“CO_2 Neutral Energy Security for Switzerland ”

accepted by “Frontiers in Energy Research: Process and Energy Systems Engineering“ (2024)

CO_2 Neutral Energy Security for Switzerland

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[c)] *Christoph Nützenadel AG, Turbinenstrasse 60, CH-8005 Zürich, Switzerland*
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[e)] *Formerly Empa Materials Science and Technology, 8600 Dübendorf, Switzerland.*

ABSTRACT

An analysis of the technical opportunities and economic consequences of 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.

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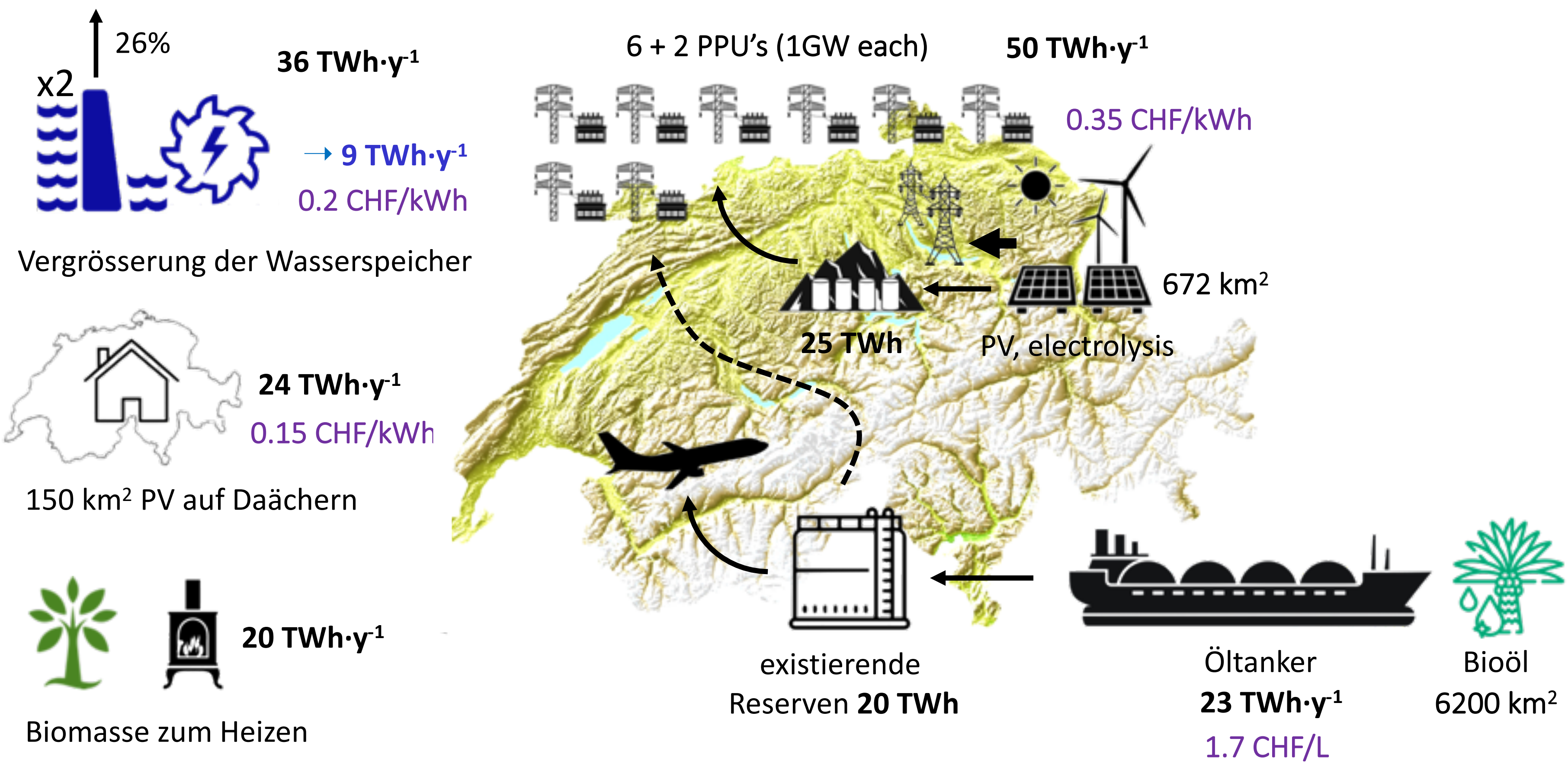
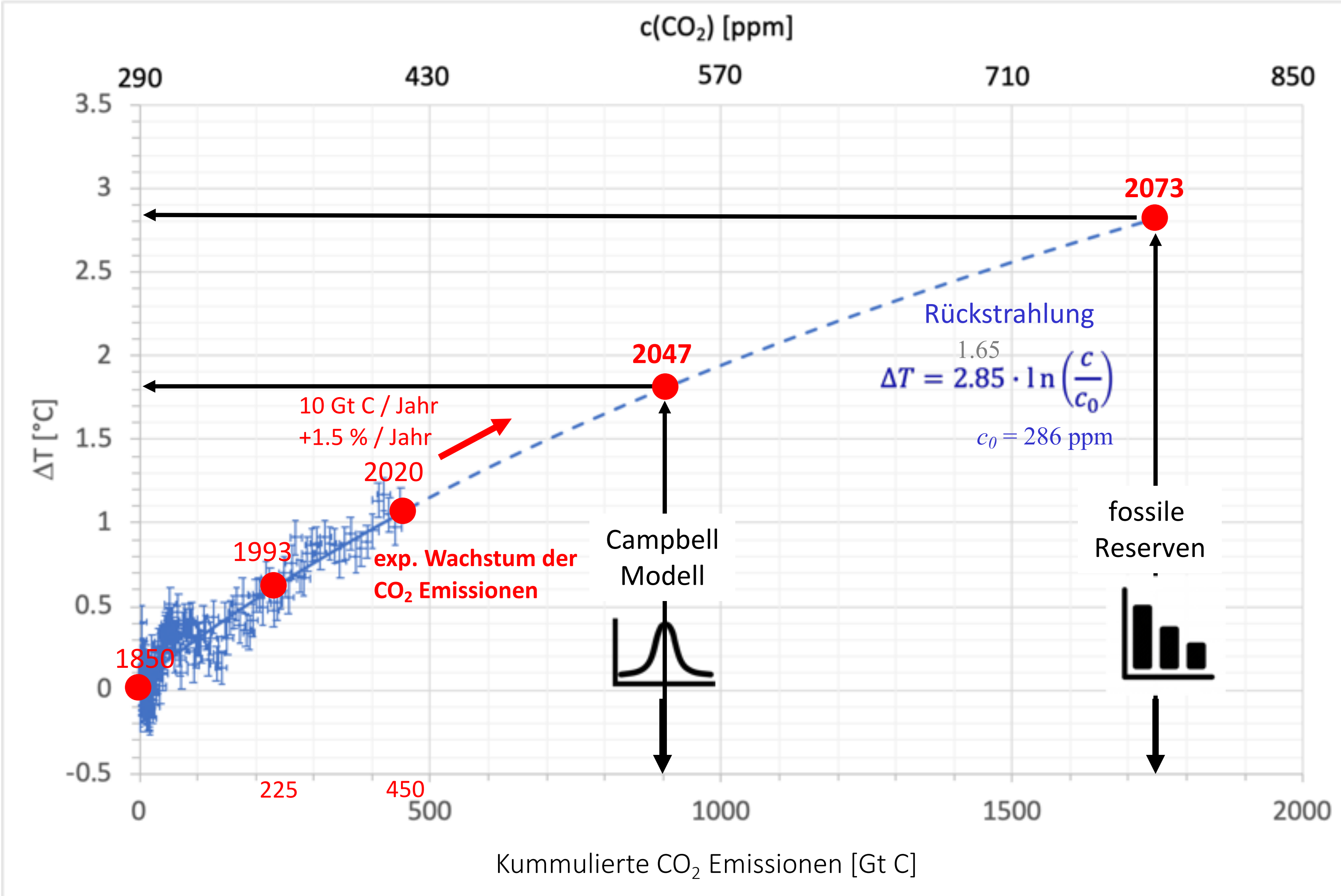
Erneuerbare Energie Lösung (Beispiel)



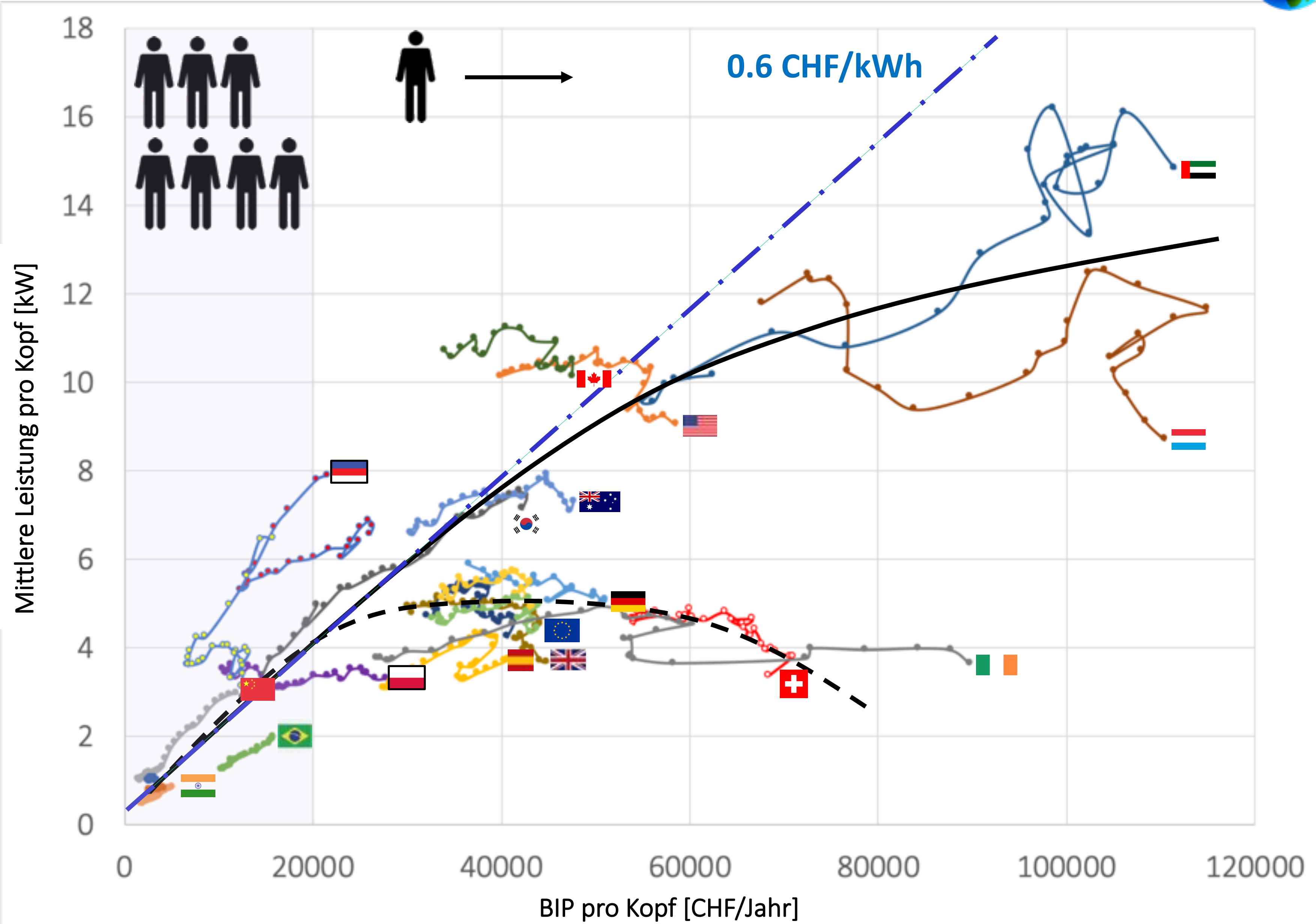
Senken des Energieverbrauchs durch Wärmenutzung, Wärmespeicher, Isolation

Globale Erwärmung vs. kumulierte CO_2 Emissionen



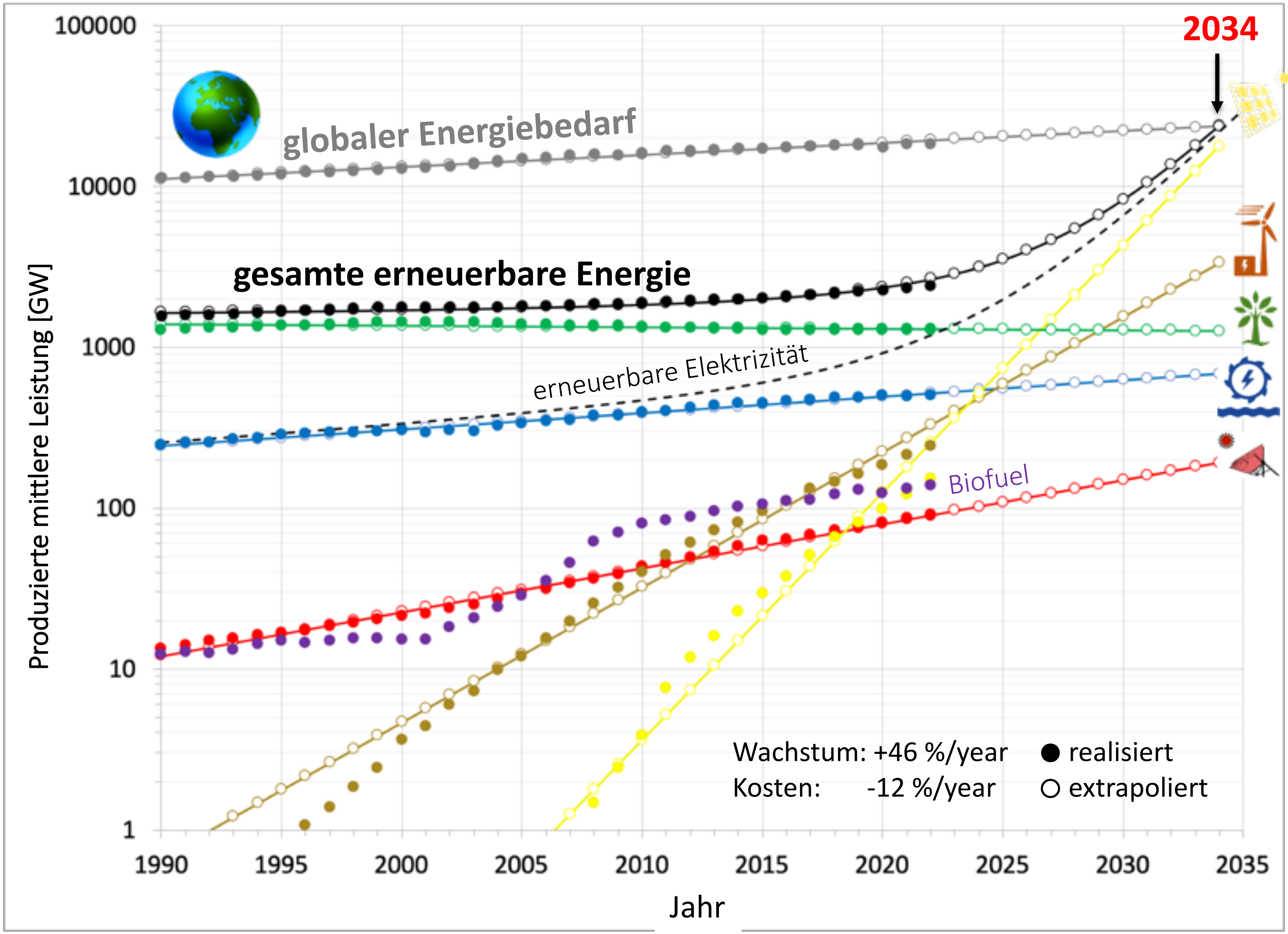
Ref.: http://www.globalwarmingequation.info/global%20warming%20eqn.pdf and Ollila, A. (2014), “The potency of carbon dioxide (CO2) as a greenhouse gas”, Development in Earth Science, Vol. 2, pp. 20-30, available at: www.seipub.org/des/paperInfo.aspx?ID=17162

Energie und Wirtschaft



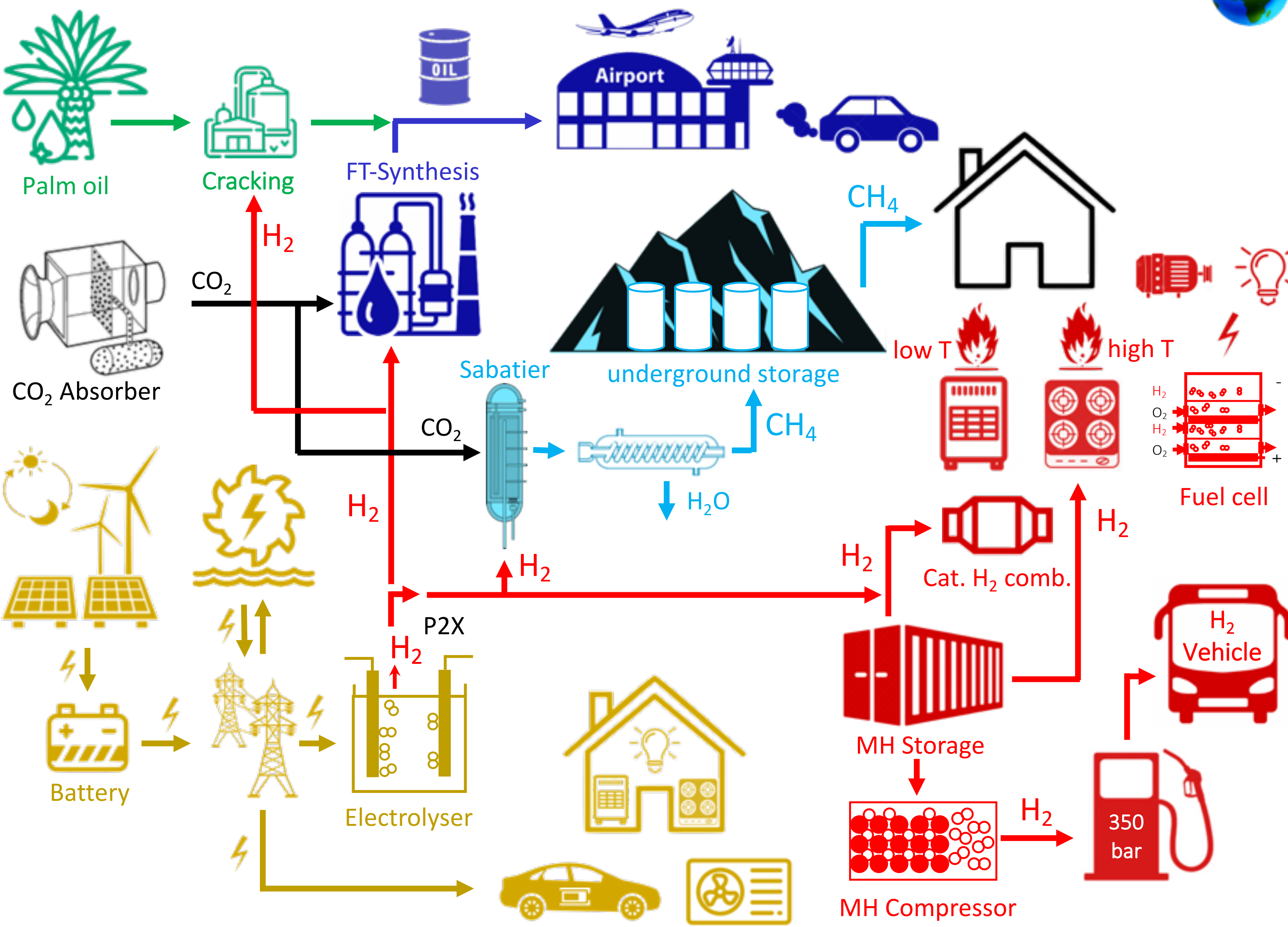
Ref.: https://ourworldindata.org/grapher/energy-use-per-capita-vs-gdp-per-capita

Globale erneuerbare Energieproduktion



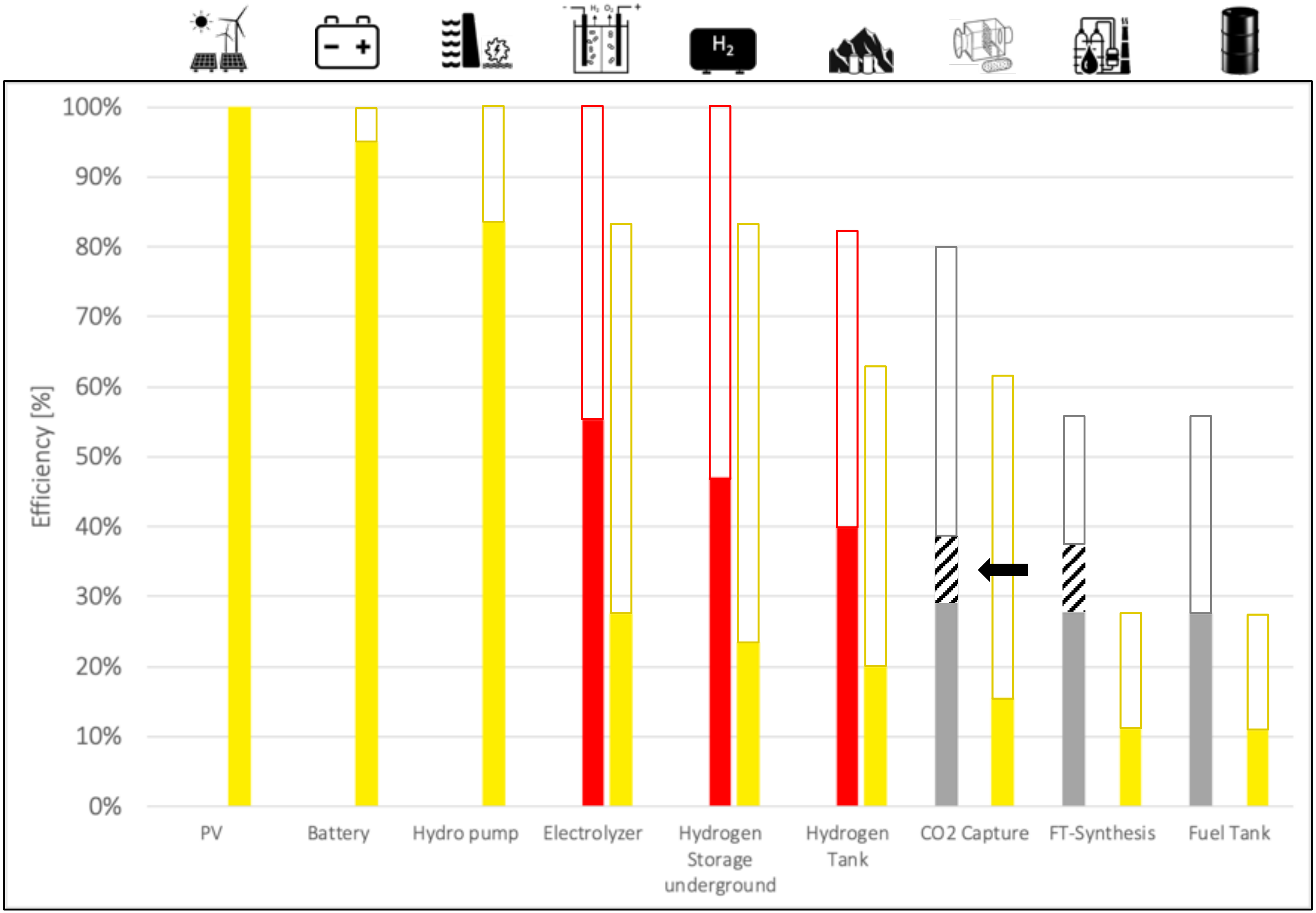
Ref.: https://ourworldindata.org/energy. https://www.pv-magazine.com/2023/02/16/global-solar-installations-may-hit-350-6-gw-in-2023-says-trendforce/#:~:text=2022, and https://ourworldindata.org/energy

Erneuerbare Energiesysteme

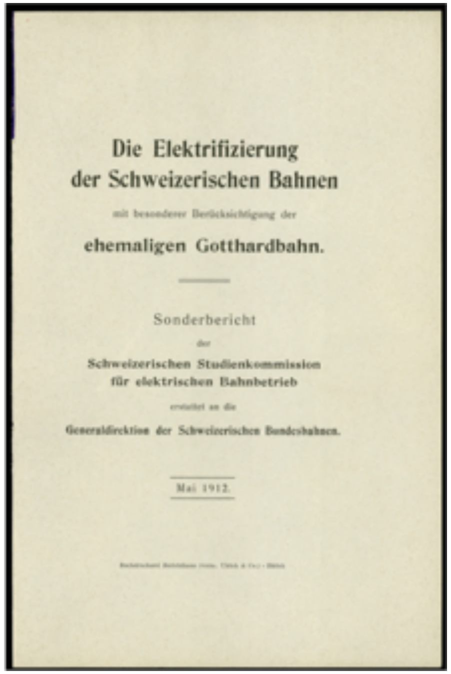


Effizienz entlang der Energiewandlung

Power to X (P2X)



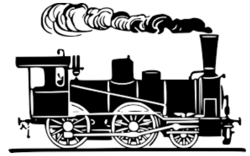
Energiewende in der Schweiz 1912


Die Elektrifizierung
der Schweizerischen Bahnen
mit besonderer Berücksichtigung der
ehemaligen Gotthardbahn.

Sonderbericht
der
Schweizerischen Studienkommission
für elektrischen Bahnbetrieb
erstattet an die
Generaldirektion der Schweizerischen Bundesbahnen.

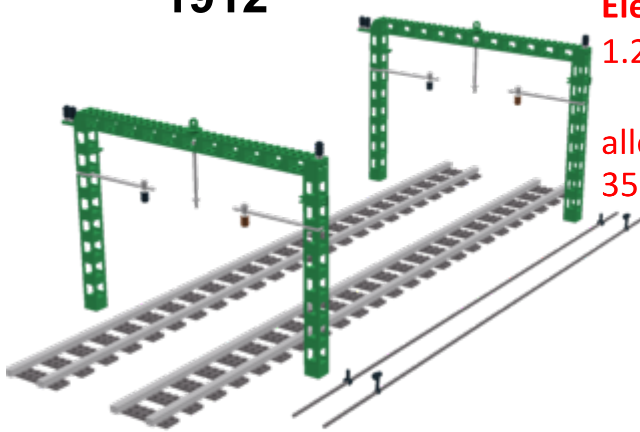
Mai 1912.

1912



1912

Ref.: "Die Elektrifizierung der Schweizerischen Bahnen mit besonderer Berücksichtigung der ehemaligen Gotthardbahn.", Sonderbericht der Schweizerischen Studienkommission für elektrischen Bahnbetrieb erstattet an die Generaldirektion der Schweizerischen Bundesbahnen. Mai 1912.



Elekrifizierung
1.23 – 2.6 Mio.€/km

alle 27m ein Mast,
35 – 70 k€ pro Mast

Schienennetz 62 Mio. €/km
(Autobahn 150 - 330 Mio.€/km)

Ref.: Deutschland: Lindau -München 500 Mio.€ für 189 km incl. Lärmschutz und neuem Bahnhof...
Dänemark: Gesamtes Schienennetz 1'600 Mio.€ für 1300 km

Energie Strategie

Fukushima Dai-ichi Kernkraftwerk Desaster


11. March 2011

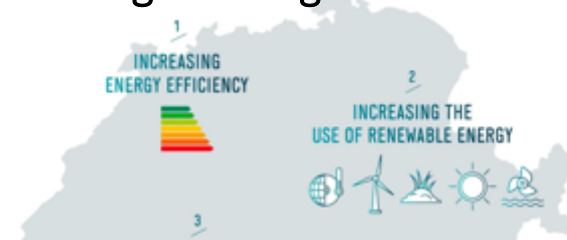

24. March 2011

11. March 2011 Erdbeben

25. Mai 2011 Der Bundesrat hat entschieden, künftig nicht mehr auf Atomkraft zu setzen. Die bestehenden Kernkraftwerke sollen so lange am Netz bleiben, wie sie sicher sind. Bestätigt durch das nationale Parlament am 8. Juni 2011.

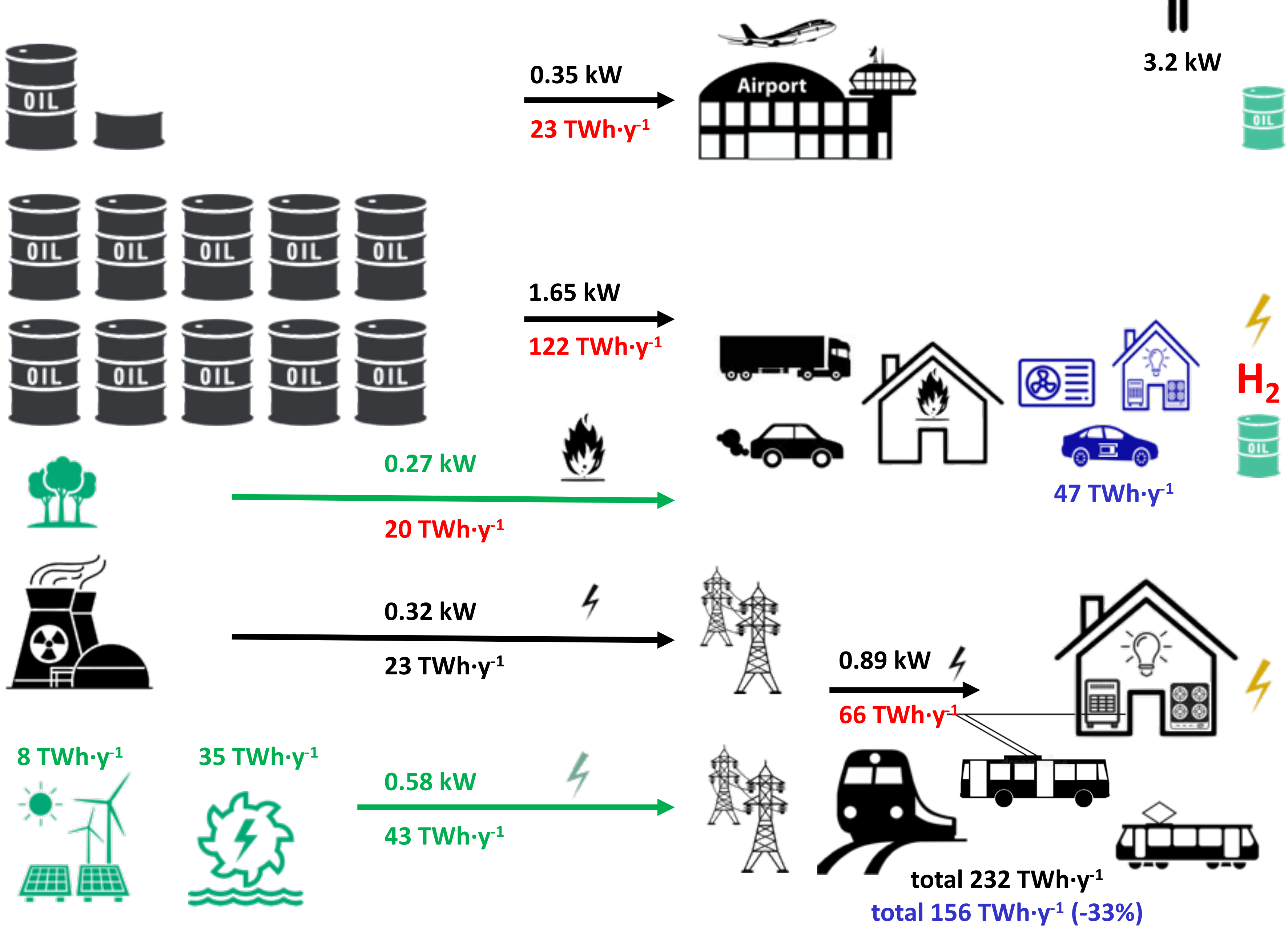
Paris Klimaabkommen 2014

Energiestrategie Schweiz 2050



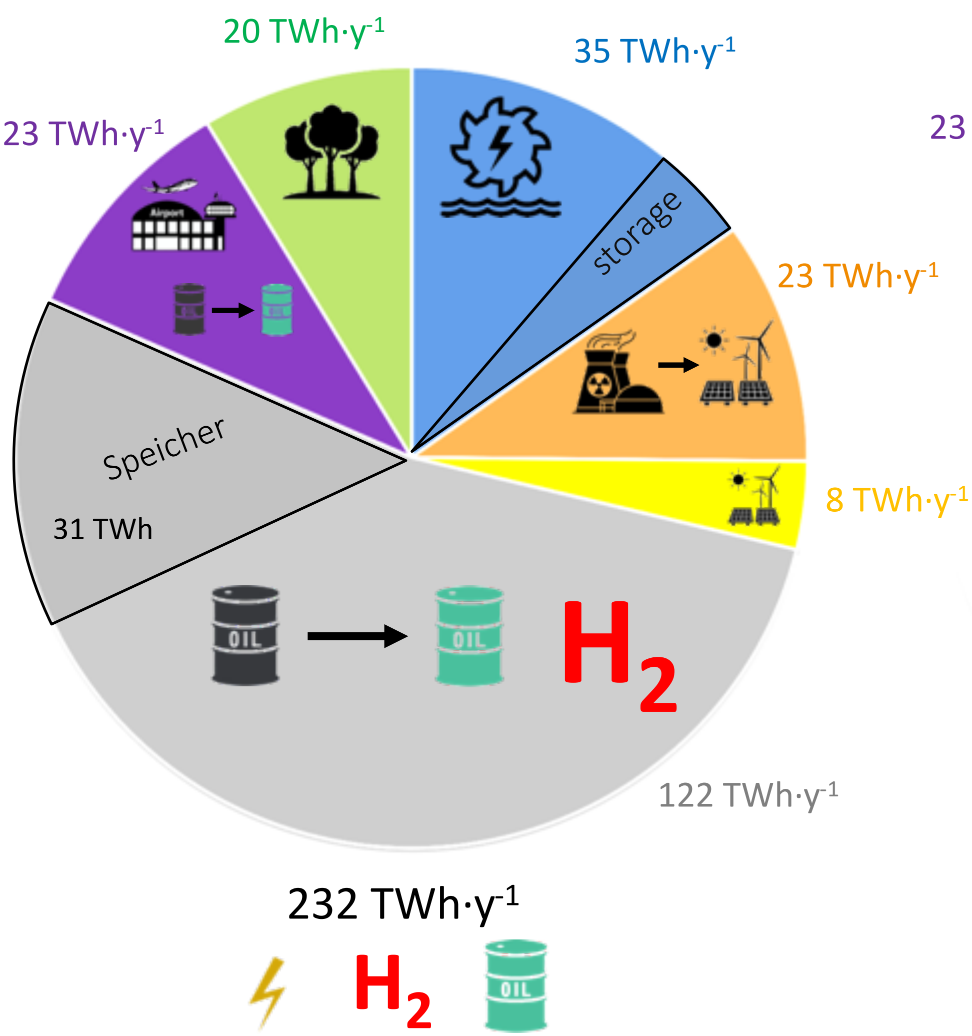
Am 21. Mai 2017 hat das Schweizer Stimmvolk das revidierte Bundesenergiegesetz angenommen. Die Ziele der Überarbeitung sind die Senkung des Energieverbrauchs, die Steigerung der Energieeffizienz und die Förderung der Nutzung erneuerbarer Energien. Zudem verbietet die überarbeitete Fassung den Bau neuer Kernkraftwerke.

Die Schweizer Energiewirtschaft 2019

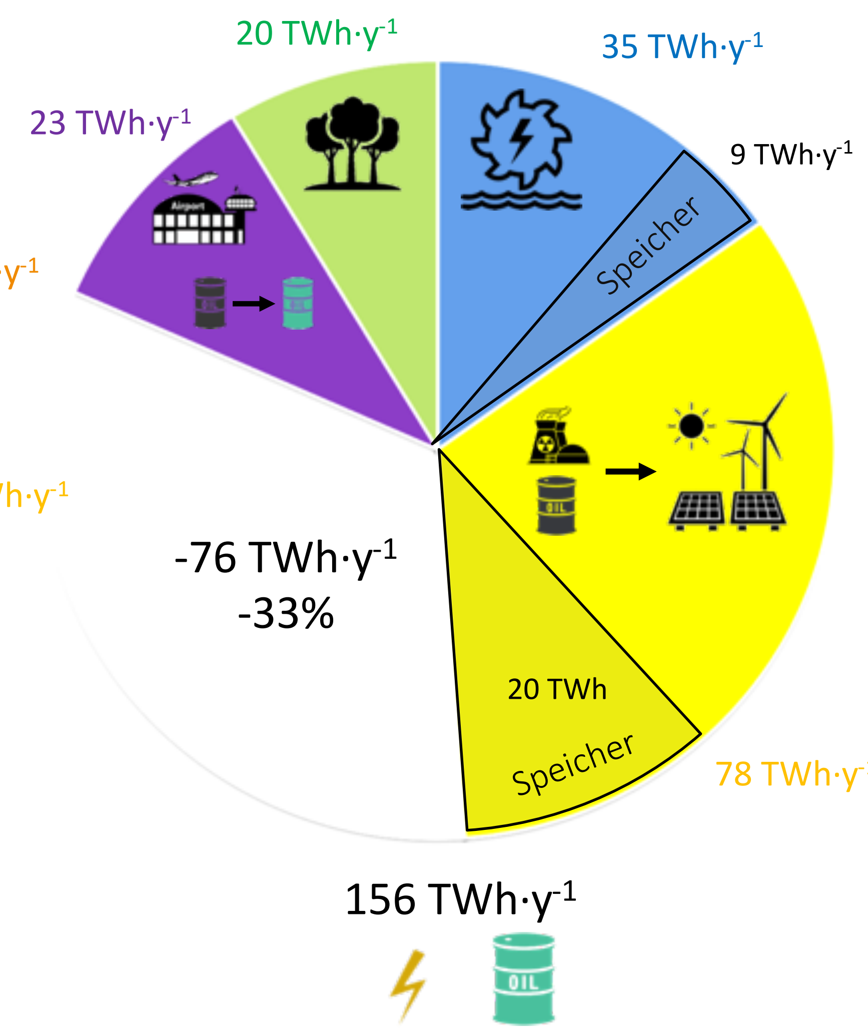


Die Schweizer Energiebedarf 2019

Energiebedarf (2019)

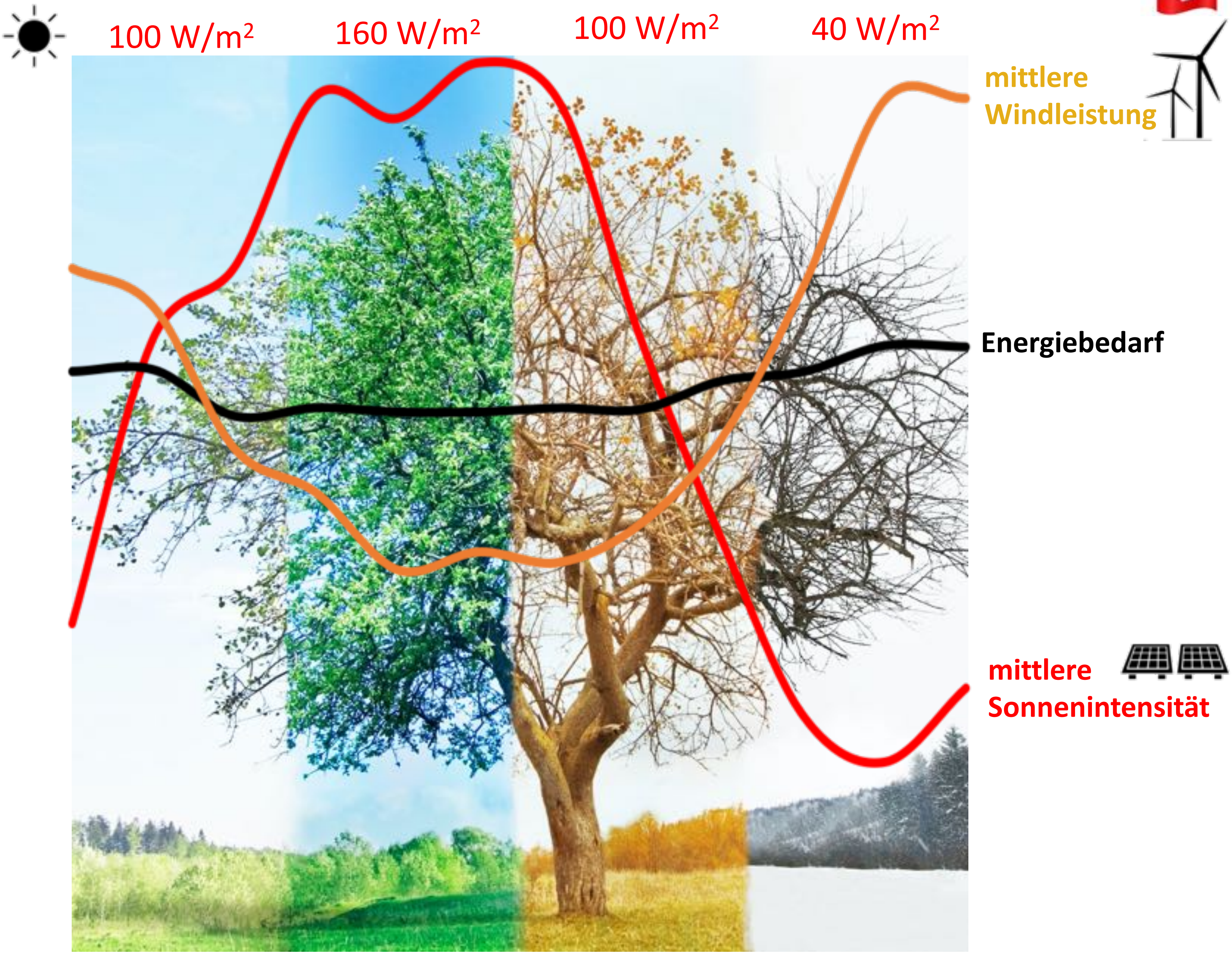


Elektrifizierung

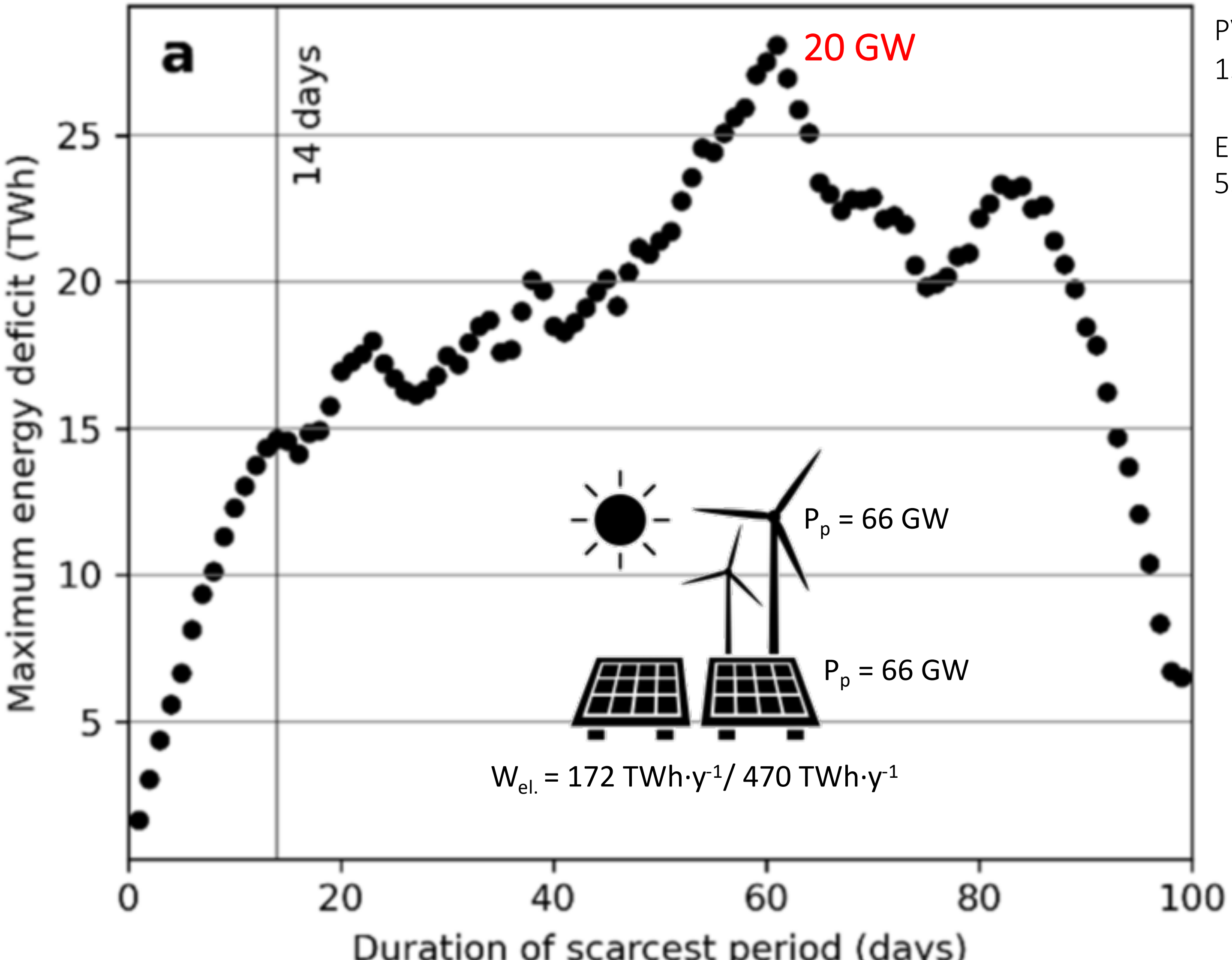


Ref.: SCHWEIZERISCHE GESAMTENERGIE STATISTIK (2019) Art.-Nr. 805.006.19 / 08.20 / 1200 / 860467013, Federal Office of Energy, Switzerland, https://www.bfe.admin.ch/bfe/de/home/versorgung/statistik-und-geodaten/energiestatistiken/gesamtenergiestatistik.exturl.html/

Jahreszeiten



Erneuerbare Energie und Speicherung



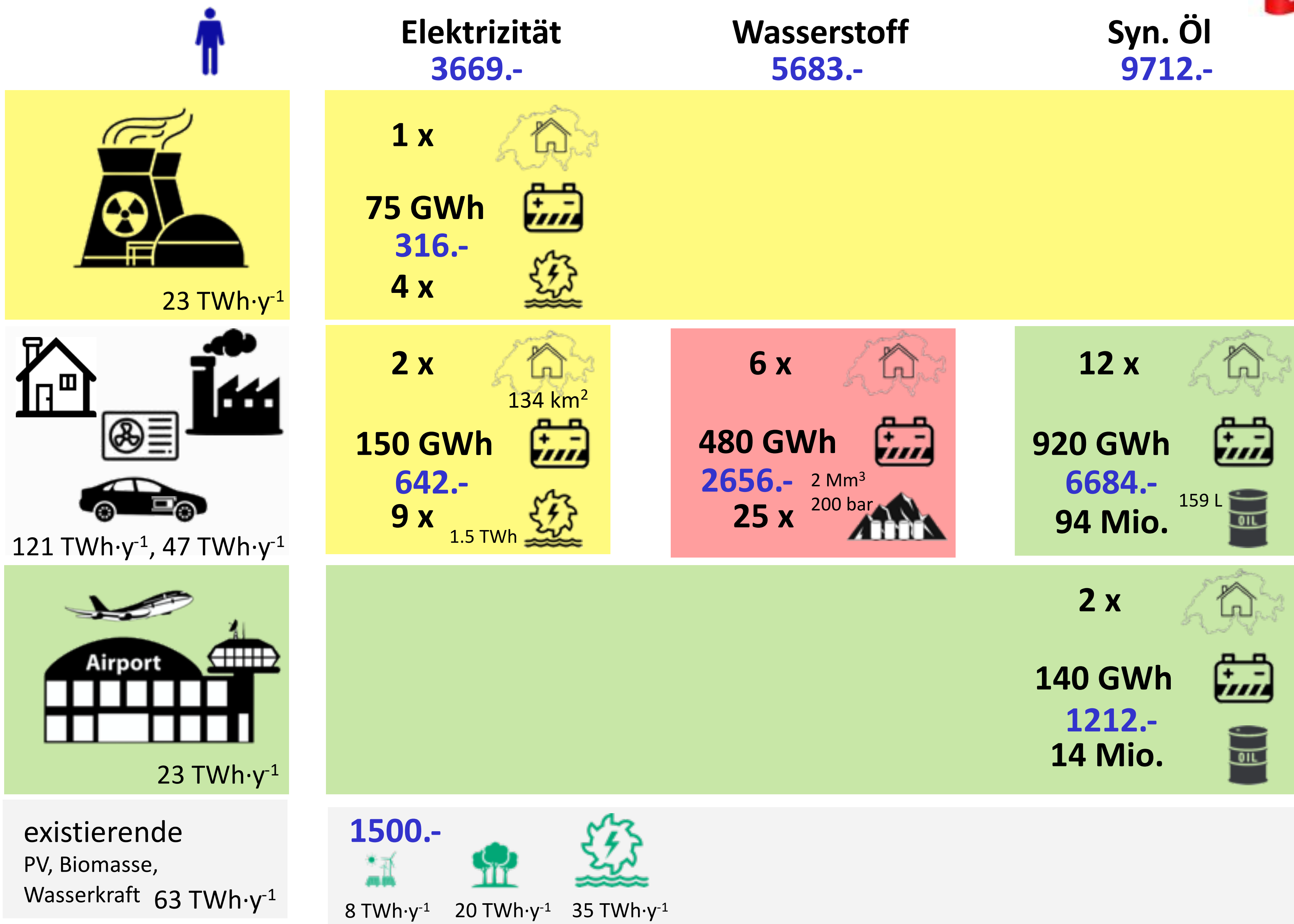
PV & Wind:
150 GW_p installiert

Elektrizität:
53 GW mittlere Leistung

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

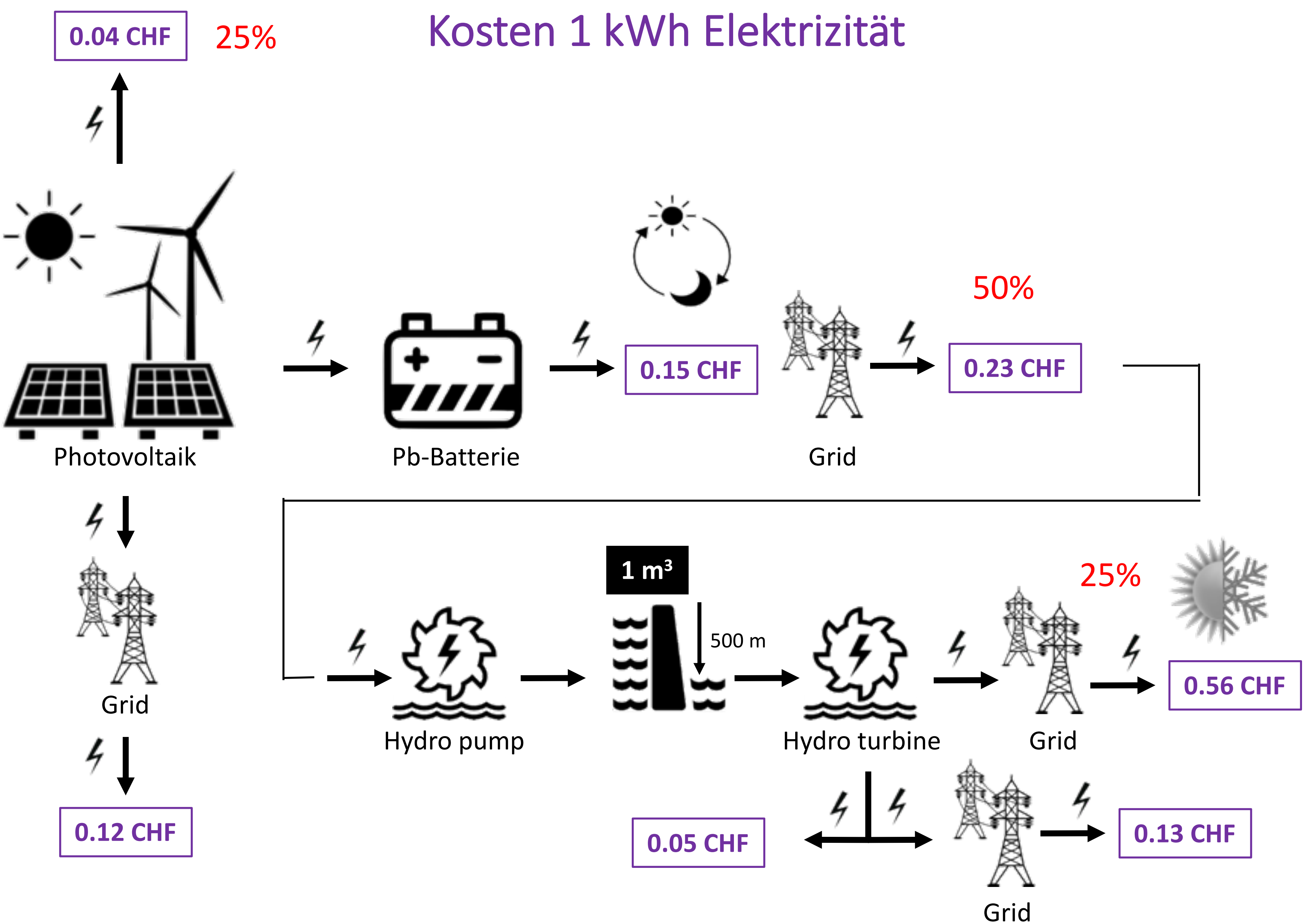
Erneuerbare Energiewirtschaft

CO_2 Neutral Energy Security for Switzerland

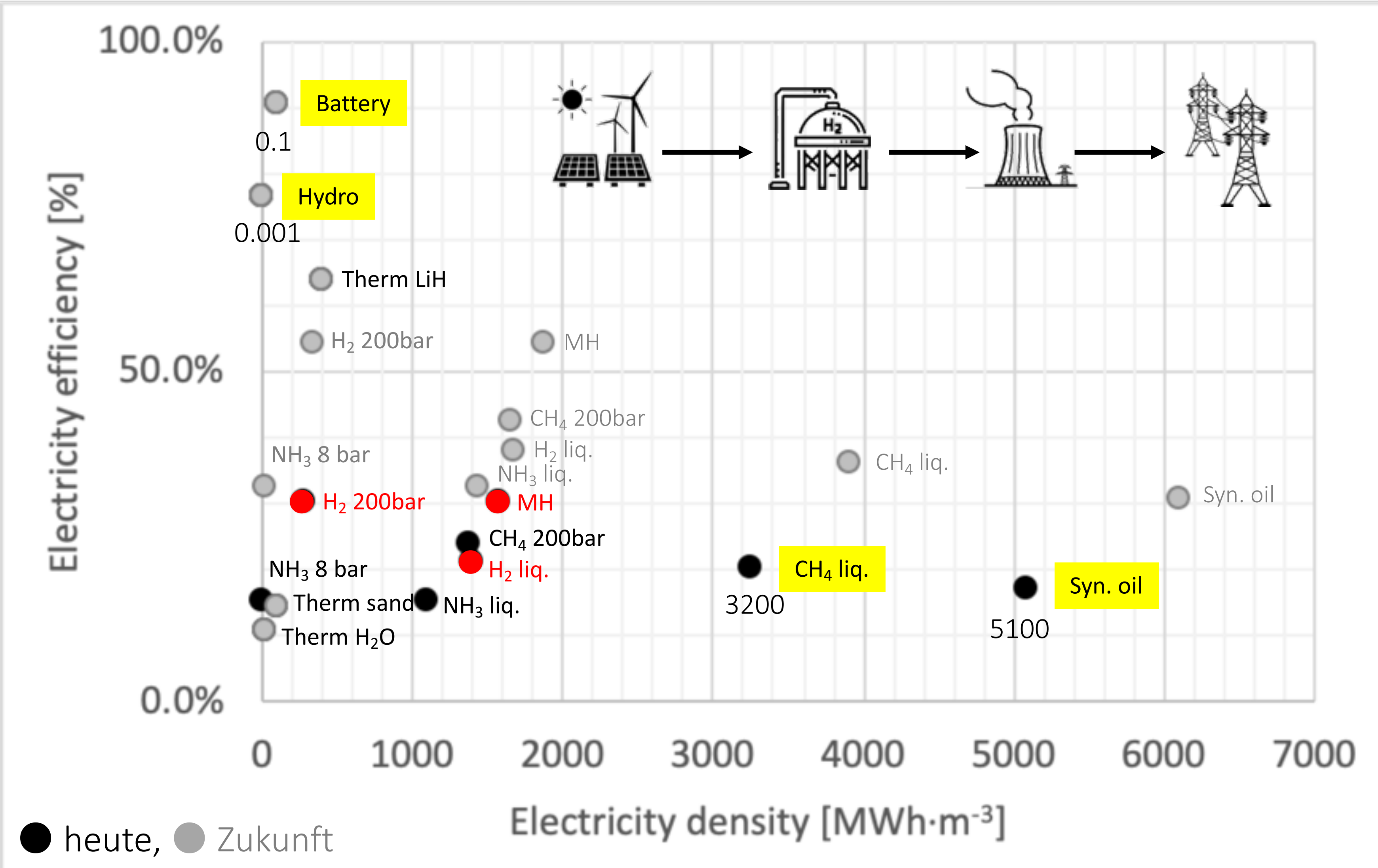


Ref.: A. ZÜTTEL, N. GALLANDAT, P. J. DYSON, L. SCHLAPBACH, P. W. GILGEN, S. ORIMO, “Future Swiss Energy Economy: the challenge of storing renewable energy”, Frontiers in Energy Research: Process and Energy Systems Engineering, 9 (2022)

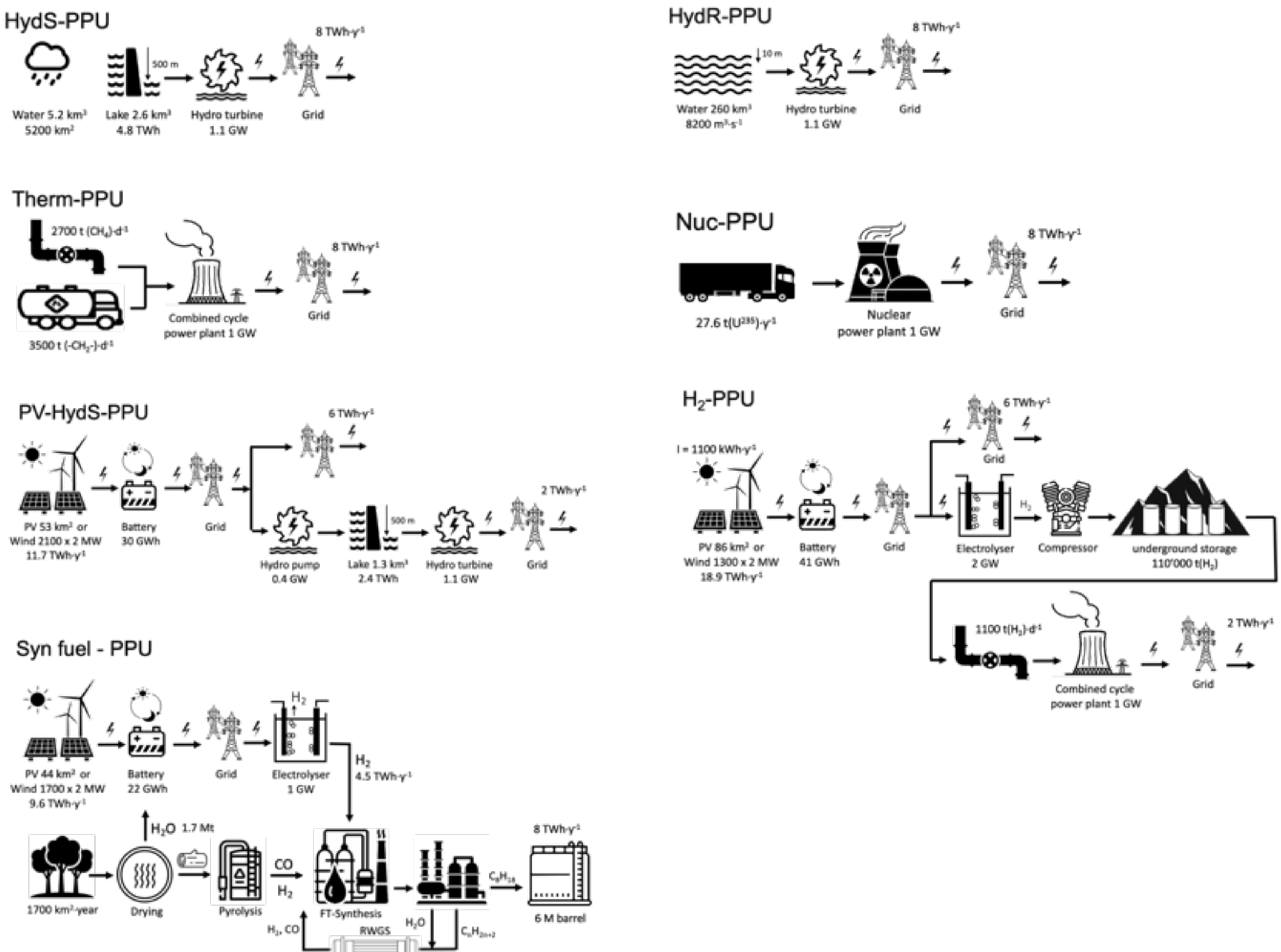
Erneuerbare Energie nach Produktion und nach Bedarf



Effizienz und Speicherdichte erneuerbarer Elektrizität

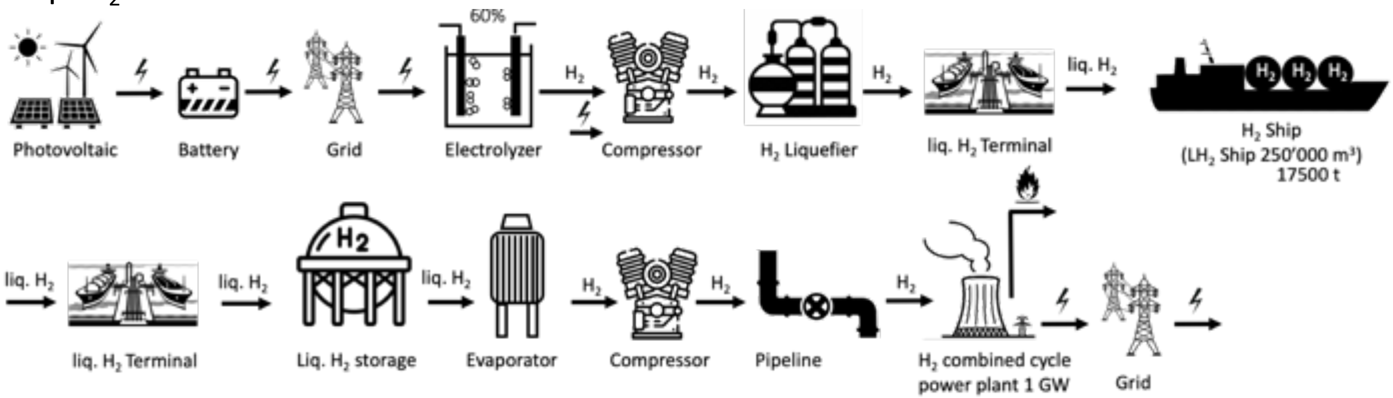


Kraftwerkseinheiten

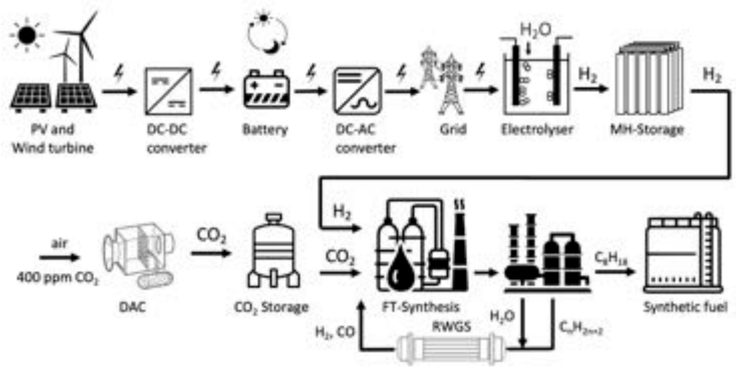


Kraftwerkseinheiten

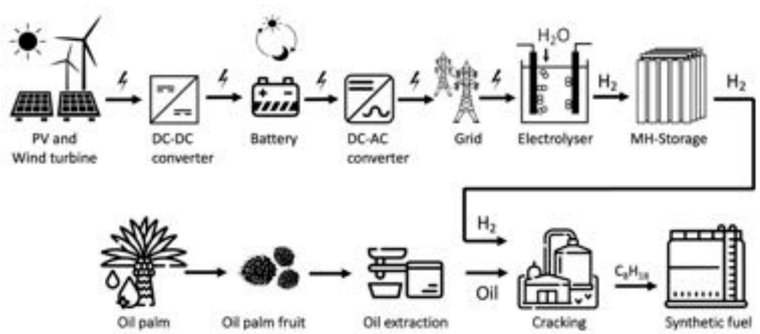
Imp. H_2



Imp. SF

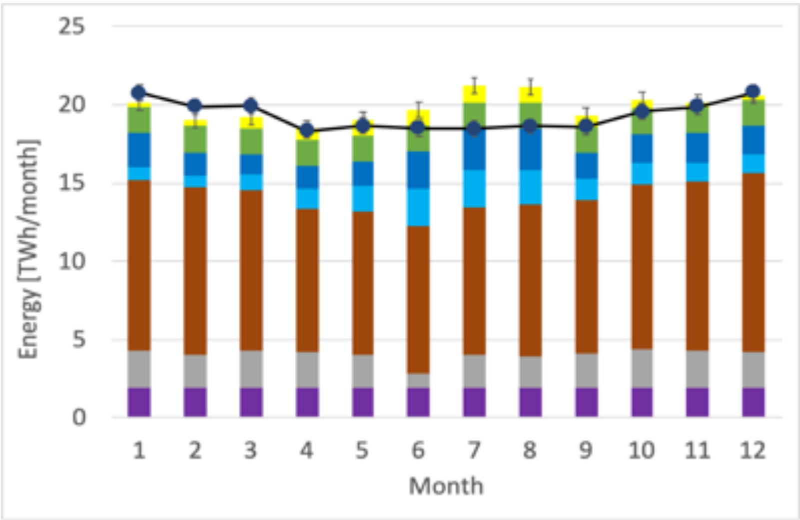


Imp. BSF

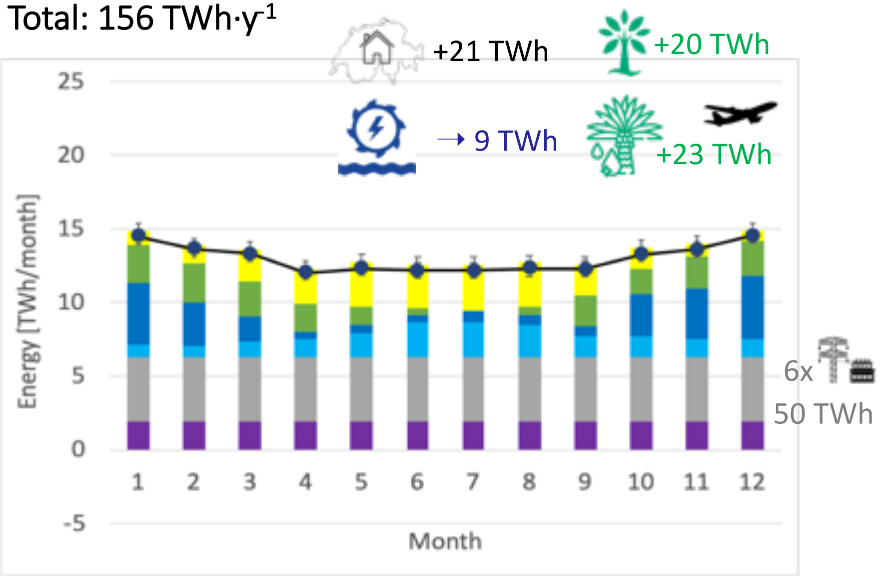


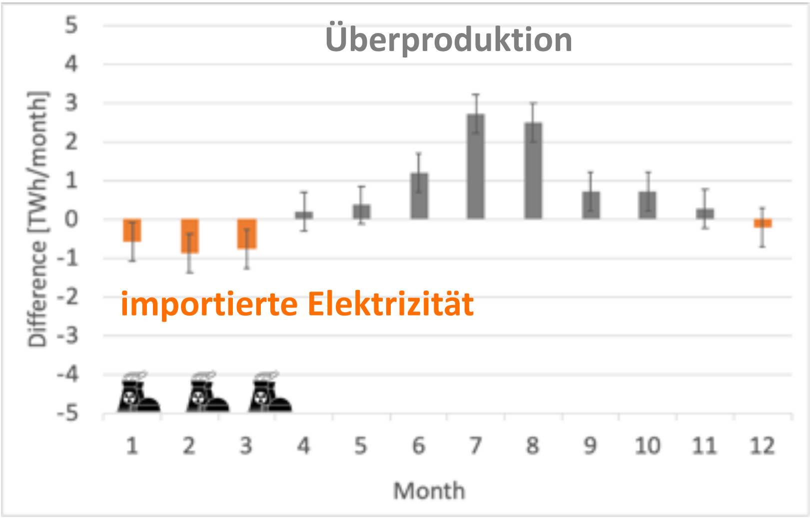
Substitution fossiler mit erneuerbare Energie

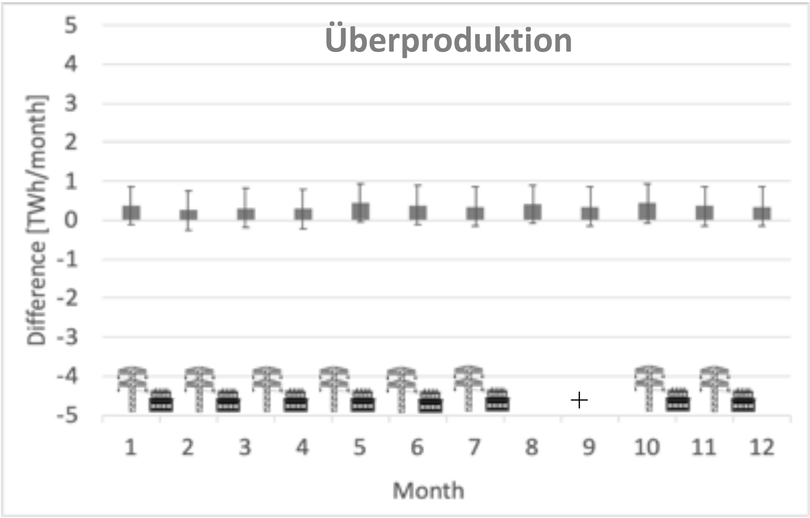
Total: 232 TWh·y-1 Fossil: 122 TWh·y-1



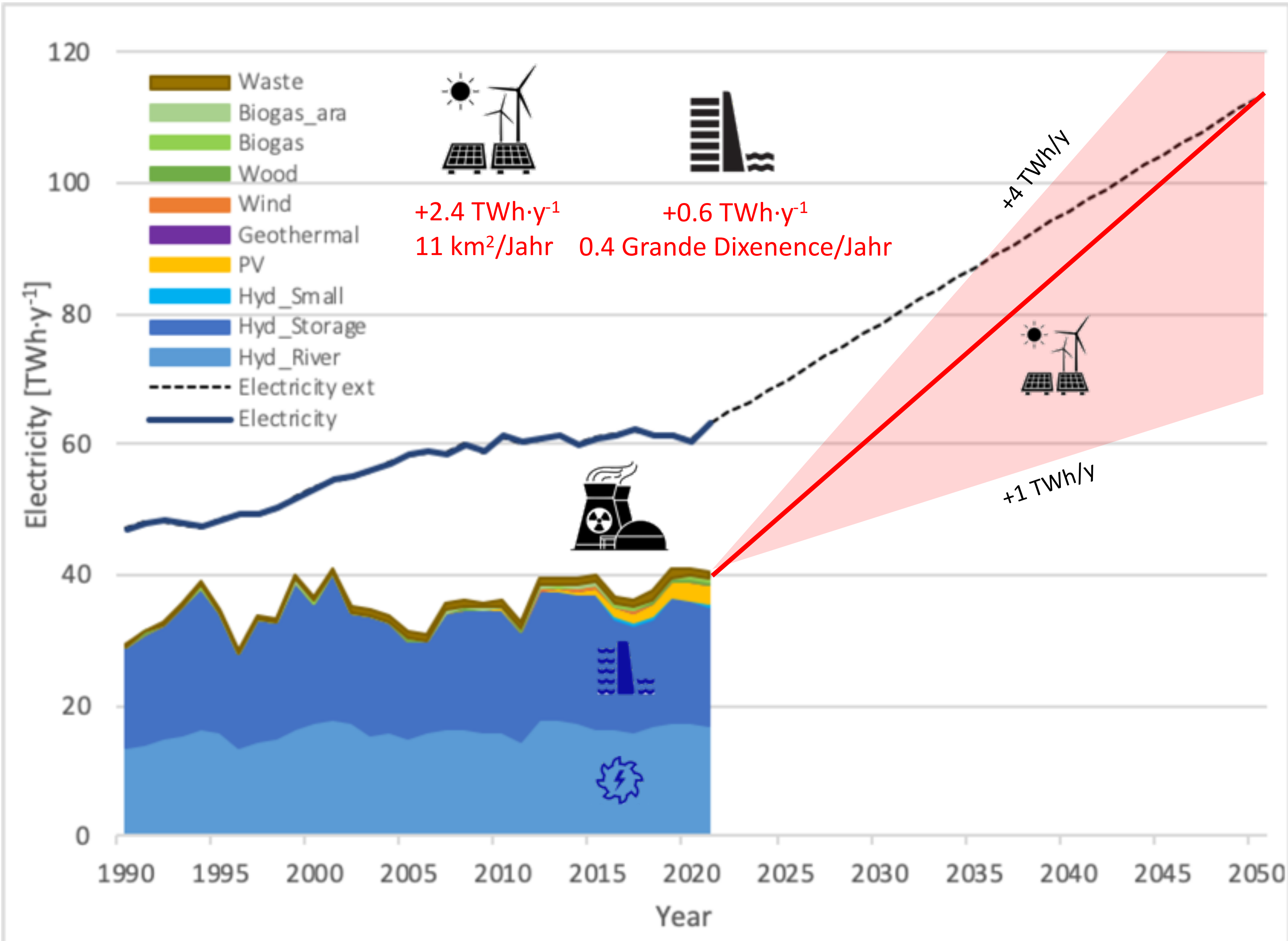
Total: 156 TWh·y-1



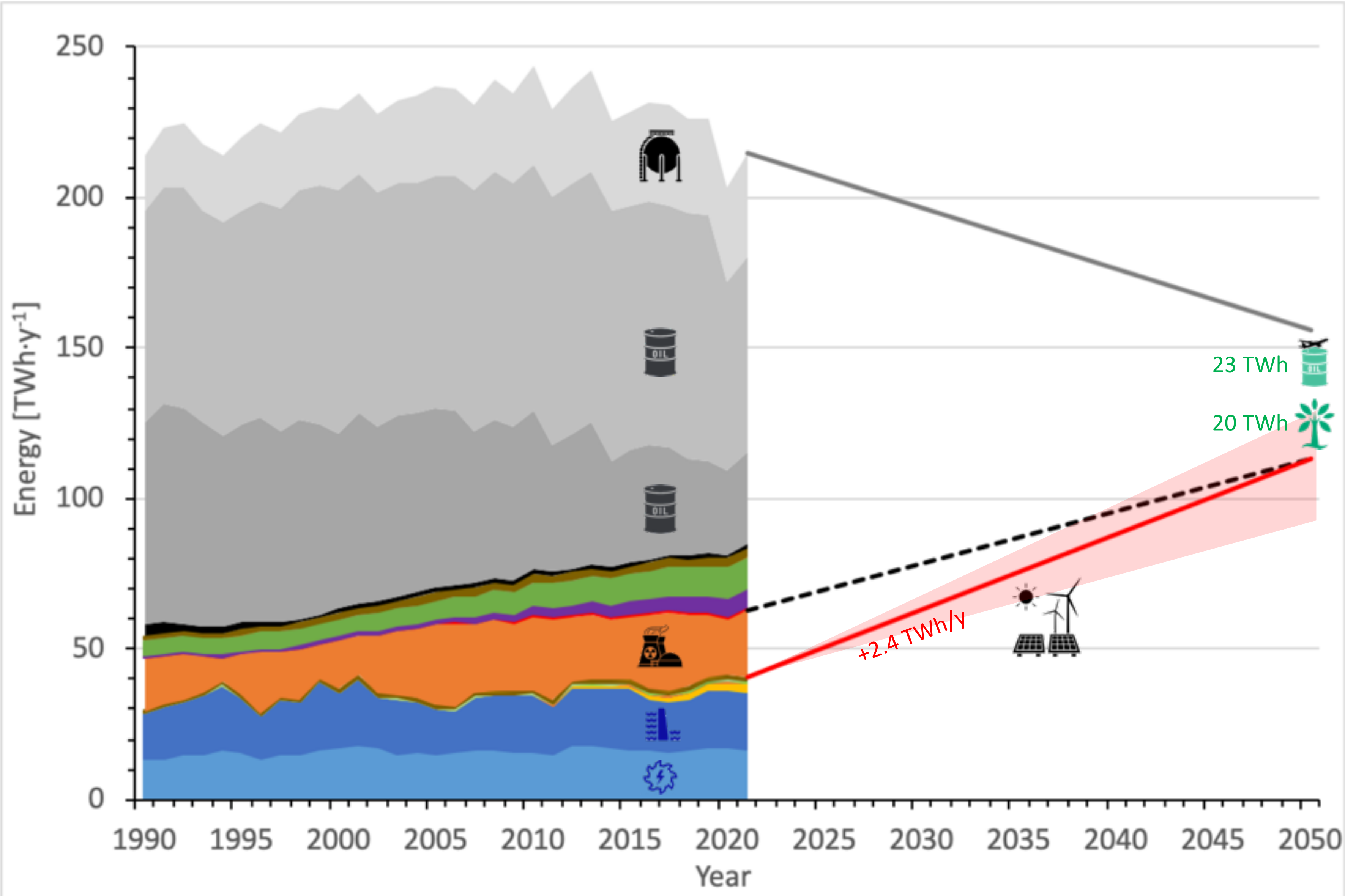




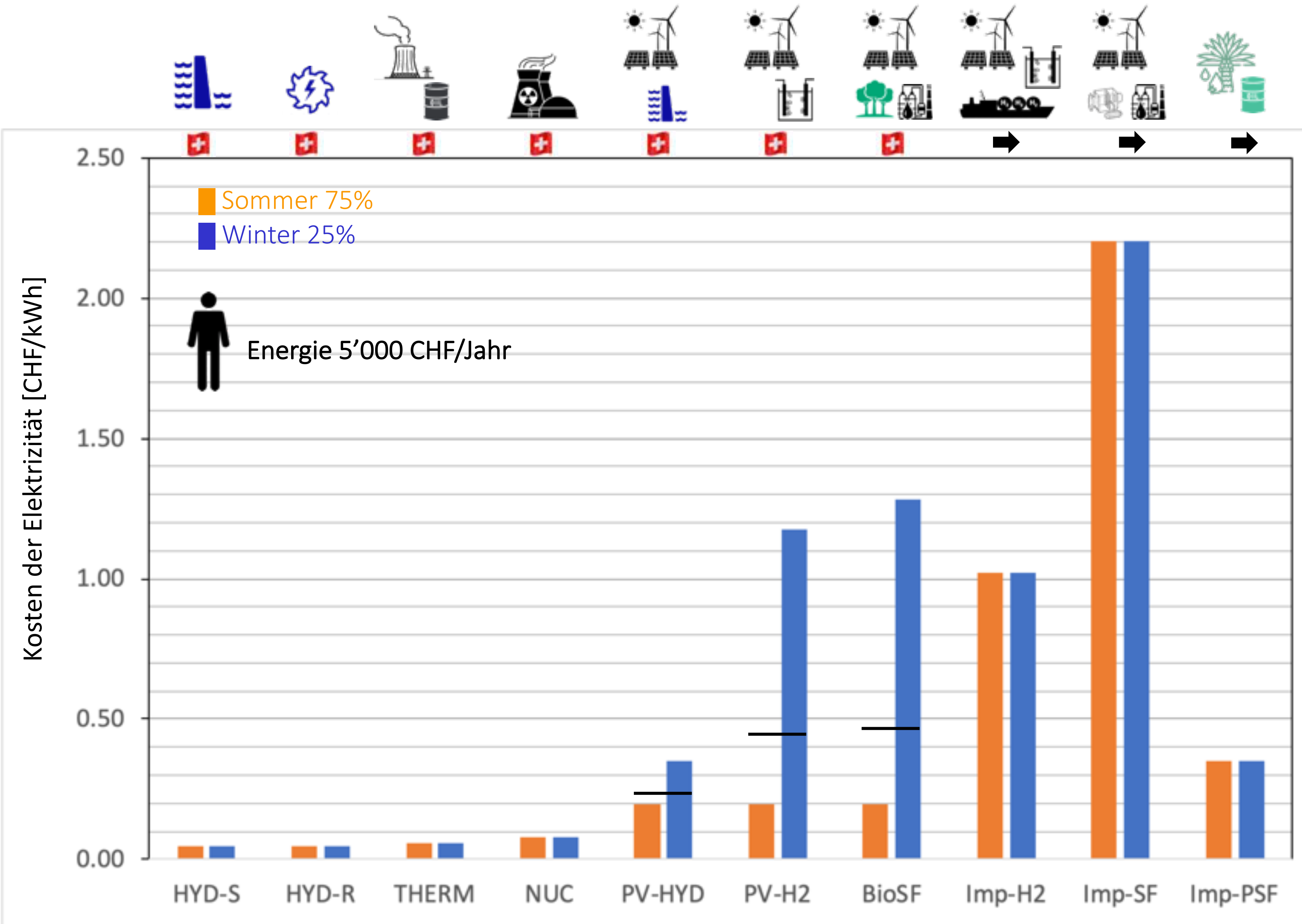
Erneuerbare Energie Entwicklung



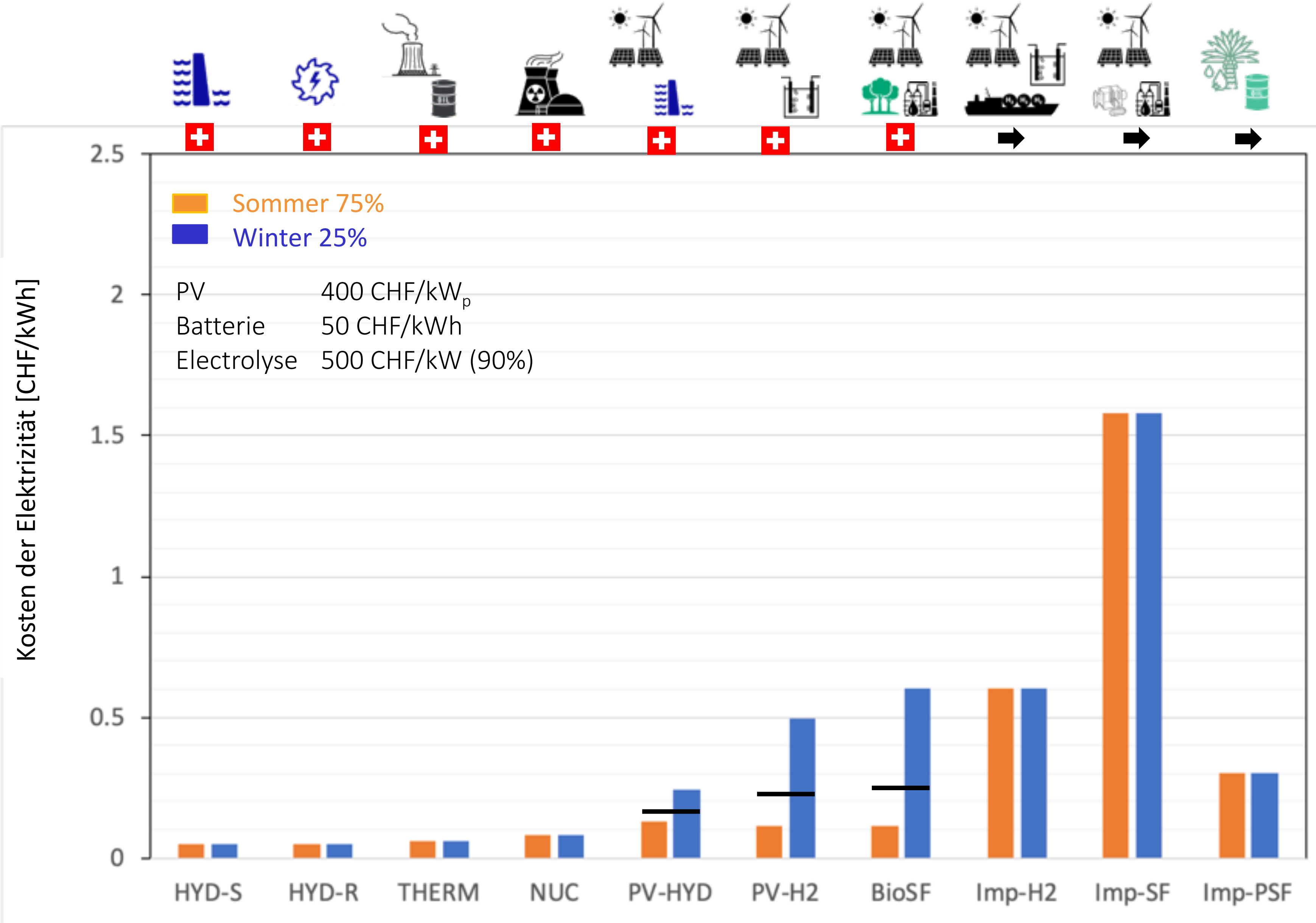
Erneuerbare Energie Entwicklung



Gestehungskosten der Elektrizität (2023)



Gestehungskosten der Elektrizität (Zukunft)



Aufwand der erneuerbaren Energie Lösungen

	2023	Gesetz		H_2	
Kosten [$CHF \cdot y^{-1}$]	3’000	2’764	3’402	4’402	4’281
CAPEX [BCHF]	0	48-72	228	Speicher 426	384
Area PV [km^2]	6	150	468	672	492
Area Bio [km^2]		(6’200)	(6’200)	(6’200)	29’400 (6’200)

(….) Ausland	H_2 →	→	→
Kosten [$CHF \cdot y^{-1}$]	9’079 Kosten	15’445 Kosten	4’623
CAPEX [BCHF]	42 (720)	30 (702)	24 (102)
Area PV [km^2]	150 (720)	150 (780)	150 (36)
Area Bio [km^2]	0 (6’200)	0 (6’200 + CO_2 13.8 $Mt \cdot y^{-1}$)	(43’400)

Aufwand der erneuerbaren Energie Lösungen

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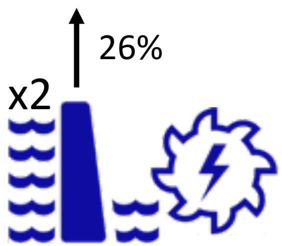
Erneuerbare Energie Lösung (Beispiel)



36 TWh·y^{-1}

→ **9 TWh·y^{-1}**

0.2 CHF/kWh

Vergrösserung der Wasserspeicher

24 TWh·y^{-1}

0.15 CHF/kWh

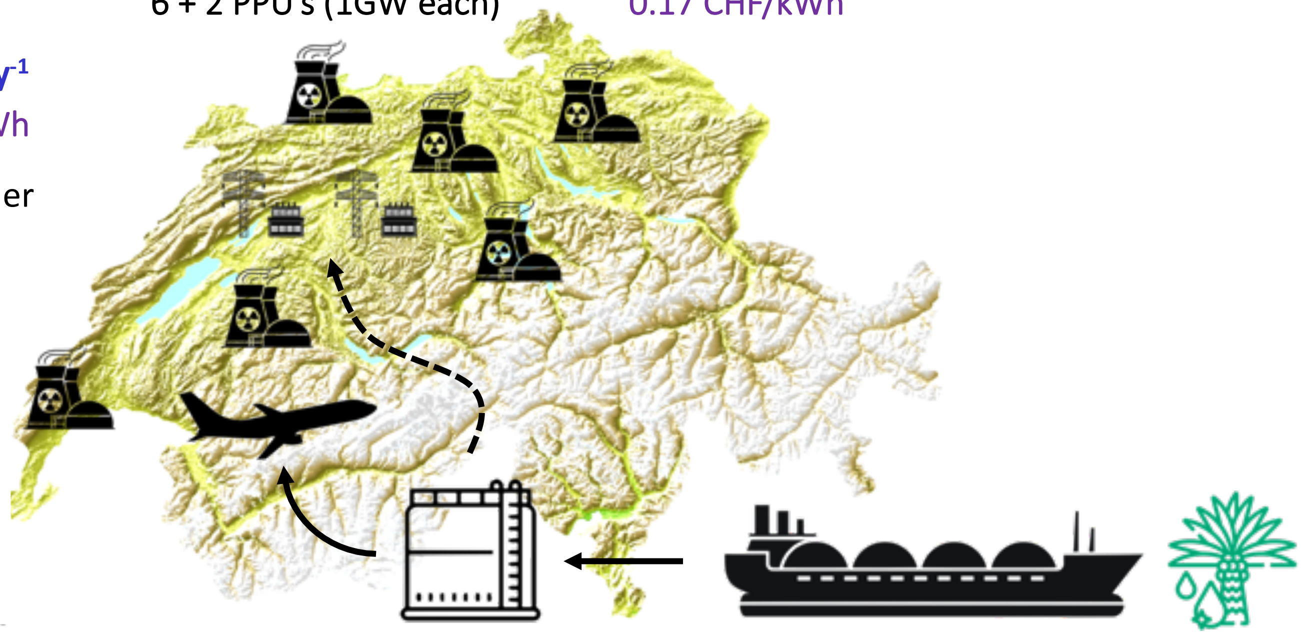
150 km^2 PV auf Daächern

20 TWh·y^{-1}

Biomasse zum Heizen

6 + 2 PPU's (1GW each)

0.17 CHF/kWh



existierende Reserven **20 TWh**

Öltanker

23 TWh·y^{-1}

1.7 CHF/L

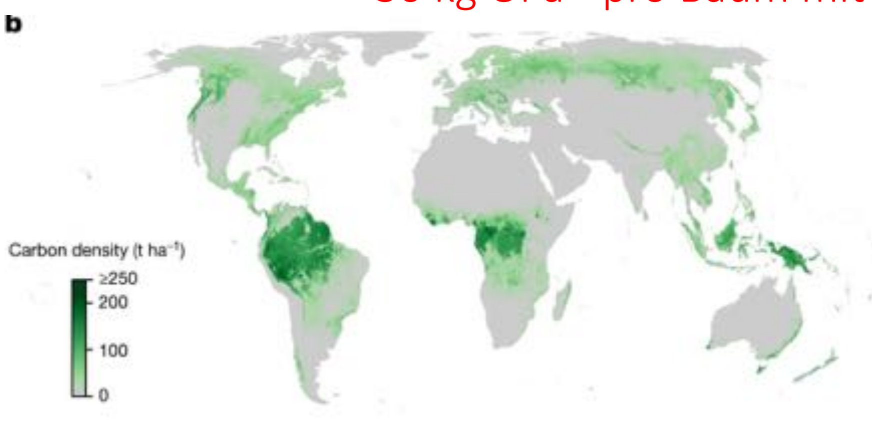
Bio-Oil

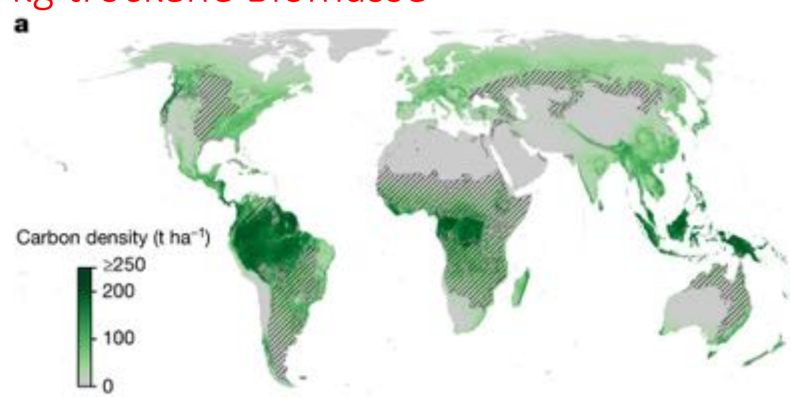
<6200 km^2

CO_2 Senken und Palmöl Produktion

Derzeit liegt die globale Kohlenstoffspeicherung in Wäldern deutlich unter dem natürlichen Potenzial, mit einem Gesamtdefizit von **226 GtC** (Modellbereich = 151 – 363 GtC) in Gebieten mit geringem menschlichen Fussabdruck. [1] Bei 142 verfügbaren Ölpalmenstämmen (OPT) pro Hektar Plantagenfläche und einer neu bepflanzten Fläche von 100.550 Hektar im Jahr 2017 belief sich das geschätzte Trockengewicht der erzeugten OPT (74.5 t ha^{-1}) auf insgesamt 7.5 Mio. t [2]. Es werden 4.0 $t \cdot ha^{-1} \cdot y^{-1}$ Palmöl produziert und die Ölpflanzen werden alle 20 Jahre neu gepflanzt.

30 kg $Öl \cdot a^{-1}$ pro Baum mit 524 kg trockene Biomasse





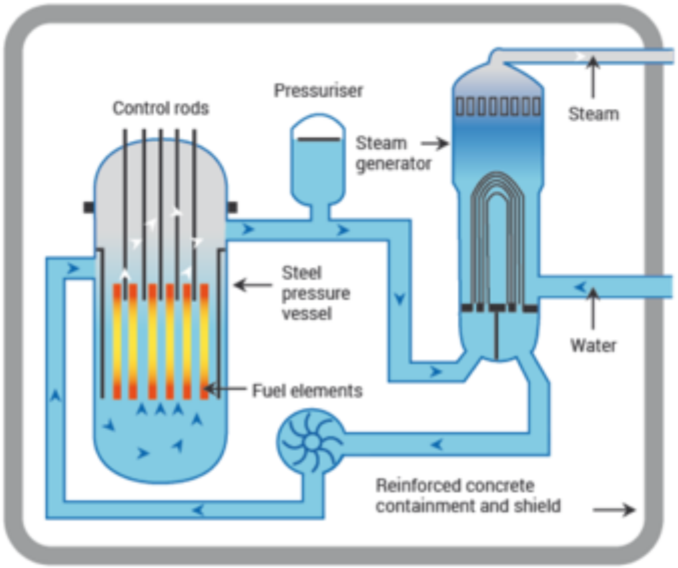
226 Gt Ölpalmen produzieren 13 Gt $Öl \cdot a^{-1}$ mehr als der Weltenergiebedarf an Öl

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

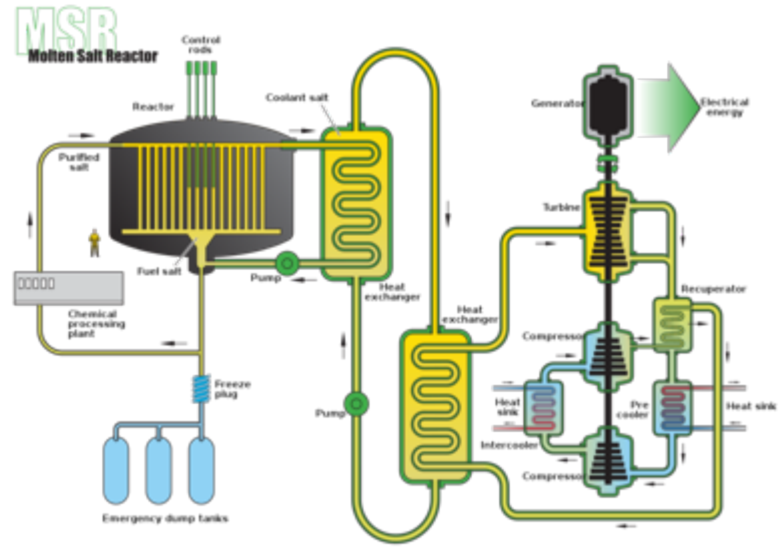
Kernreaktoren

ZUKUNFT

Uran-Spalt-Reaktoren



Thorium-Flüssigsalz-Brutreaktoren



Nachteile:

Begrenzte Uranreserven (6 % für 100 Jahre)
Gefahr des Kernschmelzens
Langlebige Isotope (Pu)
geringer Wirkungsgrad (25%)
begrenzte Wärmenutzung
Endlager von Nuc. Abfall
Kleine modulare Reaktoren (SMR)

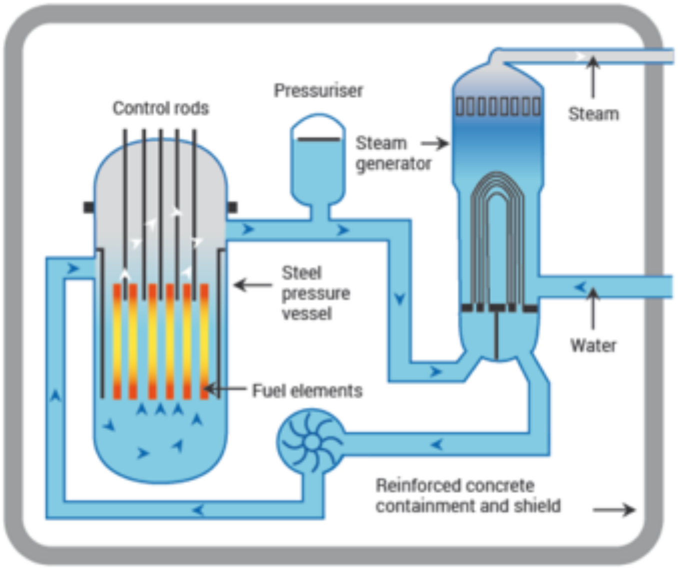
Vorteile:

Große Thoriumreserven (Verwendung von Atommüll, 95 % sind Brennstoff)
Kein Kernschmelzen möglich
Keine langlebigen Isotope
höhere T, höhere Effizienz (>25%)
Nutzung von Wärme zum Heizen
Schmelzsalzreaktor (MSR)

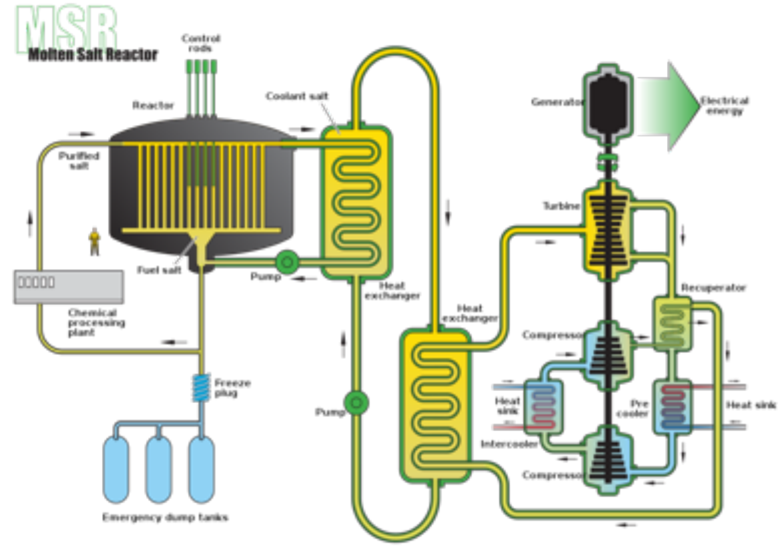
Kernreaktoren

ZUKUNFT

Uran-Spalt-Reaktoren



Thorium-Flüssigsalz-Brutreaktoren



Nachteile:

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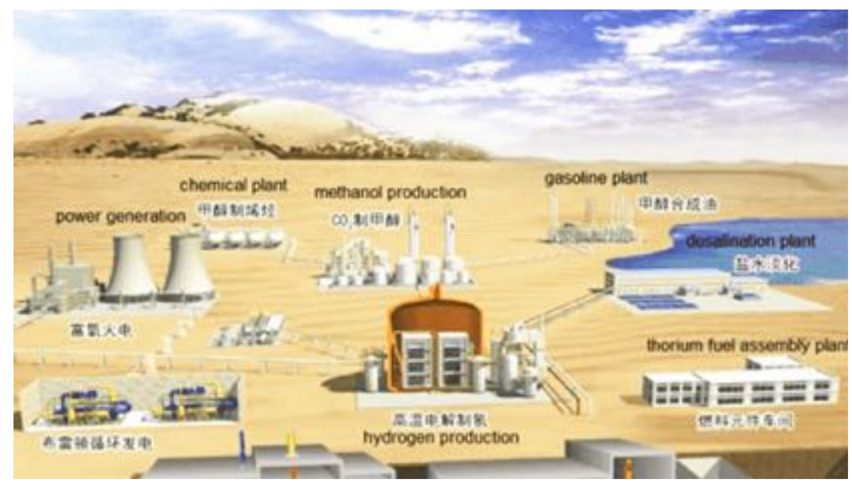
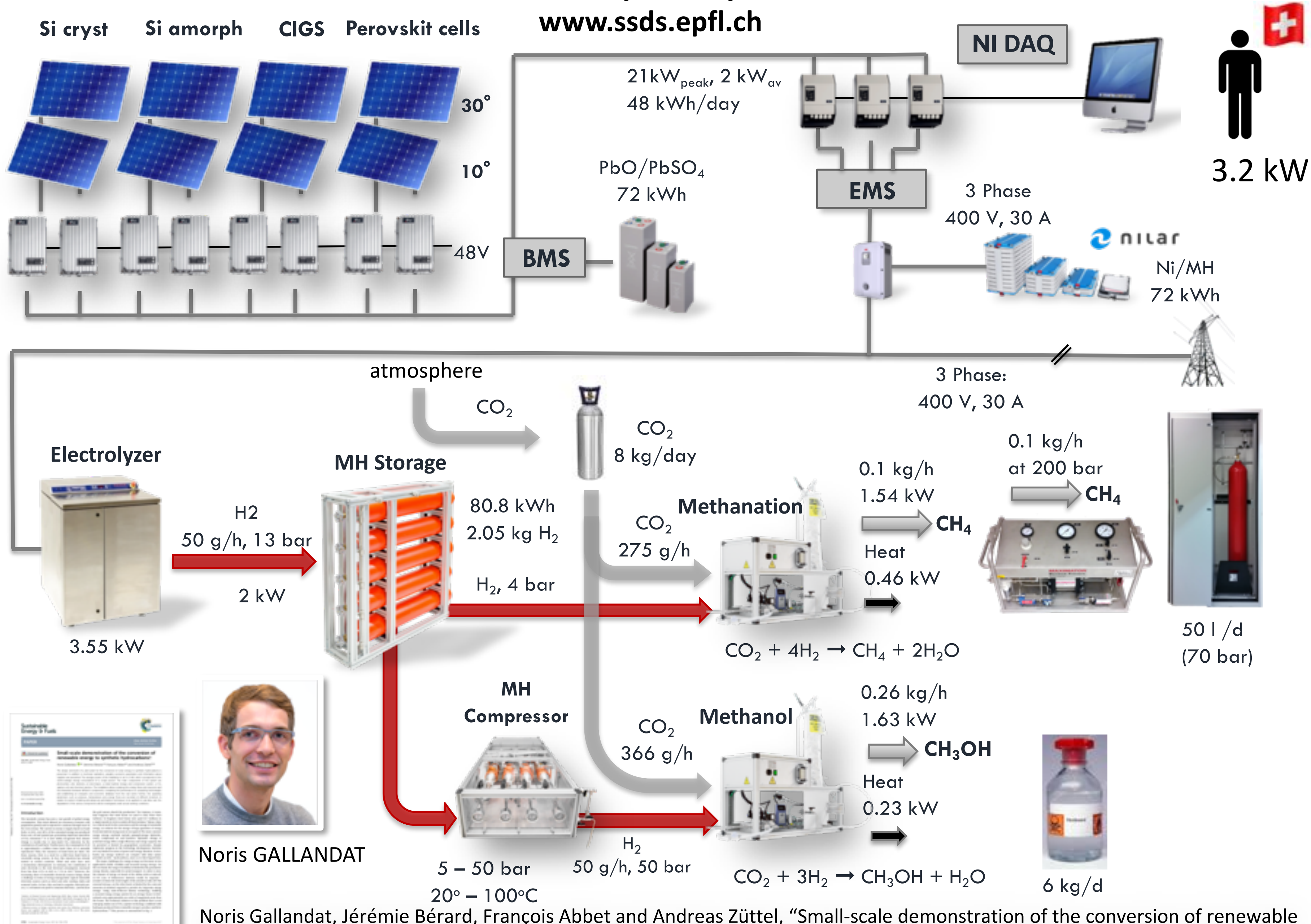
Endlager von Nuc. Abfall
Kleine modulare Reaktoren (SMR)

Ref.: https://www.world-nuclear-news.org/Articles/Operating-permit-issued-for-Chinese-molten-salt-re



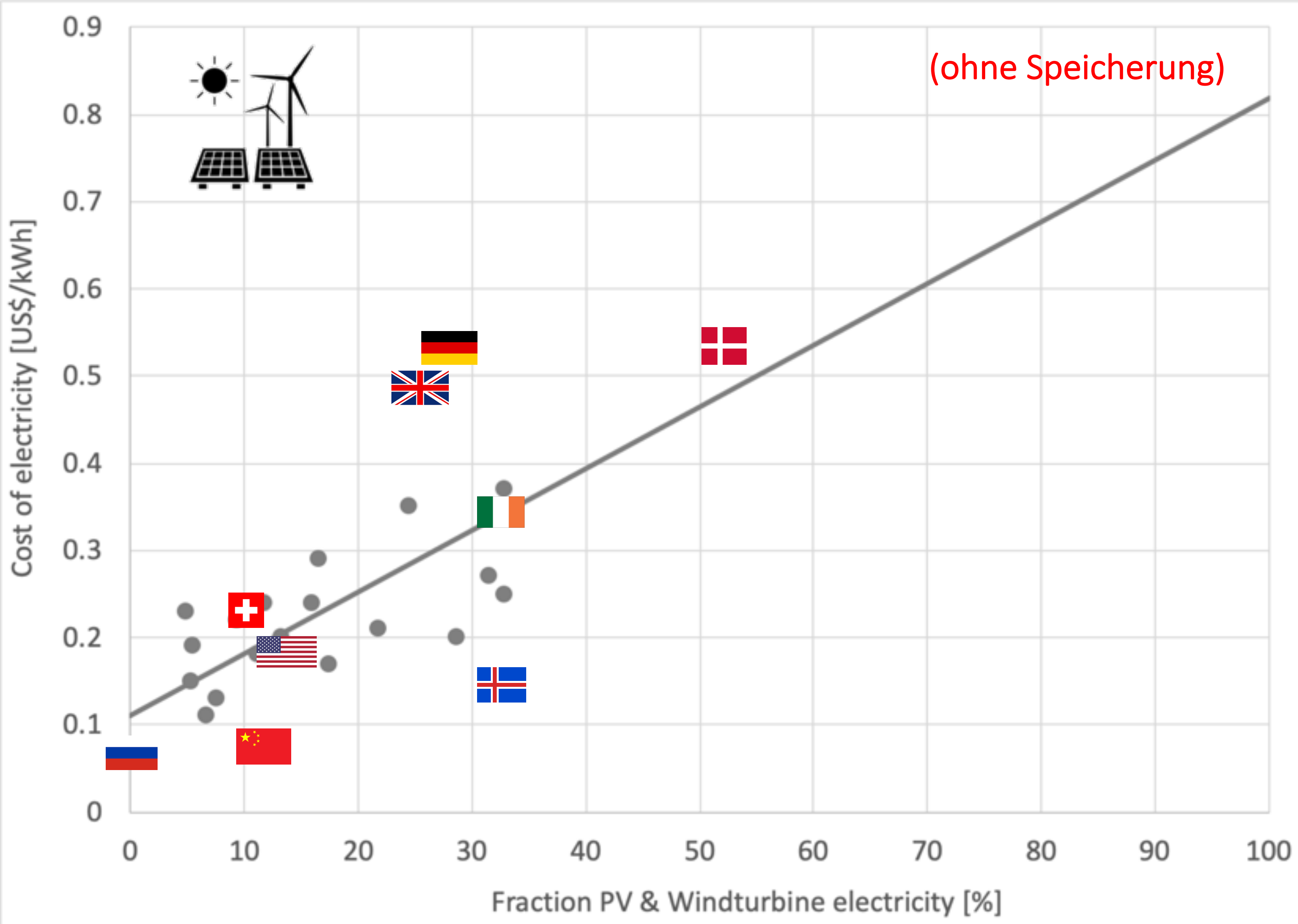
TMSR-LF1 (2 $MW_{therm.}$) construction 2018 - 2023, Wuwei city, Gansu province, China, operated since July 2023

Small Scale Demonstrator Sion (SSDS)



Noris Gallandat, Jérémie Bérard, François Abbet and Andreas Züttel, “Small-scale demonstration of the conversion of renewable energy to synthetic hydrocarbons”, Sustainable Energy & Fuels (2017).DOI: 10.1039/c7se00275k, rsc.li/sustainable-energy

Kosten der Elektrizität aus PV und Windturbinen (2023)



Ref.: https://elements.visualcapitalist.com/mapped-solar-and-wind-power-by-country/

frontiers in Energy Research

ORIGINAL RESEARCH
published: 25 January 2022
doi: 10.3389/fenrg.2021.785908

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_c, cost of the energy.

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CO_2 Neutral Energy Security for Switzerland

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ABSTRACT

An analysis of the technical opportunities and economic consequences of 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.

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.

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

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