“Die Rolle des Wasserstoffs in der Energiewende”

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ETHZ, 23. 4. 2024

“Die Rolle des Wasserstoffs in der Energiewende”

Alle Formen der erneuerbaren Energiewandlung wachsen exponentiell aber unterschiedlich schnell. In Kürze wird der Punkt erreicht wo Wasserkraft, Windkraft und Photovoltaik gleich viel und zusammen 1.8 TW durchschnittliche Leistung und damit knapp 10% des Weltenergieverbrauchs beitragen. Die kurzzeitigen Schwankungen von Wind- und PV-Produktion müssen durch lokale Speicher abgedämpft werden und die saisonalen Unterschiede können durch Energieträger ausgeglichen werden. Wasserstoff ist das Schlüsselelement zwischen Elektrizität und chemischen Energieträgern, wie reiner Wasserstoff, Methan oder längerkettigen Kohlenwasserstoffen. Die Umwandlungen sind mit Energieverlusten verbunden, welche heute technisch noch stark von den thermodynamisch möglichen abweichen. Wasserstoff kann durch Elektrolyse von Wasser hergestellt werden und in Brennstoffzellen, in Kolbenmotoren oder Turbinen wieder zur Produktion von Elektrizität eingesetzt werden. Die Speicherung von Wasserstoff ist unter Druck, flüssig oder in Hydriden möglich. Die für die Anwendung entscheidenden Kriterien sind Energieeffizienz und Energiekosten. Die Effizienz liegt bei ca. 25% und die Kosten, welche stark von den Elektrizitätskosten abhängen, zwischen 8 und 20 CHF/kgH_2. Die Wasserstoffproduktion näher am Äquator erfordert eine kleinere PV-Fläche und ist somit günstiger, erfordert aber die Verflüssigung, Transport und Speicherung des Wasserstoffs, so dass die Kosten beim Verbraucher nur noch ca. 20% tiefer liegen. Die Elektrolyse hat ein grosses Potential in der zukünftigen Steigerung der Effizienz und der Senkung der Kosten.

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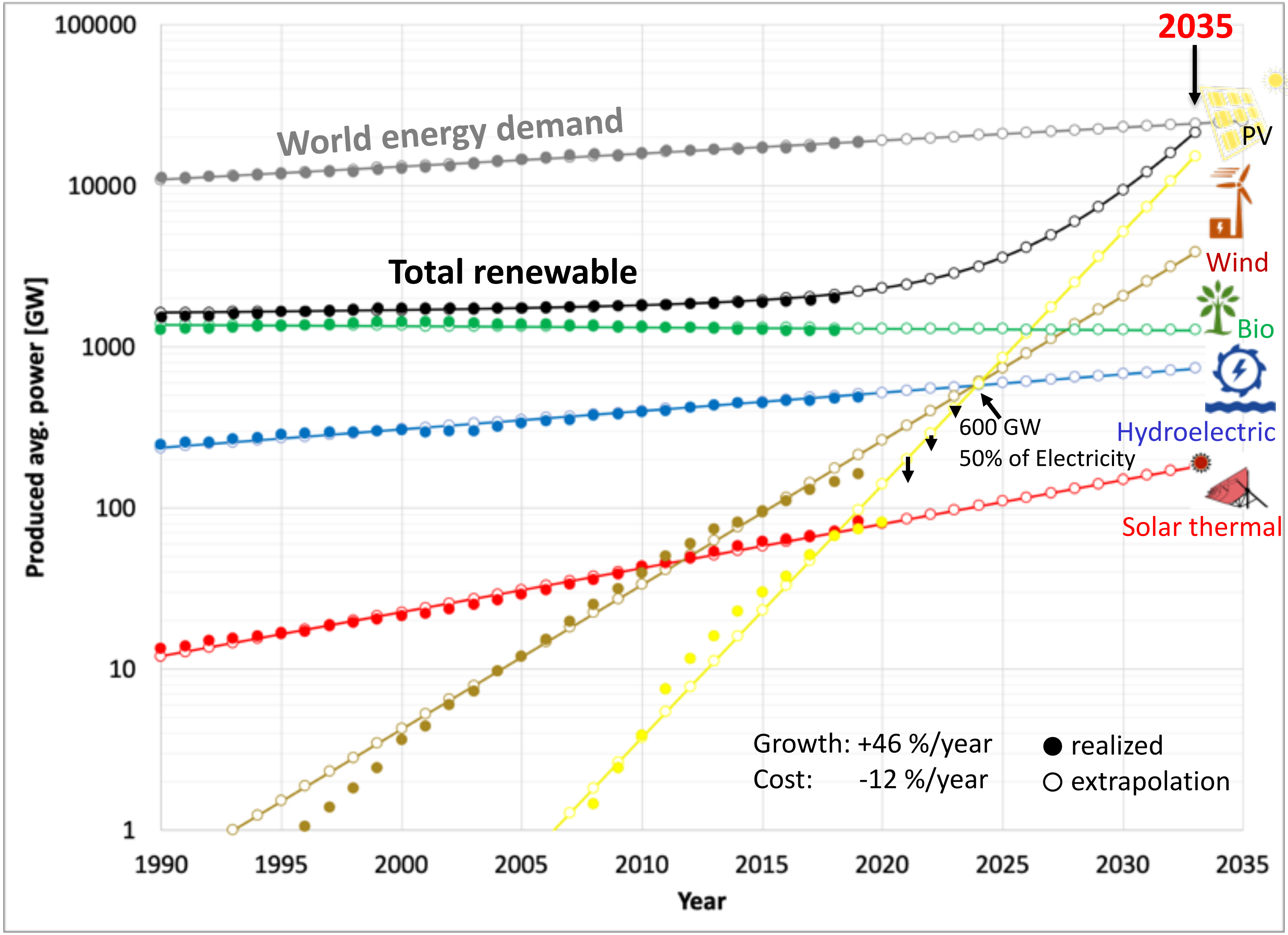
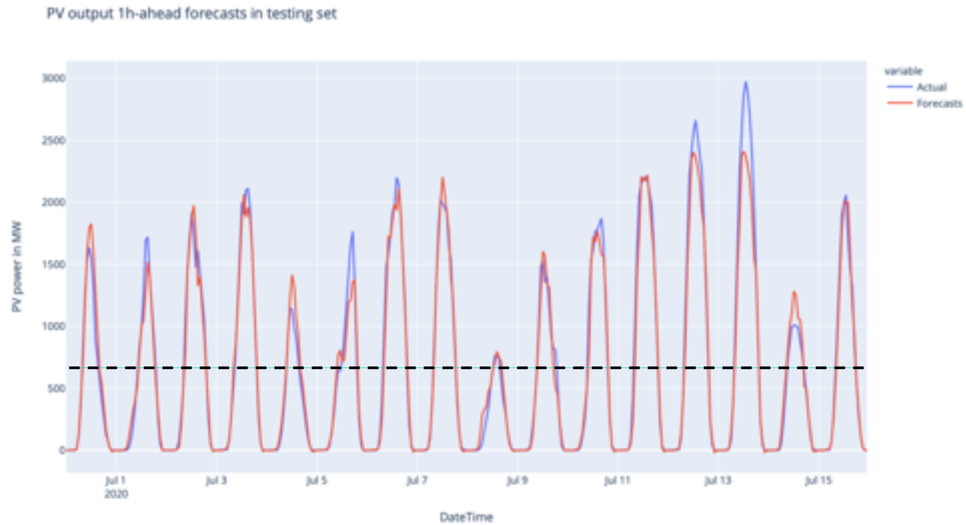
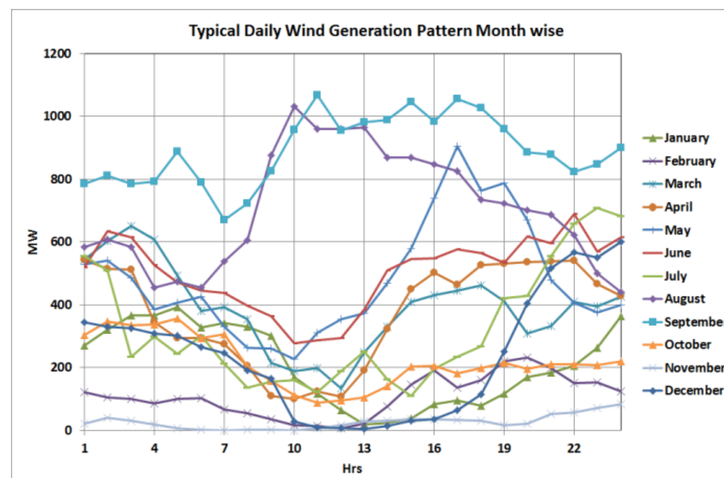
Global renewable energy production



Ref.: https://ourworldindata.org/energy and https://www.pv-magazine.com/2023/02/16/global-solar-installations-may-hit-350-6-gw-in-2023-says-trendforce/#:~:text=2022

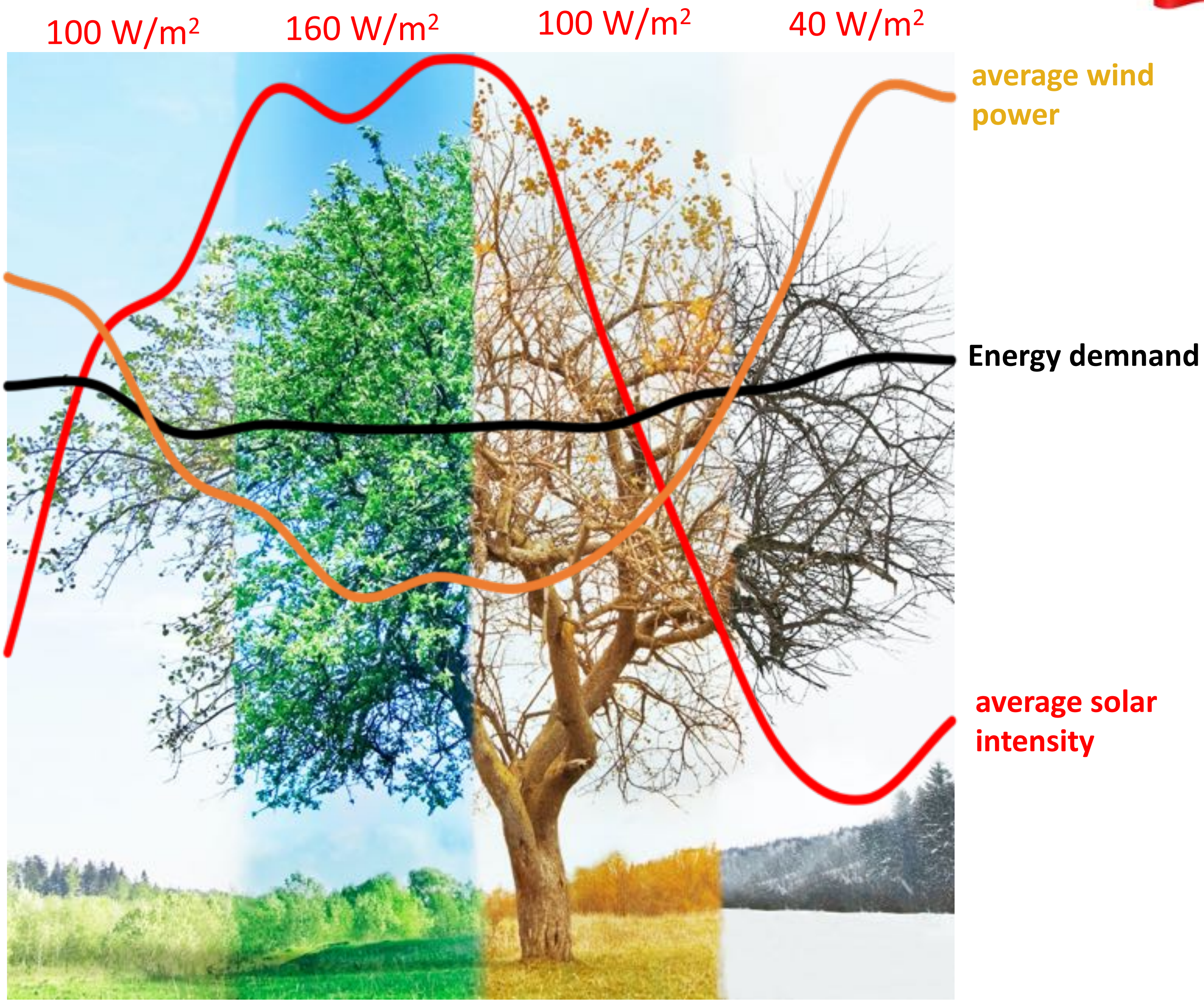
Intermittence of power production





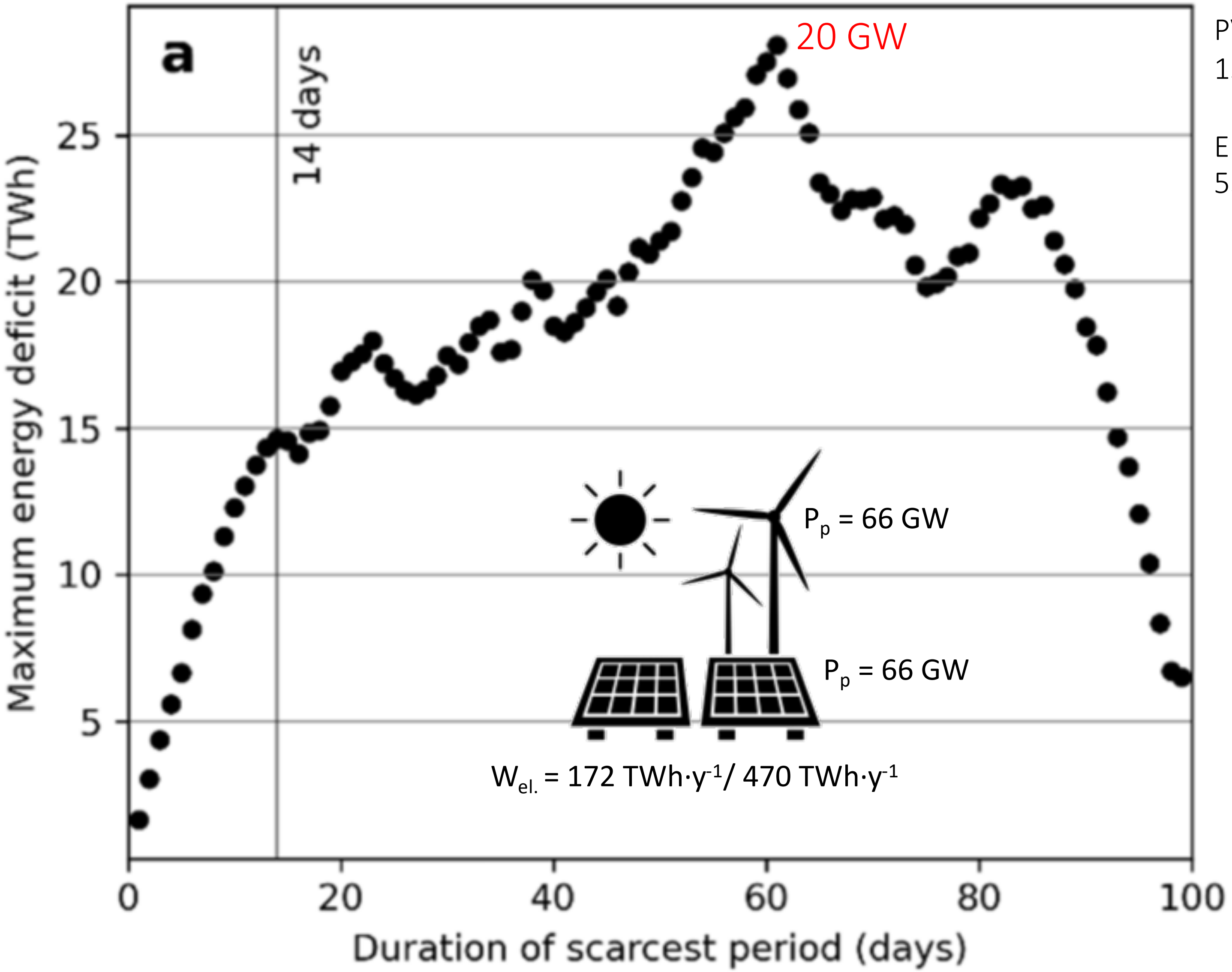
Ref.: https://medium.com/@hamzarabi303/time-series-forecasting-of-photovoltaic-solar-energy-generation-with-xgboost-b0da6293caeb https://www.researchgate.net/figure/Typical-day-wind-generation-pattern-in-each-month-of-a-year_fig4_322095782/download

Seasons in Switzerland



Hydrogen as renewable energy carrier

Renewable energy supply

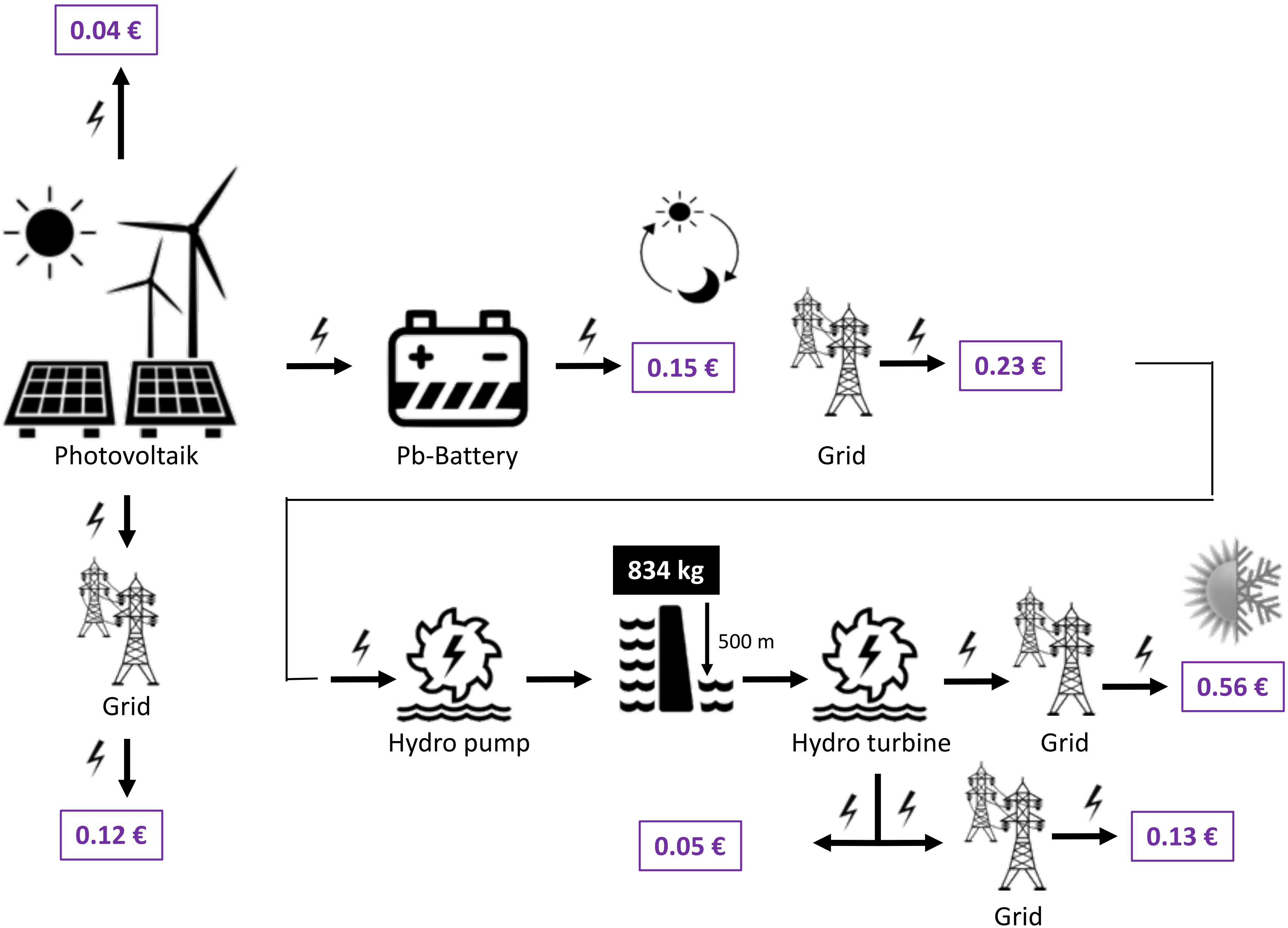


PV & wind:
150 GW_p installed

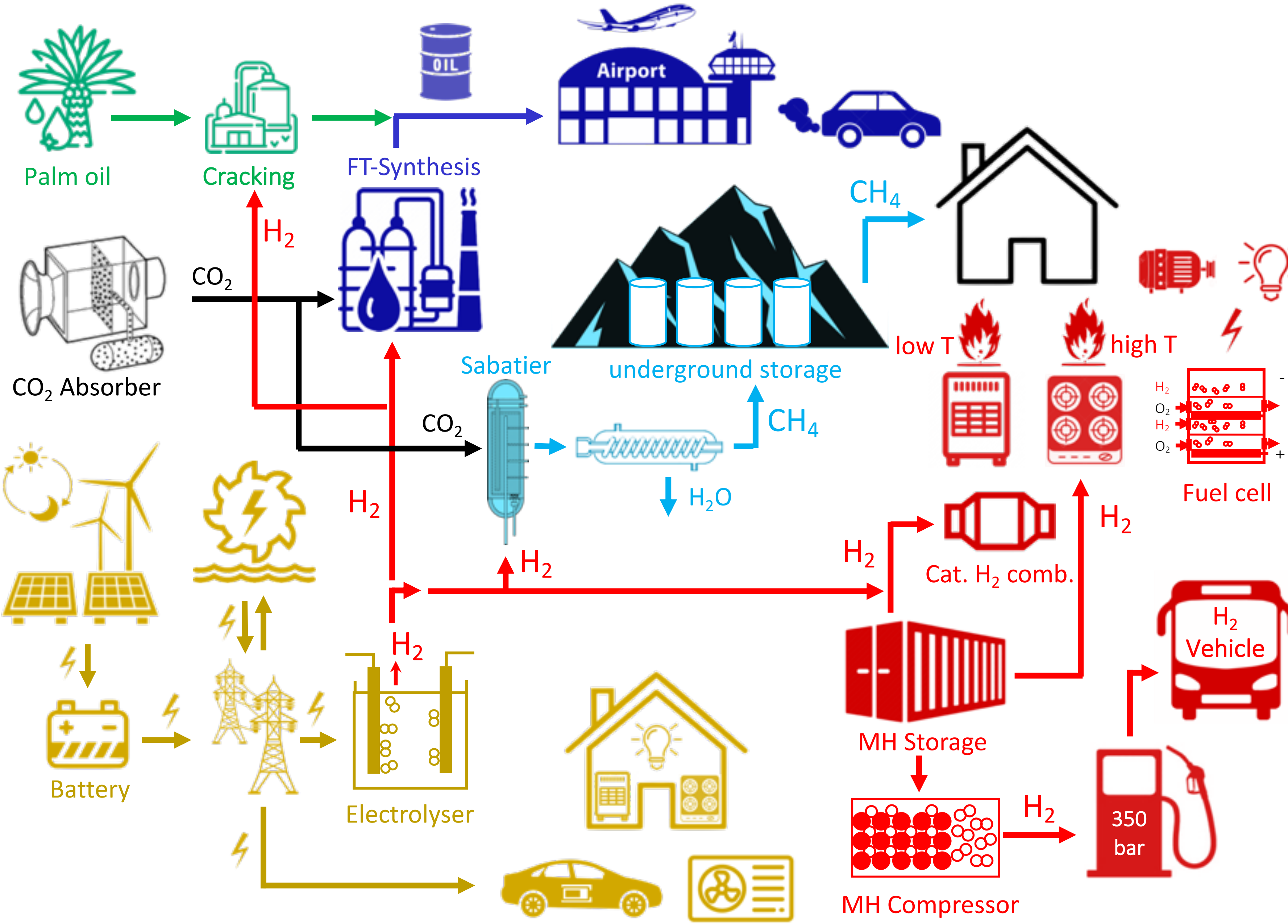
Electricity:
53 GW average power

Ref.: Oliver Ruhnau, and Staffan Qvist,"Storage requirements in a 100% renewable electricity system: extreme events and inter-annual variability", Environ. Res. Lett. 17 (2022) 044018, https://doi.org/10.1088/1748-9326/ac4dc8

Cost of 1 kWh of electricity



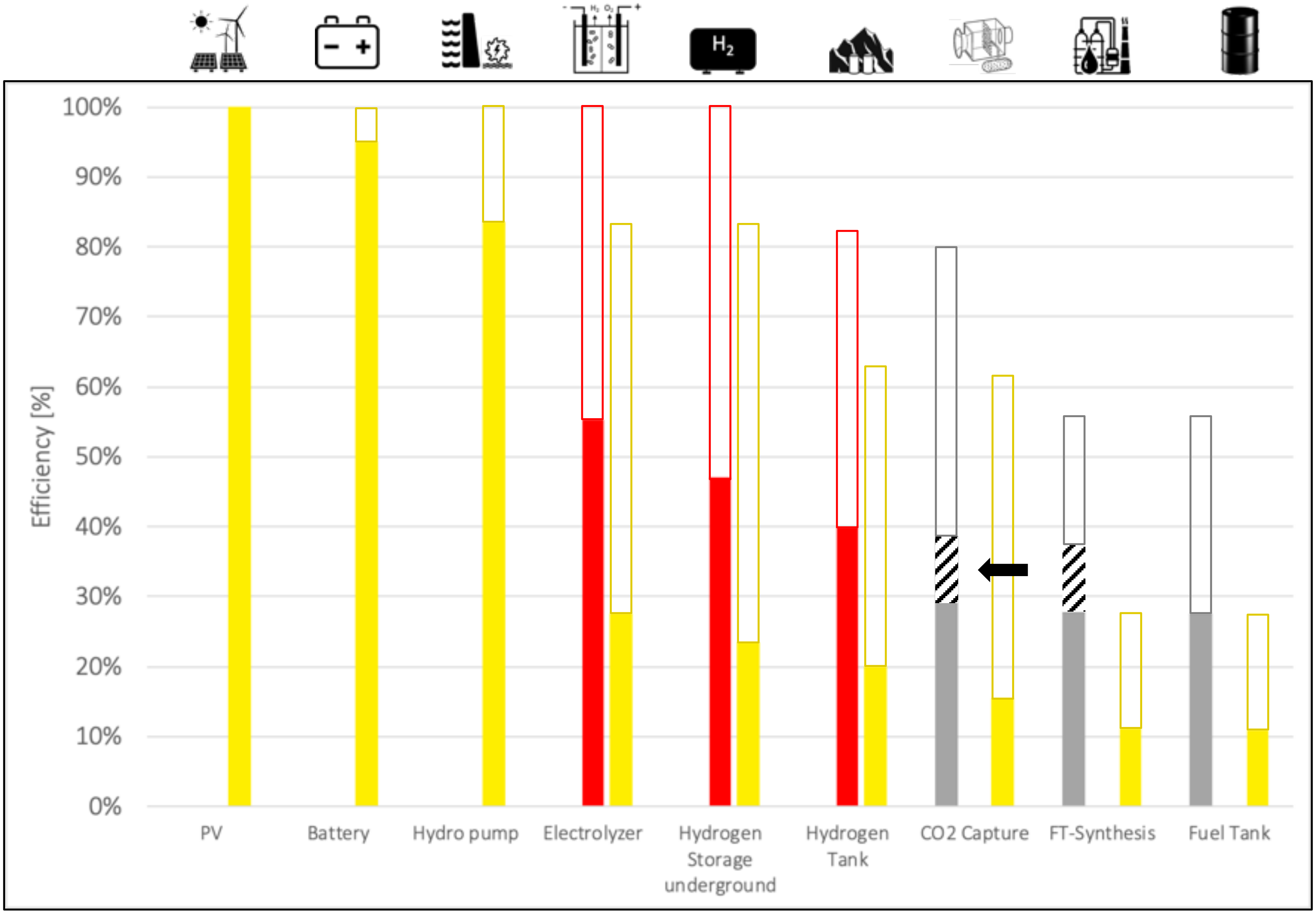
Renewable energy systems



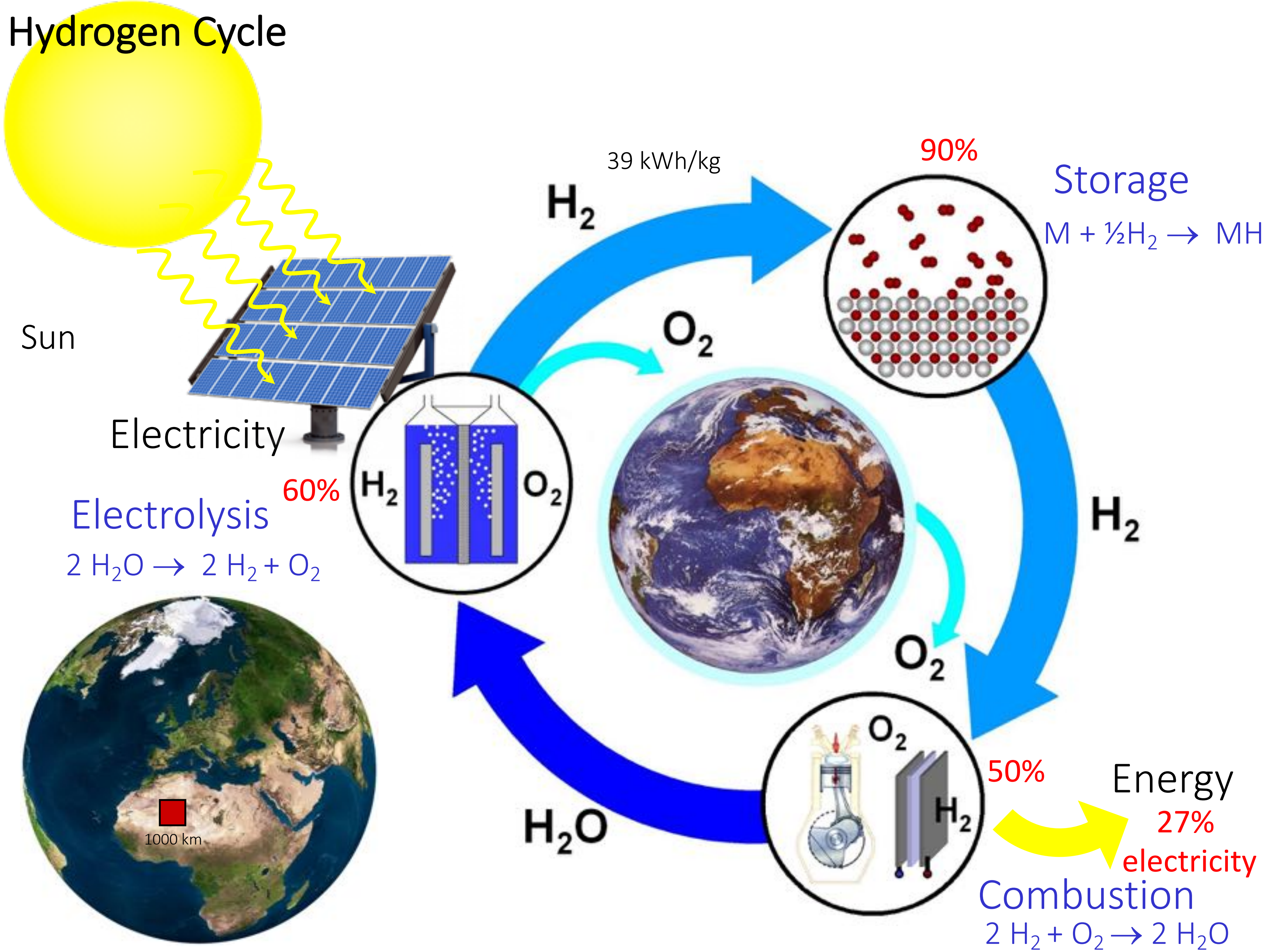
Hydrogen as renewable energy carrier

Efficiency of energy conversion

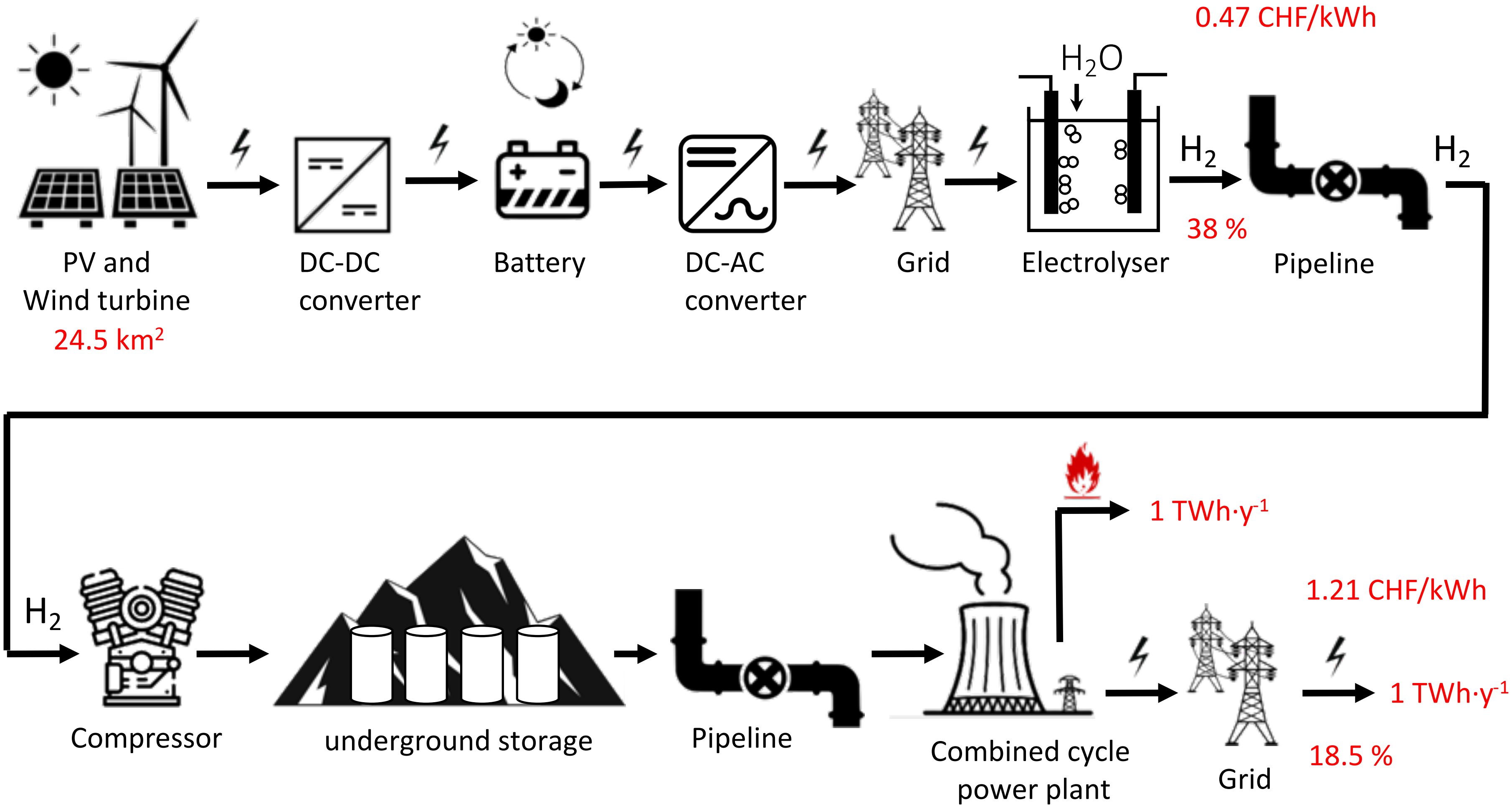
Power to X (P2X)



Hydrogen Cycle

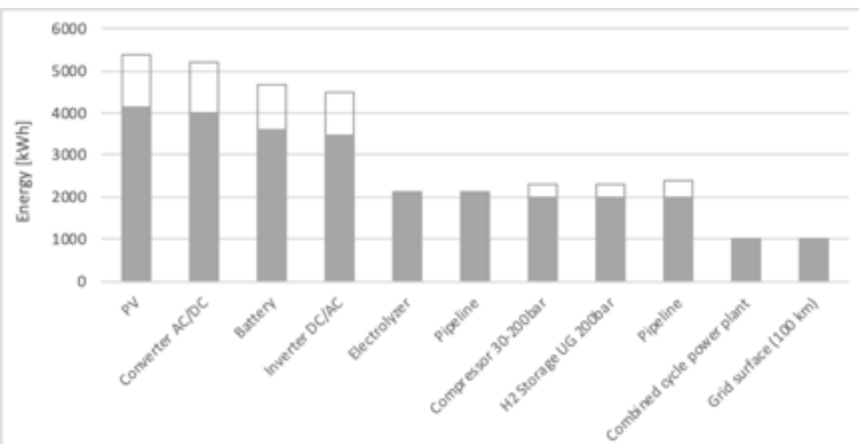


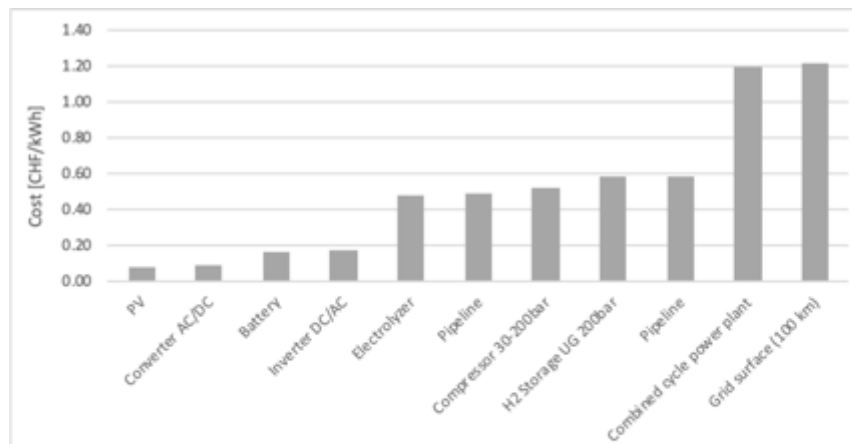
PV, hydrogen, electricity



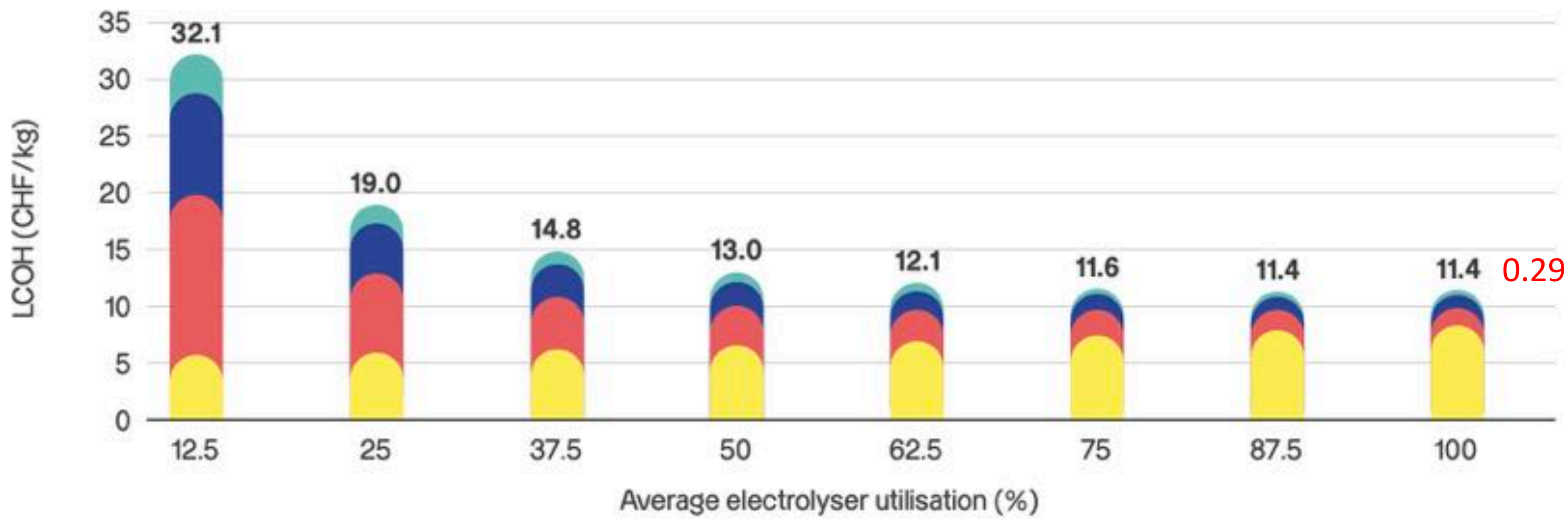
PV, hydrogen, electricity

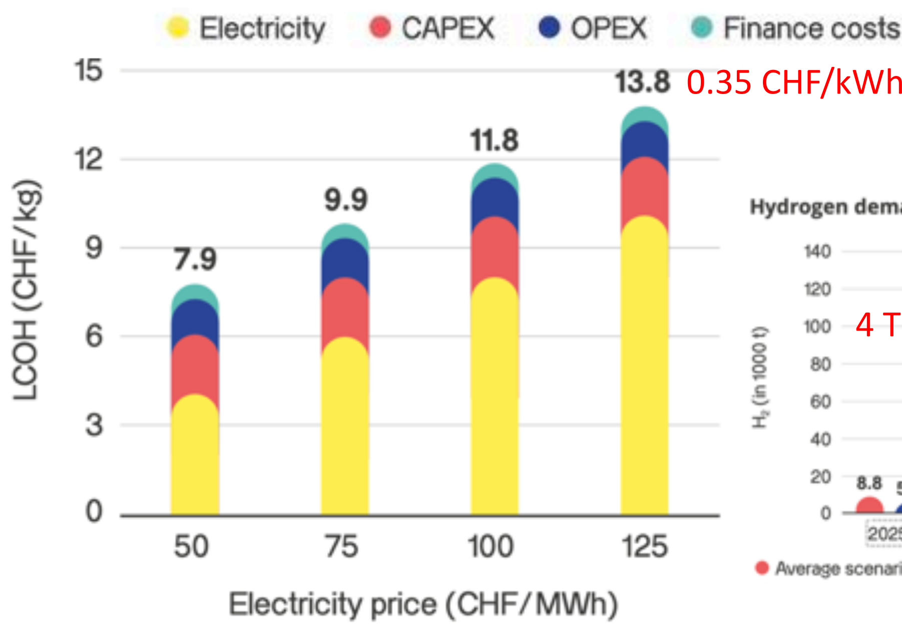
Int. [kWh/(y·m2)]:	1100			PeakP [kW] =	4.904								
Efficiency [%]:	20.0%	Area fac.:	2.5	Avg. P [kW] =	0.616								
Area [m2]:	24.52	**Area real [m2]:**	**61.30**	Max. avg P =	1.848								
					per year								
Hydrogen production with PV													
Converter	*Efficiency [%]*	*W [kWh/kWh]*	*Cost/W [CHF/kWh]*	*Investment [CHF/kW]*	*W [kWh]*	*W [kWh]*	*Wel. [kWh]*	*Cost cum [CHF]*	*Cost/Wcum [CHF/kWh]*	*Size unit*	*Size [kW or kWh]*	CAPEX [CHF]	Cost cont.
PV	100.00%	0	0.071	1607	4148	5395	1247	380	0.07	W [kWh·y-1] =	5394.74	7883	0.0705
Converter AC/DC	97.00%	0	0.008	318	4023	5233	1210	423	0.08	Pp [kW] =	4.90	1561	0.0103
Battery	89.00%	0	0.065	117	3581	4657	1077	727	0.16	C [kWh] =	22.17	2587	0.0752
Inverter DC/AC	97.00%	0	0.008	318	3473	4518	1044	763	0.17	Pp [kW] =	1.64	523	0.0129
Electrolyzer	60.00%	0.02	0.108	2227	2084	2084	42	988	0.47	Pp [kW] =	1.59	3551	0.3053
Pipeline	99.00%	0.001	0.009	1591	2063	2063	2	1008	0.49	Pp [kW] =	0.96	1523	0.0141
Compressor 30-200b	97.00%	0.15	0.011	612	2001	2001	300	1029	0.51	Pp [kW] =	0.95	579	0.0257
H2 Storage UG 200b	100.00%	0.15	0.071	1	2001	2001	300	1172	0.59	C [kWh] =	2001.20	1820	0.0715
Pipeline	100.00%	0.2	0.000	155	2001	2001	400	1172	0.59	Pp [kW] =	0.32	49	0.0000
Combined cycle pow	50.00%	0	0.023	2561	1001	1001	0	1195	1.19	Pp [kW] =	0.16	404	0.6087
Grid surface (100 km	99.94%	0	0.015	1342	1000	1000	0	1210	1.21	Pp [kW] =	0.16	212	0.0160
	18.5%					Auxillary:	1044		**1.21**			20692	1.2102
Efficiency =	**18.5%**							**H2 [CHF/kg] =**	**18.69**		**CAPEX [CHF] =**	**20'692**	

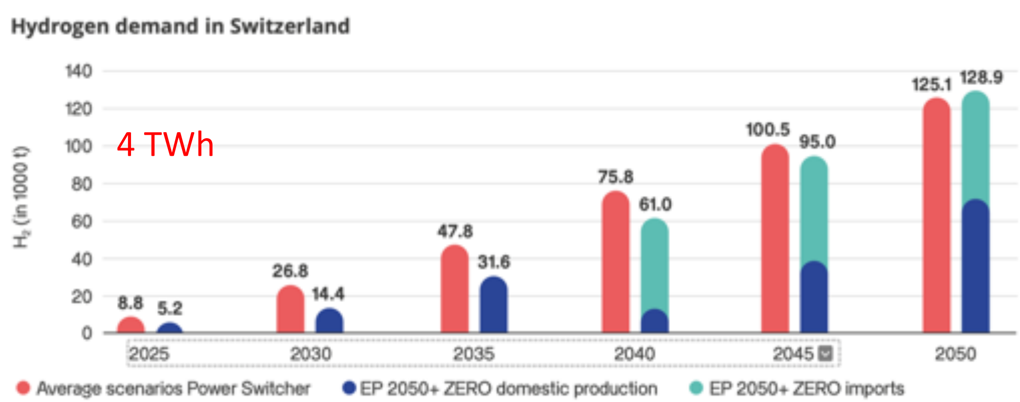




$LCOH_2$ after electrolysis

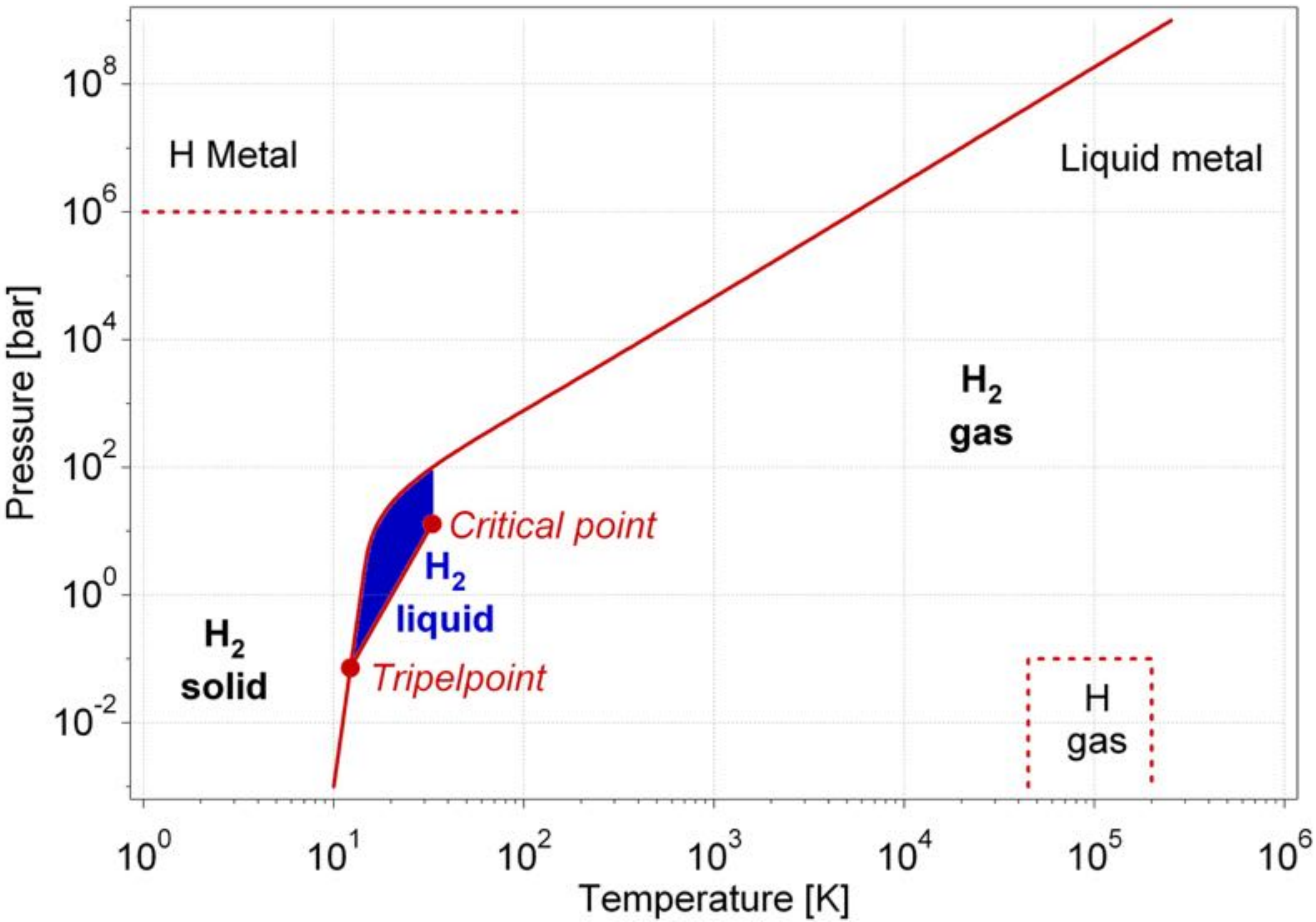






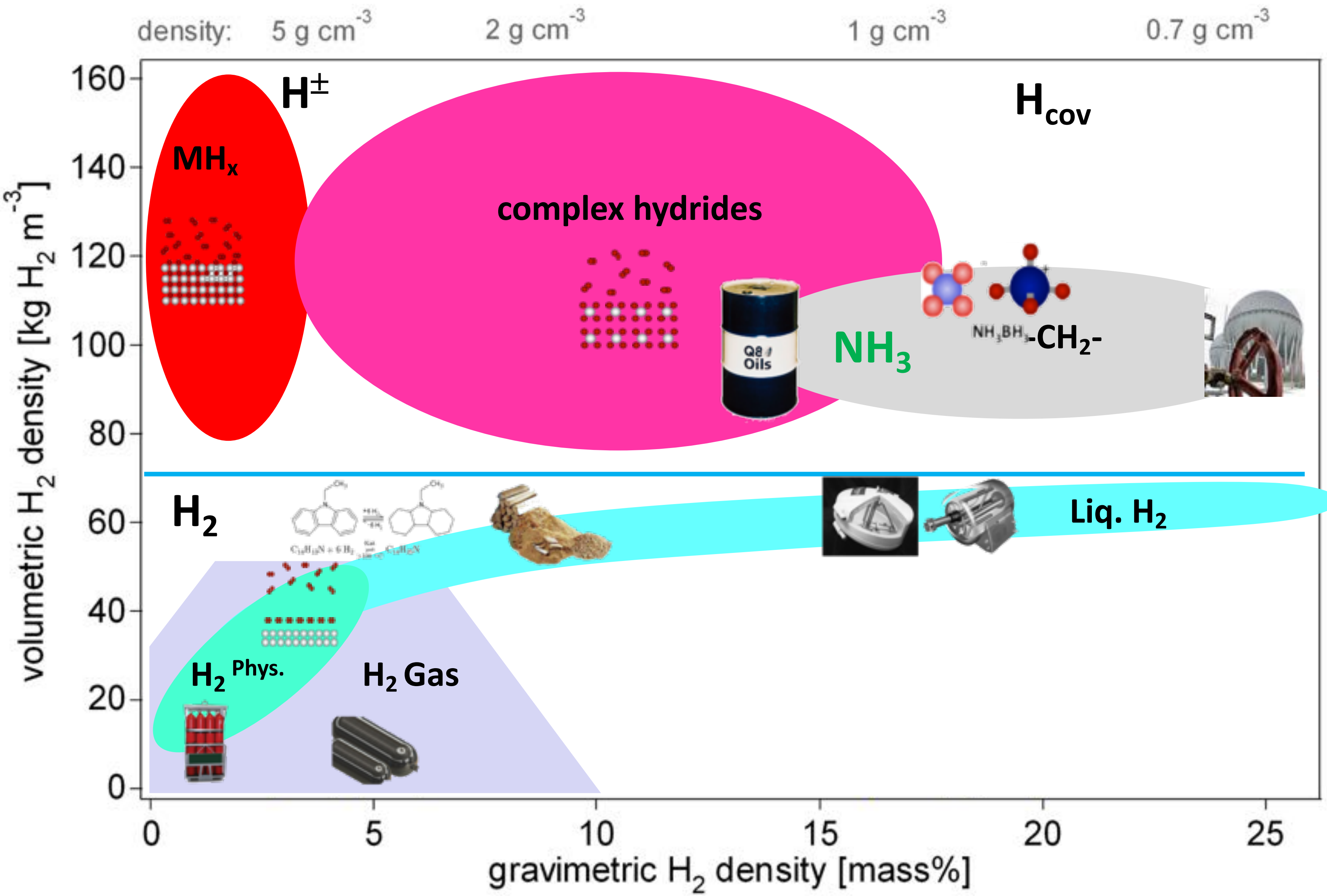
Ref.: Luka Cuderman, Stephan Weber, "White paper: The role and potential of hydrogen in Switzerland", Axpo Holding AG, 14 November 2023

Primitive Phase diagram



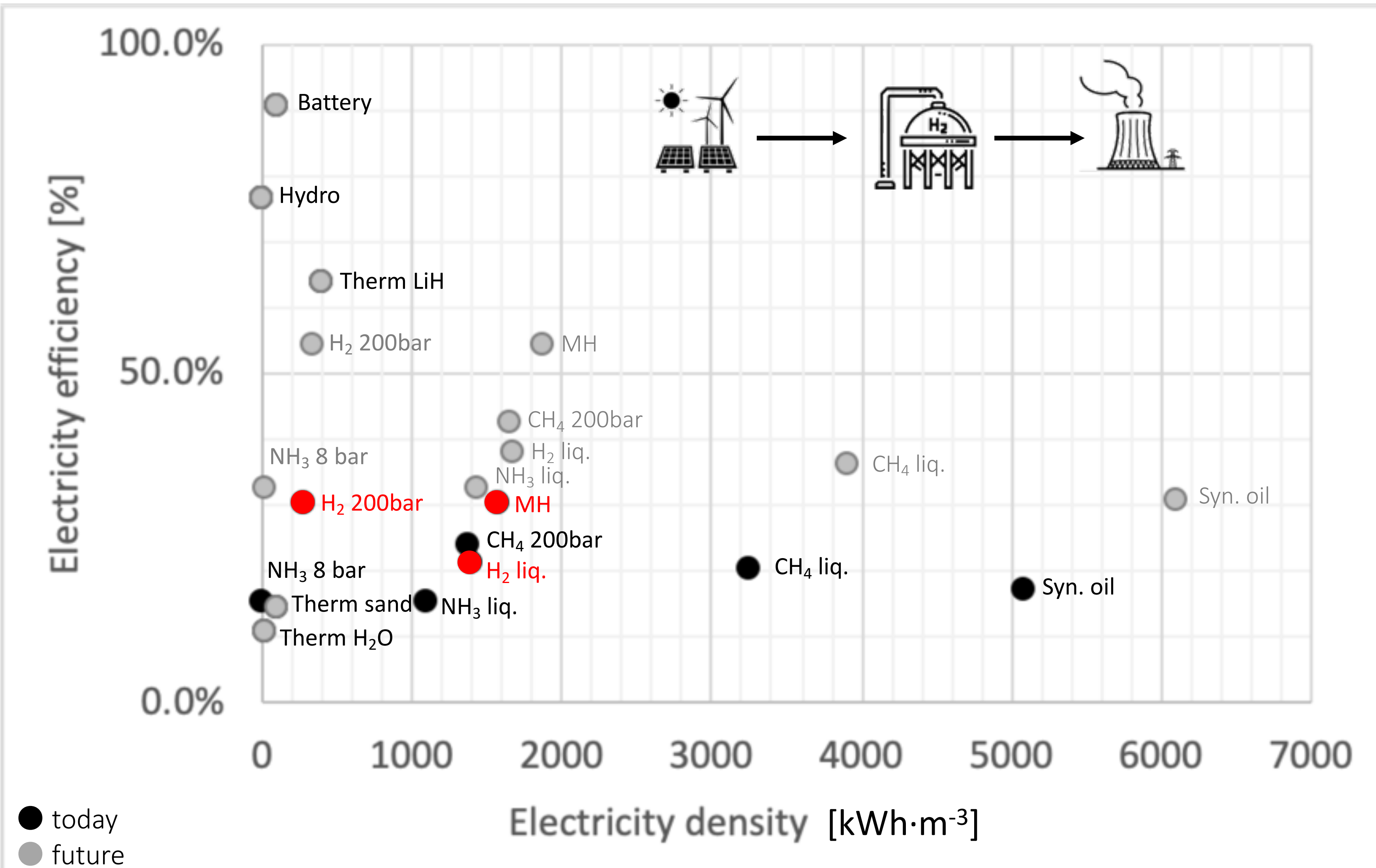
Ref: W. B. Leung, N. H. March and H. Motz, Physics Letters 56A (6) (1976), pp. 425-426

Hydrogen density

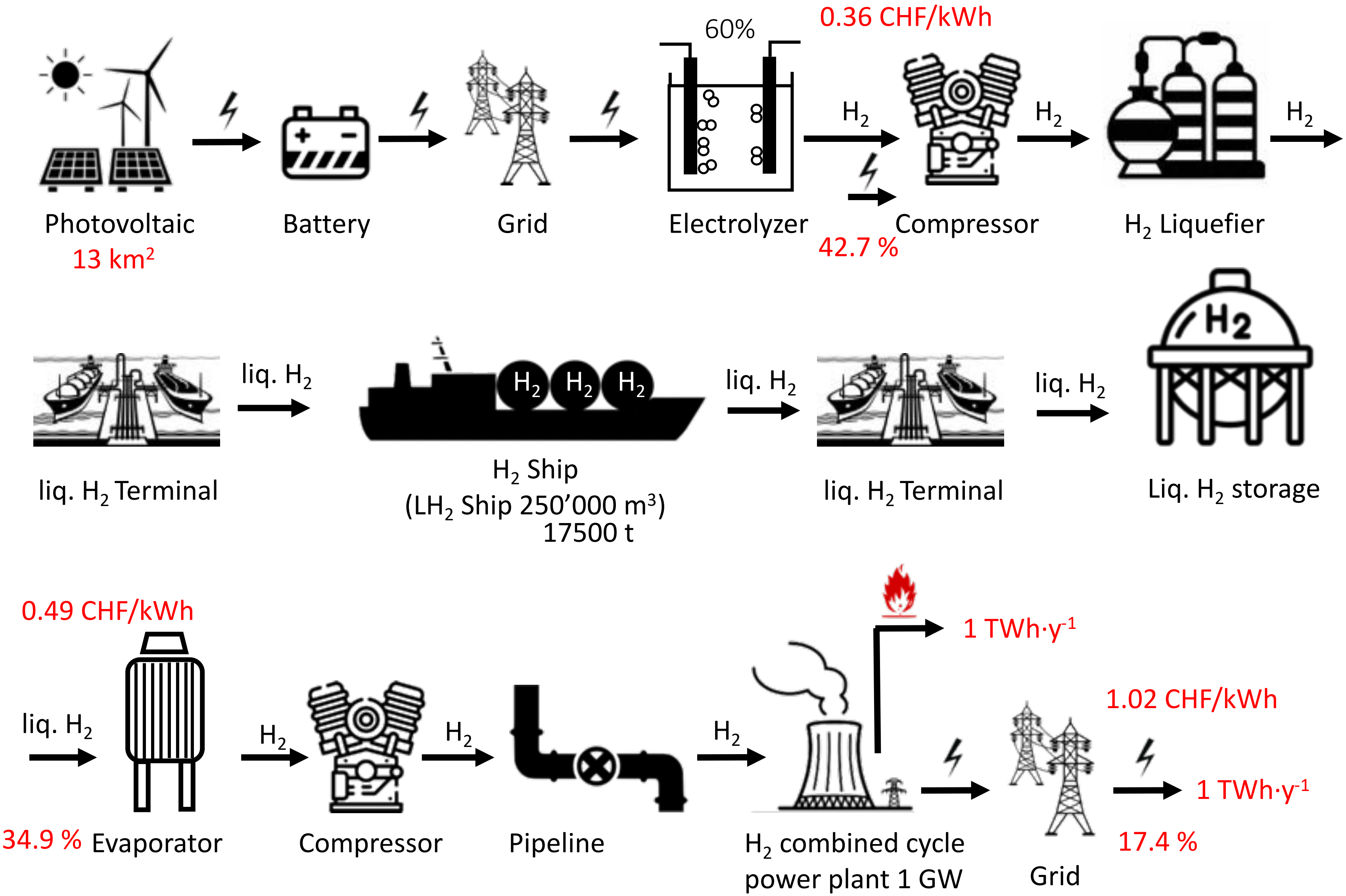


Ref: A. Züttel, “Materials for hydrogen storage”, materialstoday, Septemper (2003), pp. 18-27

Efficiency and storage density of renewable electricity

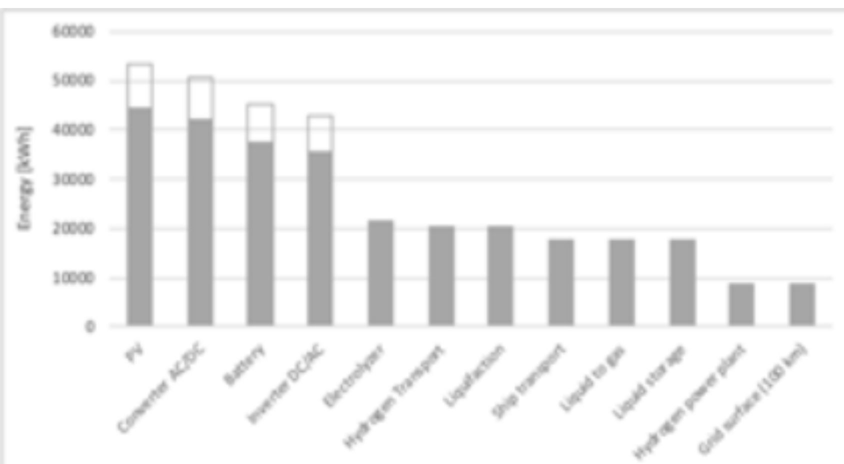


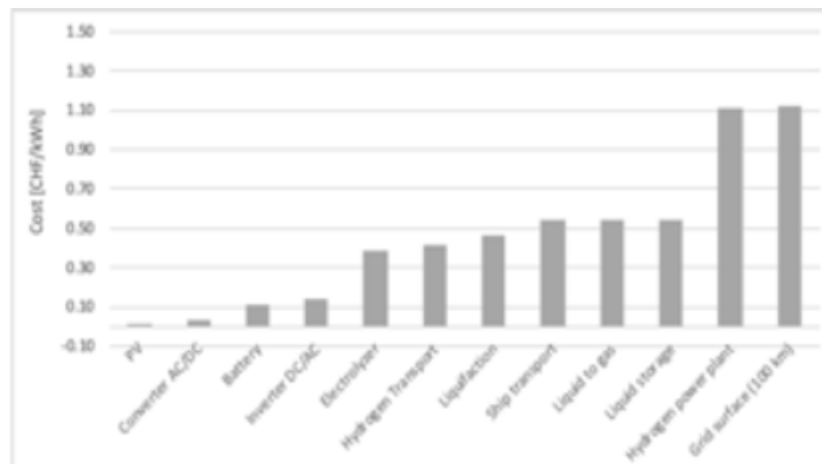
Imported Hydrogen



Imported hydrogen

Int. [kWh/(y·m2)]:	2200			PeakP [kW] =	22.697								
Efficiency [%]:	20.0%	Area fac.:	2	Avg. P [kW] =	5.700								
Area [m2]:	113.48	**Area real [m2]:**	**226.97**	Max. avg P =	11.400								
					per year								
Import of hydrogen from Australia													
Converter	*Efficiency [%]*	*W [kWh/kWh]*	*Cost/W [CHF/kWh]*	*Investment [CHF/kW]*	*W [kWh]*	*W [kWh]*	*Wel. [kWh]*	*Cost cum [CHF]*	*Cost/Wcum [CHF/kWh]*	*Size unit*	*Size [kW or kWh]*	CAPEX [CHF]	Cost cont.
PV	100.00%	0	0.012	536	42413	49933	7520	587	0.01	W [kWh·y-1] =	49933.30	12161	0.0118
Converter AC/DC	97.00%	0	0.022	845	41141	48435	7294	1632	0.03	Pp [kW] =	22.70	19181	0.0219
Battery	89.00%	0	0.065	117	36615	43107	6492	4443	0.10	C [kWh] =	136.80	15963	0.0694
Inverter DC/AC	97.00%	0	0.022	845	35517	41814	6297	5345	0.13	Pp [kW] =	5.07	4287	0.0248
Electrolyzer	60.00%	0.02	0.108	2227	21310	21310	0	7644	0.36	Pp [kW] =	3.42	7615	0.2309
Hydrogen Transport	95.00%	0.04	0.010	3182	20245	20245	0	7838	0.39	Pp [kW] =	3.25	10340	0.0284
Liquifaction	100.00%	0.25	0.029	6116	20245	20245	0	8424	0.42	Pp [kW] =	3.25	19870	0.0290
Ship transport	86.00%	0	0.008	6	17410	17410	0	8565	0.49	Pp [kW] =	2.79	17	0.0759
Liquid to gas	100.00%	0	0.000	24	17410	17410	0	8568	0.49	Pp [kW] =	2.79	68	0.0002
Liquid storage	100.00%	0	0.000	12	17410	17410	0	8569	0.49	C [kWh] =	938.86	11483	0.0001
Hydrogen power pla	50.00%	0	0.023	2561	8705	8705	0	8771	1.01	Pp [kW] =	1.40	3578	0.5153
Grid surface (100 km	99.94%	0	0.015	1342	8700	8700	0	8903	1.02	Pp [kW] =	1.40	1874	0.0159
	17.4%	6297.2	Auxillary power						**1.02**			106'438	1.0234
Efficiency =	**17.4%**					442		**H2 [CHF/kg] =**	**19.39**		**CAPEX [CHF] =**	**106'438**	

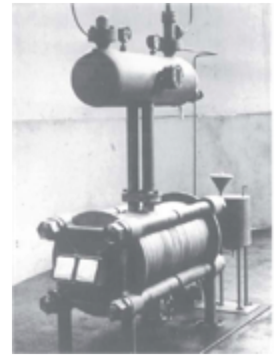




Swiss hydrogen history

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 2001
in Monthey

Ratrac MH & ICE 2004

H_2 FC Street sweeper
Hy.move 2009

Energy self sufficient house 2016

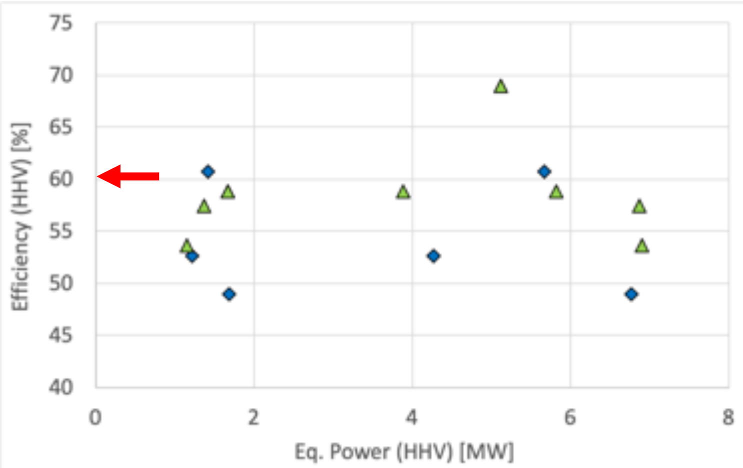
PEM Fuel cell 2004-17

Hyundai H_2 trucks 2020

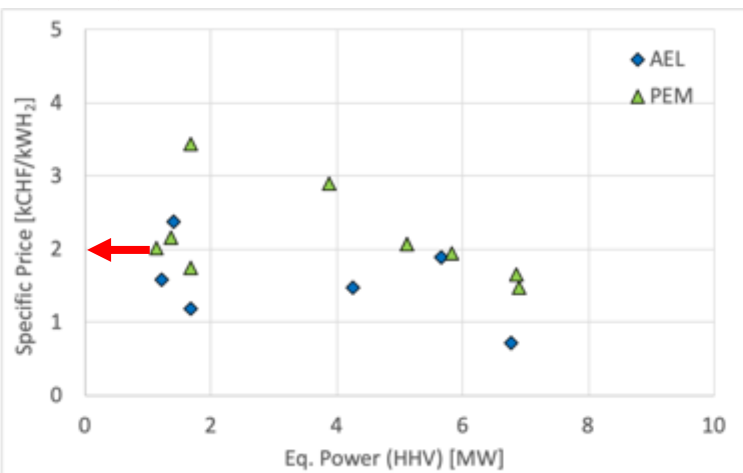
DASH MH-FC Storage
System 2021

Challenges and potential developments

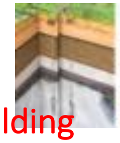
Electrolysis efficiency



Electrolysis cost



Hydrogen storage

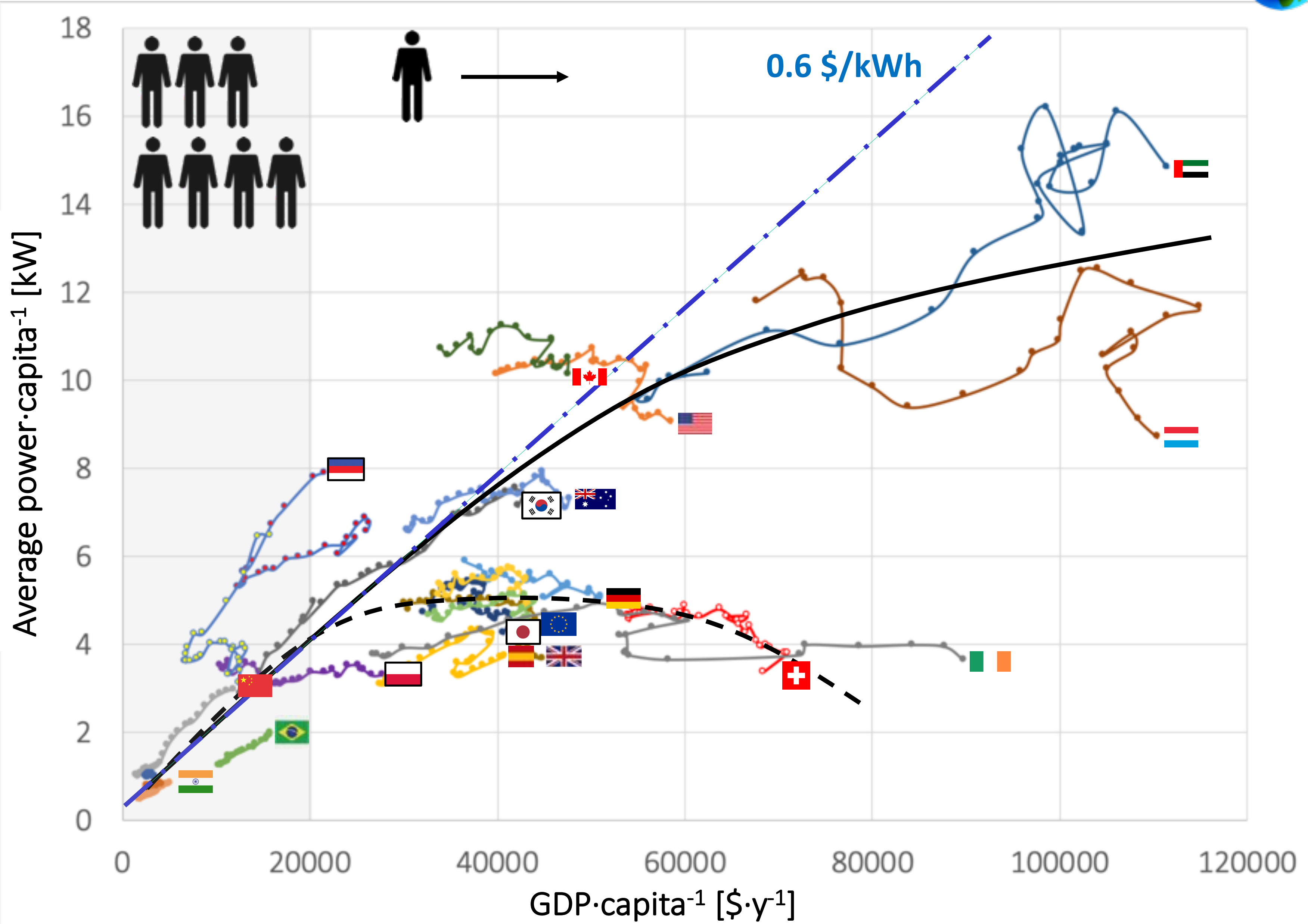


cost and energy for building

Parameter	Dimension	Underground storage (salt cavern)	Buried pipes	Cylindrical tank aboveground
Siting	–	Central location	Regional location	Onsite (e.g., a refueling station)
Assumed geometric volume	m^3	500,000	6800	110
Length/width	m/m			19/3
Pressure range	MPa	6–18	2–7	2–5
Min. H_2 energy contents	MWh	80,000	370	6.5
Max. H_2 energy contents	MWh	200,000	1200	16
Net usable H_2 energy contents	MWh	125,000	850	9.0
Energy density	Wh/l	250	125	85
Net capacity	t	3700	25	0.3
Investment costs	M€	107 (incl. aboveground plant and cushion gas)	12	0.08–0.12
Life expectancy	a	30	50	20
Interest rate	%/year	5.5	5.5	5.5
Capital costs	€/year	7,500,000	680,000	10,000
Spec. static storage costs[a]	€/kg	2	27	25–37
Equivalent annual full load cycles[b]	Cycles/year	6	100	150
Spec. dynamic storage costs[c]	€/t	330	270	165–250
Source		HyUnder (2014)	Bünger et al. (2014)	Bünger et al. (2014)

Ref.: https://www.sciencedirect.com/topics/engineering/large-scale-hydrogen-storage#:~:text=At%20a%20large%20scale%2C%20hydrogen,in%20large%2Dscale%20aboveground%20containments.

Energy and economy



Ref.: https://ourworldindata.org/grapher/energy-use-per-capita-vs-gdp-per-capita

Hydrogen in Mobility

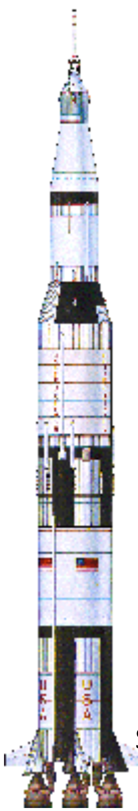

Francois Isaac de Rivaz (1813)


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)

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