"A heuristic model for the global energy transition"
"全球能源转型的启发式模型"

上海大学
Shanghai University

Academic talk
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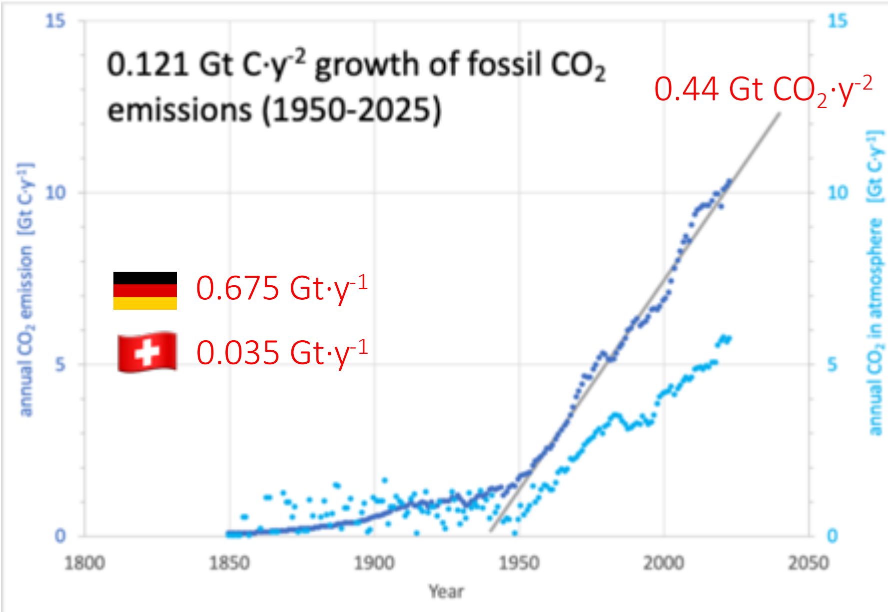
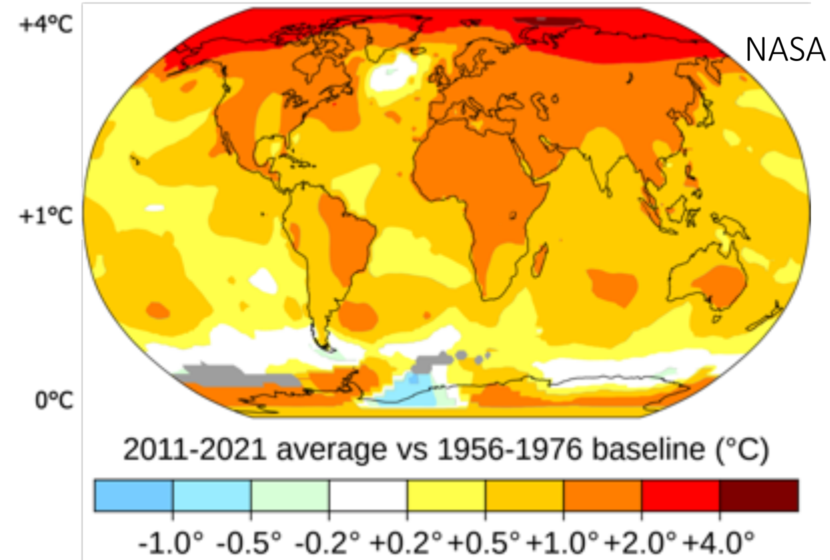
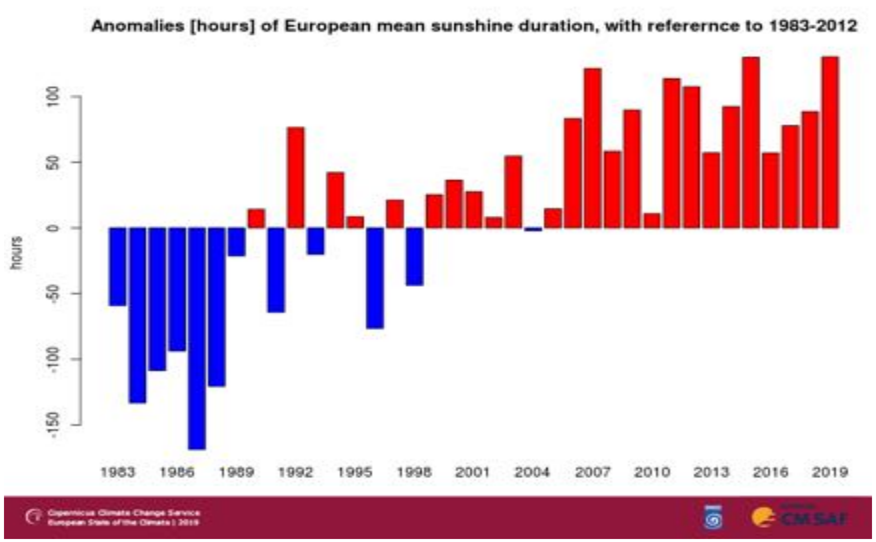
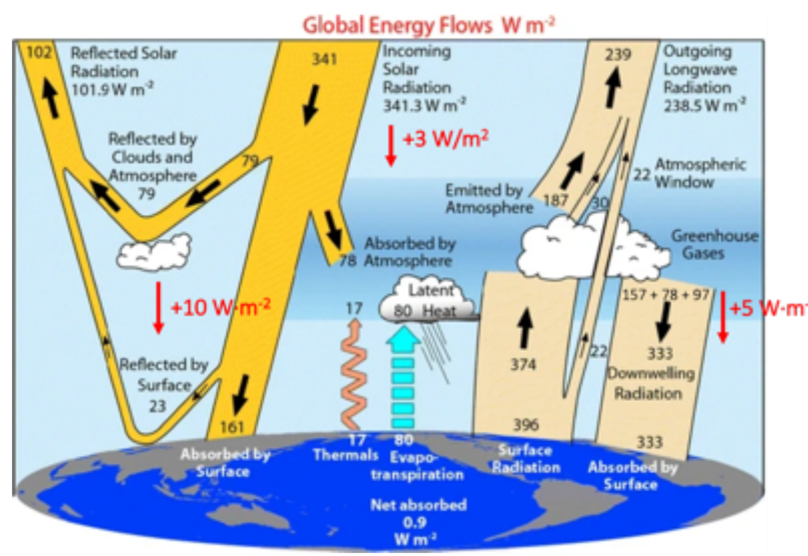
CO_2 emissions and climate change





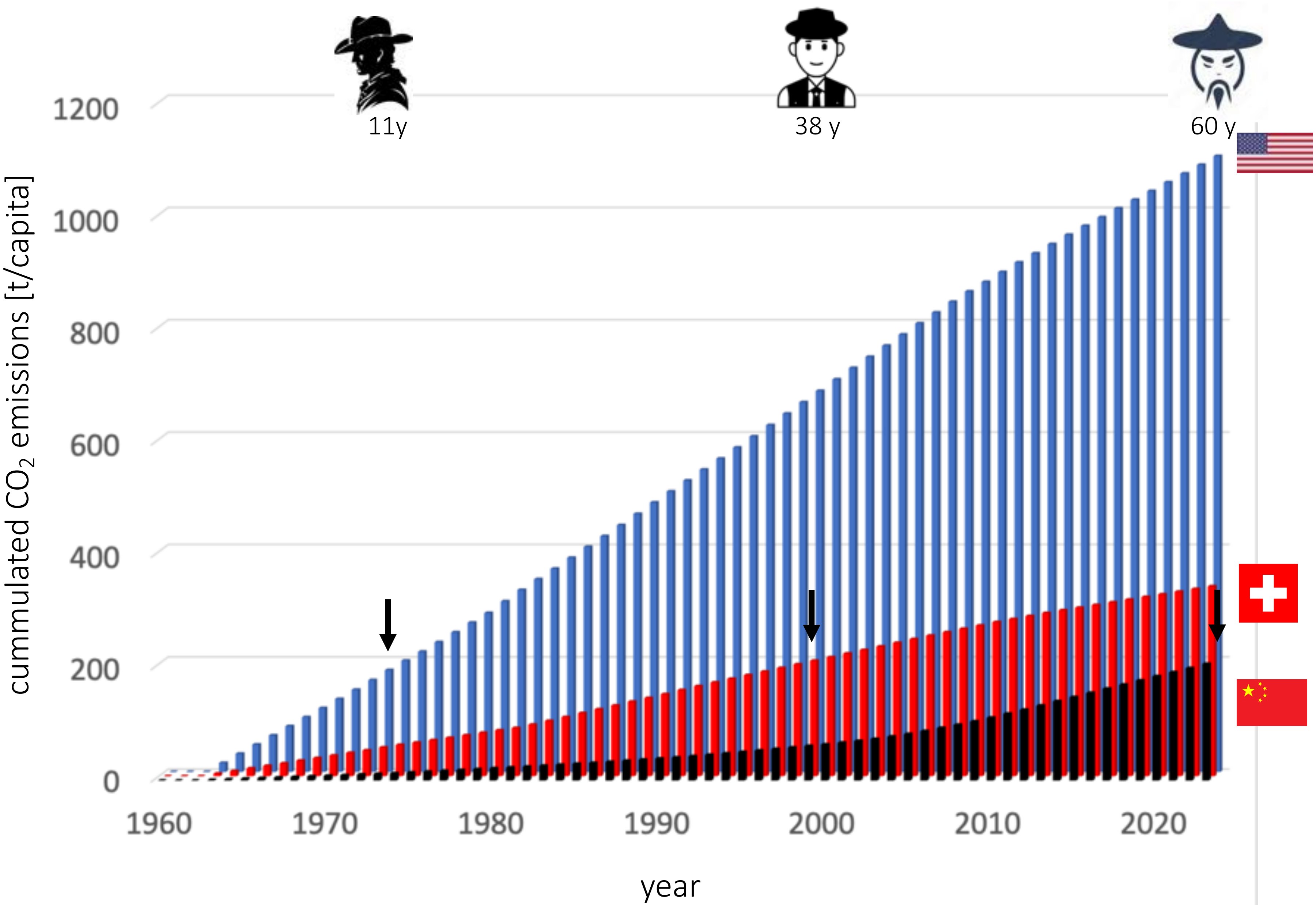




333 W/m² → ΔT = 33°C

0.1°C/(W·m⁻²)

Cummulated CO_2 Emissions over 60 years



Horse manure 130 years ago

Horse manure in 1894

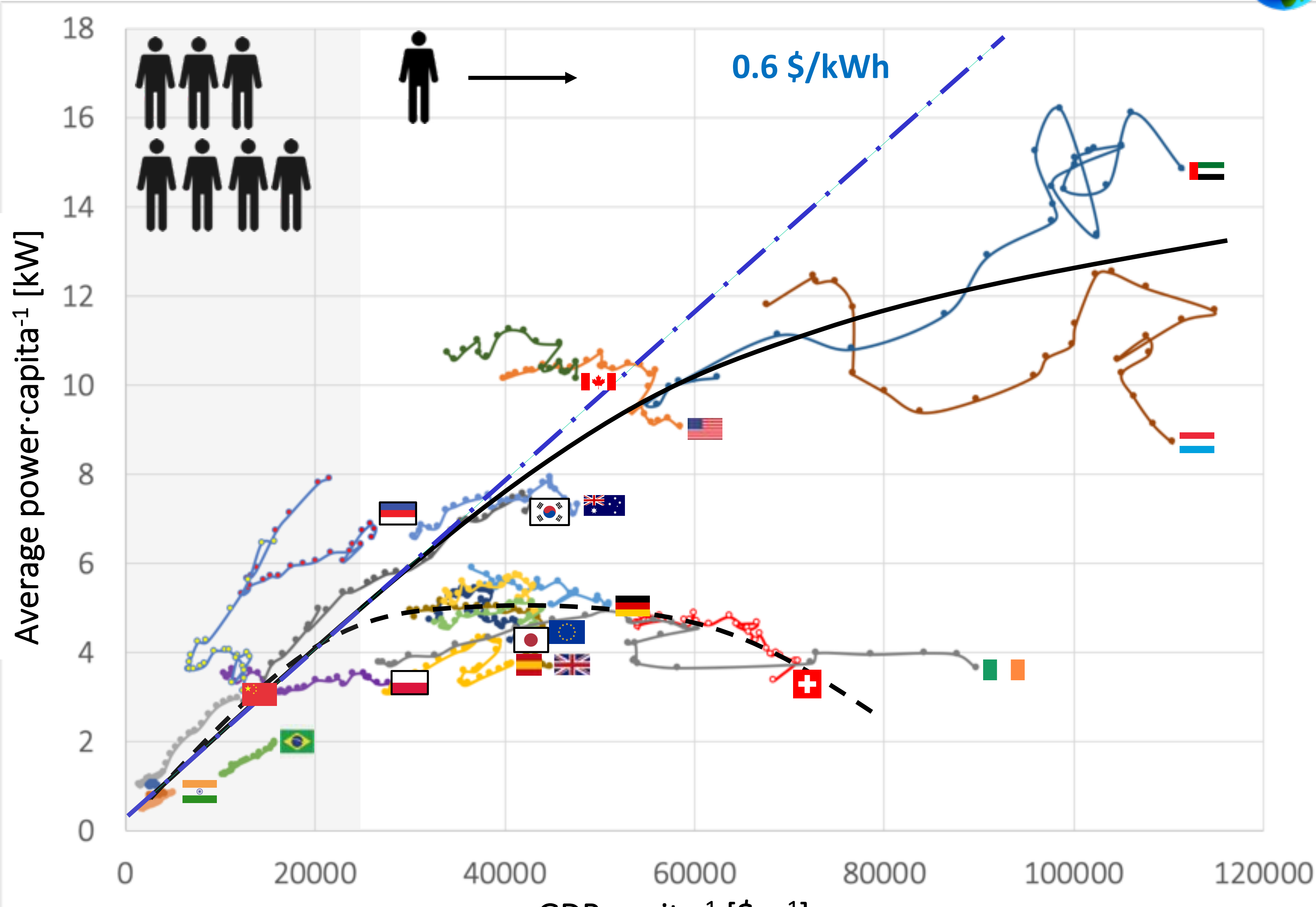
Crisis, we need to reduce the number of horses!

Remove manure

Capture manure at point source

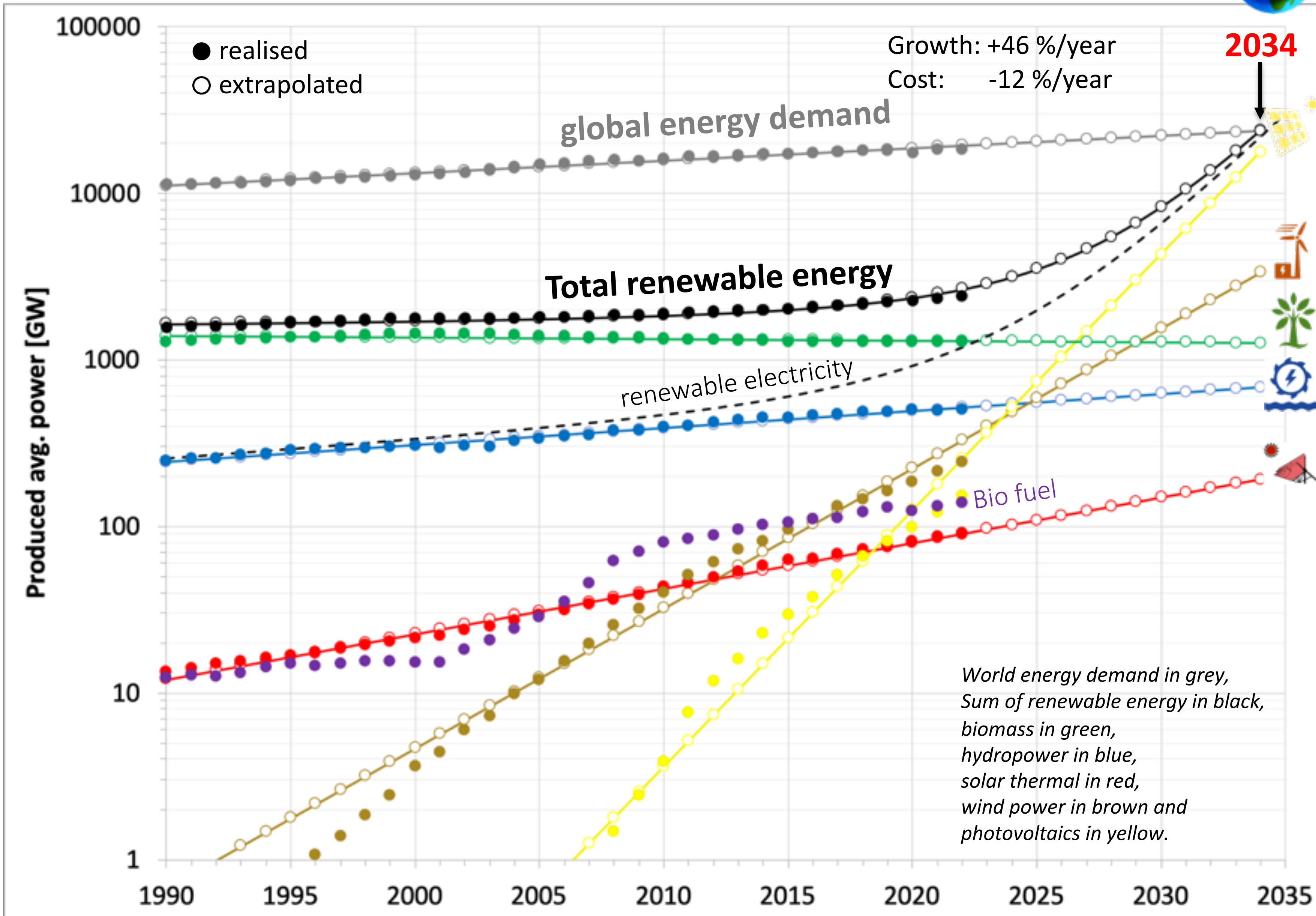
Solution: new technology!

Energy and economy



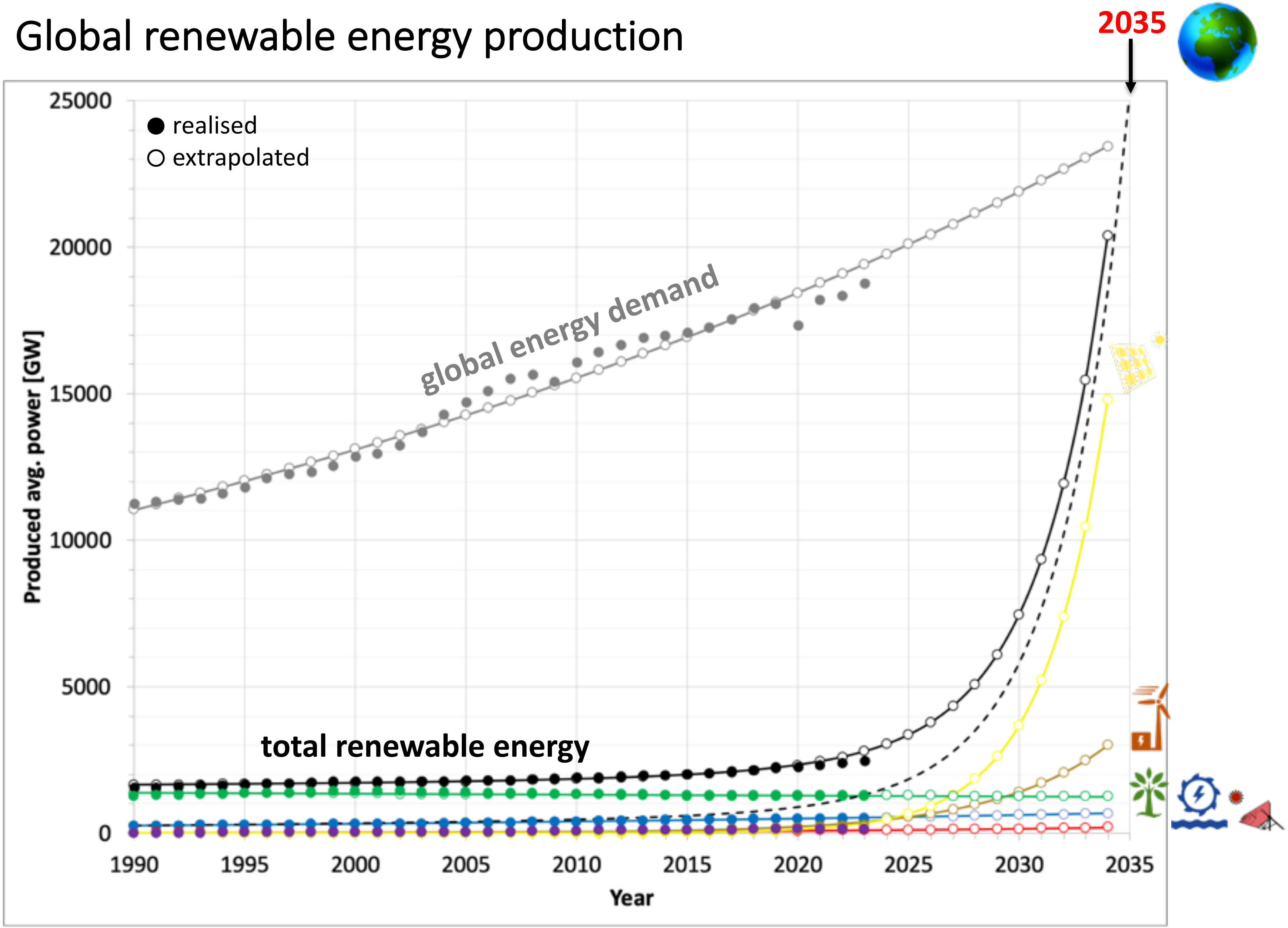
Ref.: https://ourworldindata.org/grapher/energy-use-per-capita-vs-gdp-per-capita

Global renewable energy production



Ref.: https://ourworldindata.org/energy

Global renewable energy production



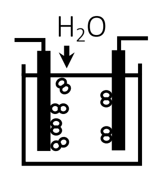
Ref.: https://ourworldindata.org/energy. https://www.pv-magazine.com/2023/02/16/global-solar-installations-may-hit-350-6-gw-in-2023-says-trendforce/#:~:text=2022, and https://ourworldindata.org/energy

Agriculture before industrialization

Local agriculture

PV on the roof of the house

Sauerkraut, cheese, and bacon



Battery, hydrogen, pressurized cylinder

Agriculture today


Agriculture (seasonal)


Greenhouse (all year round)


Agriculture (global)


Transport / Distribution


Wholesaler / Warehouse

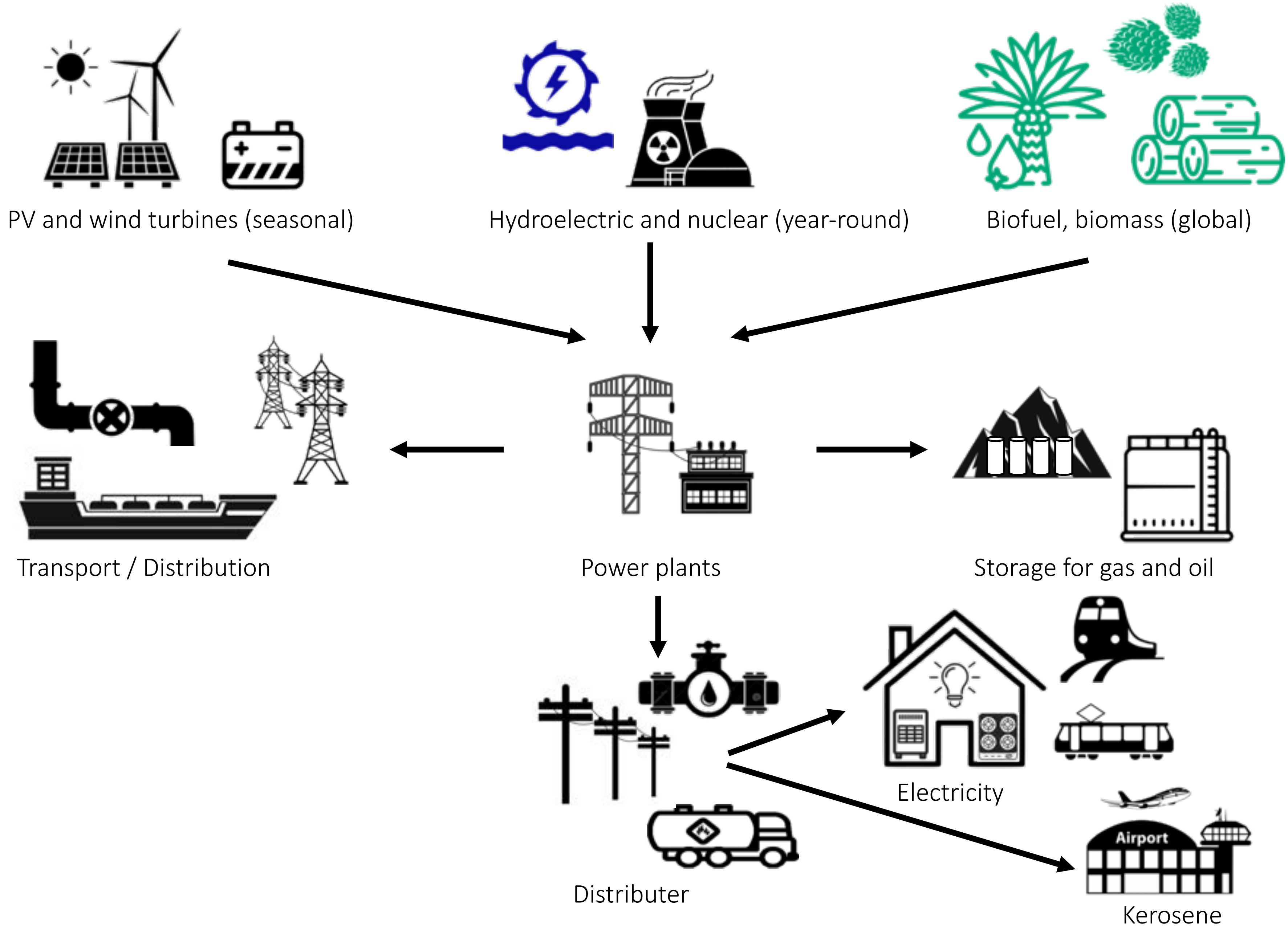

Preservation / Deep freezing


Retailer

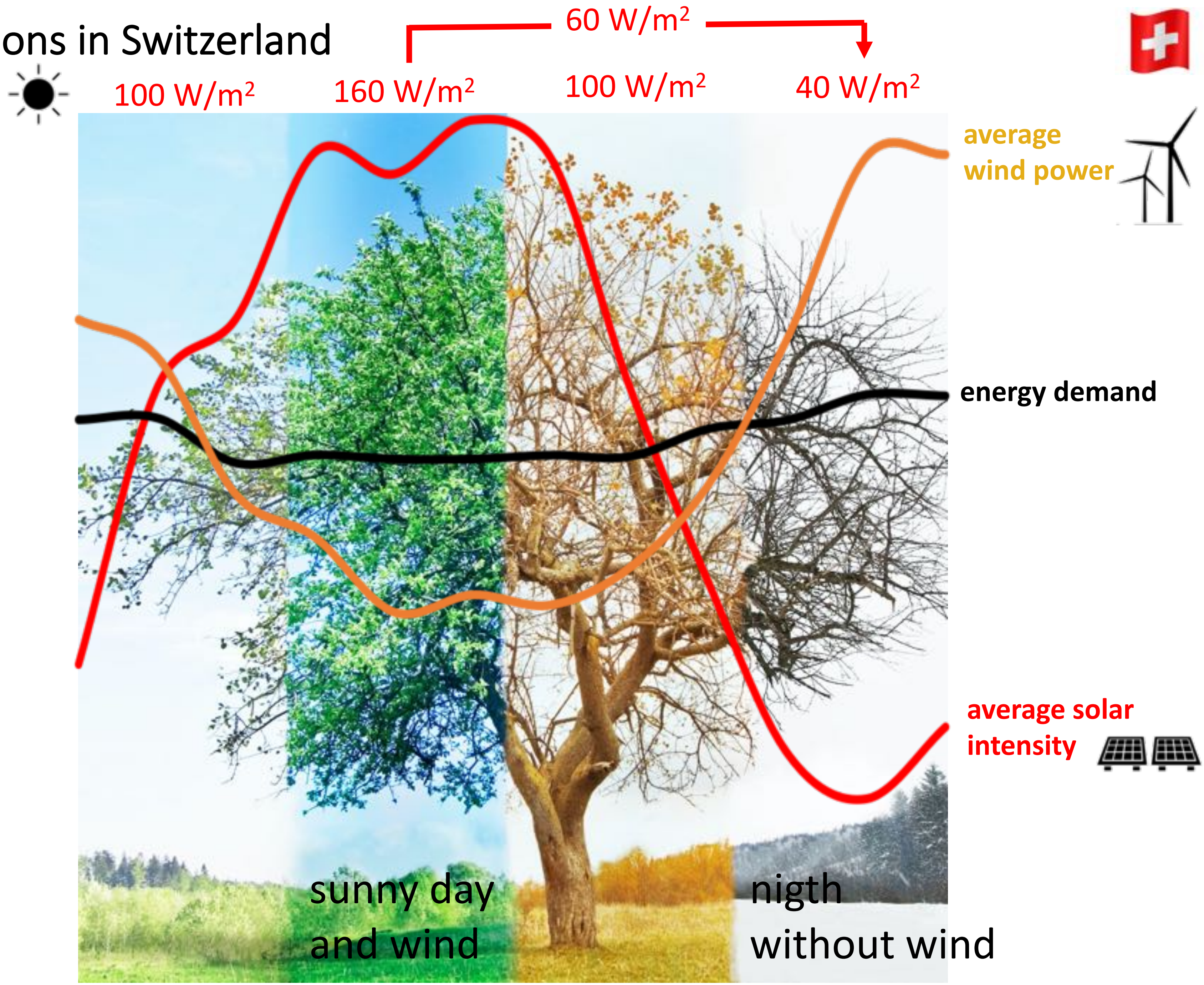

Convenience food


Kitchen

Renewable energy industry



Seasons in Switzerland



Storage model

The size of the storage required to shift the energy produced by photovoltaics (PV) from summer to winter depends on the shape of the solar intensity curve and the demand curve over the year. In a first-order approximation, the curves are linear between the minimum and maximum, and the size of the storage is calculated:

$E_P = (P_{P,S} + P_{P,W})\cdot t/2$

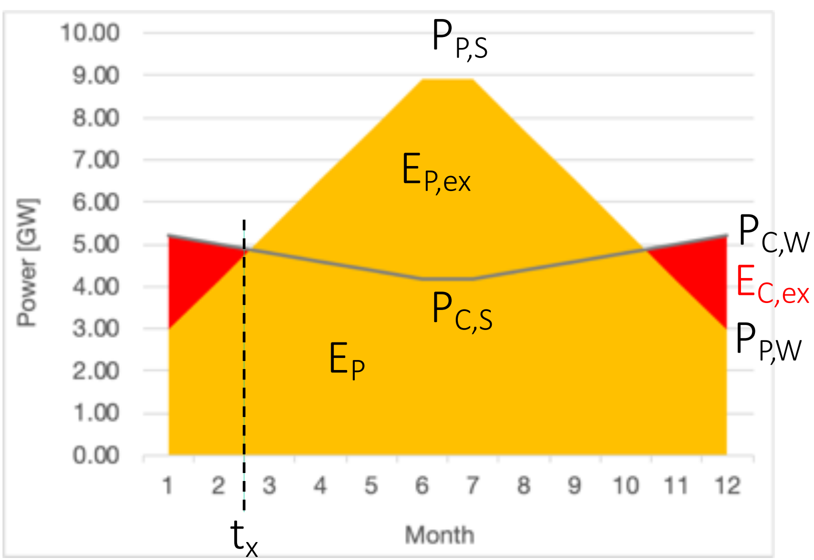
$E_{P,ex} = (P_{P,S} - P_{C,S})\cdot(t/2-t_x)$

$E_C = (P_{C,S} + P_{C,W})\cdot t/2$

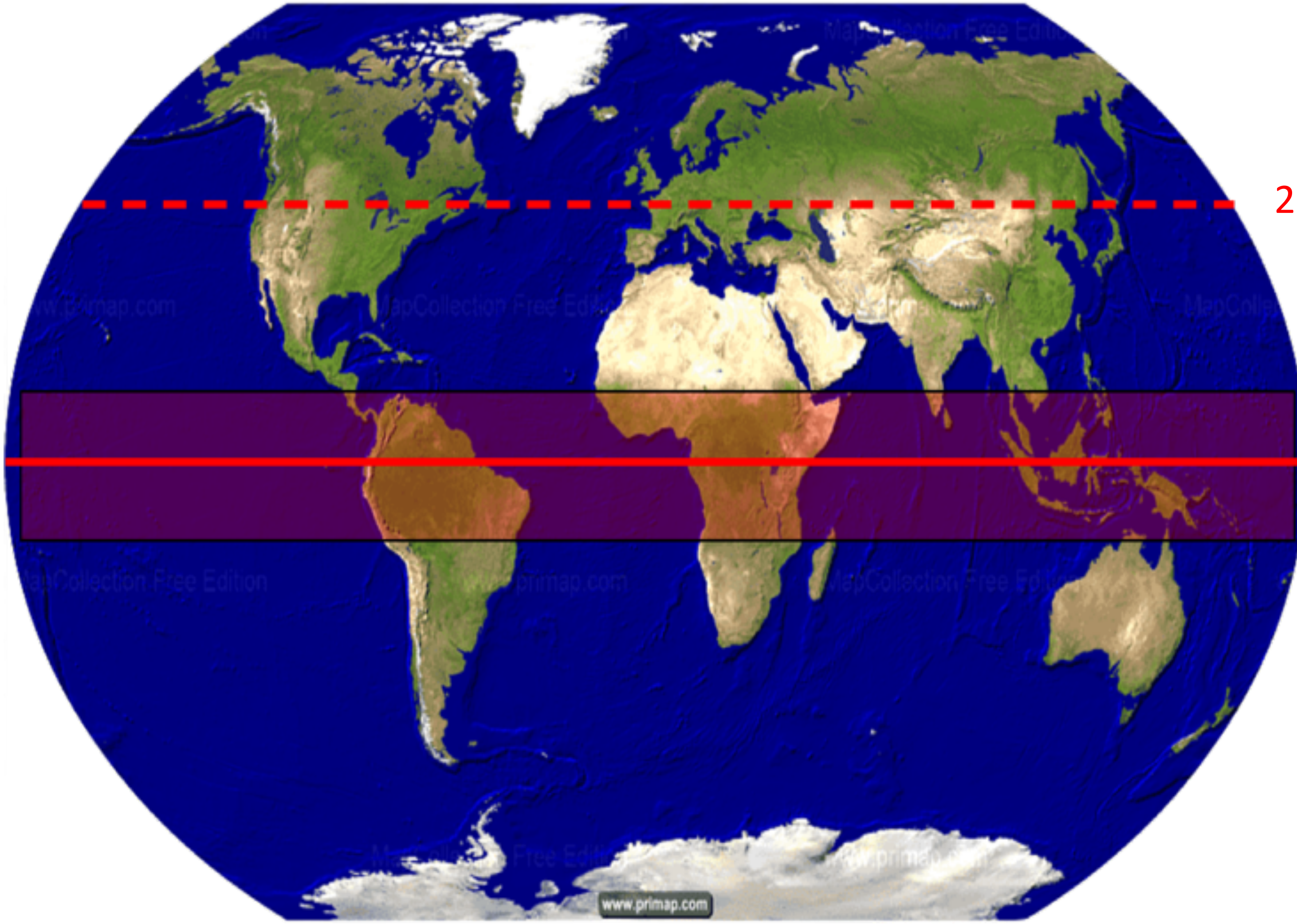
$E_{C,ex} = (P_{C,W} - P_{P,W})\cdot t_x$

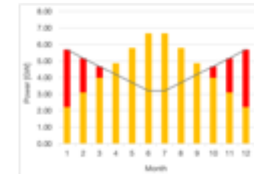
$t_x = t/2\cdot(P_{P,W} - P_{C,W})/(P_{C,S} - P_{C,W} - P_{P,S} + P_{P,W})$

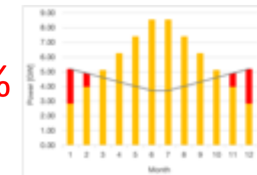
$P_{P,ex} > P_{C,ex}$: $S = P_{C,ex}$

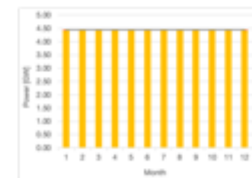


Renewable energy and storage



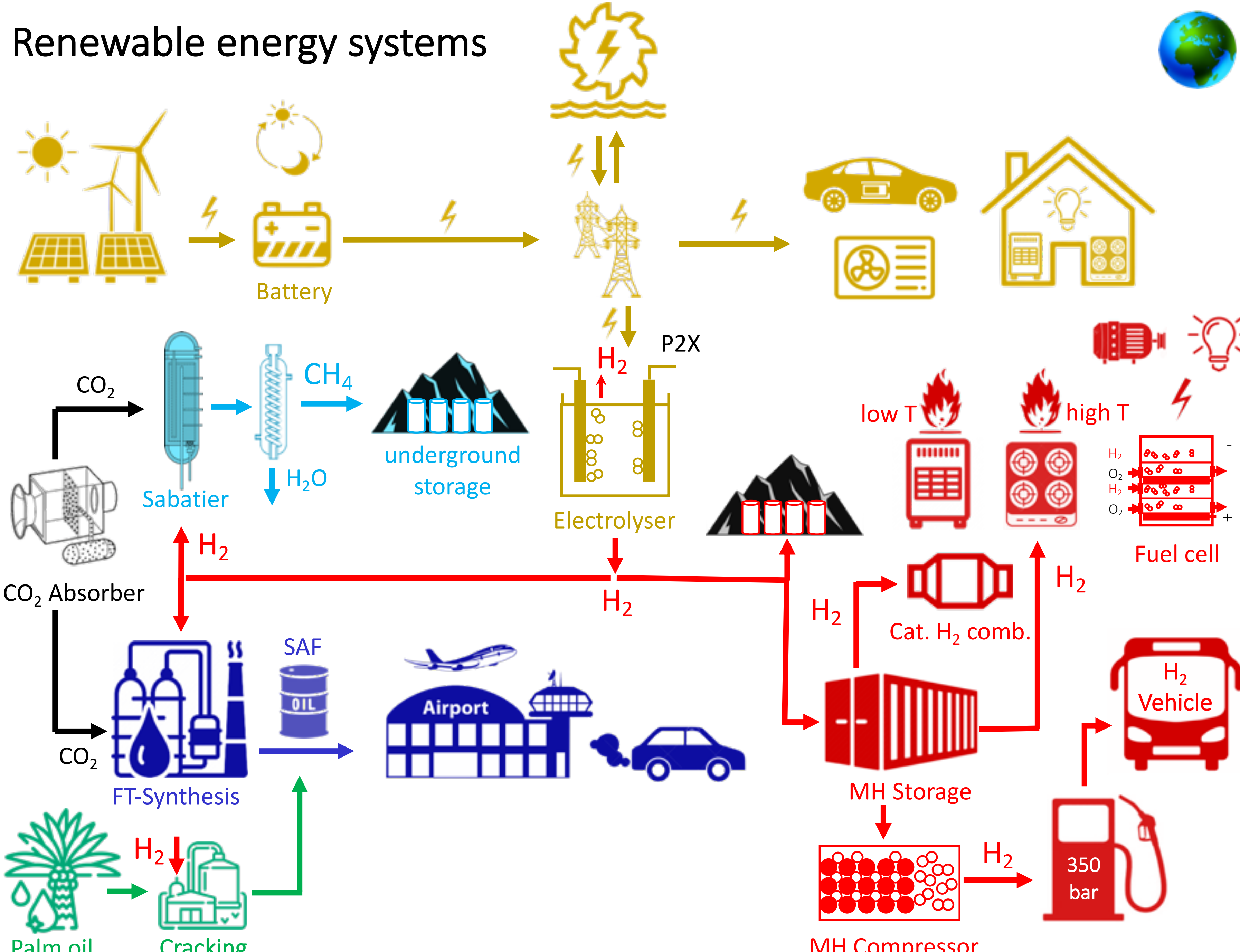




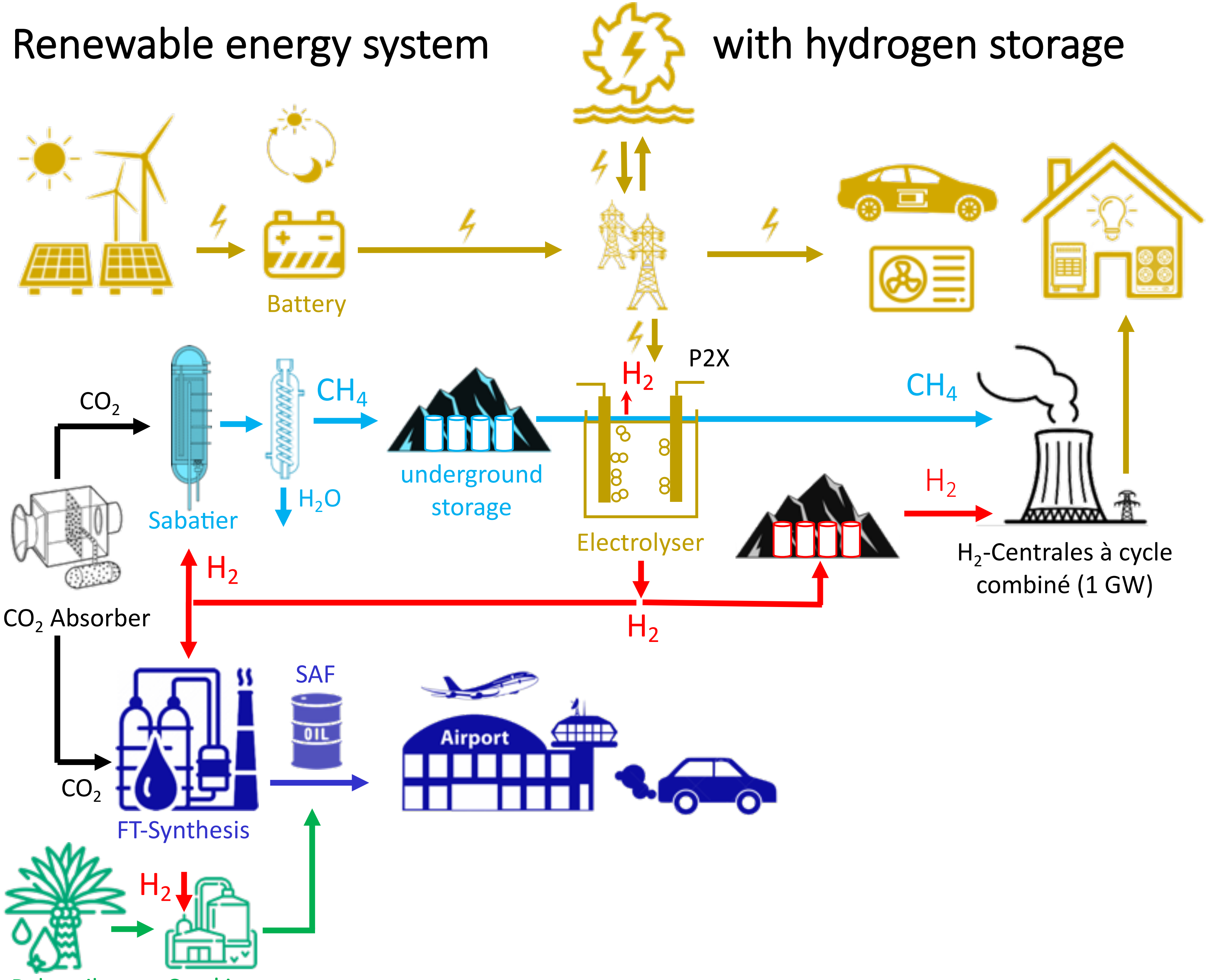


A heuristic model for the global energy transition

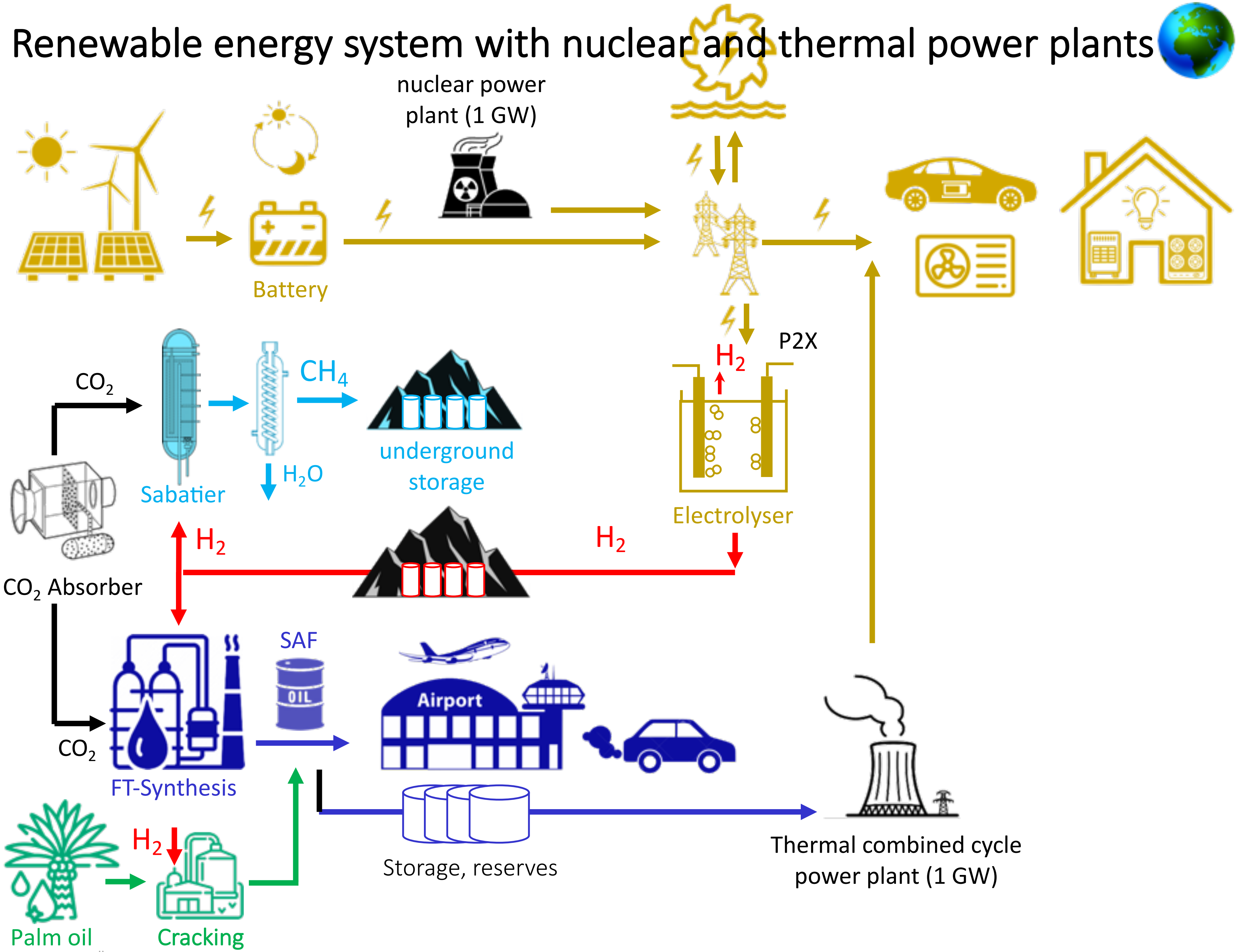
Renewable energy systems



Renewable energy system with hydrogen storage

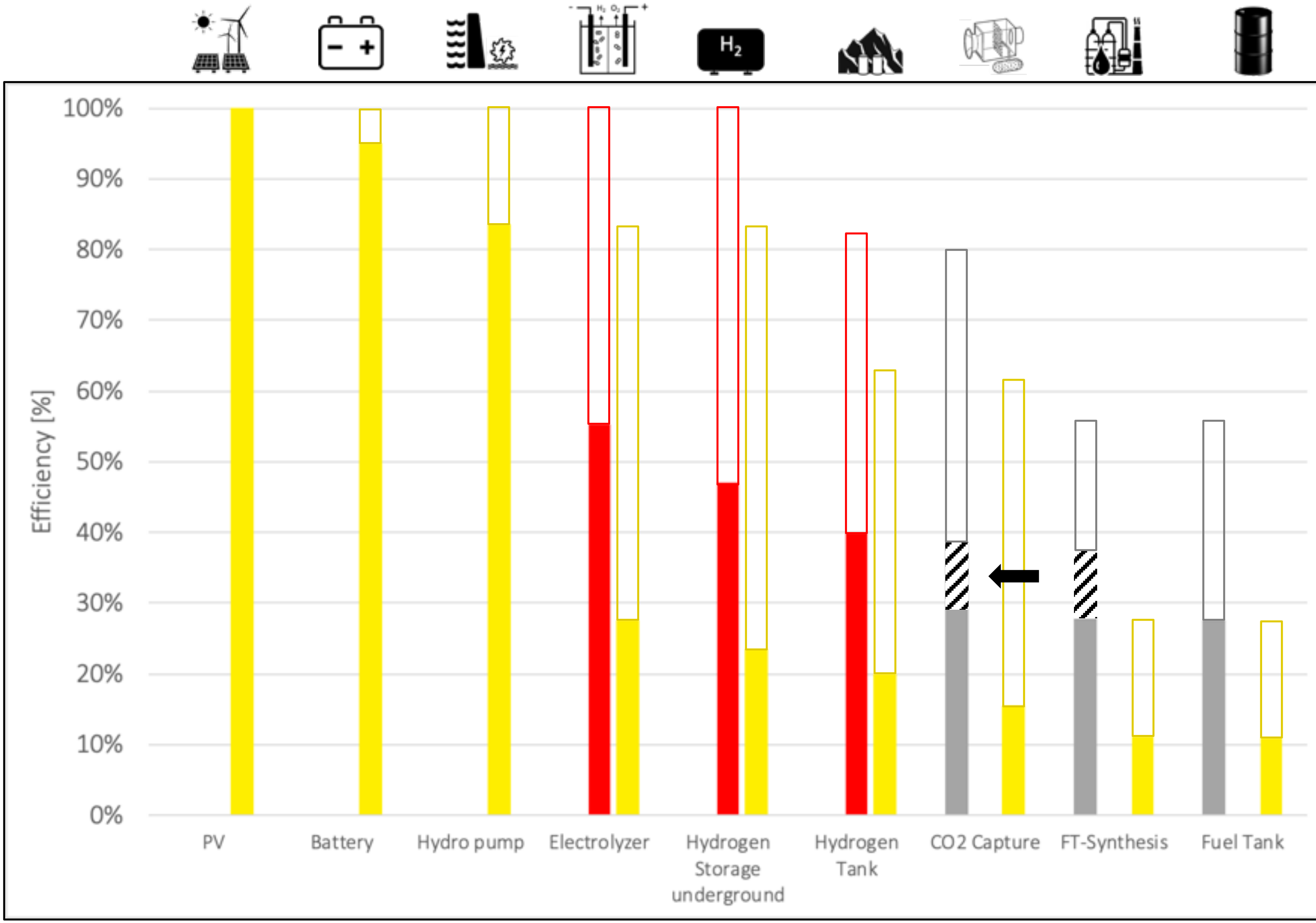


Renewable energy system with nuclear and thermal power plants

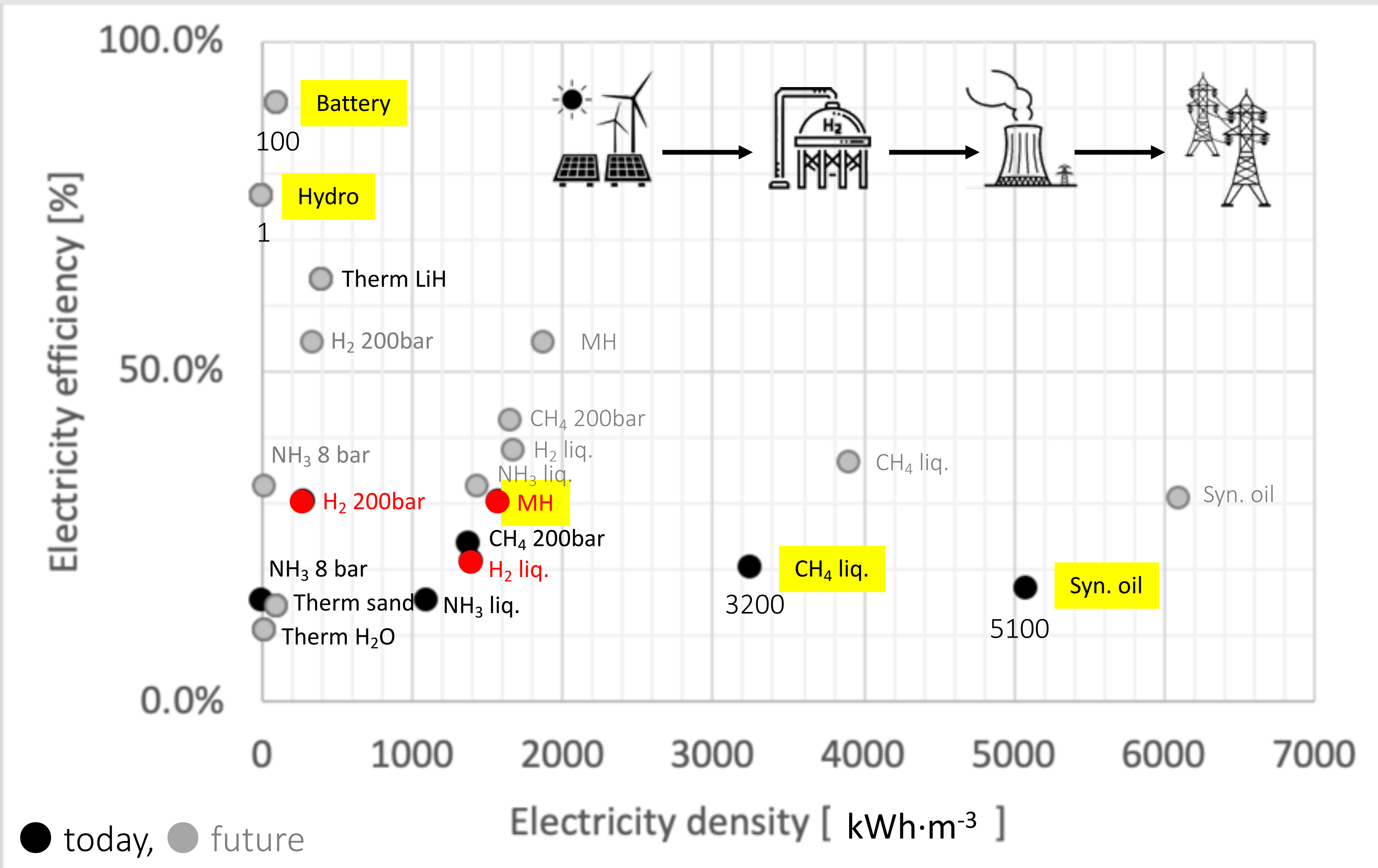


Efficiency of energy conversion

Power to X (P2X)

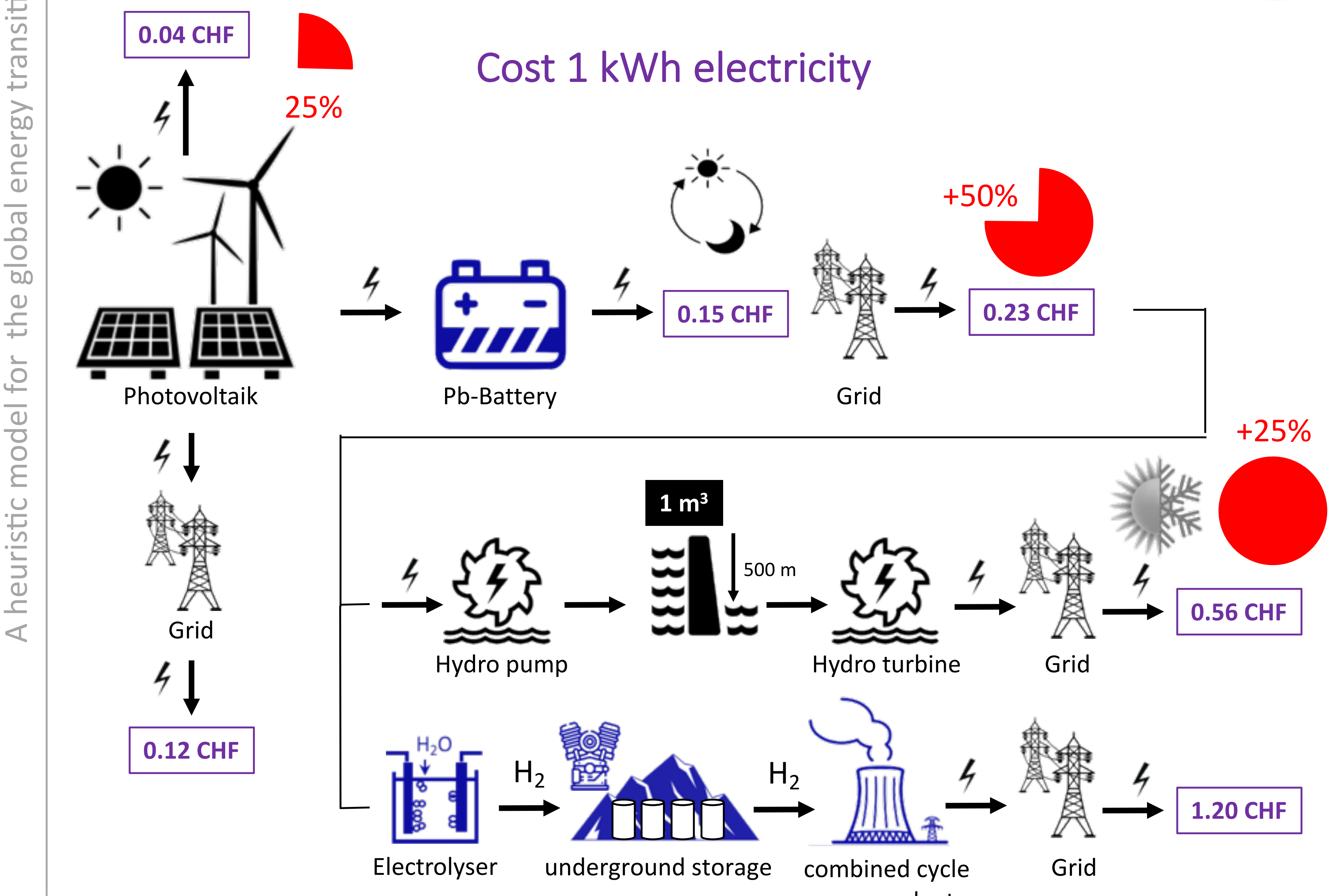


Efficiency and storage density of renewable electricity



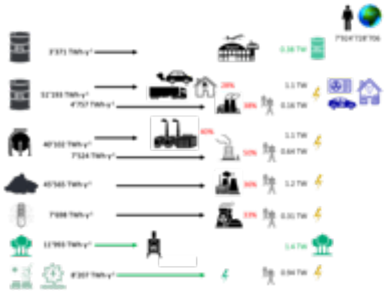
Ref.: Andreas ZÜTTEL, Christoph NÜTZENADEL, Louis SCHLAPBACH, Paul W. GILGEN "Power plant units for CO_2 Neutral Energy Security in Switzerland", Frontiers in Energy Research: Process and Energy Systems Engineering, 12:1336016 (2024).

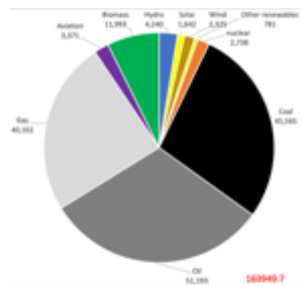
Renewable energy from production to "on demand"

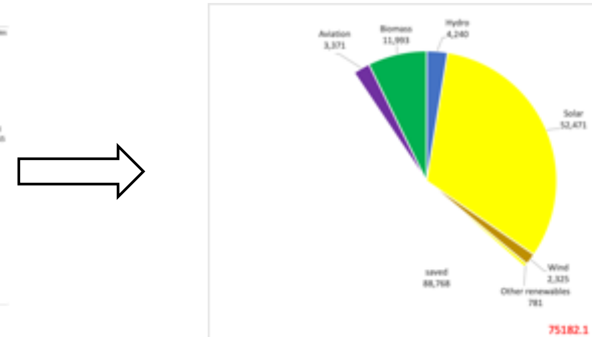


Heuristic model for the energy transition

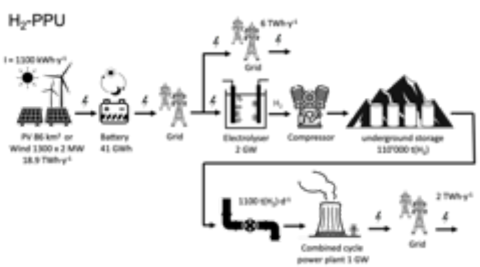
Analysis of the energy production and use

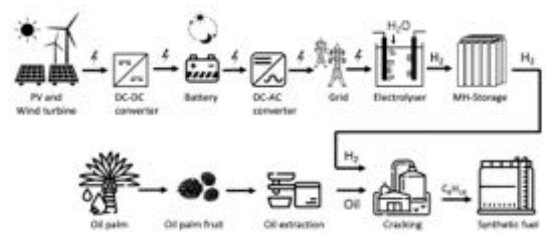






Generalized solutions with Power Plant Units (PPUs)



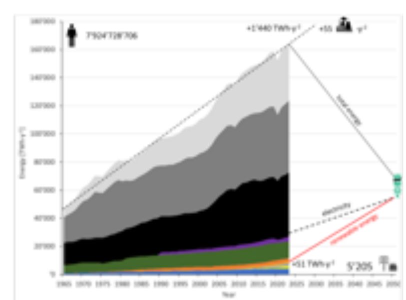


Electrification

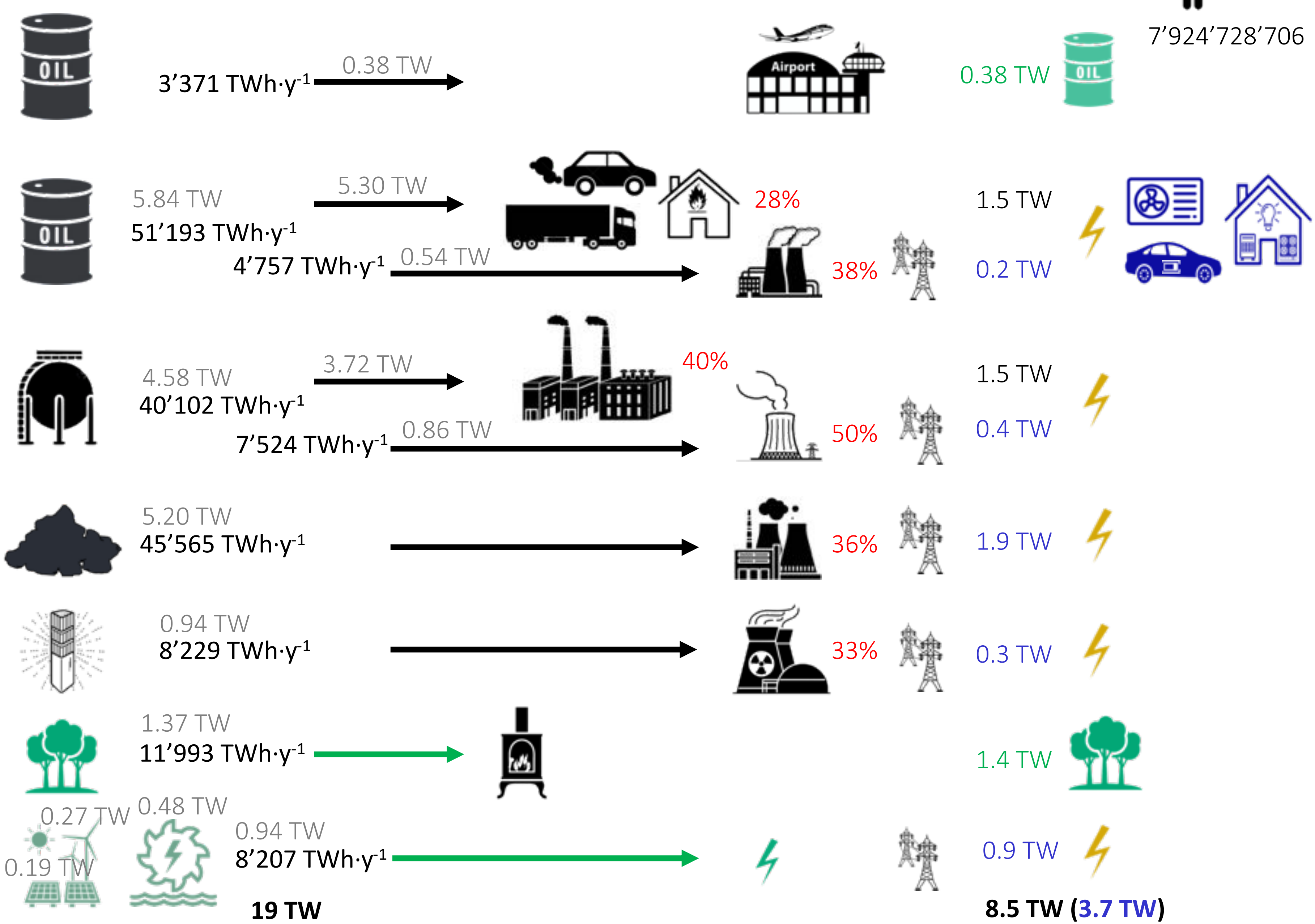
CO_2 neutral fuel

Optimized technical solution and minimized economic impact

KWE's	W_{el} + Q [TWh·y⁻¹]	LCOE [€·kWh⁻¹]	CAPEX [G€]	OPEX [G€·y⁻¹]	TCS [G€·y⁻¹]	Fläche (PV) [km²]	Bemerkungen
	8.7 + 17.4	0.05	5.5	0.3	0.4	1	Energie, Import U, kompakt, billig
	8.7 + 8.7	0.11	3	0.9	0.9	1	Import Erdgas, fossil, CCS
	8.7 (75%)	0.13	9.6 + 6	1	1.1	100	Energielücke, gross
H_2	8.7 + 2.2	0.45	71	1	3.9	150	universal, sehr gross, teuer
	8.7 + 8.7	0.3	2	3.0	3.1	1	Import, billige Speicher
	8.7	0.05	2	0.1	0.1	10	local, dynamisch billig, Speicher
	8.7	0.16	2 + 6	0.5	1.4	850	Meeresbucht, Gezeiten



Global energy supply (2023)

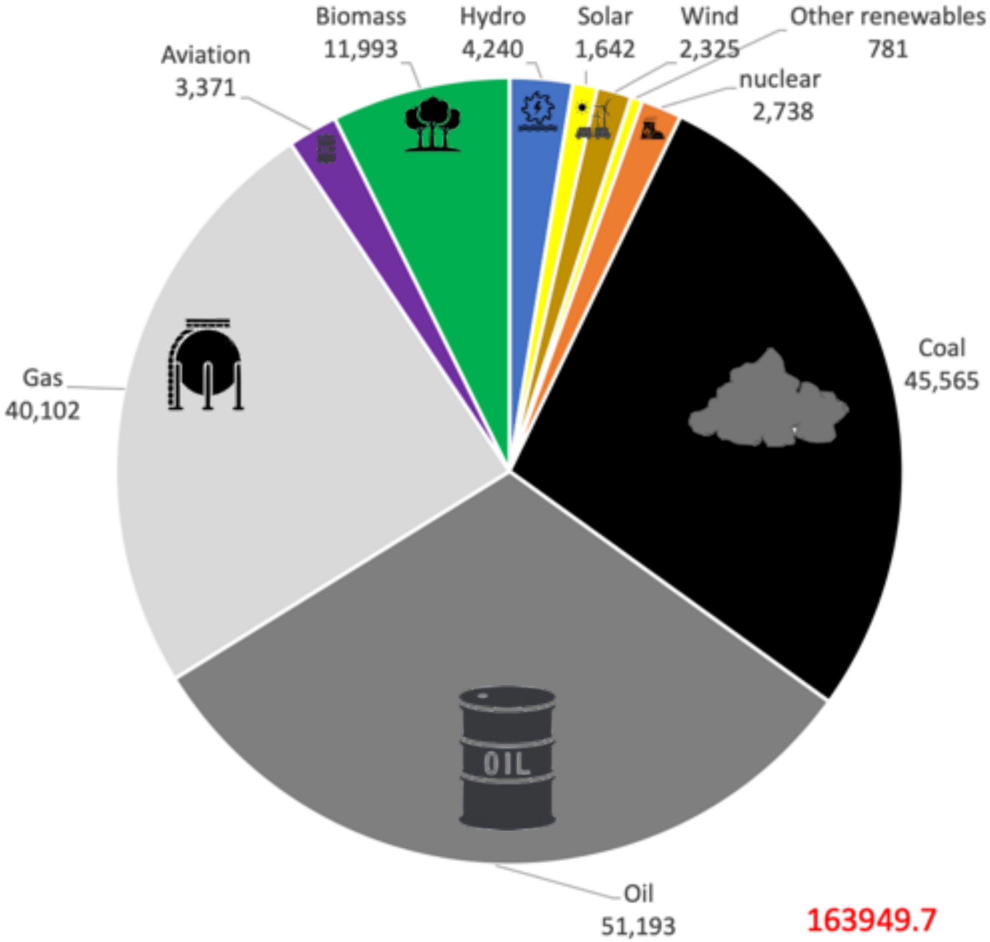


Global energy transition

Energy in [TWh·y^{-1}]

current

2023

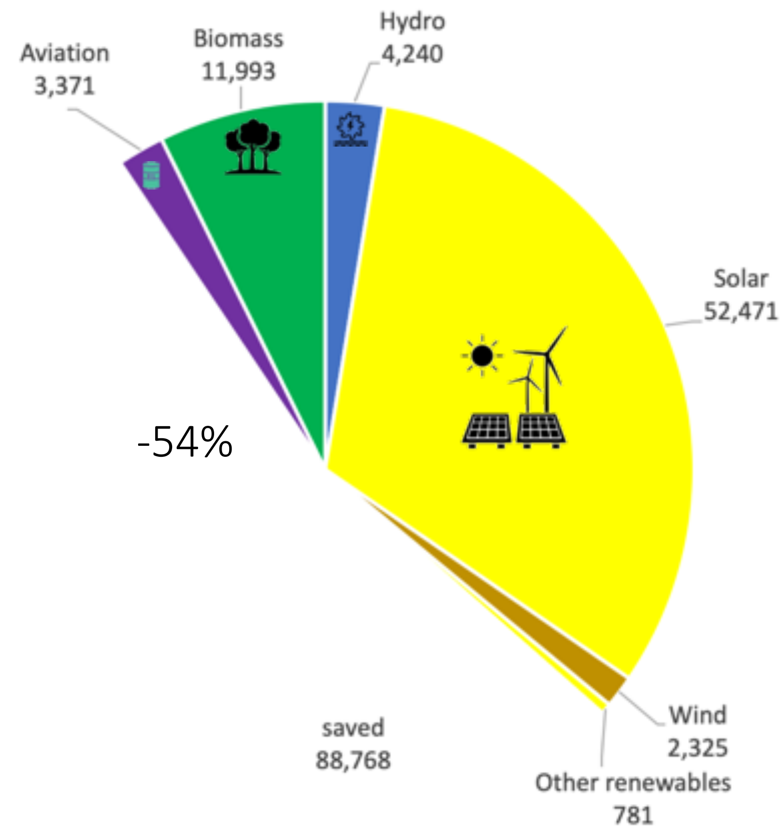


163949.7

18.7 TW

electrification

2050

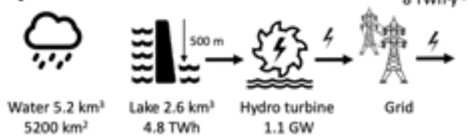


75182.1

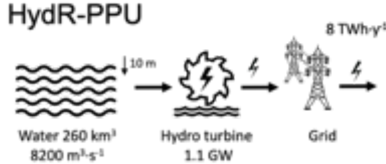
8.6 TW

Power plant units (1 GW, 8.7 TWh/y)

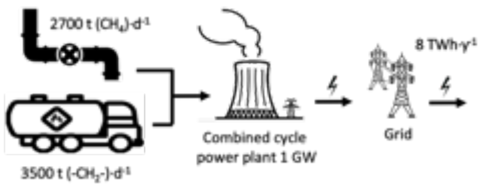
HydS-PPU



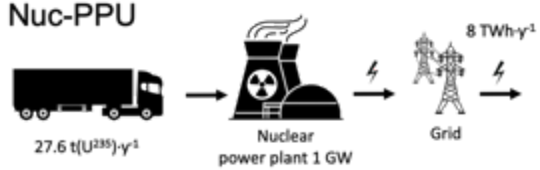
HydR-PPU



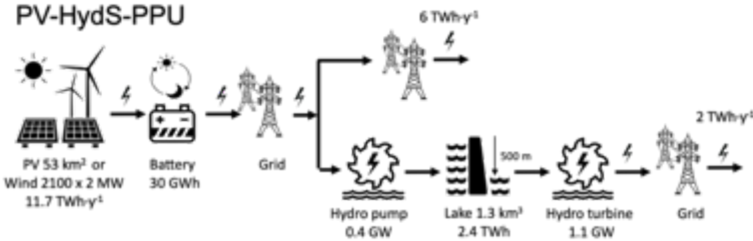
Therm-PPU



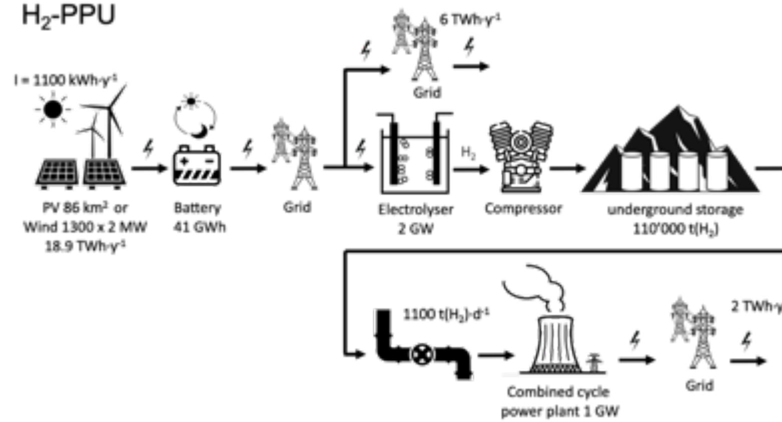
Nuc-PPU



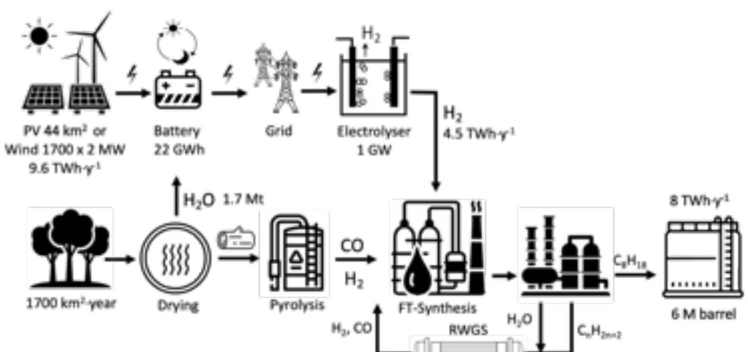
PV-HydS-PPU



H_2-PPU

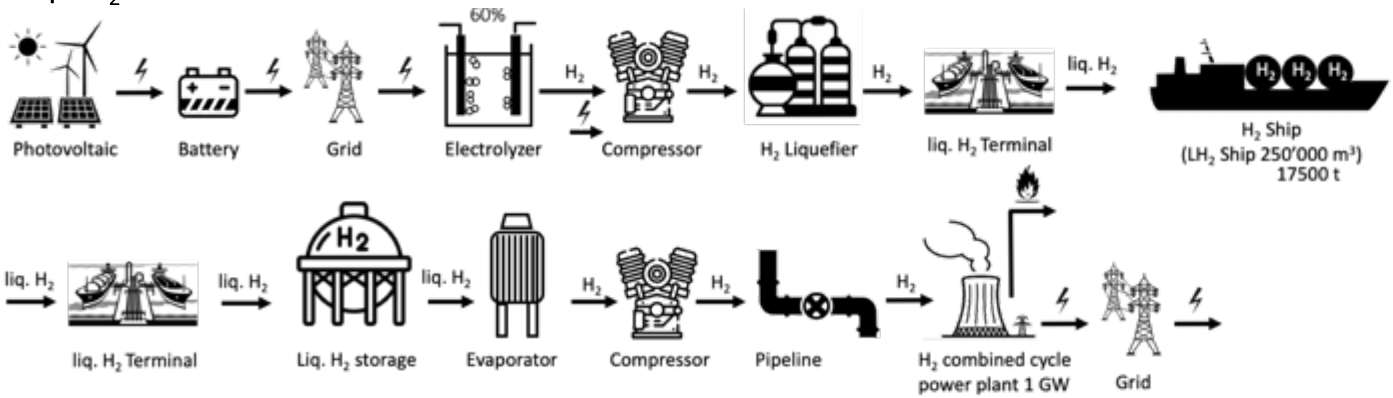


Syn fuel - PPU

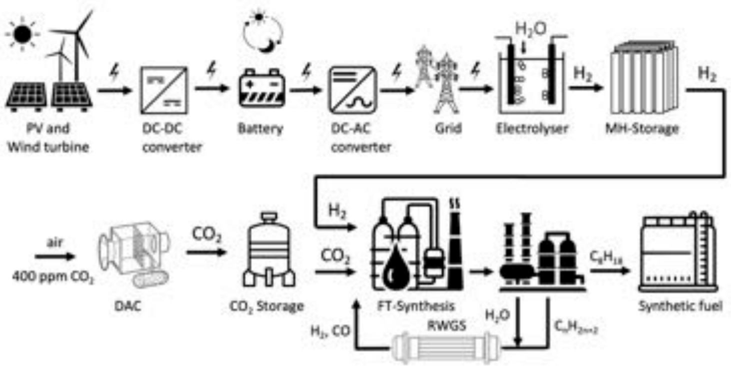


Power plant units (1 GW, 8.7 TWh/y)

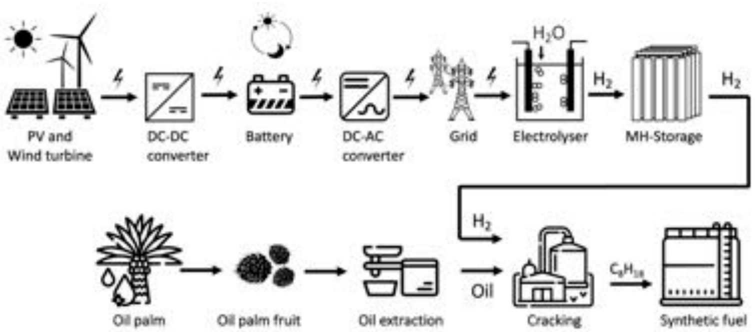
Imp. H_2



Imp. SF

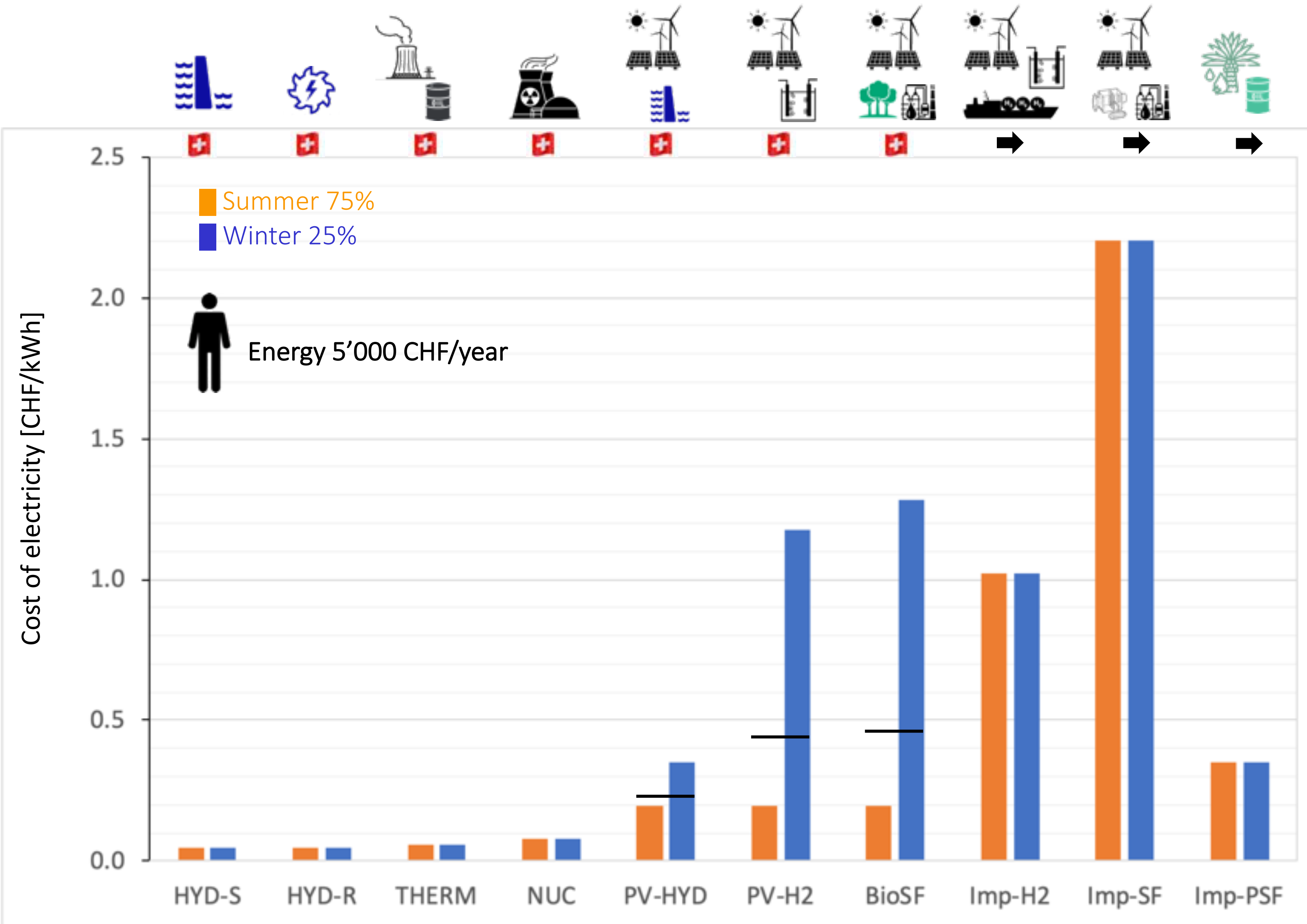


Imp. BSF

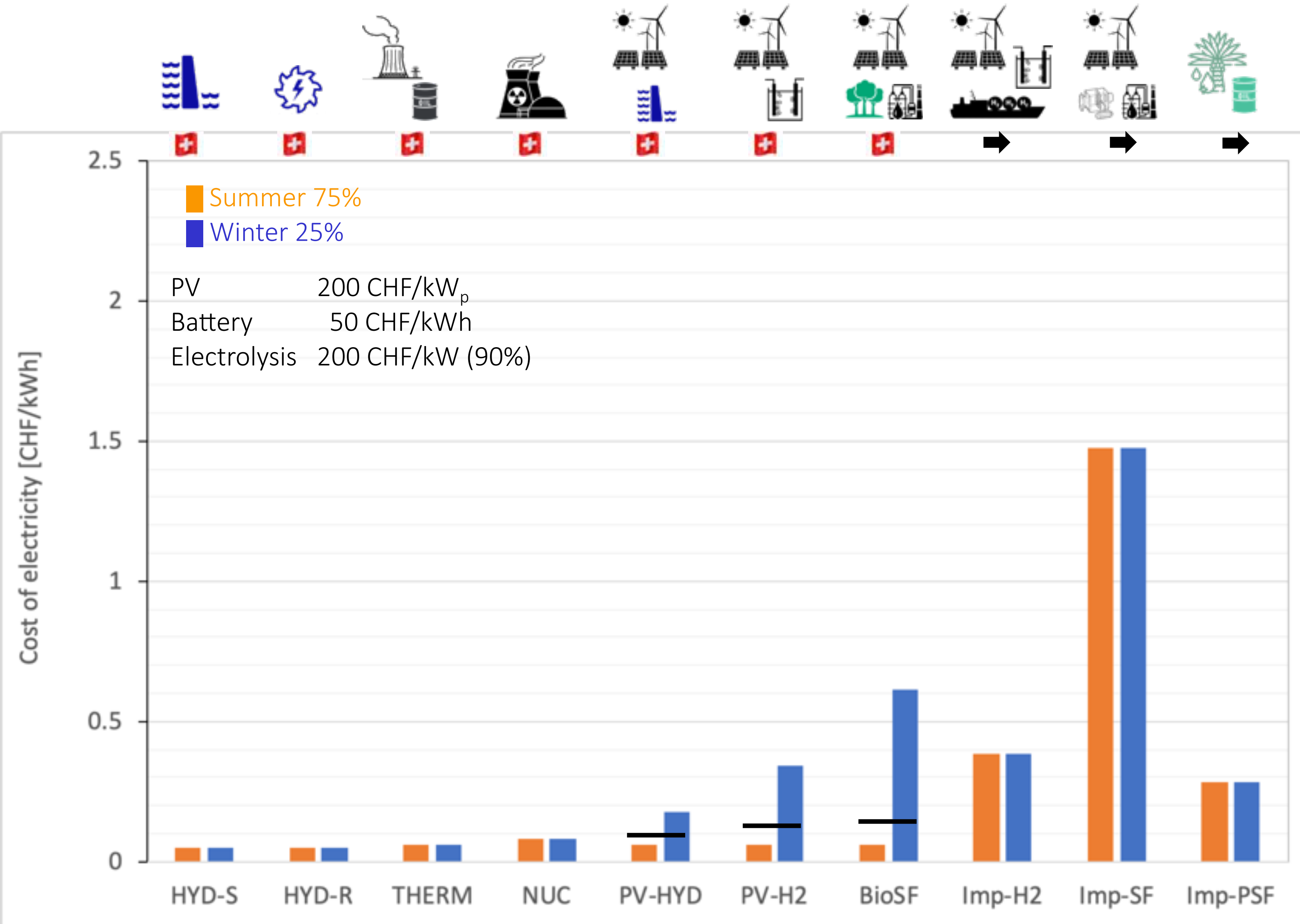


A heuristic model for the global energy transition

Cost of electricity (2023)



Cost of electricity in future



Power plant units (PPU), energy, cost and space

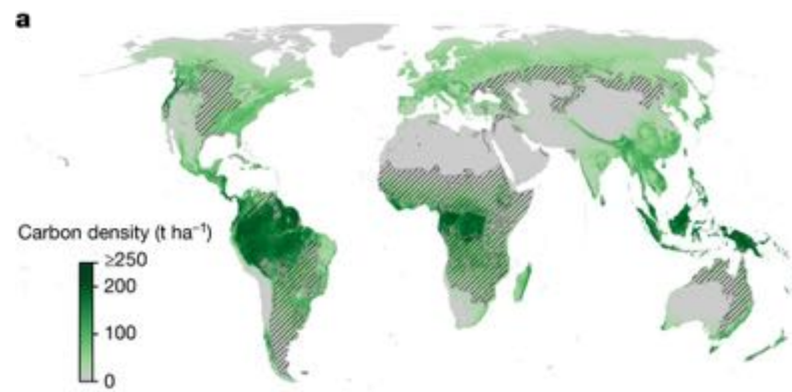
PPU's	$W_{el.}$ + Q [TWh·y⁻¹]	**LCOE [€·kWh⁻¹]**	CAPEX [G€]	OPEX [G€·y⁻¹]	TCS [G€·y⁻¹]	**Area (PV) [km²]**	Remarks
	8.7	**0.05**	2	0.1	0.4	**5**	local, dynamic cheap, storage
	8.7 + 17.4	**0.08**	5.5	0.3	0.4	**1**	energy, import U, compact, cheap
	8.7 + 8.7	**0.11**	3	0.9	0.9	**1**	import nat. gas, fossil, CCS
	8.7 (75%)	**0.13**	9.6 + 6	1	1.1	**100**	not sufficient, large
	8.7	**0.16**	2 + 6	0.5	1.4	**850**	sea, tide
	8.7 + 8.7	**0.34**	2	1.2	3.5	**30 (4800)**	import, easy to store
H_2	8.7 + 2.2	**0.45**	84	1	4.6	**150**	universal, very large, expensive

Uranium: 200 t of natural uranium (0.7%) yields 20 tons of uranium (5%), natural uranium costs 130 €/kg
Battery costs 100 €/kWh, service life 8 years
PV costs 1200 €/kW_p, produces 220 kWh-m⁻²-y⁻¹, peak power 1 kW-m⁻²
Palm oil costs 0.7 €/L, energy content syn. oil 10 kWh/L, costs 1.7 €/L
Hydrogen is less than 6.7 €/kg cheaper than palm oil import and hydrogenation and less than 2 €/kg cheaper than hydropower.
Hydropower needs valleys and differences in altitude, nuclear power needs a change in legislation, PV with battery only covers 75%, PV with battery and hydrogen is the most expensive but most universal, palm oil with hydrogenation is an import of a controversial product but easy and cheap to store.

Carbon sinks and 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.

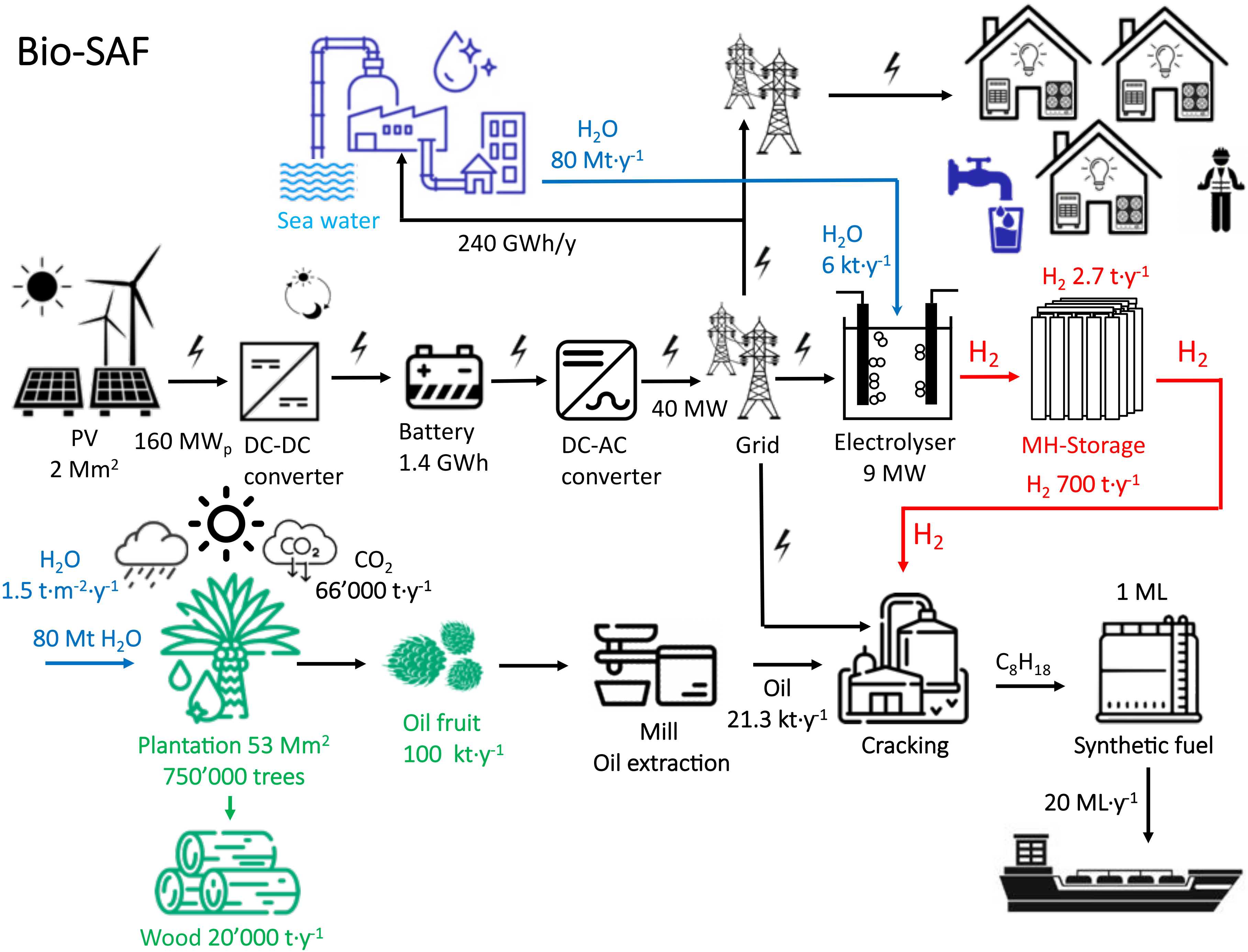
30 kg oil·y^{-1} per tree with 524 kg dry biomass



226 Gt palm tree produce 13 Gt oil·y^{-1} the current world fossil energy demand

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

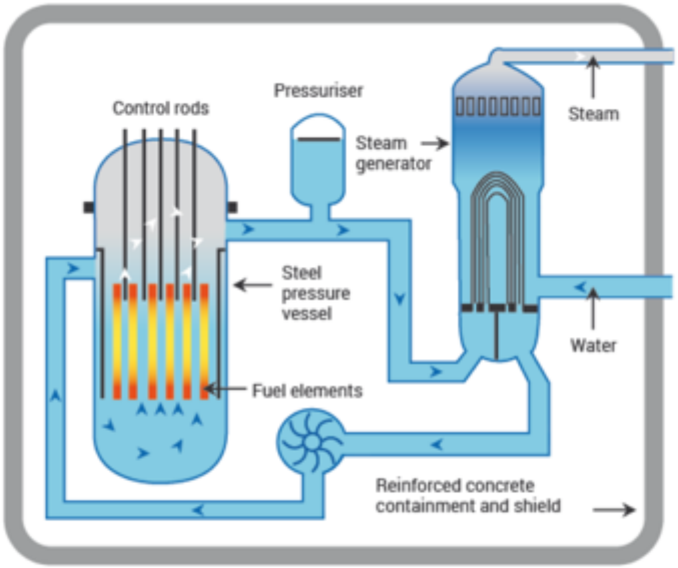
Bio-SAF


Sea water
H$_2$O
80 Mt·y^{-1}
240 GWh/y
H$_2$O
6 kt·y^{-1}
H$_2$ 2.7 t·y^{-1}
PV
2 Mm^2
160 MW$_p$
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$_2$O
1.5 t·m^{-2}·y^{-1}
CO$_2$
CO$_2$
66'000 t·y^{-1}
80 Mt H$_2$O
Plantation 53 Mm^2
750'000 trees
Wood 20'000 t·y^{-1}
Oil fruit
100 kt·y^{-1}
Mill
Oil extraction
Oil
21.3 kt·y^{-1}
Cracking
C$_8$H$_{18}$
1 ML
Synthetic fuel
20 ML·y^{-1}

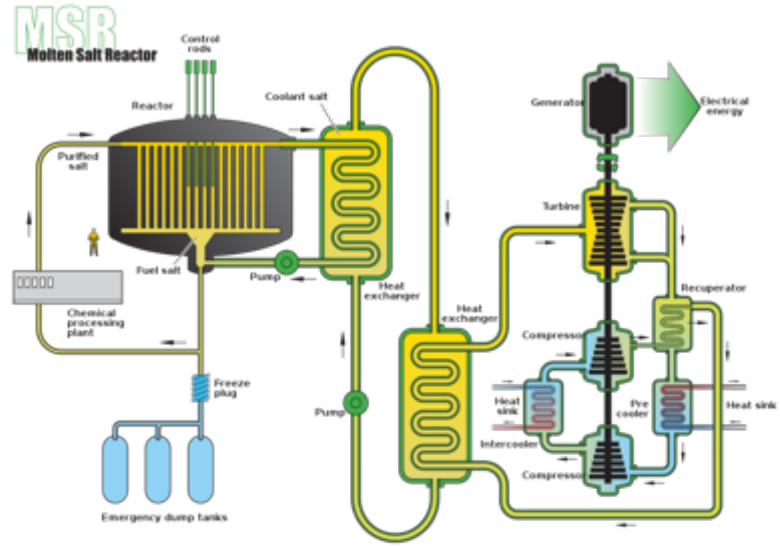
Nuclear reactors

Future

Uranium fission reactor



Thorium molten salt breading reactor



Disadvantages:

Limited uranium reserves (6% for 100 years)
Danger of core meltdown
Long-lived isotopes (Pu)
low efficiency (25%)
limited heat use
Nuc final repository. Waste
Small Modular Reactors (SMR)

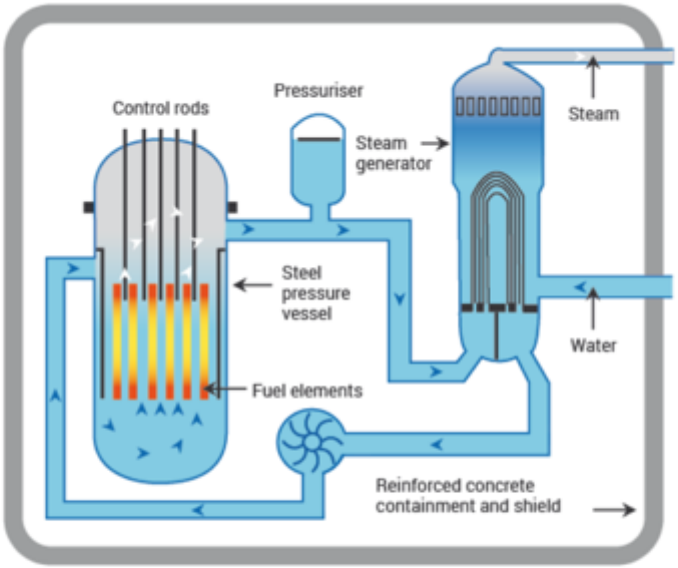
Advantages:

Large thorium reserves (use of nuclear waste, 95% is fuel)
No core meltdown possible
No long-lived isotopes
higher T, higher efficiency (>25%)
Using heat for heating
Molten Salt Reactor (MSR)

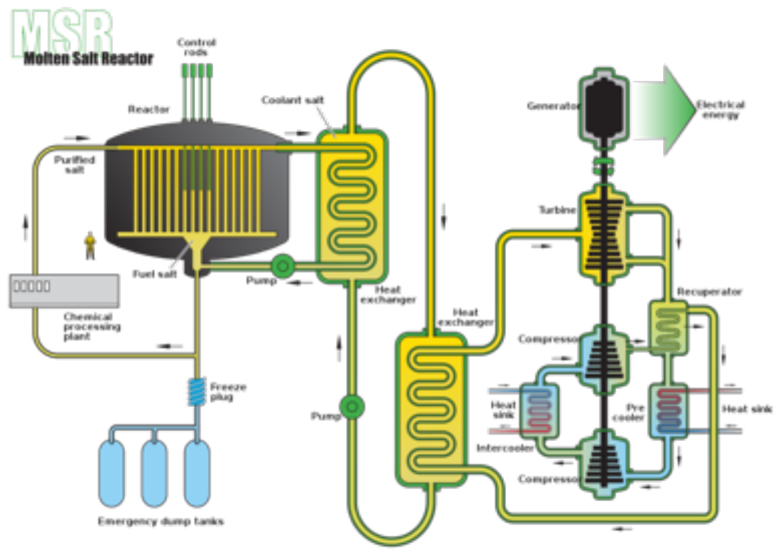
Nuclear reactors

Future

Uranium fission reactor



Thorium molten salt breading reactor



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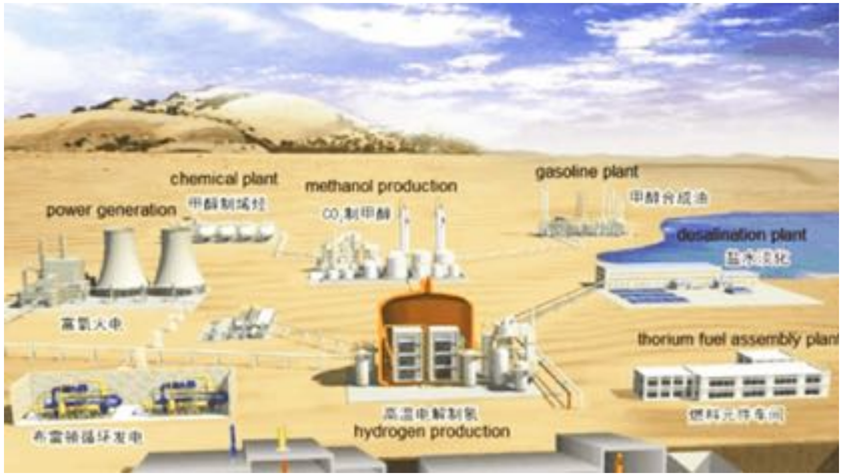
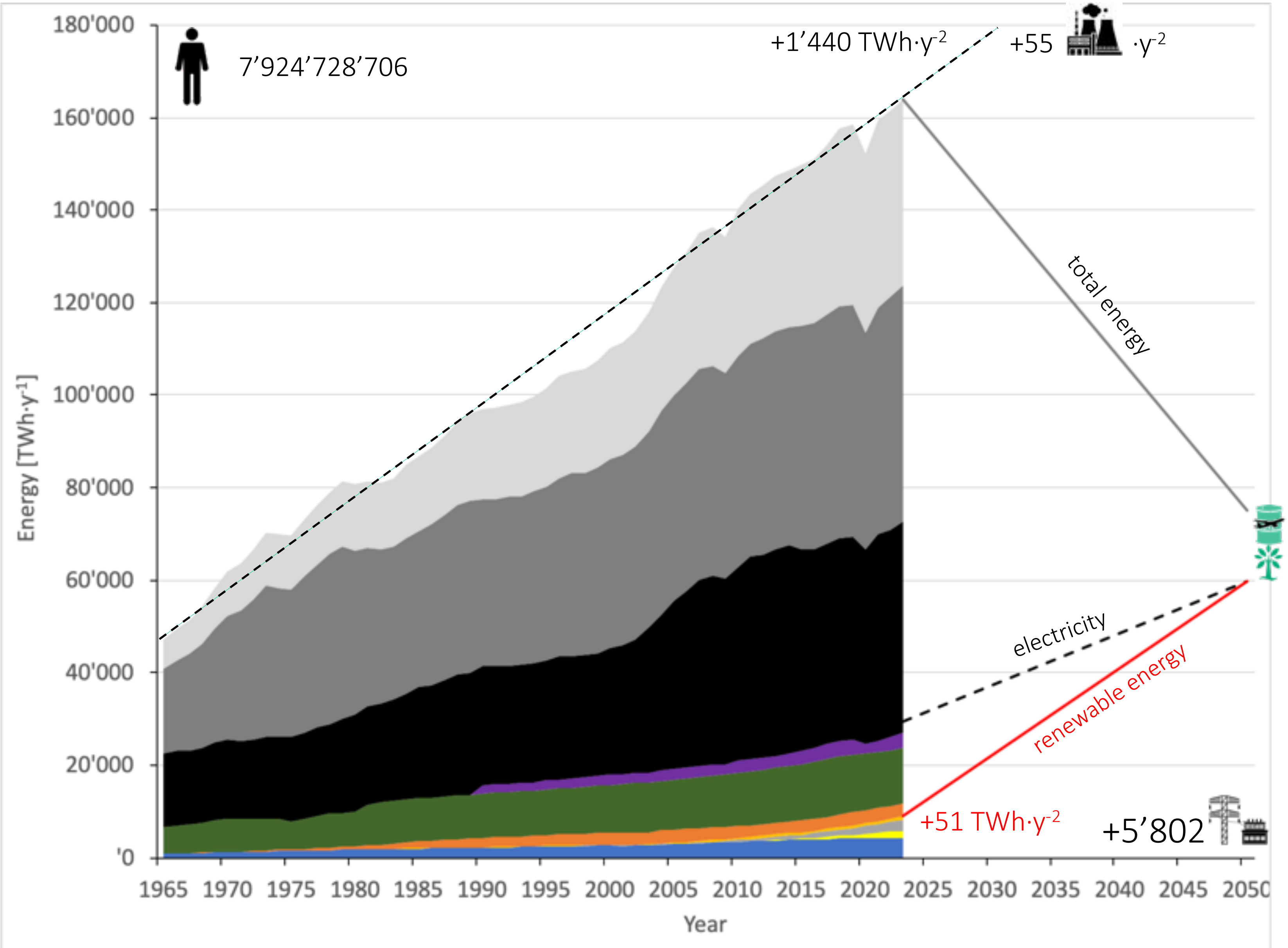
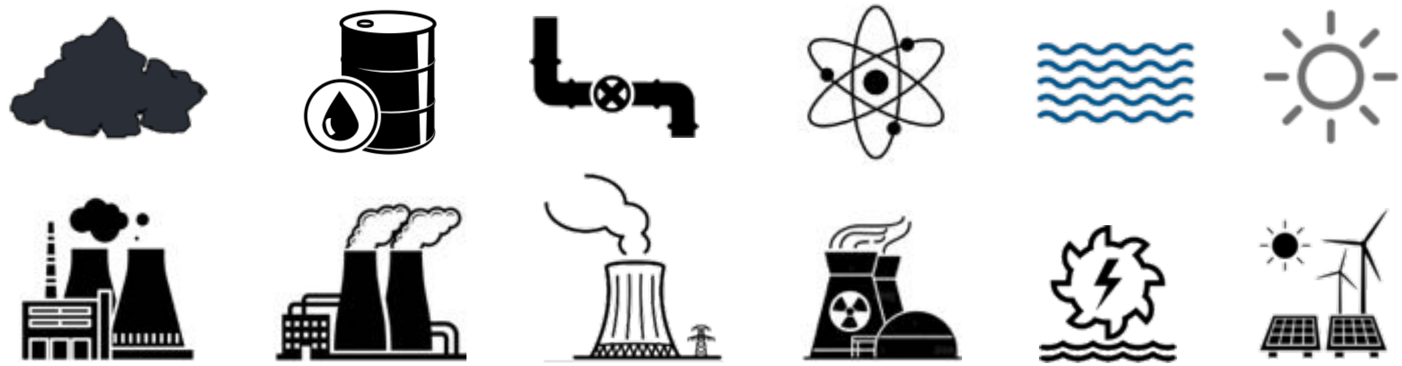


TMSR-LF1 (2 $MW_{therm.}$) construction 2018 - 2023, Wuwei city, Gansu province, China, operated since July 2023

Global energy development

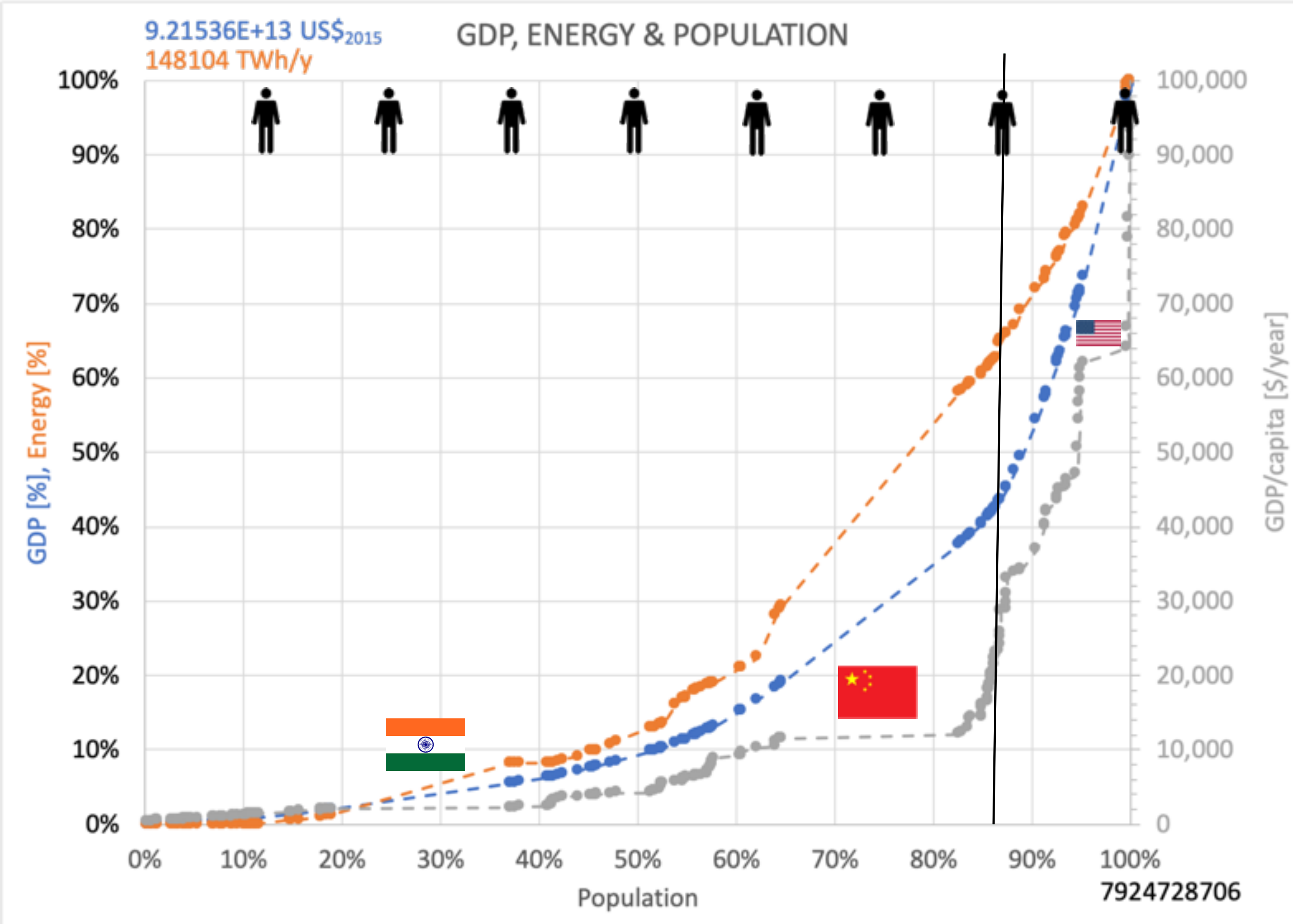


Global power plants (PP)



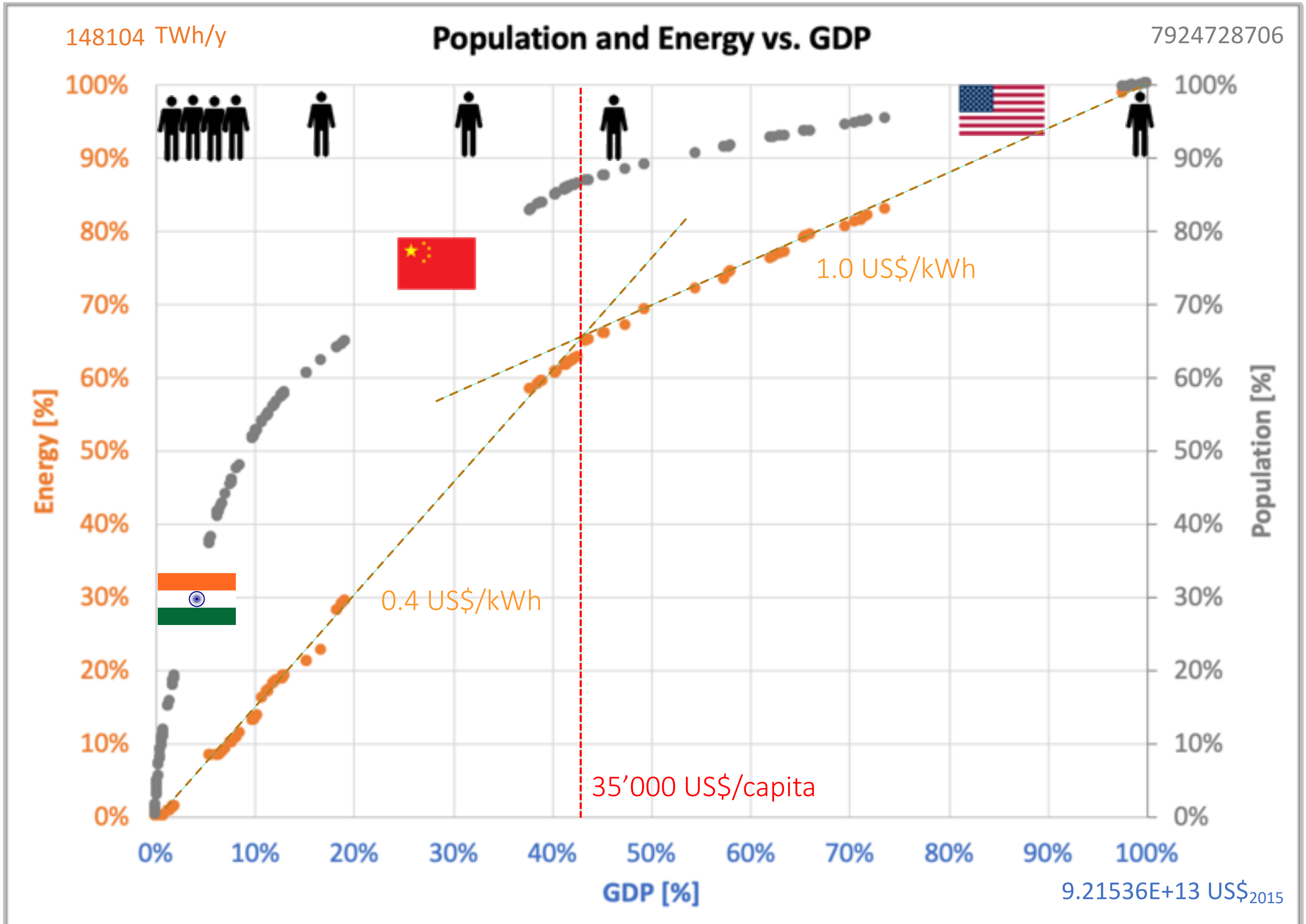
							TOTAL
Electricity generation							
P [TW]:	1.9	0.2	0.4	0.3	0.5	0.5	**3.7**
P [TW]:	5.2	0.5	0.8				6.5
PP:	2400	2281	1000	440	5000		
PPU [1 GW]:	1872	200	400	310	480	460	3722
m C [Gt·y^{-1}]	5.5	0.33	0.34	0	0	0	6.2
direct applications of fossil fuels							
P [TW]:	0	5.3 (1.5)	3.8 (1.5)				8.5
m C [Gt·y^{-1}]	0	3.0	1.6	0	0	0	4.7
substitution of fossil energy							
PPU [1 GW]:	*1872*	*1687*	*1912*	*310*	*0*	*0*	*+5781*

GDP, Energy vs. Population



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

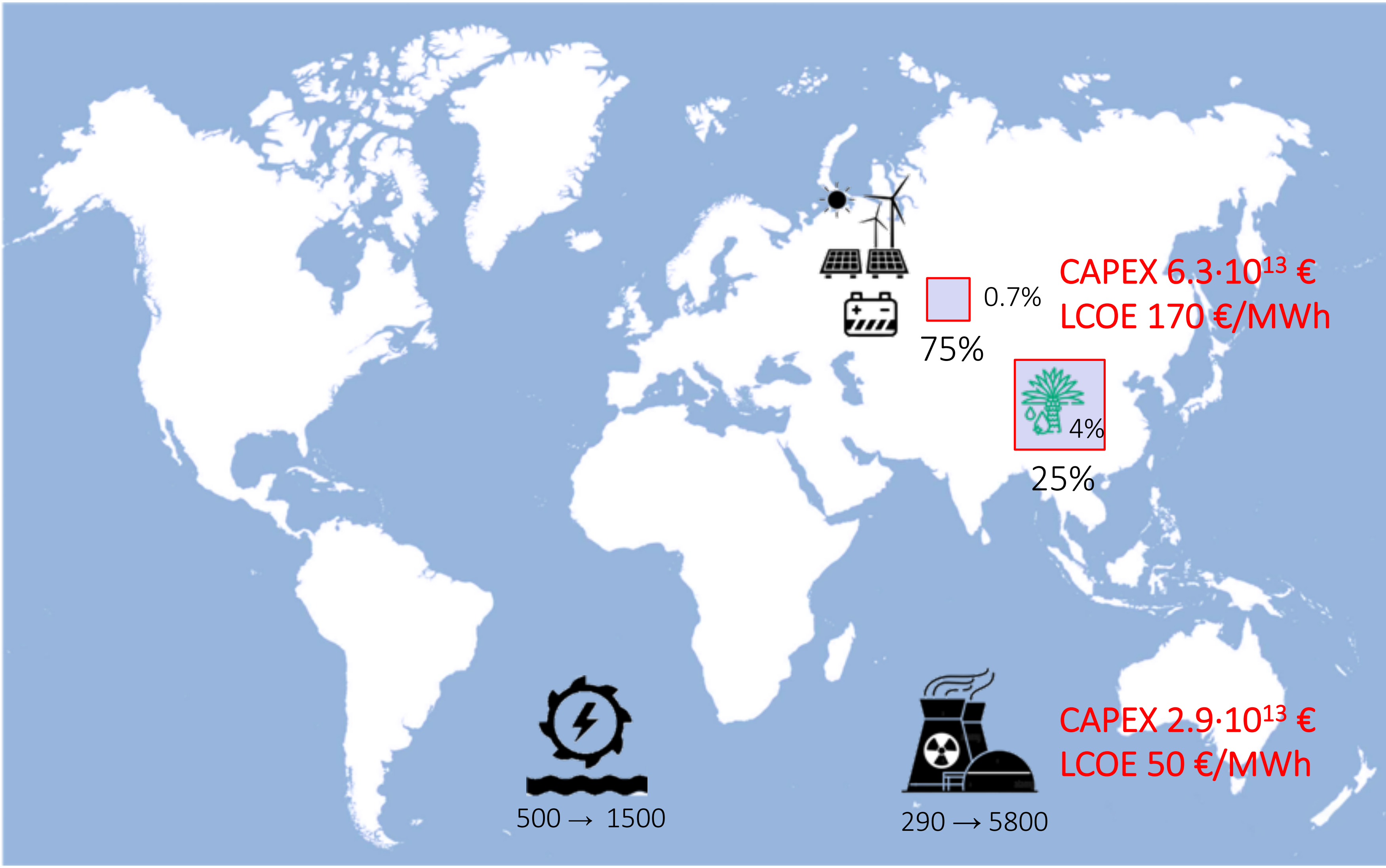
Global Energy, Population vs. GDP

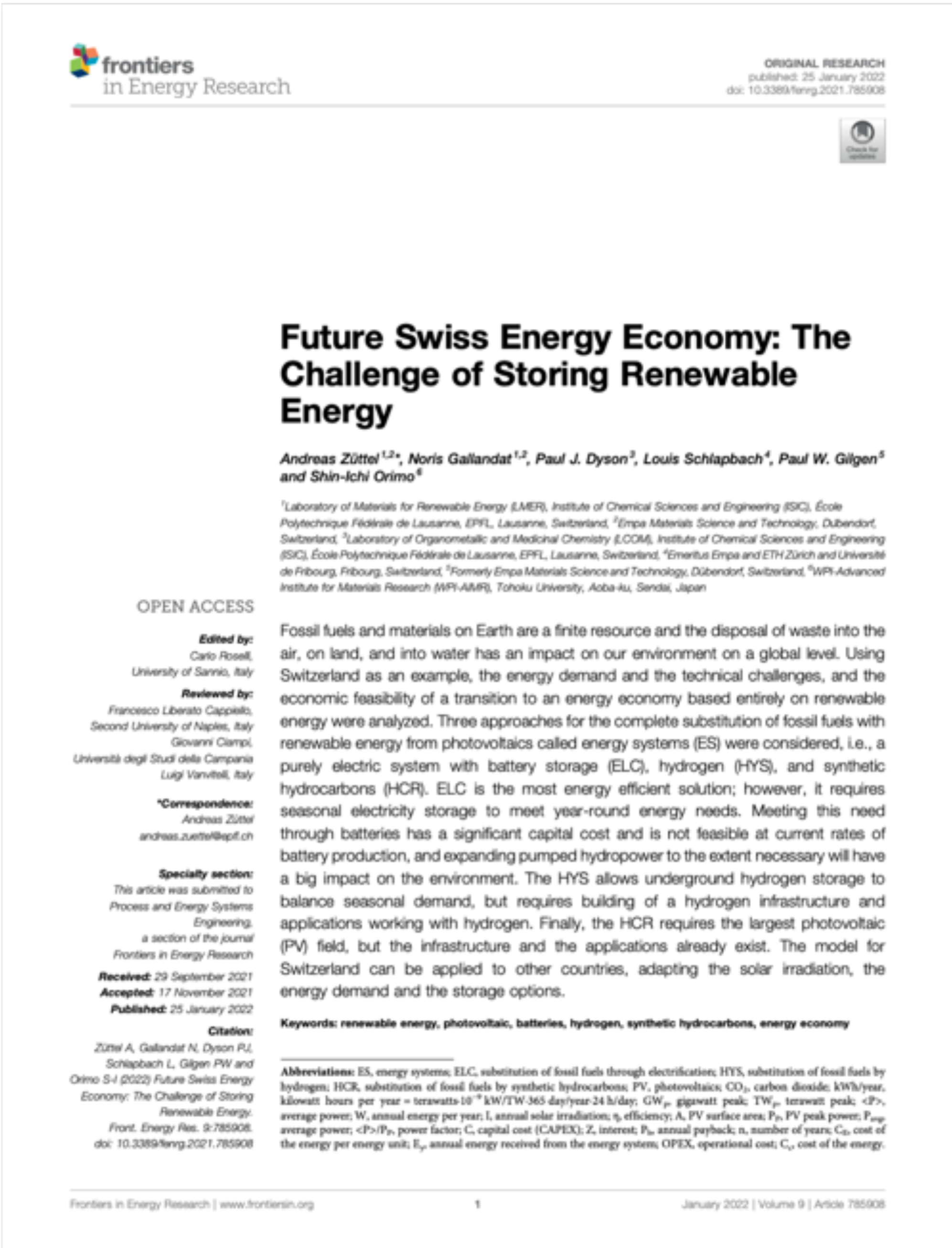


Ref.: https://ourworldindata.org/grapher/energy-use-per-person-vs-gdp-per-capita

CO_2 neutral future energy economy

Earth: 510’000’000 km^2
Land area: 149’000’000 km^2
GDP: $9.2 \cdot 10^{13}$ US$





frontiers in Energy Research

ORIGINAL RESEARCH
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Future Swiss Energy Economy: The Challenge of Storing Renewable Energy

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Fossil fuels and materials on Earth are a finite resource and the disposal of waste into the air, on land, and into water has an impact on our environment on a global level. Using Switzerland as an example, the energy demand and the technical challenges, and the economic feasibility of a transition to an energy economy based entirely on renewable energy were analyzed. Three approaches for the complete substitution of fossil fuels with renewable energy from photovoltaics called energy systems (ES) were considered, i.e., a purely electric system with battery storage (ELC), hydrogen (HYS), and synthetic hydrocarbons (HCR). ELC is the most energy efficient solution; however, it requires seasonal electricity storage to meet year-round energy needs. Meeting this need through batteries has a significant capital cost and is not feasible at current rates of battery production, and expanding pumped hydropower to the extent necessary will have a big impact on the environment. The HYS allows underground hydrogen storage to balance seasonal demand, but requires building of a hydrogen infrastructure and applications working with hydrogen. Finally, the HCR requires the largest photovoltaic (PV) field, but the infrastructure and the applications already exist. The model for Switzerland can be applied to other countries, adapting the solar irradiation, the energy demand and the storage options.

Keywords: renewable energy, photovoltaic, batteries, hydrogen, synthetic hydrocarbons, energy economy

Abbreviations: ES, energy systems; ELC, substitution of fossil fuels through electrification; HYS, substitution of fossil fuels by hydrogen; HCR, substitution of fossil fuels by synthetic hydrocarbons; PV, photovoltaics; CO_2, carbon dioxide; kWh/year, kilowatt hours per year = terawatts·10^{-9} kW/TW·365 day/year·24 h/day; GW_p, gigawatt peak; TW_p, terawatt peak; <P>, average power; W, annual energy per year; I, annual solar irradiation; η, efficiency; A, PV surface area; P_P, PV peak power; P_{avg}, average power; <P>/P_P, power factor; C, capital cost (CAPEX); Z, interest; P_b, annual payback; n, number of years; C_E, cost of the energy per energy unit; E_y, annual energy received from the energy system; OPEX, operational cost; C_v, cost of the energy.

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Power plant units for CO_2 neutral energy security in Switzerland

Andreas Züttel[1,2]*, Christoph Nützenadel[3], Louis Schlapbach[4] and Paul W. Gilgen[5]

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A new concept based on Power Plant Units, able to deliver renewable energy on demand, for the transition from fossil fuels to renewable energy in Switzerland is presented. The technically realized efficiencies showed that complete electrification leads to the most efficient energy system and cheapest electricity. The electricity demand is expected to almost double, and the overall energy cost will increase by 20% compared to 2019. However, the technical challenges of seasonal electricity storage, without any reserves and redundancy, amounts to 20 TWh. Hydropower and PV without storage produce the cheapest electricity. Future nuclear fission technologies, e.g., molten salt Thorium breading reactor - currently still in an experimental stage–might become the most economical and least environmental impact solution for CO_2 neutral continuous electricity production. The opportunities for a massive increase of hydroelectric production are limited, already shifting the use of water (9 TWh) from summer to winter is a great challenge. PV and hydrogen production in Switzerland have the advantage to provide approximately 75% of the electricity without seasonal storage leading to significantly lower electricity cost than from imported hydrogen or synthetic hydrocarbons. The most economical solution for aviation and reserves is imported bio-oil converted to synthetic Kerosene, for which large storages already exist.

KEYWORDS
renewable energy, energy storage, cost of energy, power plant units, CO_2 free, nuclear

Highlights

- Renewable energy on demand is essential for replacing fossil fuels and can be realized by combining intermittent energy supplies like photovoltaic and wind with battery and seasonal storage in a power plant unit.
- Importing renewable energy carriers requires a storage capacity similar to the seasonal storage for domestic production of renewable energy.
- Renewable energy production in Switzerland with seasonal storage and importing renewable energy carriers is a technical and economic challenge, respectively.
- The fuel for aviation and the energy reserves for the power plant units can be realized with synthetic oil produced by hydriding bio-oil, avoiding the need for new large and expensive storage systems and CO_2 capture from the atmosphere.
- Thermal power plants fueled with renewable energy carriers provide equal amounts of electricity and heat. Both forms of energy are of high value in the wintertime.

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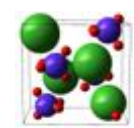

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