogen Storage

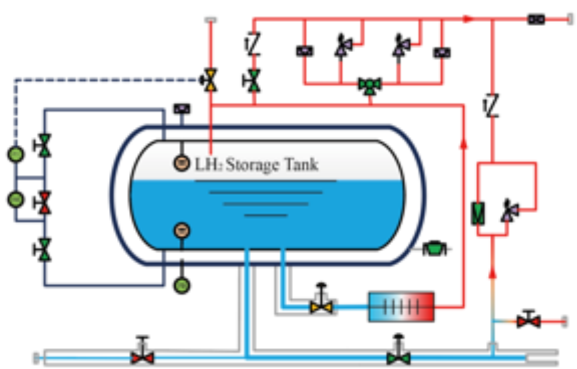
loss 0.1 – 3%/day

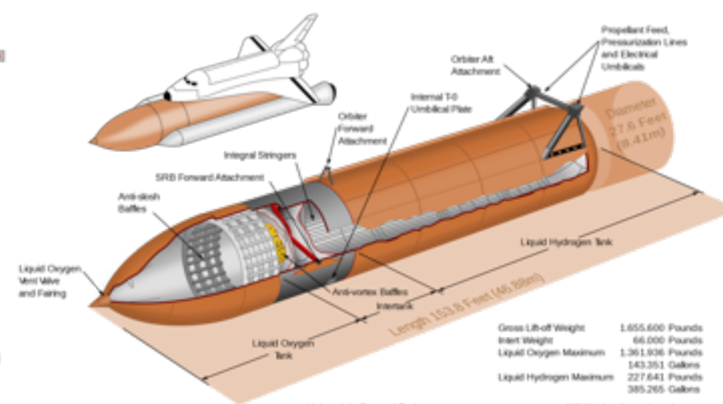
>9 mass%



Current Liquid Hydrogen Storage

Future Liquid Hydrogen Storage

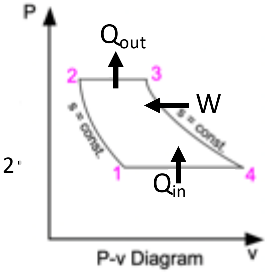


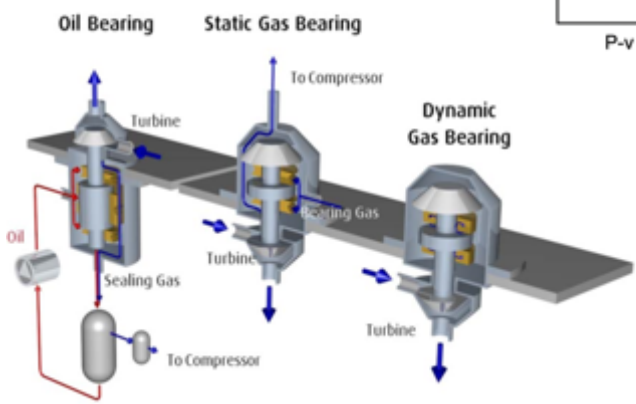


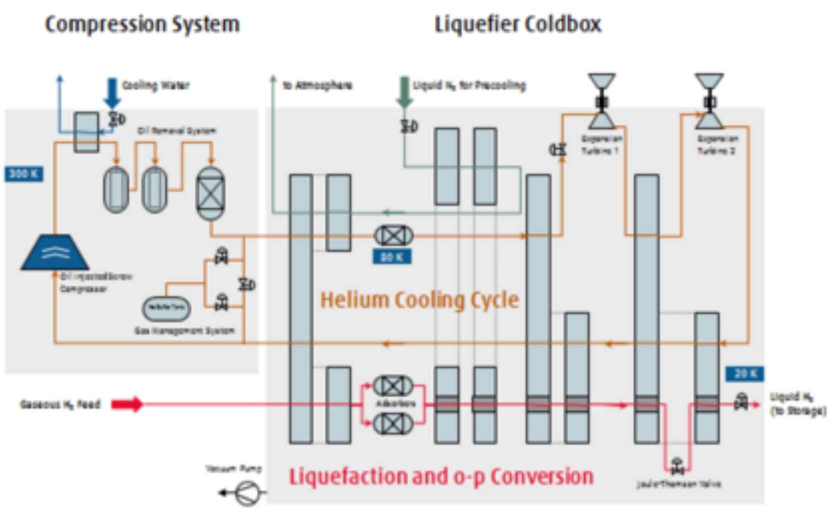
3.1. Liquefaction Technology for Hydrogen

Brayton cycle

Refrigeration of Helium solely with expansion turbines.
Energy demand: 12.3 to 13.4 kWh/kg H_2.

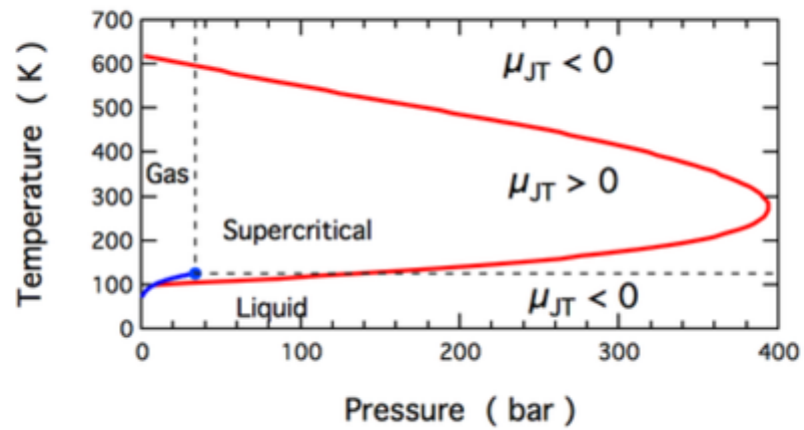


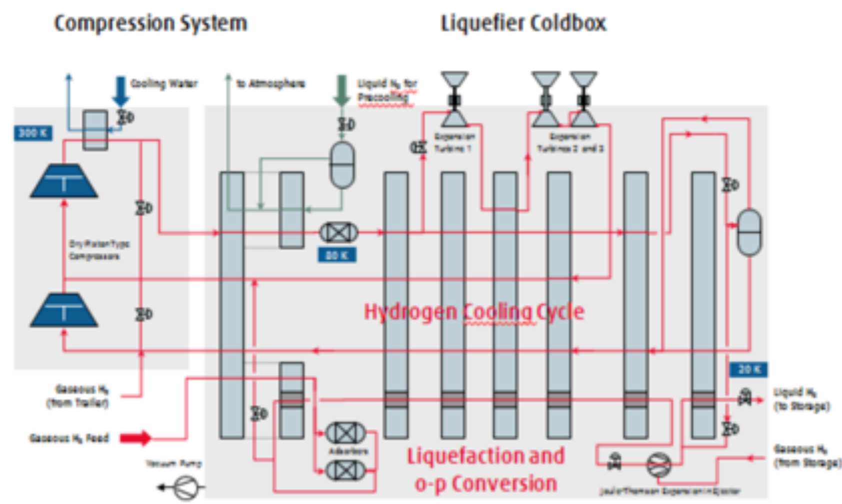




Claude cycle

Recycle compressors refrigeration loop with expansion by turbines and finally via a Joule-Thomson valve. Energy demand: 10.8 to 12.7 kWh/kgH_2





Ref.: K. Ohlig and L. Decker, “The Latest Developments and Outlook for Hydrogen Liquefaction Technology”, *Linde Kryotechnik AG, Pfungen, CH-8422, Switzerland*

3.2. Theoretical minimum work for the liquefaction of H_2

Based on the Carnot cycle with a heat sink at 300 K, the ideal work of liquefaction can be expressed as

$$W_L = \Delta H \frac{(T_a - T_e)}{T_e}$$

where the ideal work of liquefaction W_L = 11.62 MJ kg^{-1} (3.228 kWh kg^{-1}) for LH_2; ΔH the change in enthalpy between initial (gaseous) state and final (liquid) state; T_a the ambient (or heat sink) temperature; and T_e the equilibrium condensing temperature of the o-H_2-to-p-H_2 conversion.

The ideal work of liquefaction can also be represented as the sum of work inputs:

$$W_L = W_{cooling} + W_{conversion} + W_{condensation}$$

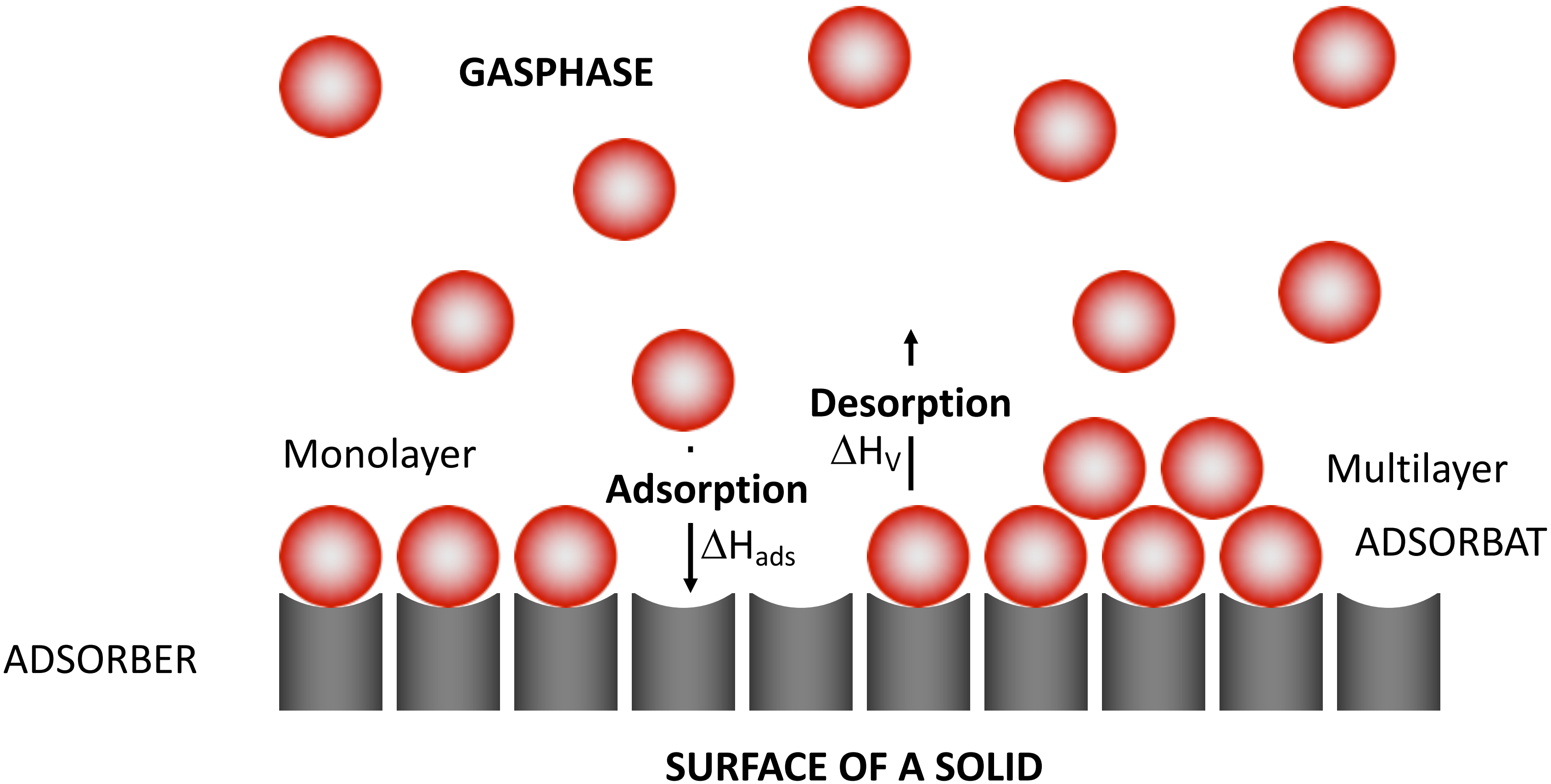
where $W_{cooling}$ is the work input to reduce the hydrogen gas temperature; $W_{conversion}$ the work input to convert o-H_2 to p-H_2; and $W_{condensation}$ the work input for gas-to- liquid conversion.

$Q_{cooling} = 5/2 \cdot 8.314 \cdot 500 \cdot 250 = 2598\ kJ\ kg^{-1}$
$Q_{conversion} = 703\ kJ\ kg^{-1}$
$Q_{condensation} = 447\ kJ\ kg^{-1}$

Q_{liq} = 1 kWh kg^{-1}

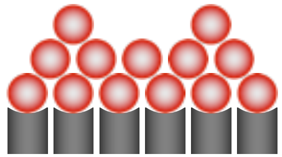
Ref.: Bonadio, Luigi, “Liquid”, Encyclopedia of Electrochemical Power Sources, Elsevier (2009)

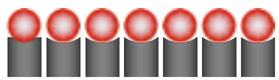
4. Physisorption of Hydrogen

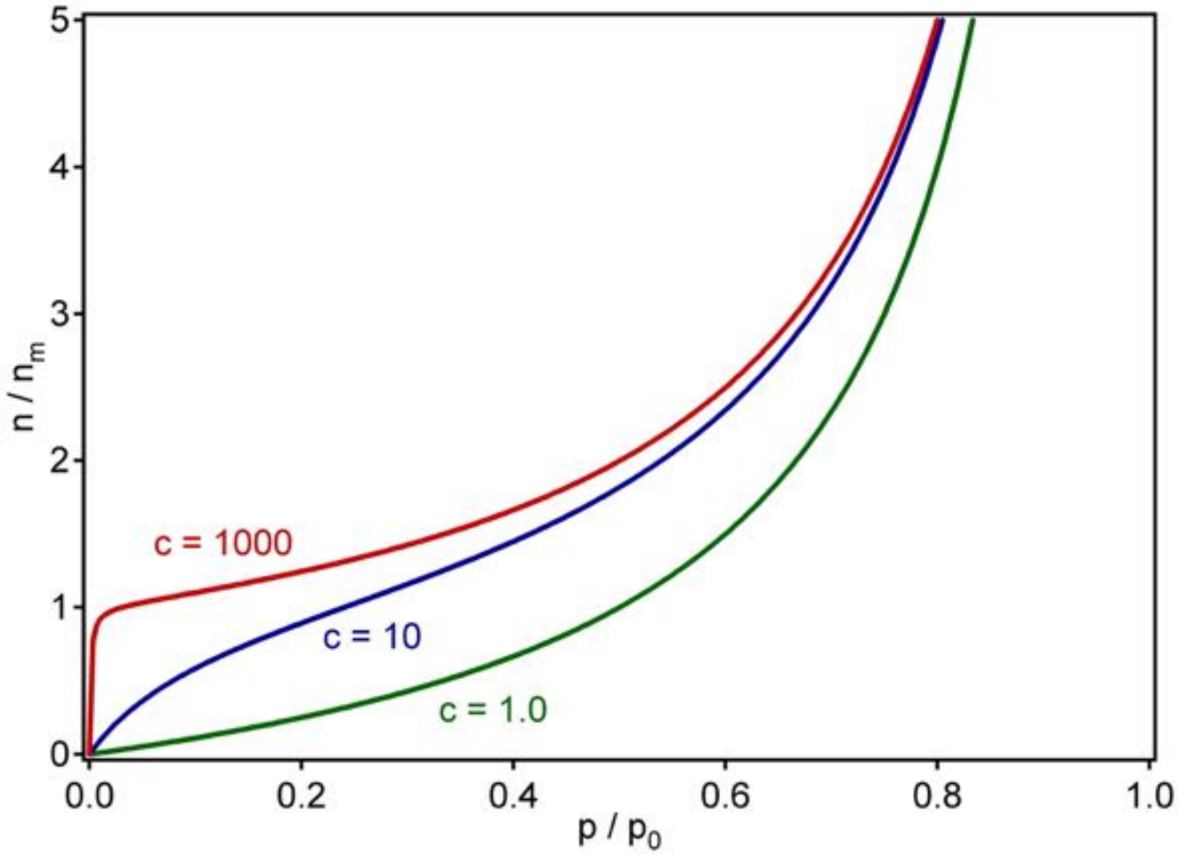


Ref.: Stephen Brunauer, P. H. Emmett, Edward Teller: Adsorption of Gases in Multimolecular Layers. In: Journal of the American Chemical Society. Band 60, Nr. 2 (1938), pp. 309–319, doi:10.1021/ja01269a023

4.1. BET Model







$$c = e^{\frac{\Delta H_{ads} - \Delta H_V}{k \cdot T}}$$

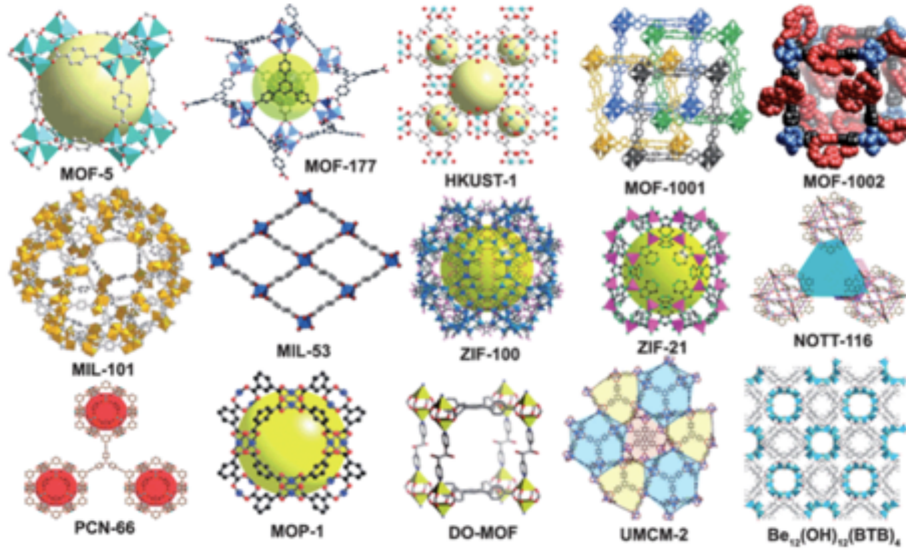
$$\frac{n}{n_m} = \frac{c \cdot \beta}{(1-\beta)\cdot(1+(c-1)\cdot\beta)} \qquad \beta = F \cdot \frac{k_a^0}{k_d^0} e^{\frac{\Delta H_V}{k \cdot T}} = \frac{p}{p_0}$$

linear form: $$\frac{1}{n[(p_0/p)-1]} = \frac{c-1}{n_m \cdot c} \cdot \left(\frac{p}{p_0}\right) + \frac{1}{n_m \cdot c}$$

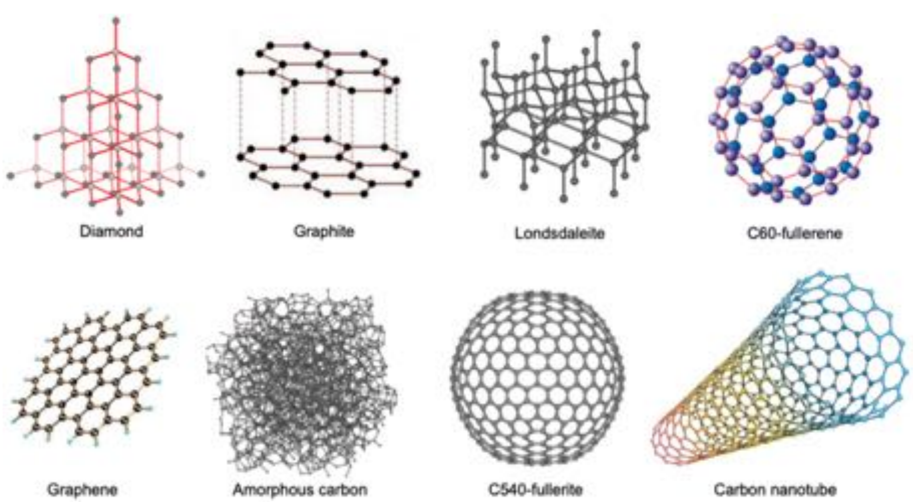
$y = a \cdot x + b$
$n_m = (a+b)^{-1}$
$c = 1+a/b$

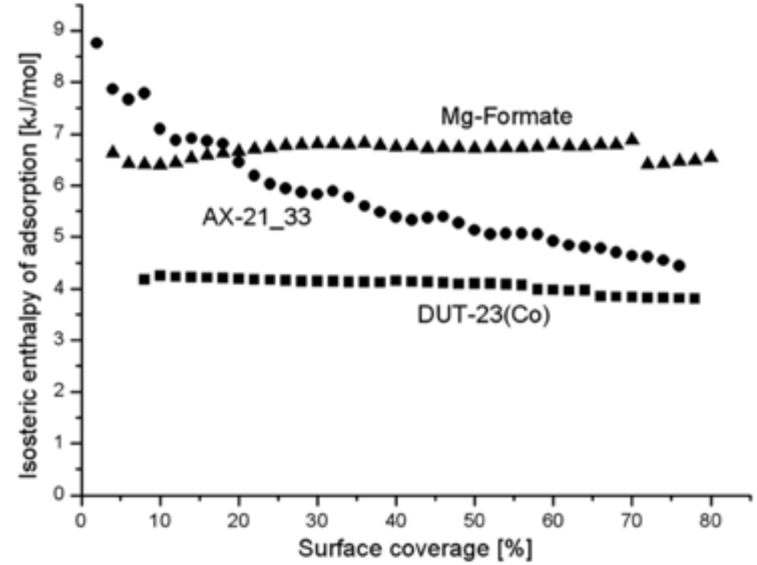
Ref.: Stephen Brunauer, P. H. Emmett, Edward Teller: Adsorption of Gases in Multimolecular Layers. In: Journal of the American Chemical Society. Band 60, Nr. 2 (1938), pp. 309–319, doi:10.1021/ja01269a023

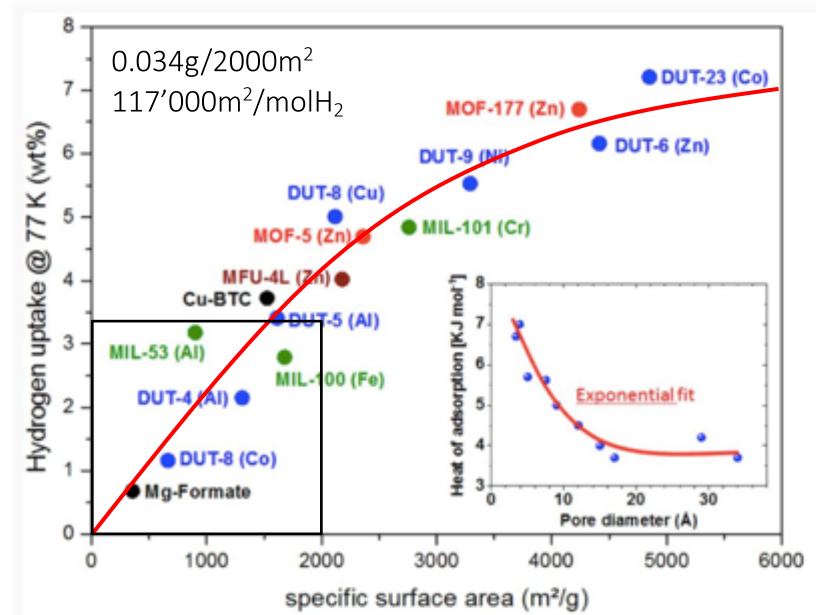
4.2. High Surface Area Materials



Zhonghua Xiang et al., *Energy Environ. Sci.* **3** (2010) 1469



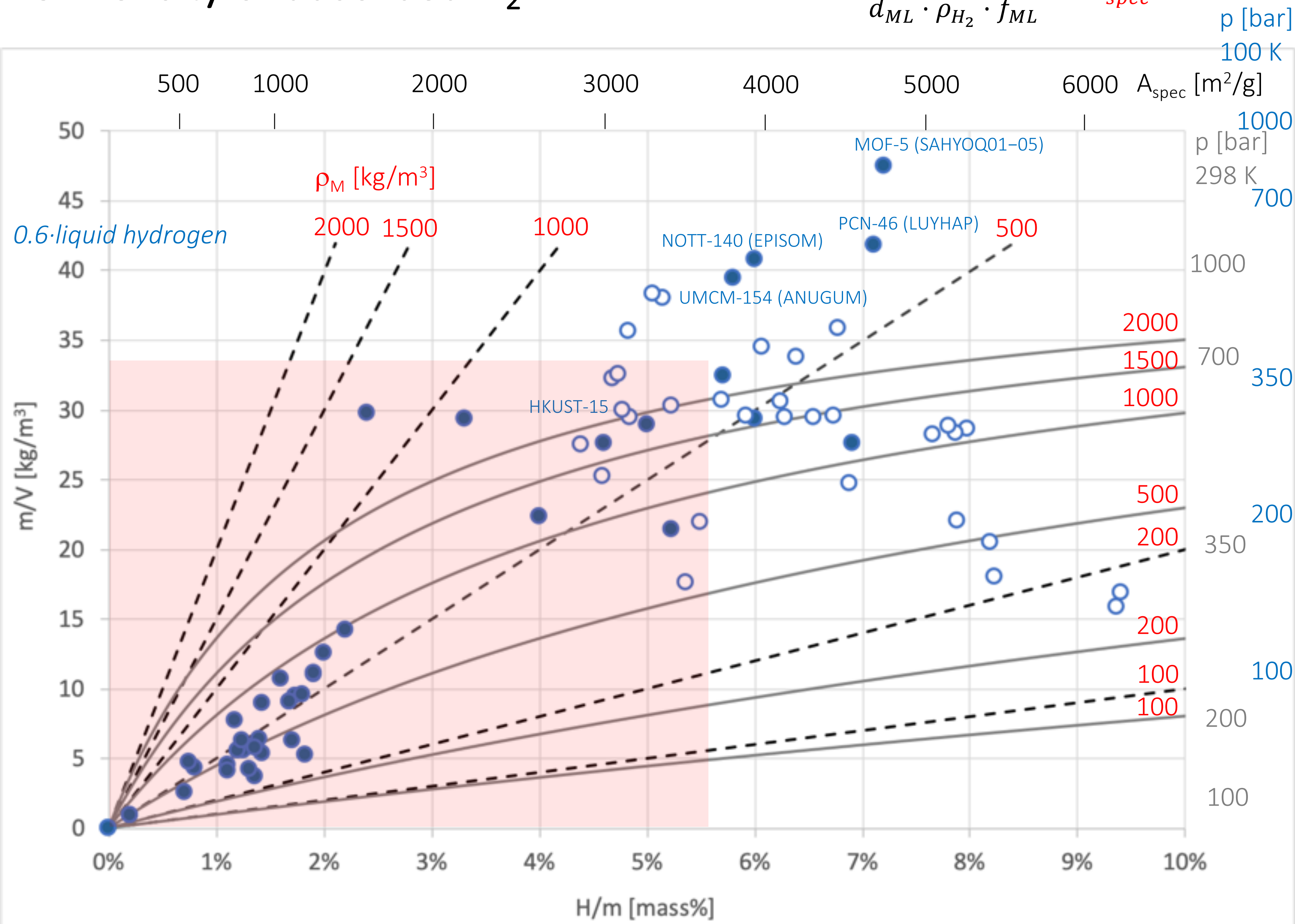




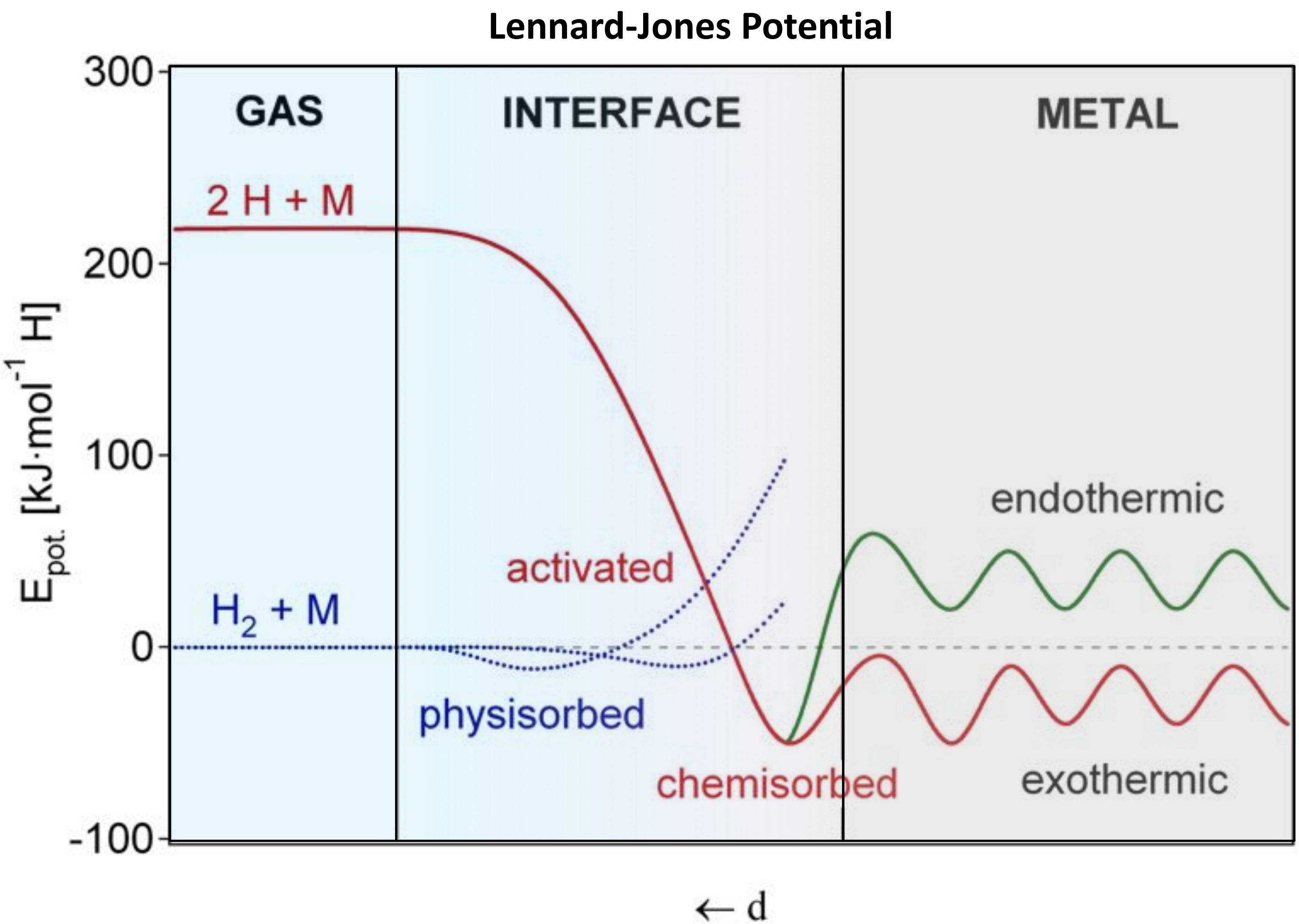
Ref.: Maurice Schlichtenmayer and Michael Hirscher, „Nanosponges for hydrogen storage", J. Mater. Chem., 22 (2012), 10134.

4.3. Density of adsorbed H_2

$$\frac{m\%}{d_{ML} \cdot \rho_{H_2} \cdot f_{ML}} = A_{spec}$$



5. Metal Hydrides

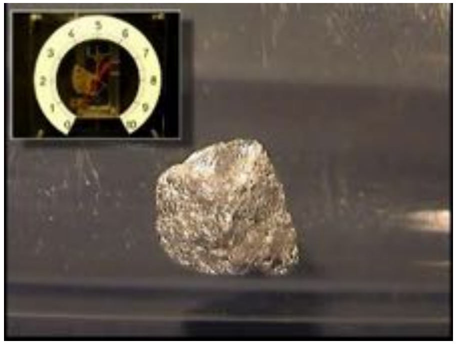


Ref.: J. E. Lennard-Jones, Trans. Faraday Soc. 28 (1932), pp. 333.
L. Schlapbach, Chapter 1, L. Schlapbach (Ed.) in Intermetallic Compounds I, Springer Series Topics in Applied Physics, Vol. 63, Springer–Verlag, 1988, p. 10.

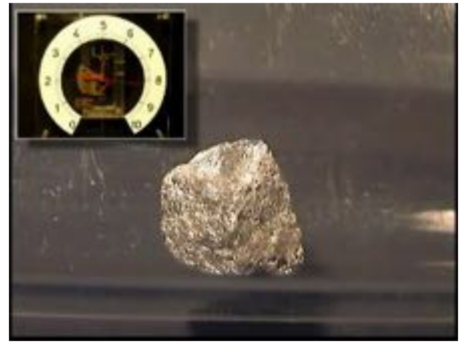
5.1.a) Hydrogen Absorption Film

Ph. Mauron, M. Bielmann, Empa, Switzerland

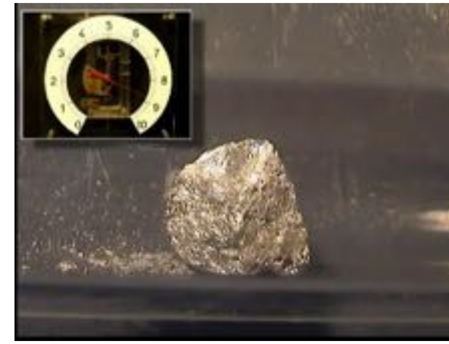
5.1.b) Hydrogen Absorption Sequences **$ZrMn_{1.5}$**



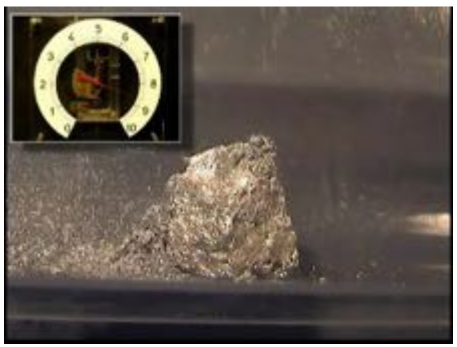
0 sec (vacuum)



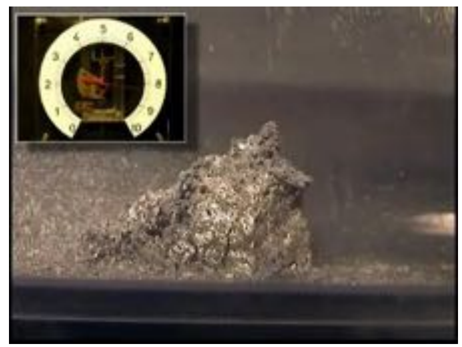
5 sec (8 bar H_2)



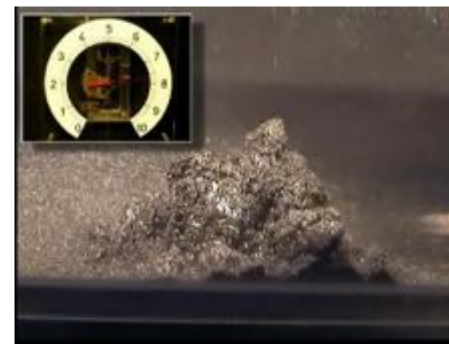
8 sec (8 bar H_2)



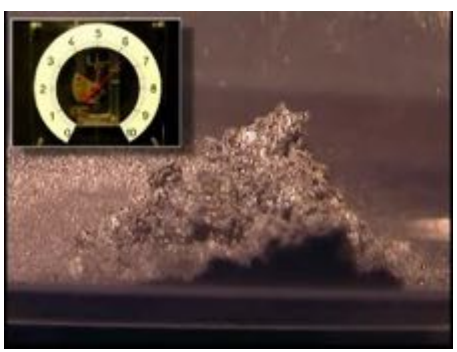
15 sec (8 bar H_2)



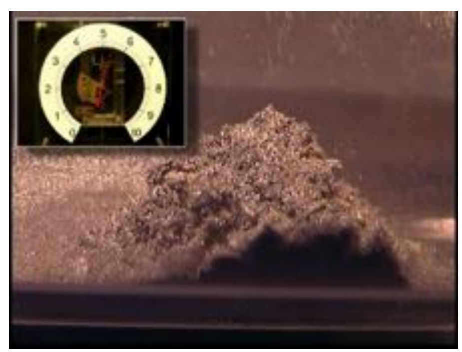
20 sec (8 bar H_2)



30 sec (7 bar H_2)

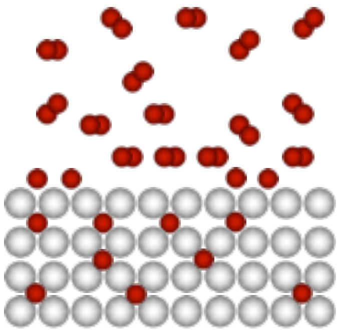


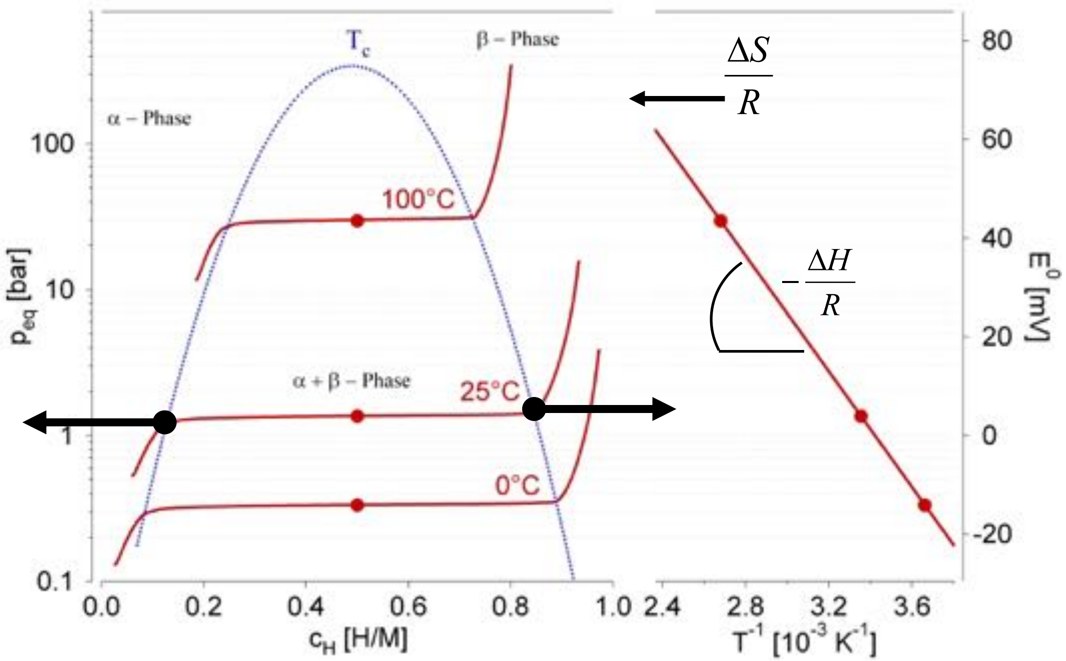
45 sec (6 bar H_2)

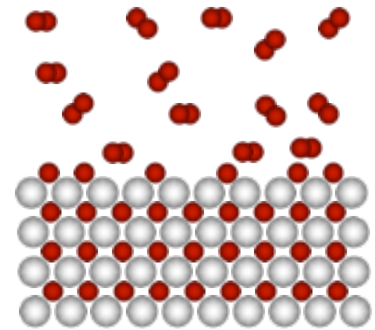


60 sec (5 bar H_2)

5.5. Equilibrium and Phase Transition







α-Phase
Solid Solution

α+β-Phase

β-Phase
Hydride Phase

$$\frac{1}{2}\ln\left(\frac{p}{p_0}\right) = k \cdot T \cdot \ln(c_H)$$

$$\ln\left(\frac{p}{p_0}\right) = -\frac{\Delta H^0}{R \cdot T} + \frac{\Delta S^0}{R}$$

$$\frac{1}{2}\ln\left(\frac{p}{p_0}\right) = k \cdot T \cdot \ln(c_H)$$

Van't Hoff equation

MH_x $(0 < x < 0.1)$

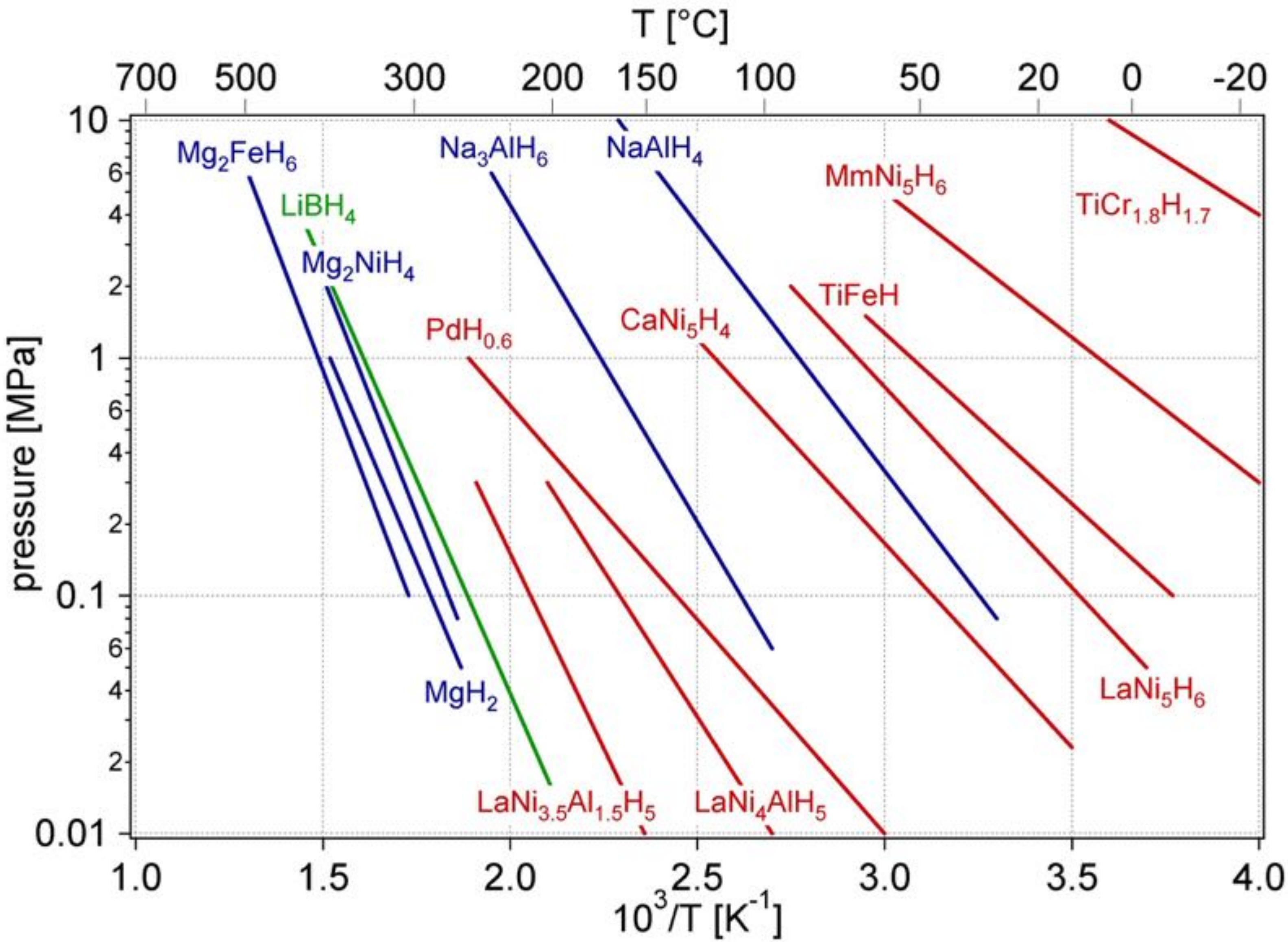
~~H↔H~~, $\Delta V/V = k \cdot c_H$

MH_x $x = \{1, 2, 3, \ldots\}$

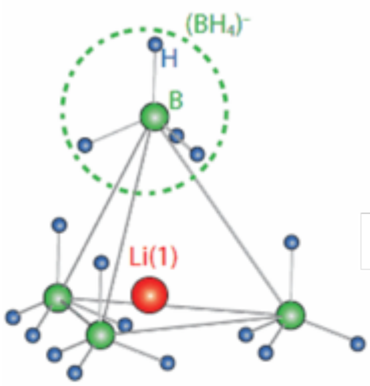
H↔H

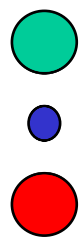
5.6. Van't Hoff Plot

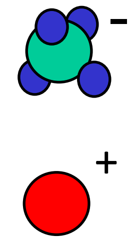
$$\ln\left(\frac{p}{p_0}\right) = -\frac{\Delta H^0}{R \cdot T} + \frac{\Delta S^0}{R}$$



6. Complex Hydrides





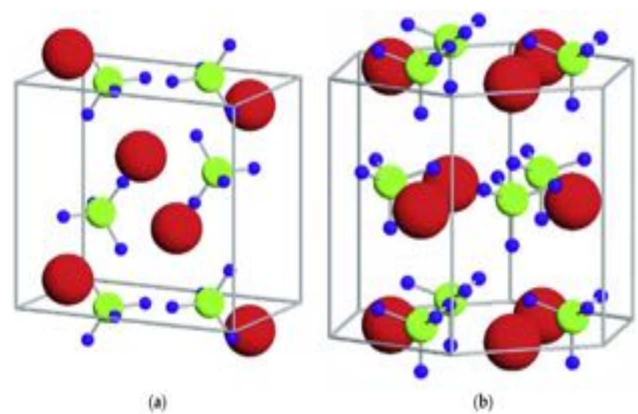


ionic crystal (salt)

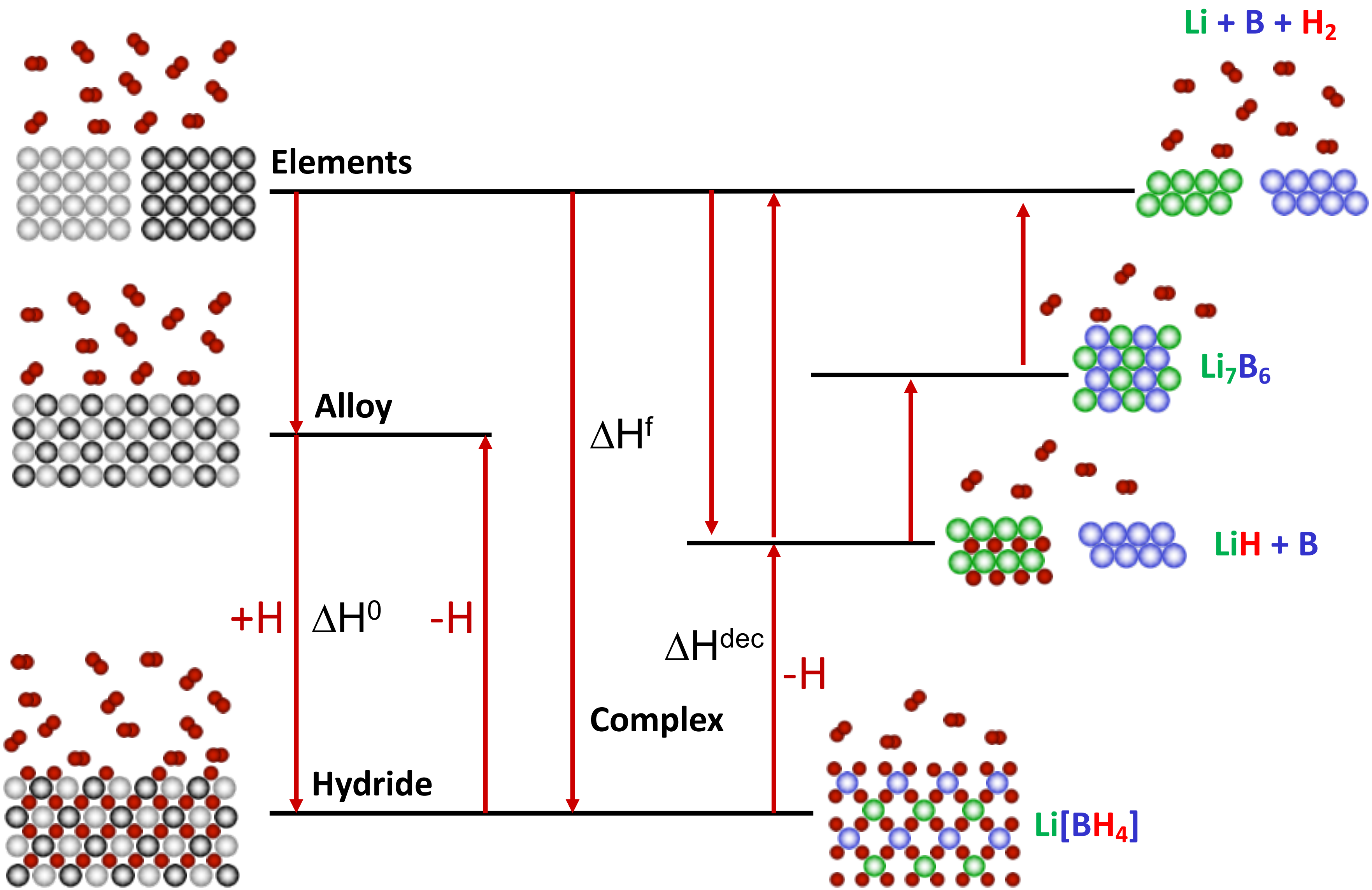
Table of Pauling Electronegativity Values

	IA	IIA	IIIB	IVB	VB	VIB	VIIB	VIII	VIII	VIII	IB	IIB	IIIA	IVA	VA	VIA	VIIA	VIIIA
1	1 H 2.1																	2 He
2	3 Li 1.0	4 Be 1.5											5 B 2.0	6 C 2.5	7 N 3.0	8 O 3.5	9 F 4.0	10 Ne
3	11 Na 0.9	12 Mg 1.2											13 Al 1.5	14 Si 1.8	15 P 2.1	16 S 2.5	17 Cl 3.0	18 Ar
4	19 K 0.8	20 Ca 1.0	21 Sc 1.3	22 Ti 1.5	23 V 1.6	24 Cr 1.6	25 Mn 1.5	26 Fe 1.8	27 Co 1.8	28 Ni 1.8	29 Cu 1.9	30 Zn 1.6	31 Ga 1.6	32 Ge 1.8	33 As 2.0	34 Se 2.4	35 Br 2.8	36 Kr
5	37 Rb 0.8	38 Sr 1.0	39 Y 1.2	40 Zr 1.4	41 Nb 1.6	42 Mo 1.8	43 Tc 1.9	44 Ru 2.2	45 Rh 2.2	46 Pd 2.2	47 Ag 1.9	48 Cd 1.8	49 In 1.8	50 Sn 1.8	51 Sb 1.9	52 Te 2.1	53 I 2.5	54 Xe
6	55 Cs 0.7	56 Ba 0.9	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl 1.8	82 Pb 1.9	83 Bi 1.9	84 Po 2.0	85 At 2.2	86 Rn
7	87 Fr 0.7	88 Ra 0.9	89 Ac	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110	111	112		114		116		

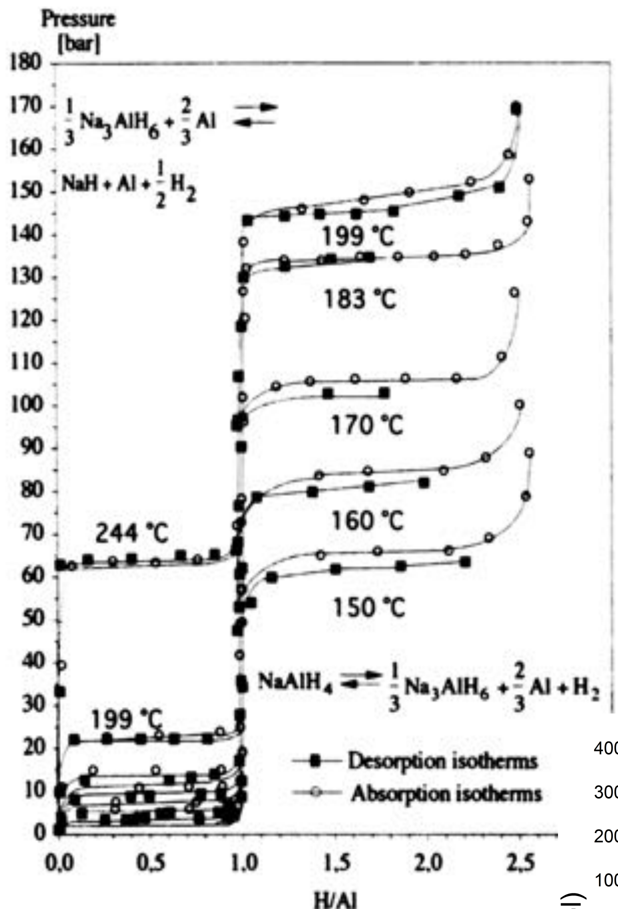
Lanthanides	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
Actinides	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr



6.1. Comparison Metal Hydrides vs. Complex Hydrides

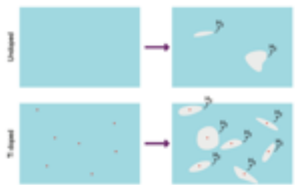


6.2. Catalytic Hydrogen Release

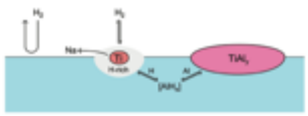


Ref.: B. **Bogdanovic**, M. **Schwickardi**, "*Ti-doped alkali metal aluminium hydrides as potential novel reversible hydrogen storage materials*", Journal of Alloys and Compounds **253** (1997), 1-9.

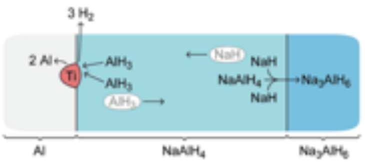
Nucleation/Phase Growth



Surface process

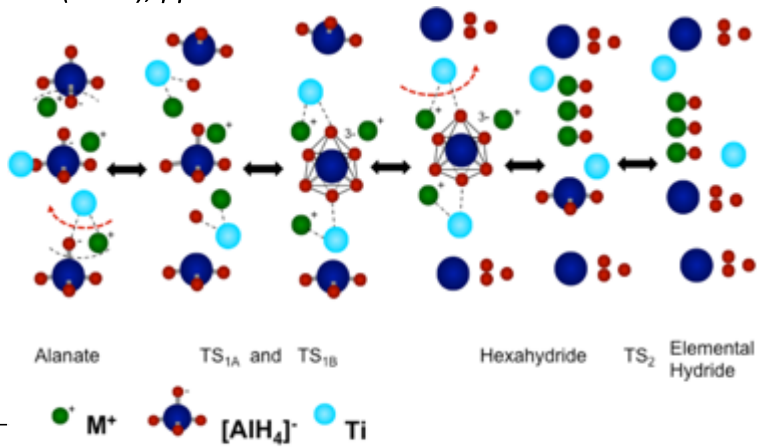


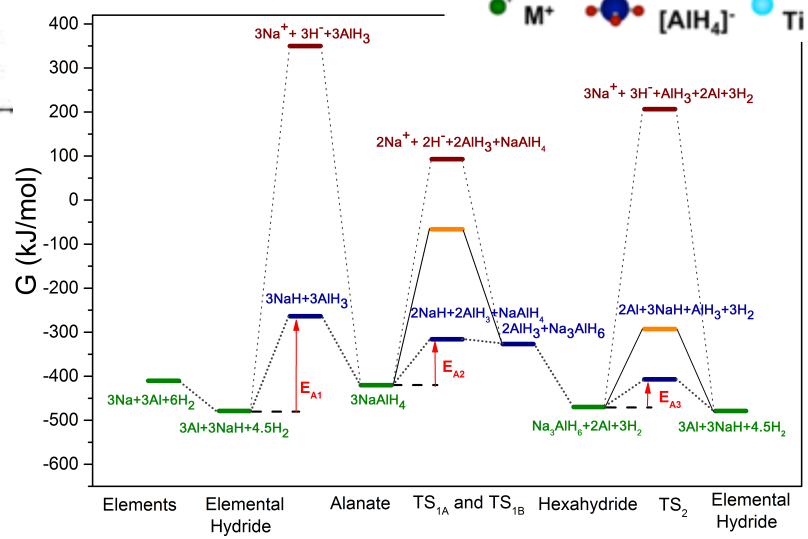
Diffusion of AlH_3, Al and NaH



Ref.: T.J. Frankcombe, „Proposed Mechanisms for the Catalytic Activity of Ti in $NaAlH_4$", Chem. Rev. ***112*** *(2012), pp. 2164 - 2178*

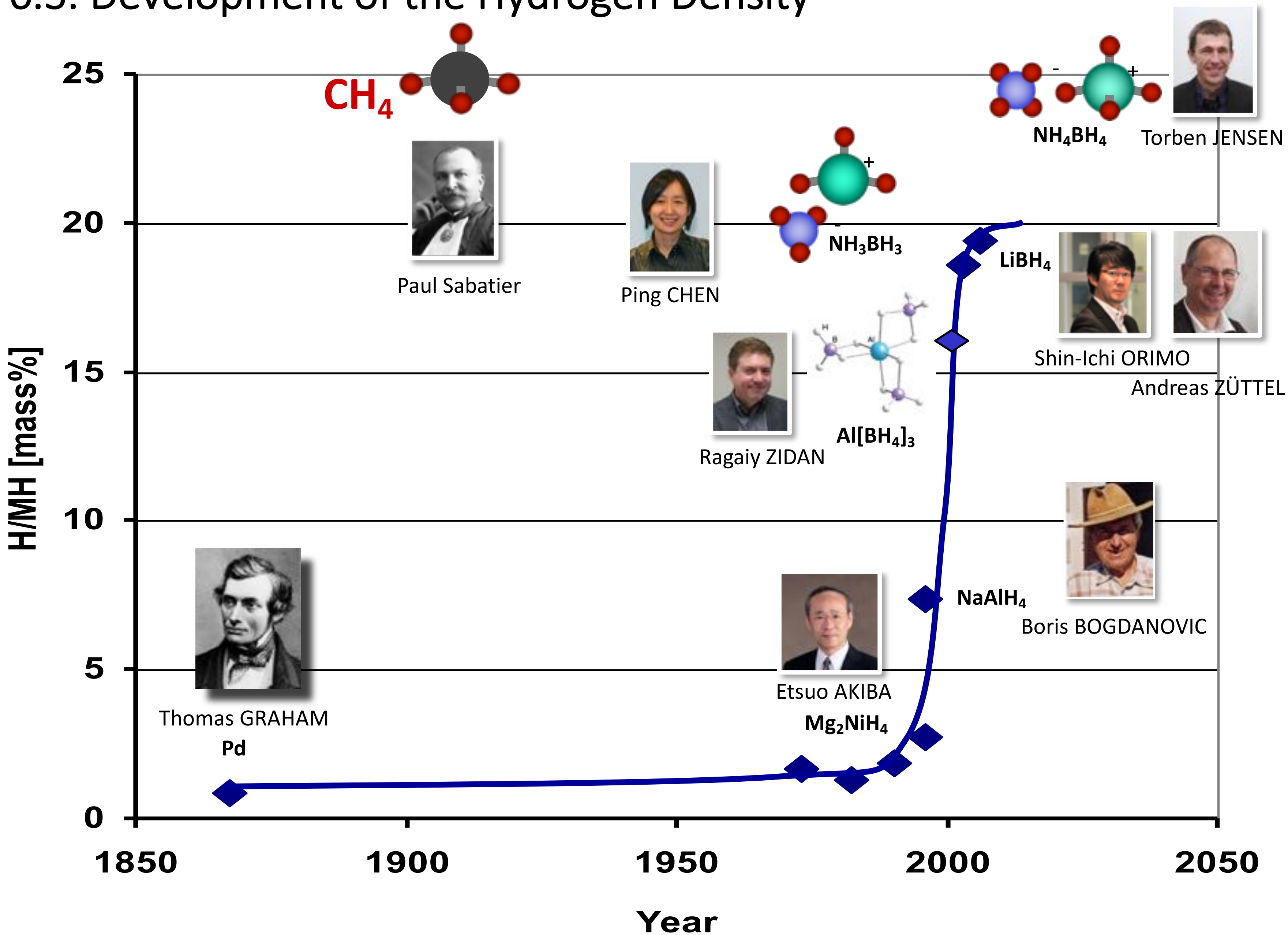
Boris BOGDANOVIC



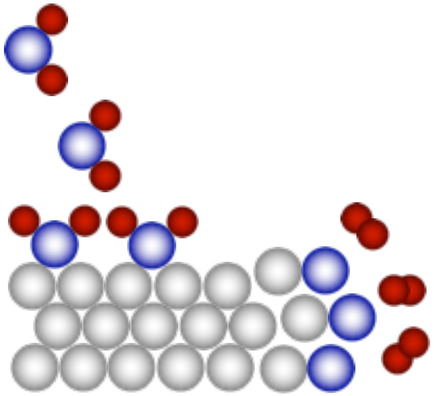


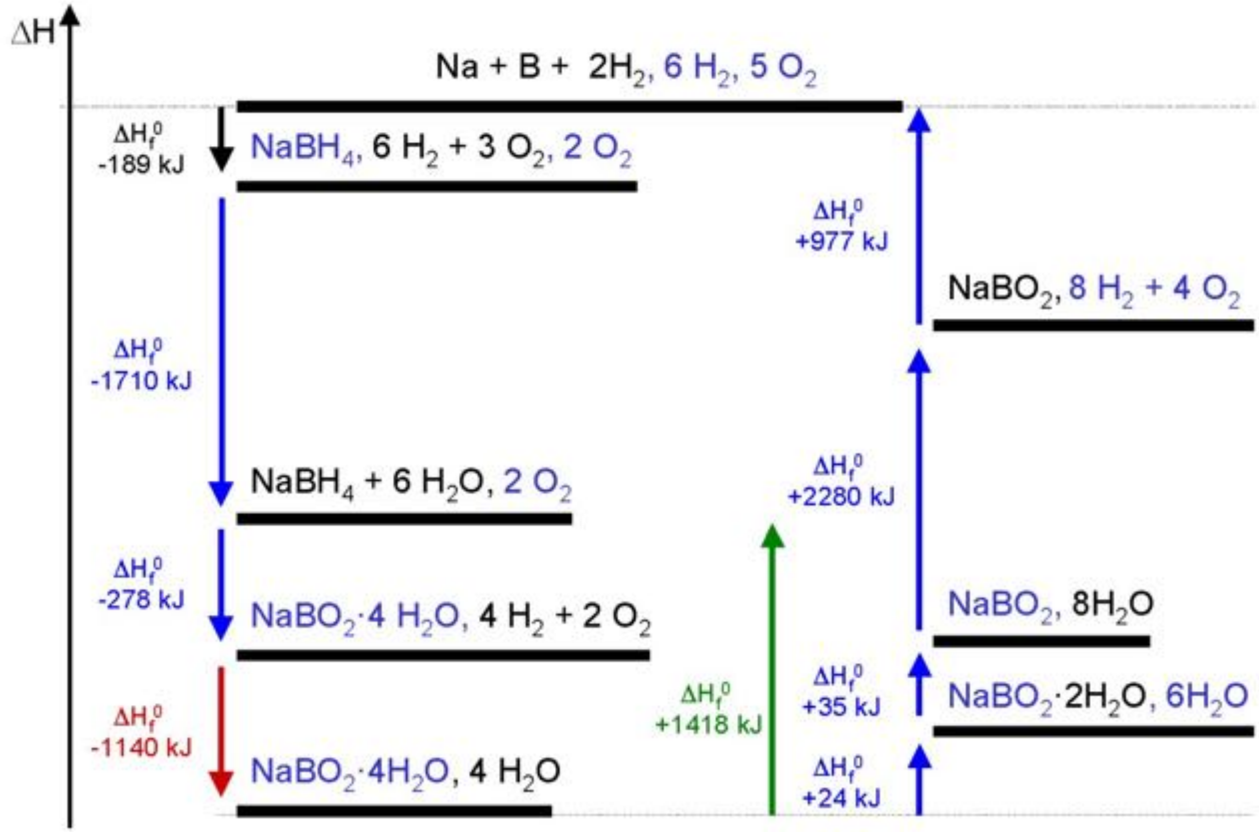
Ref.: Z. Ö. Kocabas Atakli, E. Callini, S. Kato, P.Mauron, S. Orimo, A. Züttel, "Catalyzed Hydrogen Sorption Mechanism in Alkali Alanates", Phys. Chem. Chem. Phys. ***17****:32 (2015), p. 20932-20940.*

6.3. Development of the Hydrogen Density



7. Chemical Hydrides





$NaBH_4 + 2\,H_2O \rightarrow NaBO_2 + 4\,H_2$ 21.3 mass%

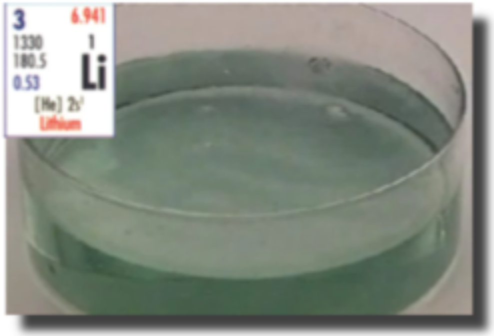
$LiBH_4 + 2\,H_2O \rightarrow LiBO_2 + 4\,H_2$ 37.0 mass%

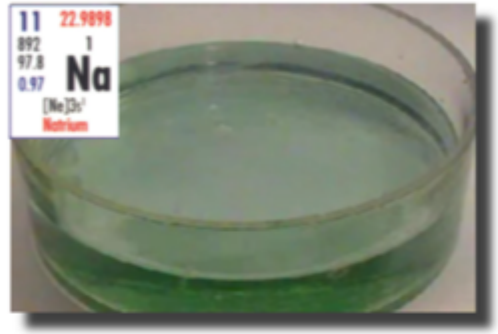
$NaBH_4 + 3\,H_2O \rightarrow NaBO_3 + 5\,H_2$ 35.7 mass%

$LiBH_4 + 3\,H_2O \rightarrow LiBO_3 + 5\,H_2$ 45.5 mass%

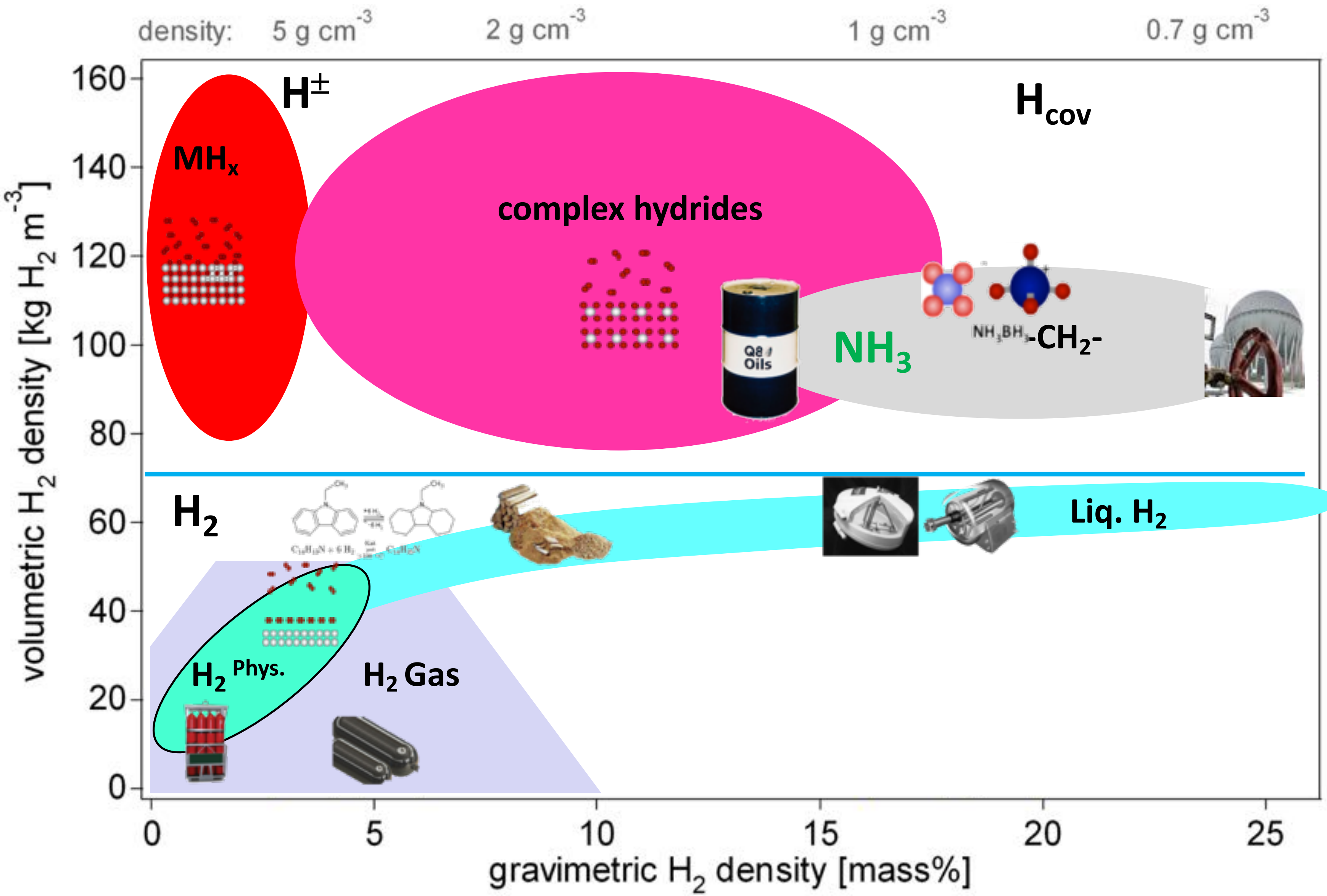
7.1.a) Reaction of Metals with Water

7.1.b) Reaction of Metals with Water





8. Hydrogen Storage Density



Ref: A. Züttel, "Materials for hydrogen storage", materialstoday, Septemper (2003), pp. 18-27

9. Hydrogen Storage in Mobility

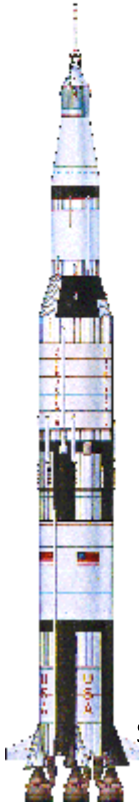

Francois Isaac de Rivaz (1813)


Hindenburg (1937)


Karl Kordesch: Austin A40 (1966)


Tupolev 155 (1988)

Hy.move (2009)


Saturn (1963)


Space Shuttle (1981)


Necar 1 (1994)


NuBus, 250kW (2002)

Necar 4 (2002)


Hyundai Nexo hydrogen car FCEV (2018)

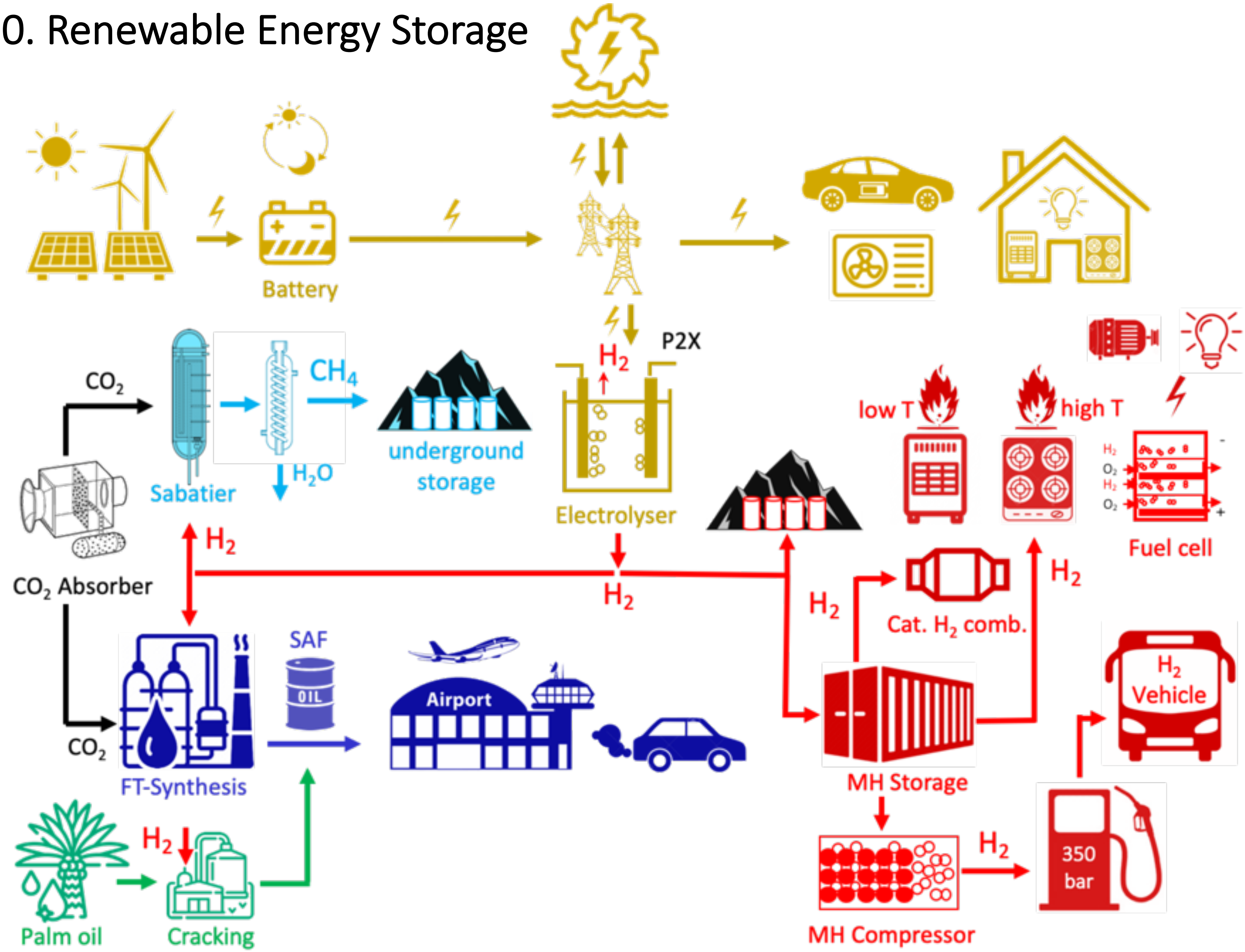

BMW (1978)


Ratrac (2004)

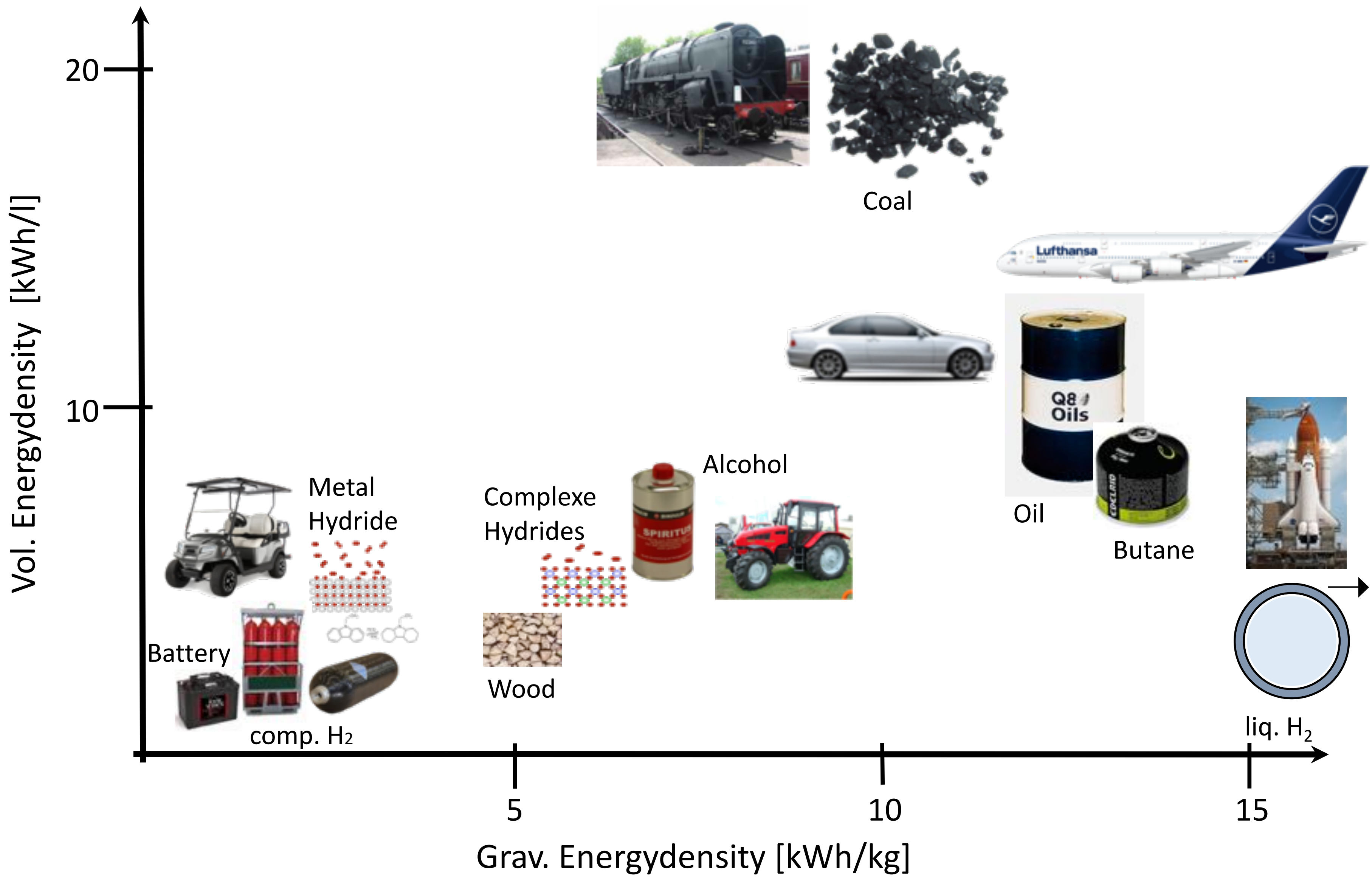

Toyota Mirai (2014)


Coradia iLint (2018)

10. Renewable Energy Storage

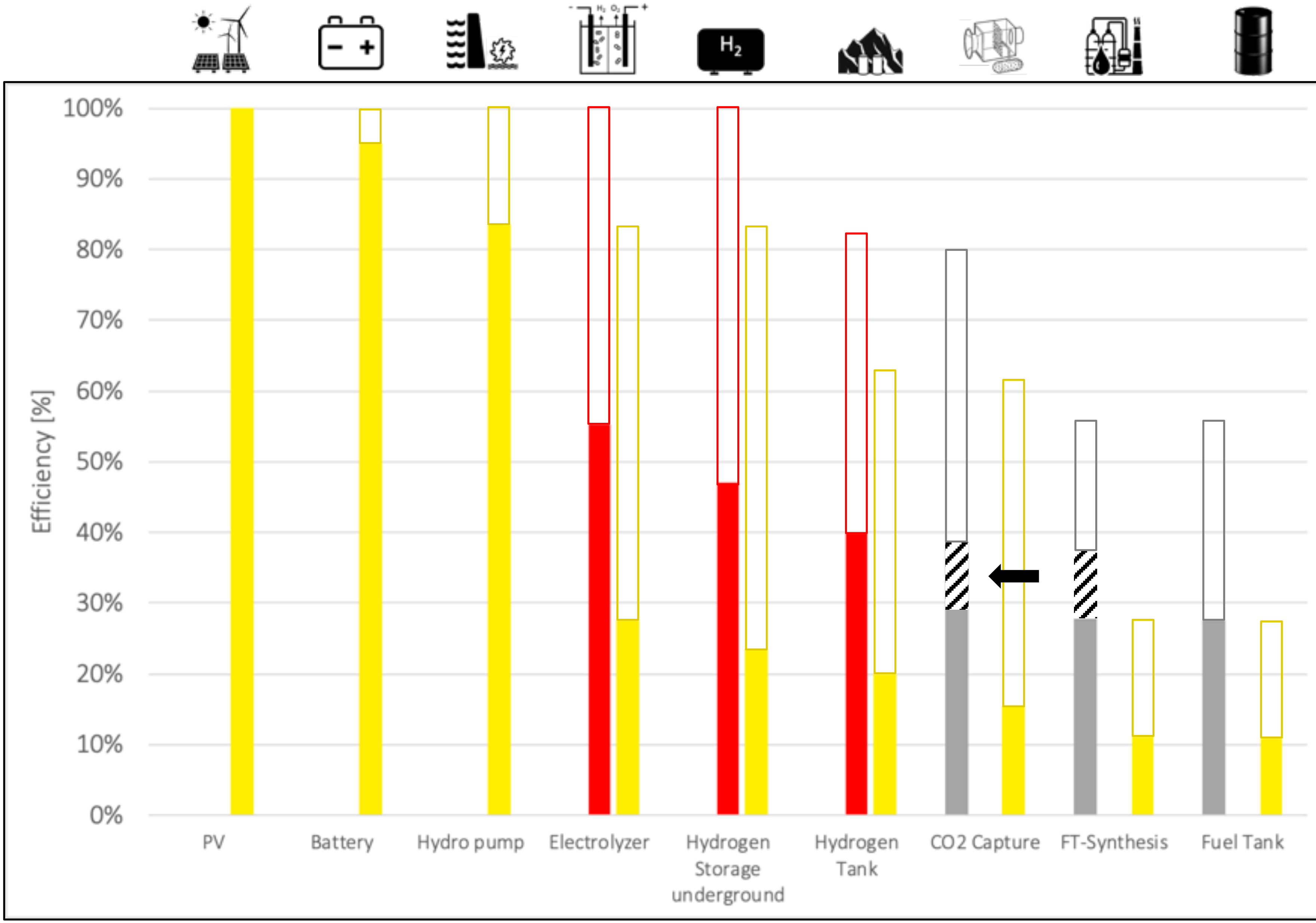


10.1. Energy Storage Density



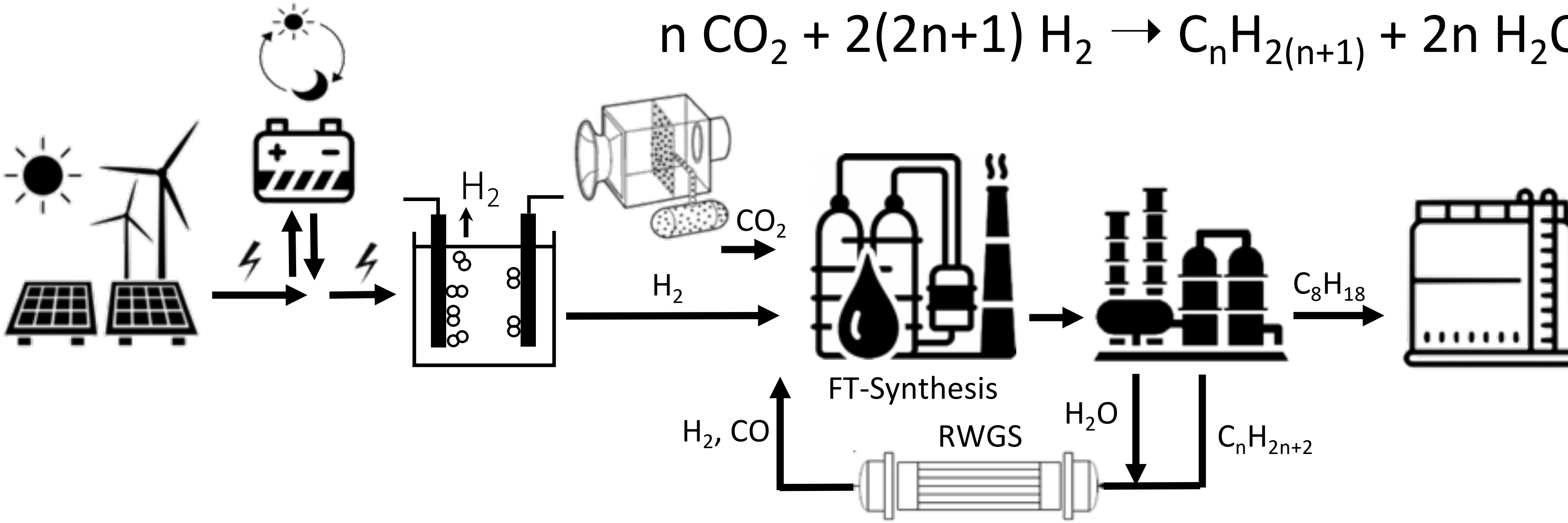
10.2. Efficiency of energy conversion

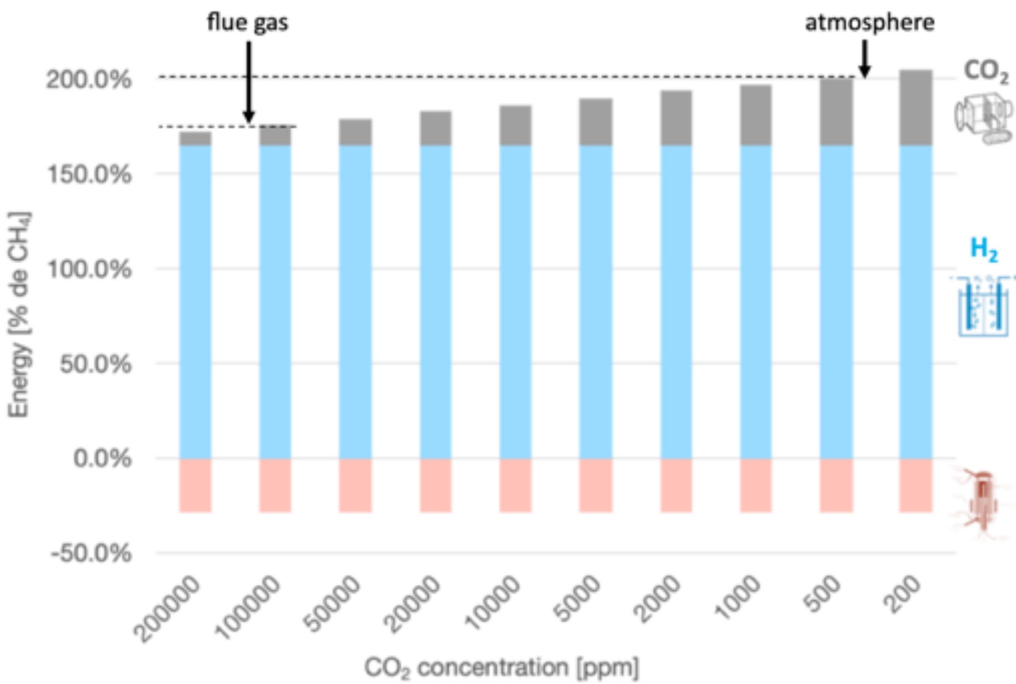
Power to X (P2X)



10.3. Synthetic Hydrocarbons

$$n\,CO_2 + 2(2n+1)\,H_2 \rightarrow C_nH_{2(n+1)} + 2n\,H_2O$$





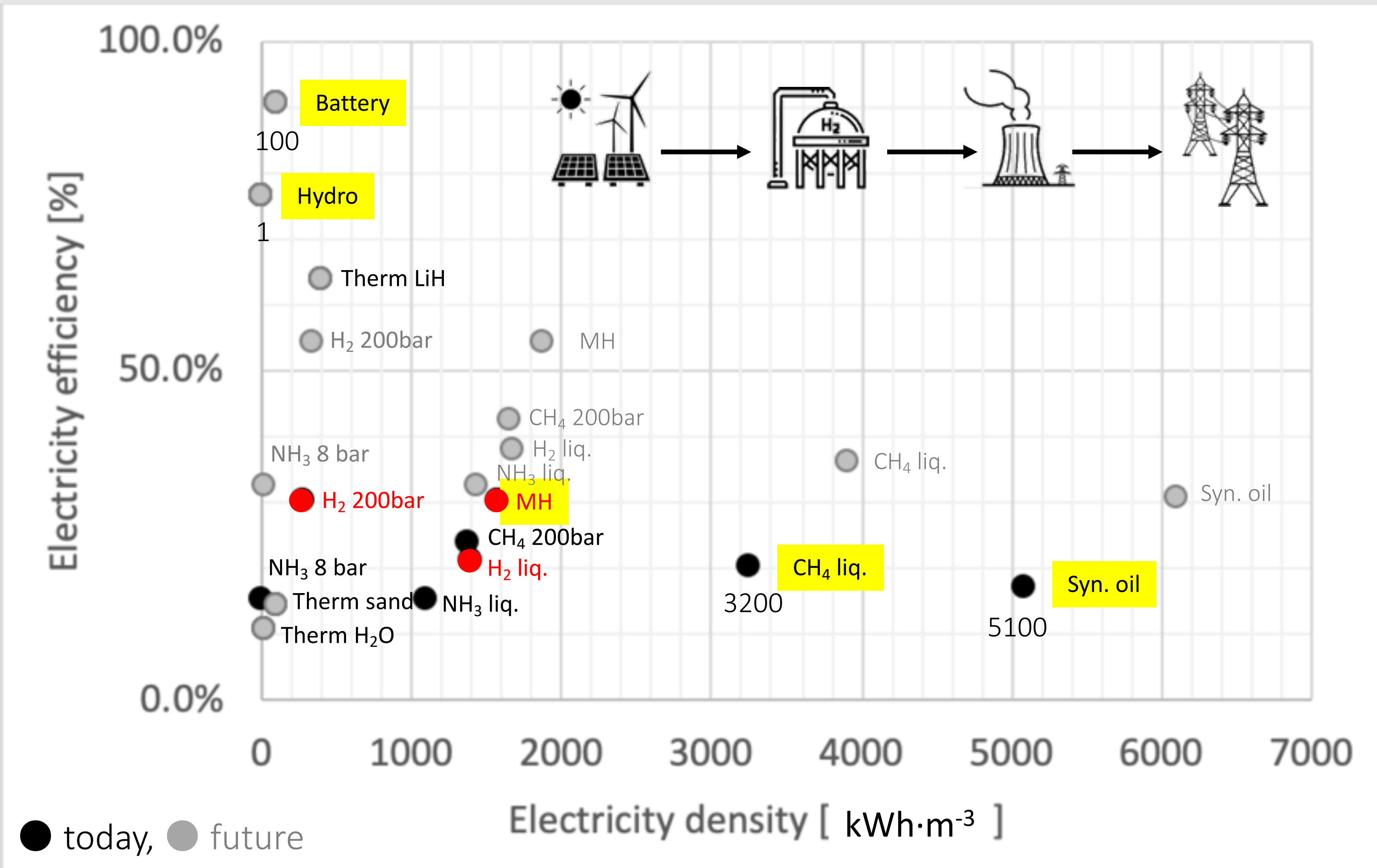
CAPEX

CO_2 capture: 1 – 5 €/kg CO_2

Synthesis: 2000 – 30000 €/kW

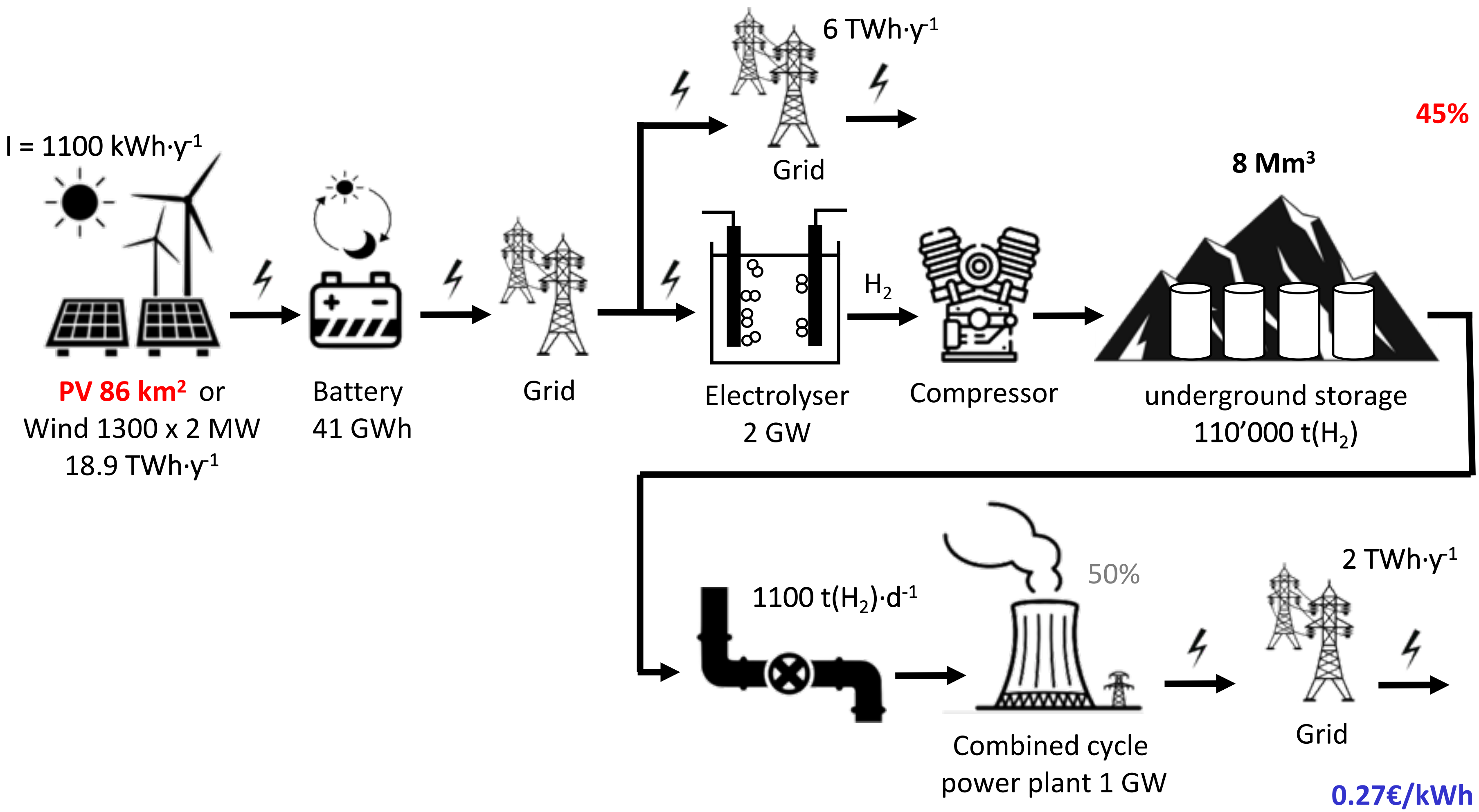
Storage: 1 €/kg HC

10.4. Efficiency and storage density of renewable electricity

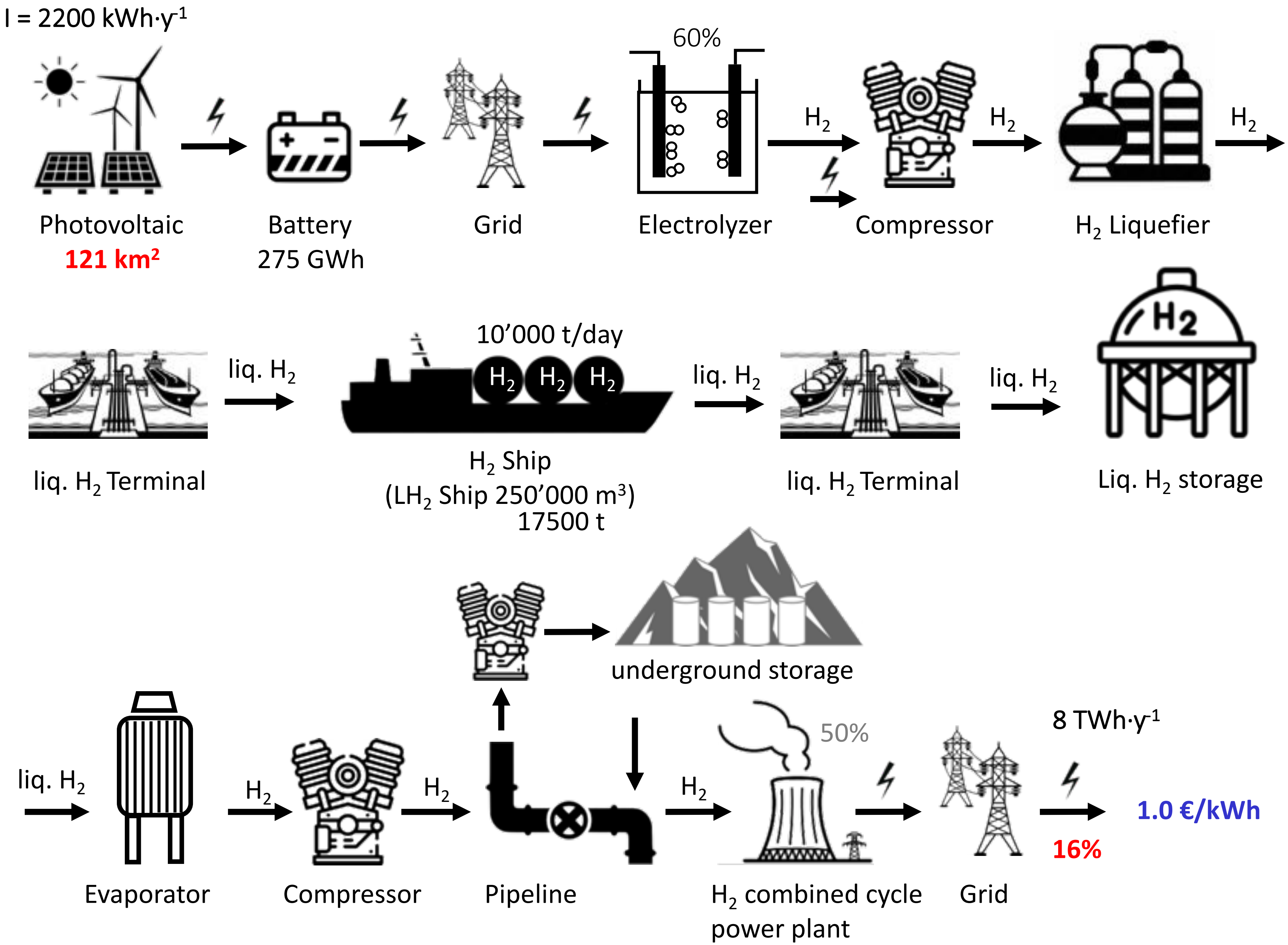


Ref.: Andreas ZÜTTEL, Christoph NÜTZENADEL, Louis SCHLAPBACH, Paul W. GILGEN "Power plant units for CO_2 Neutral Energy Security in Switzerland", Frontiers in Energy Research: Process and Energy Systems Engineering, 12:1336016 (2024).

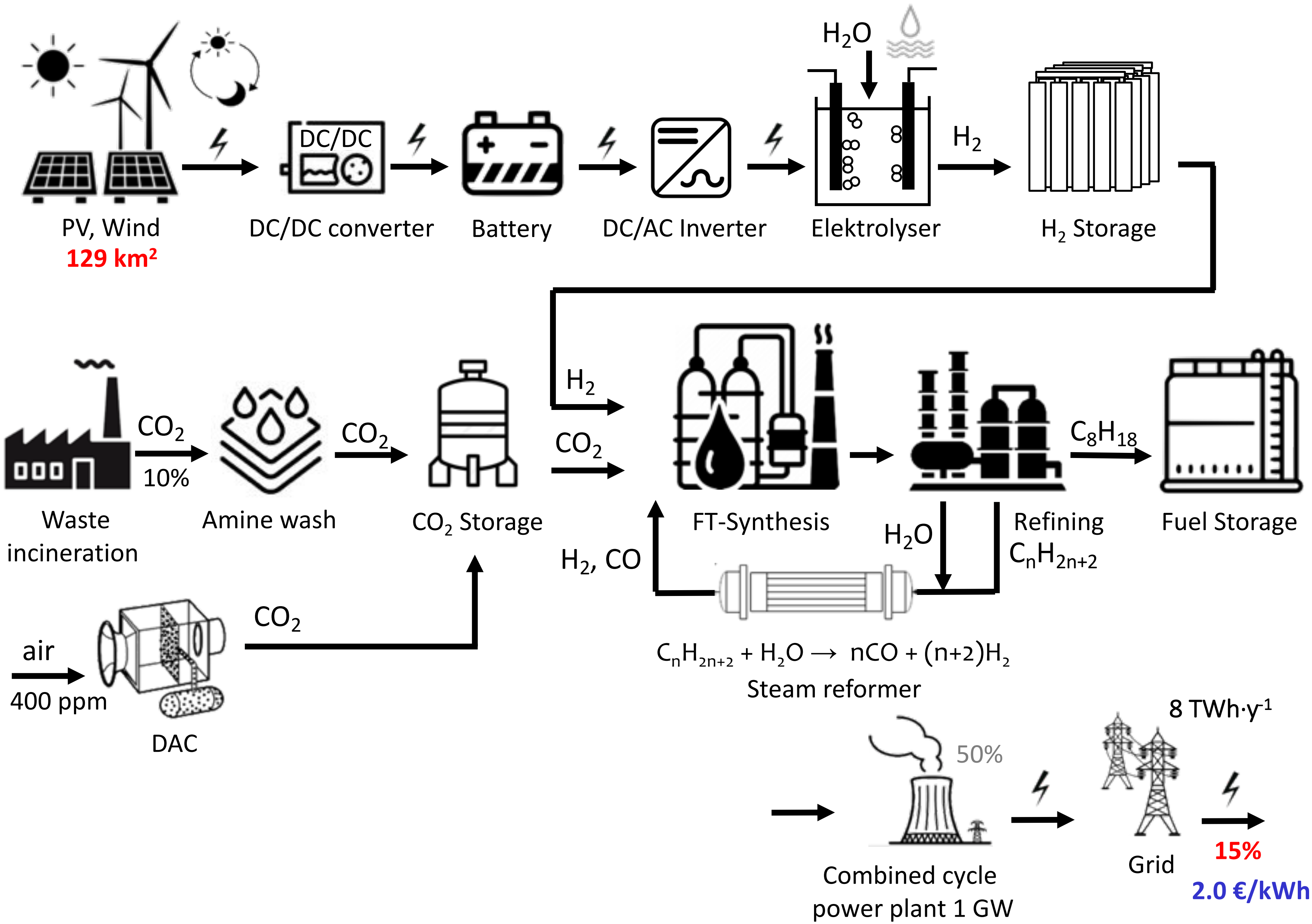
10.5. Seasonal Storage with Hydrogen



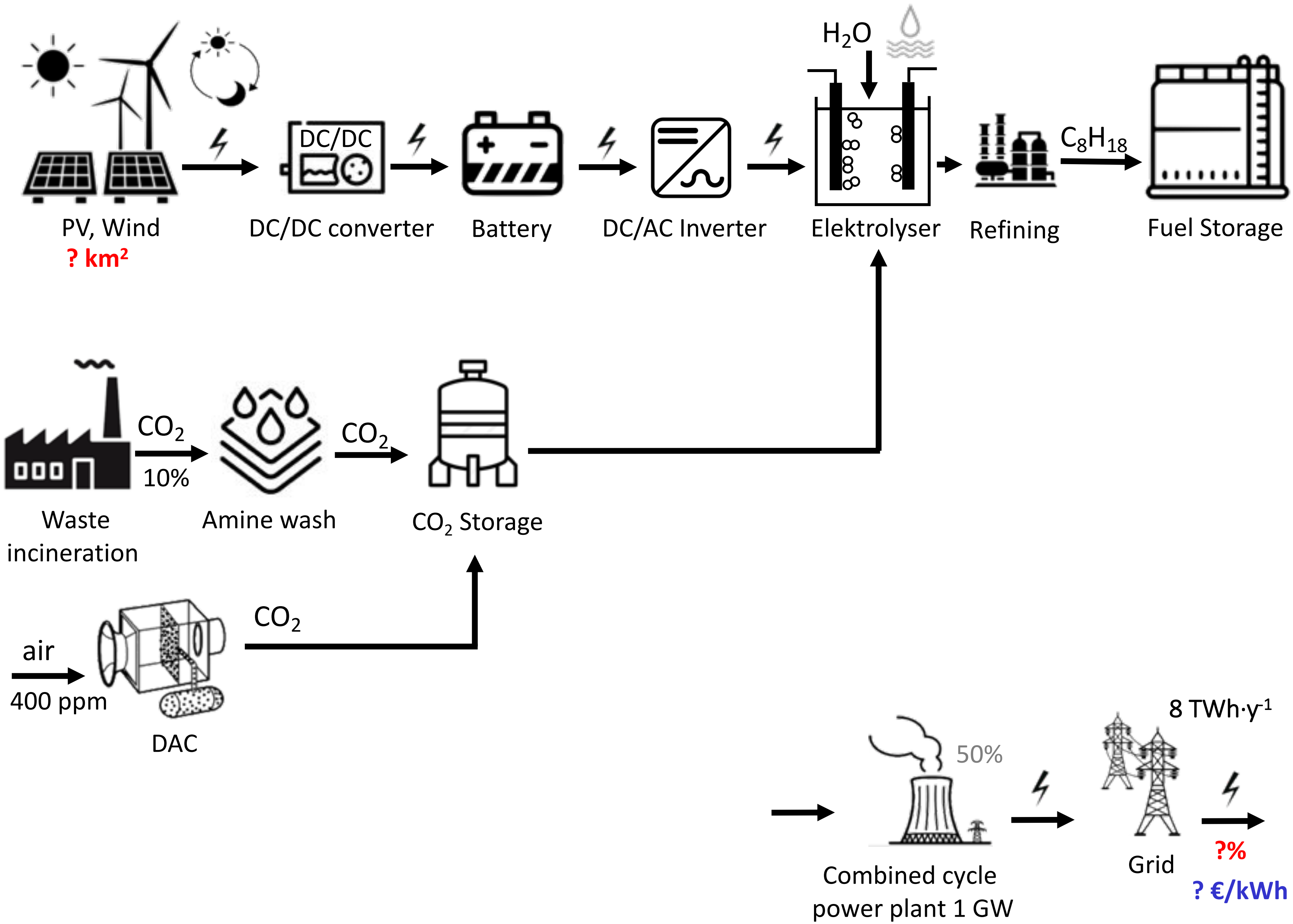
10.6. Import of liquid hydrogen



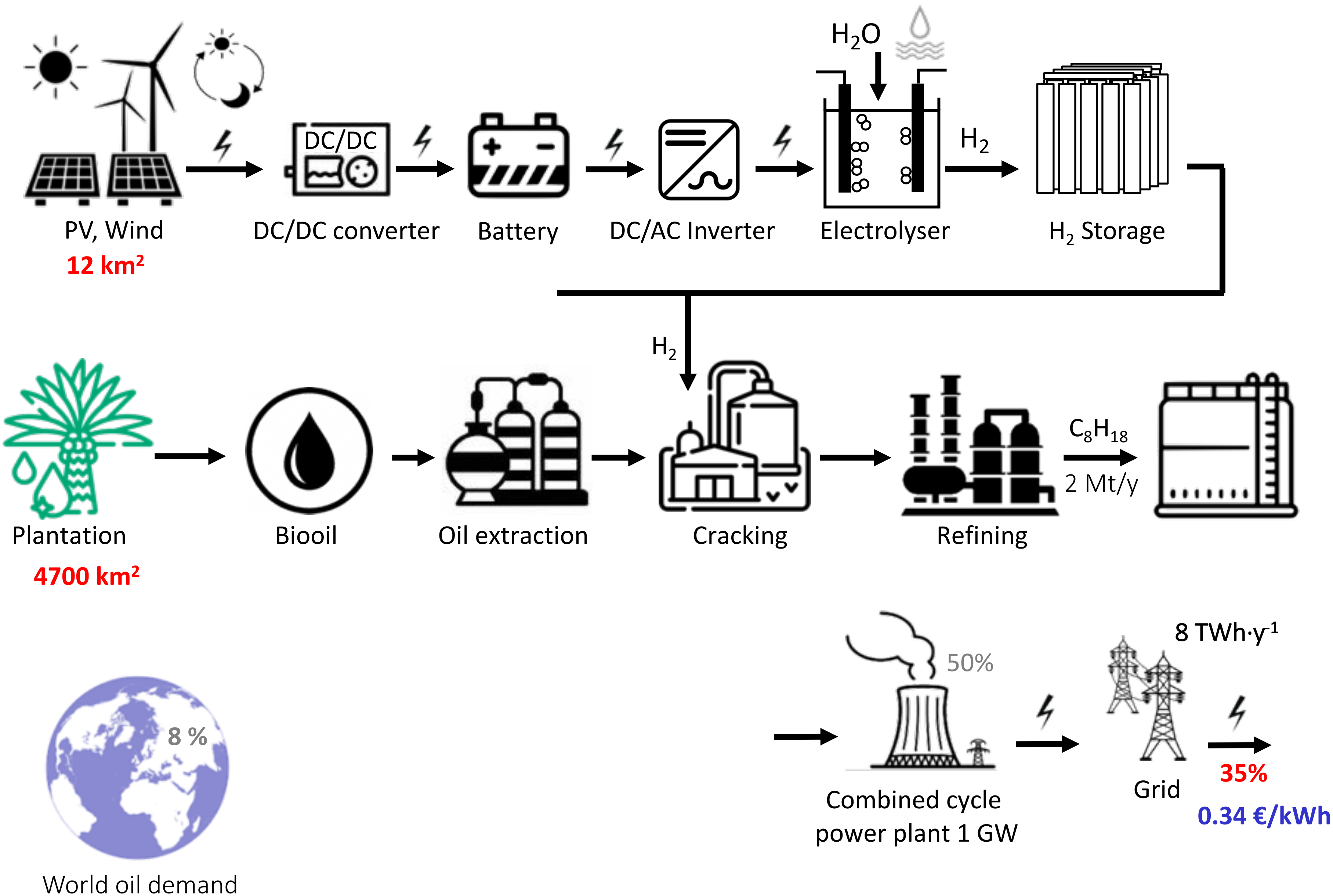
10.7. CO_2 reduction with green hydrogen and FT



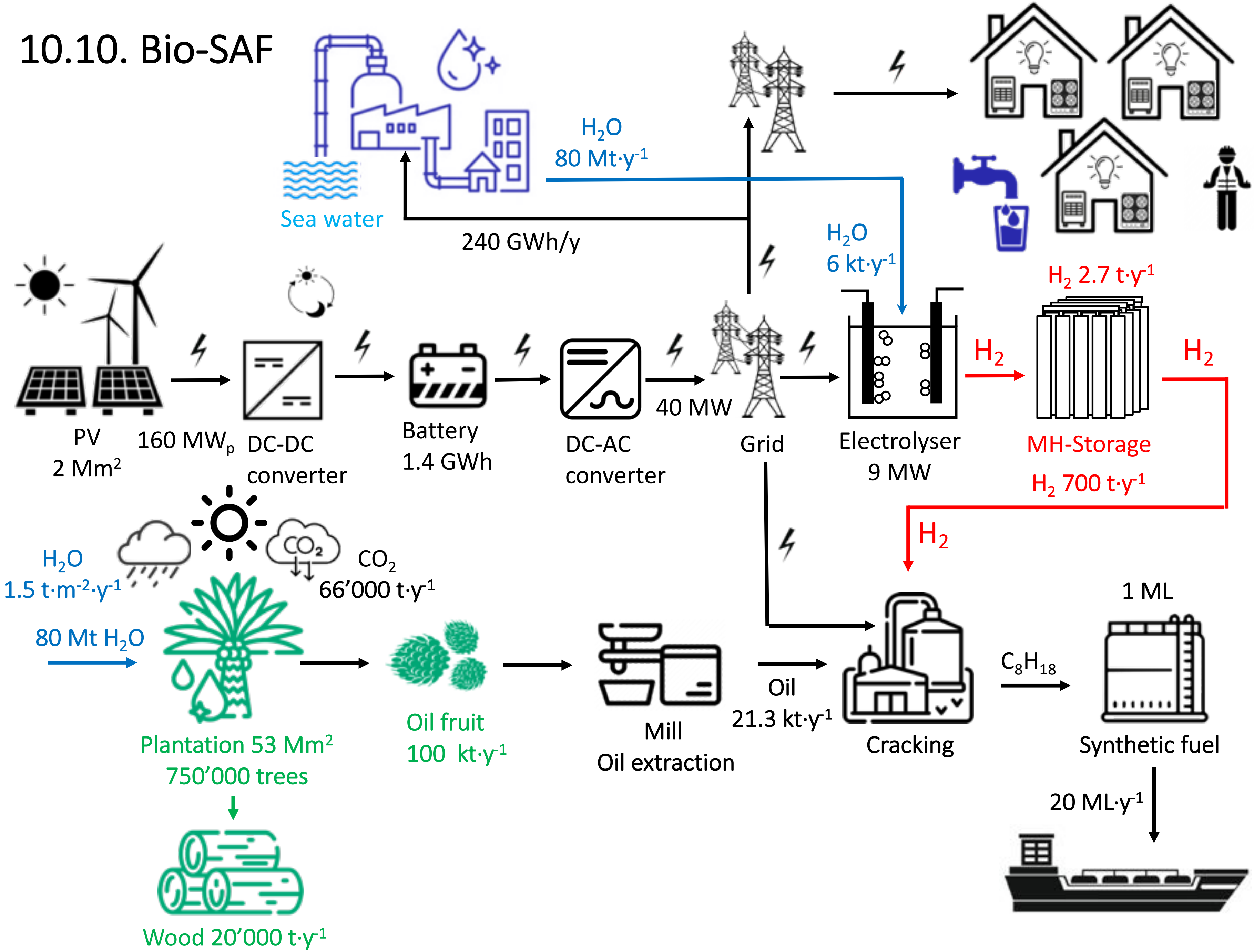
10.8. Electrochemical CO_2 reduction



10.9. Bio oil refining with hydrogen

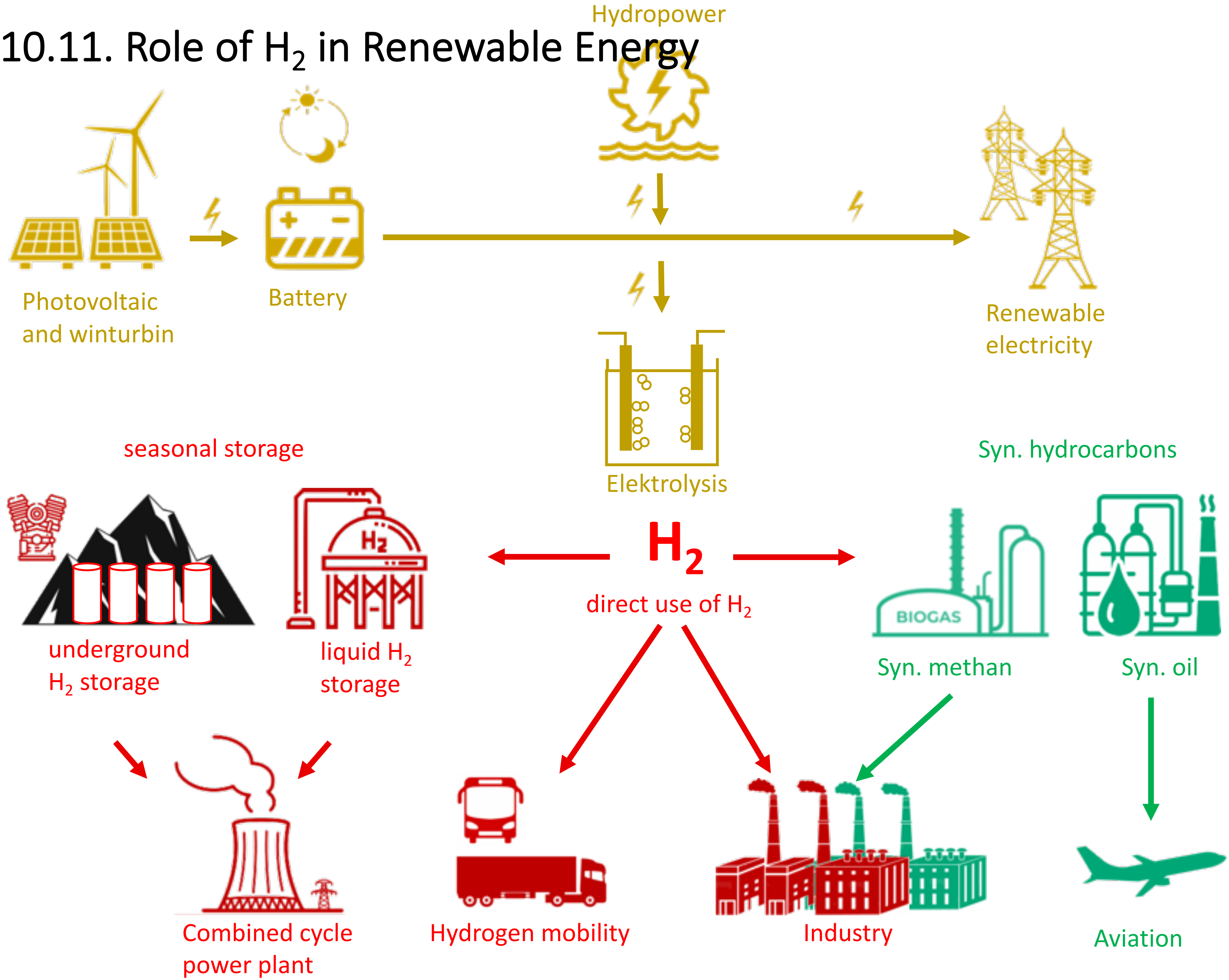


10.10. Bio-SAF



Sea water
H_2O 80 Mt·y-1
240 GWh/y
H_2O 6 kt·y-1
H_2 2.7 t·y-1
PV 2 Mm2
160 MWp
DC-DC converter
Battery 1.4 GWh
DC-AC converter
40 MW
Grid
Electrolyser 9 MW
H_2
MH-Storage
H_2 700 t·y-1
H_2
H_2
H_2O 1.5 t·m-2·y-1
CO_2
CO_2 66'000 t·y-1
80 Mt H_2O
Plantation 53 Mm2
750'000 trees
Oil fruit 100 kt·y-1
Mill
Oil extraction
Oil 21.3 kt·y-1
Cracking
C_8H_{18}
1 ML
Synthetic fuel
20 ML·y-1
Wood 20'000 t·y-1

10.11. Role of H_2 in Renewable Energy



11. Safety

LZ 129 "HINDENBURG"

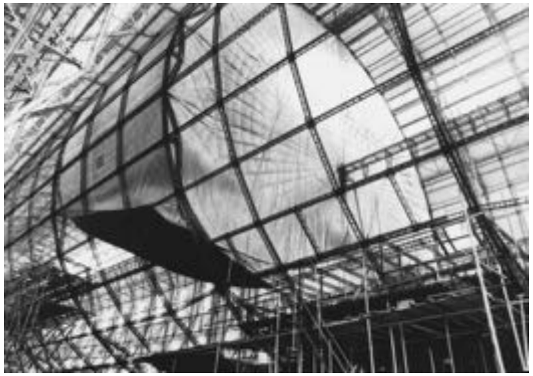
New York / Lakehurst, May 6th 1937, 6 pm

Accident:
While the airship was landing she has got on fire about 80 meters above ground level and crashed.
Fatalities:
13 of 36 passengers,
22 of 60 crew members
1 member of 228 ground staff holding the ship.

Ref.: Addison Bain, Wm. D. Van Vorst, "The Hindenburg tragedy revisited: the fatal flaw found", Int. Journal of Hydrogen Energy 24 (1999), pp. 399-403

11.1. Hindenburg accident Investigation

New investigation: The inflammable skin of the Hindenburg was ignited by an electric discharge arc between the electrostatic charged skin and the grounded metallic frame.



Ref.: Addison Bain, Wm. D. Van Vorst, "The Hindenburg tragedy revisited: the fatal flaw found", Int. Journal of Hydrogen Energy 24 (1999), pp. 399-403

11.2. Hydrogen Accidents

LZ 129 “HINDENBURG” 1937

Space Shuttle “Challenger” USA, 28.1.1986

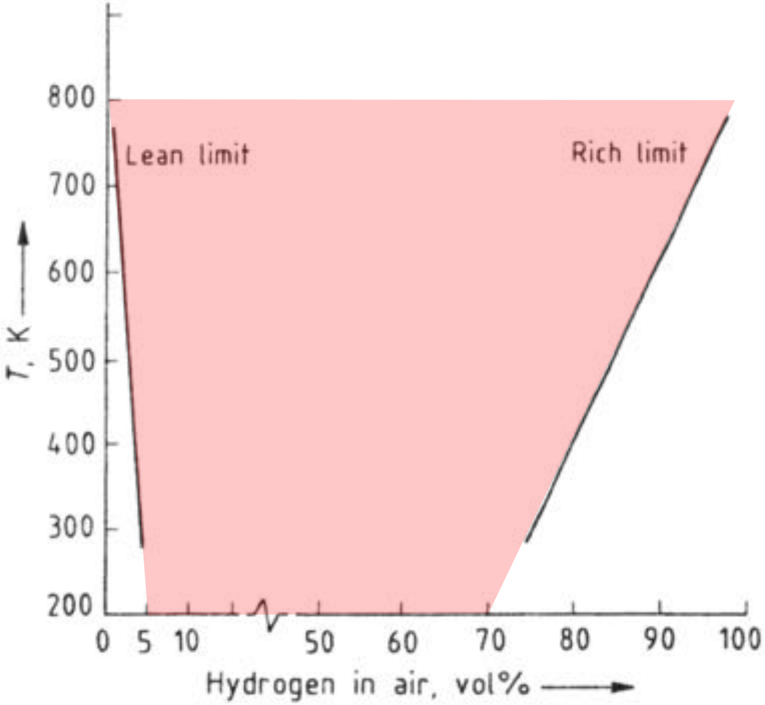
Tank explosion *Muskingum River Power Plant’s* , USA, 8.1. 2007

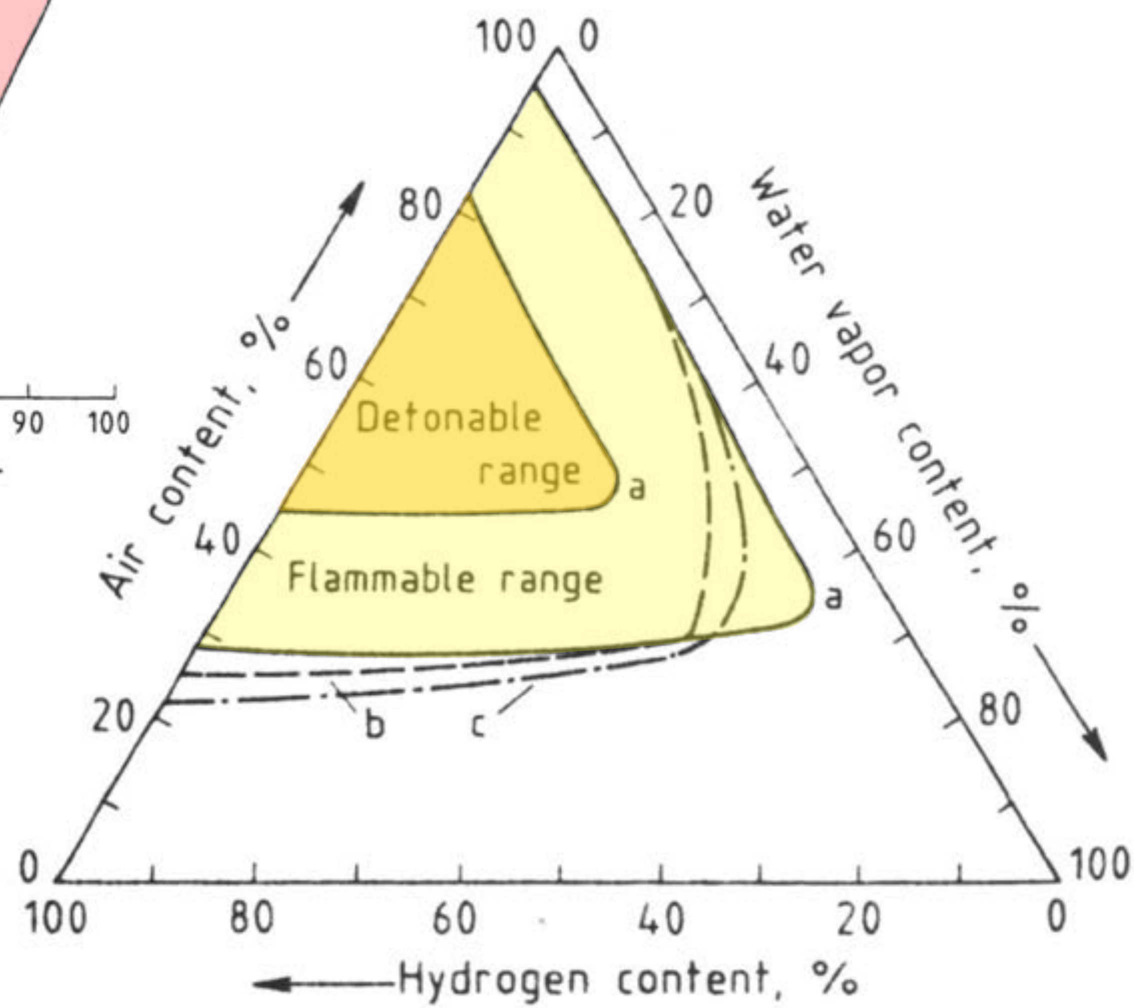
Nuclear power station in Fukushima , Japan, 12. 3. 2011

Hydrogen explosion in fueling station, Norway 5. 7. 2019

Tank explosion in Gangwon Technopark, South Korea 24. 5. 2019

11.3. Flammability & Explosion limits





11.4. Hydrogen & Elements

Allred-Rochow Electronegativity Ref: **Huheey, J.E. Inorganic Chemistry ; Harper & Row: New York, 1983**

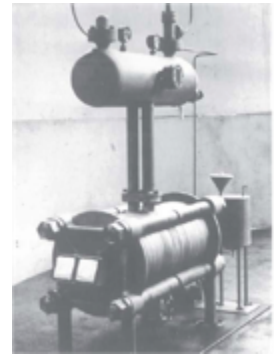
- Ionic hydrides (green)
- Covalent polymeric hydrides (magenta)
- Covalent hydrides (cyan)
- Metallic hydrides (red)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
H 2.20																	He
LiH 0.97	BeH_2 1.47											BH_3 2.01	CH_4 2.50	NH_3 3.07	H_20 3.50	HF 4.10	Ne
NaH 1.01	MgH_2 1.23											AlH_3 1.47	SiH_4 1.74	PH_3 2.06	H_2S 2.44	HCl 2.83	Ar
KH 0.91	CaH_2 1.04	ScH_2 1.20	TiH_2 1.32	VH VH_2 1.45	CrH (CrH_2) 1.56	Mn 1.60	Fe 1.64	Co 1.70	$NiH_{<1}$ 1.75	CuH 1.75	ZnH_2 1.66	(GaH_3) 1.82	GeH_4 2.02	AsH_3 2.20	H_2Se 2.48	HBr 2.74	Kr
RbH 0.89	SrH_2 0.99	YH_2 YH_3 1.11	ZrH_2 1.22	(NbH_2) 1.23	Mo 1.30	Tc 1.36	Ru 1.42	Rh 1.45	$PdH_{<1}$ 1.35	Ag 1.42	(CdH_2) 1.46	(InH_3) 1.49	SnH_4 1.72	SbH_3 1.82	H_2Tc 2.01	HI 2.21	Xe
CsH 0.86	BaH_2 0.97	LaH_2 LaH_3 1.08	HfH_2 1.23	TaH 1.33	W 1.40	Re 1.46	Os 1.52	Ir 1.55	Pt 1.44	(AuH_3) 1.42	(HgH_2) 1.44	(TlH_3) 1.44	PbH_4 1.55	BiH_3 1.67	H_2Po 1.76	HAt 1.90	Rn
Fr	Ra	AcH_2 1.00															
			CeH_3 1.06	PrH_2 PrH_3 1.07	NdH_2 NdH_3 1.07	Pm	SmH_2 SmH_3 1.07	EuH_2 1.01	GdH_2 GdH_3 1.11	TbH_2 TbH_3 1.10	DyH_2 DyH_3 1.10	HoH_2 HoH_3 1.10	ErH_2 ErH_3 1.11	TmH_2 TmH_3 1.11	(YbH_2) YbH_3 1.06	LuH_2 LuH_3 1.14	
			ThH_2 1.11	PaH_2 1.14	UH_3 1.22	NpH_2 NpH_3 1.22	PuH_2 PuH_3 1.22	AmH_2 AmH_3 1.2	Cm	Bk	Cf	Es	Fm	Md	No	Lr	

11.5. Swiss Hydrogen Developments

First H_2 ICE 1807
Francois Isaac de Rivaz

Hydroelectric plant Gampel 1898



Ewald Zdansky 1949

Alkaline Electrolyzer 4MW, 1980
Giovanola, Lurgi, IHT

PV, Electrolysis, Car, Stove
Markus Friedli 1991

Hydrogen Storage 1997
in Monthey

H_2YDROPOLE 2001

Ratrac MH & ICE 2004

H_2 FC Street sweeper
Hy.move 2009

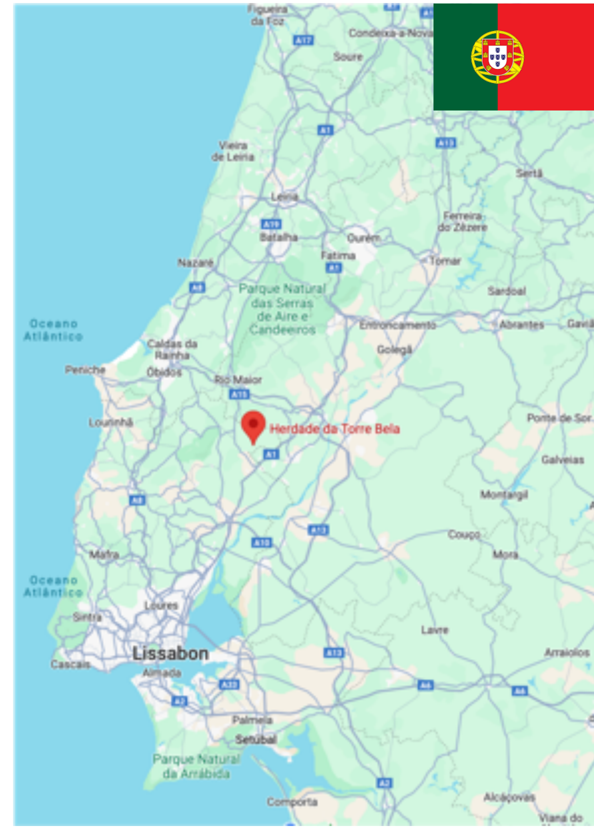
Energy self sufficient house 2016

PEM Fuel cell 2017

Hyundai H_2 trucks 2020

DASH MH-FC Storage
System 2021

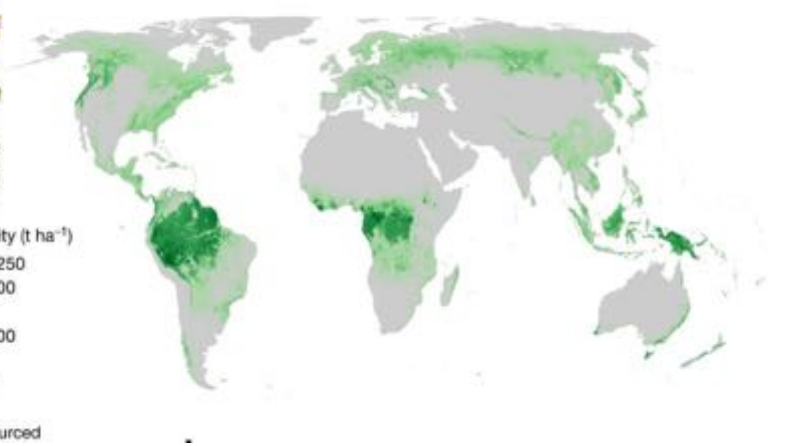
A.1. PV Plant Herdade da Torre Bela

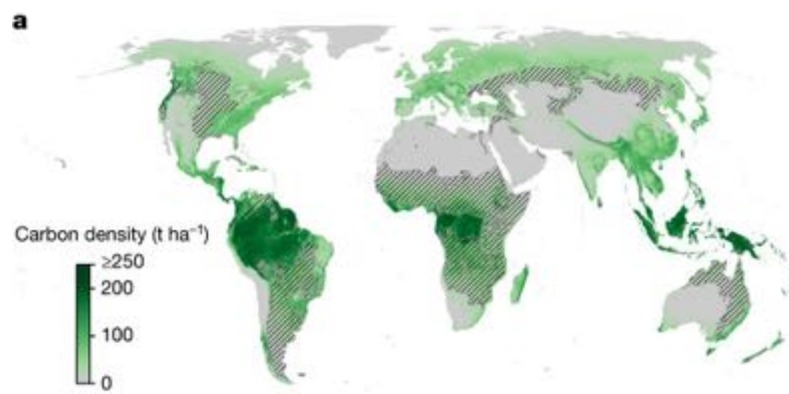


A.2. CO_2 sinks und palm oil production

At present, global forest carbon storage is markedly under the natural potential, with a total deficit of **226 Gt** (model range = 151–363 Gt) in areas with low human footprint. [1]
With 142 oil palm trunk (OPT) available per ha of plantation land and a replanted area of 100,550 ha in 2017, the estimated dry weight of OPT (**74.48 t ha^{-1}**) generated amounted to a total of 7.49 Mt [2]. 4.0 t·ha^{-1}·y^{-1} palm oil produced and the oil plants are replanted every 20 years.

30 kg oil·y^{-1} per palm tree with 524 kg dry biomass





226 Gt oil palm trees produce 13 Gt Oil·y^{-1} more than the global demand of fossil oil.

Ref.: [1] Mo, L., Zohner, C.M., Reich, P.B. et al. Integrated global assessment of the natural forest carbon potential. Nature (2023). https://doi.org/10.1038/s41586-023-06723-z
[2] Thiruchelvi Pulingam, Manoj Lakshmanan, Jo-Ann Chuah, Arthy Surendran, Idris Zainab-La, Parisa Foroozandeh, Ayaka Uked, Akihiko Kosugid, Kumar Sudesh "Oil palm trunk waste: Environmental impacts and management strategies", Industrial Crops & Products 189 (2022), 115827

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