“Energieautonomie für die Armee ”

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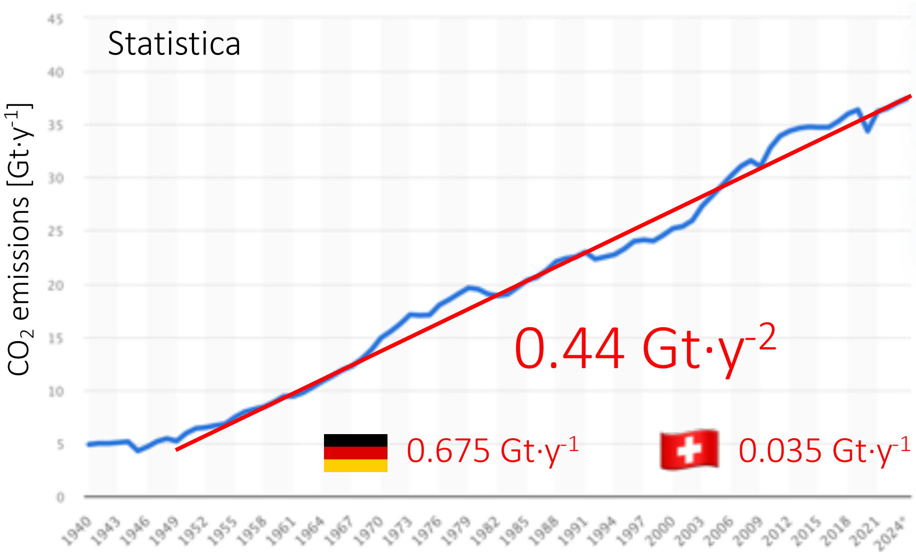
19. März 2025

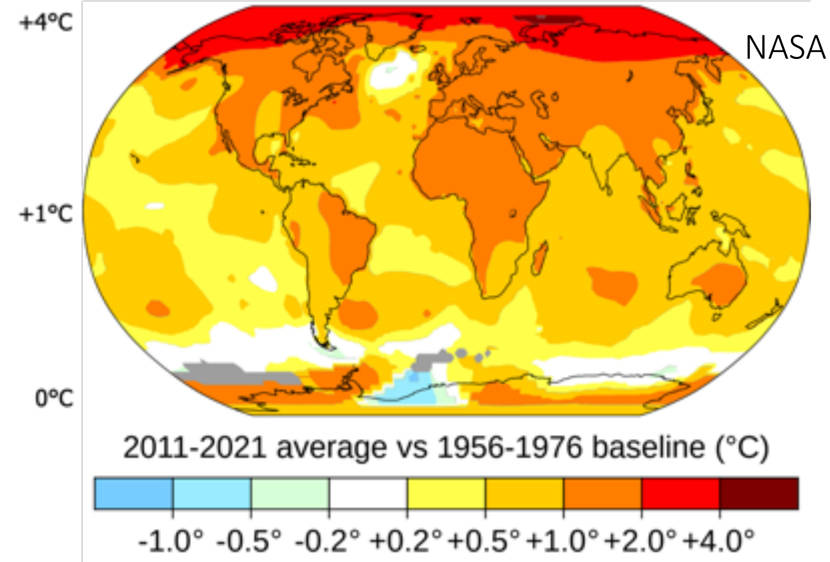
"Kraftwerkseinheiten für eine CO_2 neutrale Energieversorgung in der Schweiz"

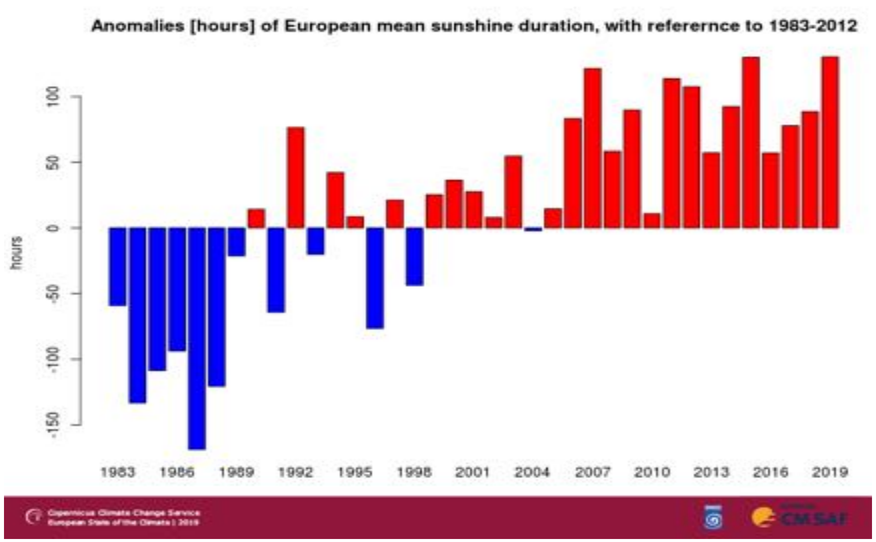
Für die Substitution fossiler Brenn- und Treibstoffe mit erneuerbaren Energie in der Schweiz wird ein neues Konzept auf der Grundlage von Kraftwerkseinheiten vorgestellt, die erneuerbare Energie nach Bedarf und mind. 1 GW liefern können. Die technisch realisierten Wirkungsgrade zeigen, dass eine vollständige Elektrifizierung zum effizientesten Energiesystem und zum billigsten Strom führt. Es wird erwartet, dass sich der Strombedarf ca. verdoppelt und die Gesamt-energie-kosten im Vergleich zu 2023 um 20% steigen werden. Die technischen Herausforderungen der saisonalen Stromspeicherung ohne jegliche Reserven und Redundanz belaufen sich jedoch auf 20 TWh. Wasserkraft und Photovoltaik ohne Speicherung produzieren den billigsten Strom. Zukünftige Kernspaltungstechnologien, z. B. der Thorium-Salzschmelze-Brutreaktor, der sich derzeit noch im Versuchsstadium befindet, könnten die wirtschaftlichste und umweltfreundlichste Lösung für eine kontinuierliche CO_2-neutrale Stromerzeugung sein. Die Möglichkeiten für eine massive Steigerung der Wasserkraft-produktion sind begrenzt, schon die Verlagerung der Wassernutzung (9 TWh) vom Sommer in den Winter ist eine grosse Herausforderung. PV- und Wasserkraftproduktion in der Schweiz haben den Vorteil, dass sie etwa 75 % des Stroms ohne saisonale Speicherung liefern können, was zu deutlich niedrigeren Stromkosten führt, als bei importiertem Wasserstoff oder synthetischen Kohlenwasserstoffen. Die wirtschaftlichste Lösung für die Luftfahrt und die Reserven ist importiertes Bioöl, das in synthetischen Diesel und Kerosin umgewandelt wird und für das es bereits grosse Tanklager gibt.

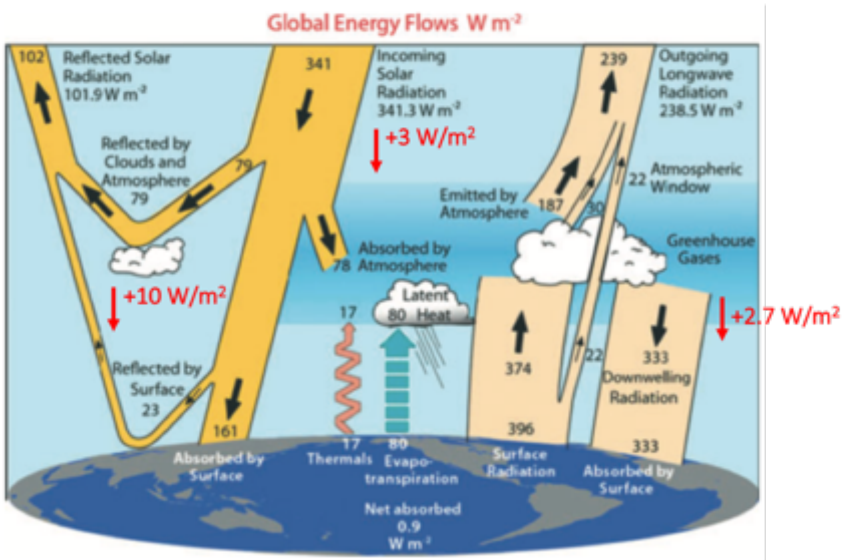
Ref.: Andreas ZÜTTEL, Christoph NÜTZENADEL, Louis SCHLAPBACH, Paul W. GILGEN "Power plant units for CO_2 Neutral Energy Security in Switzerland", Frontiers in Energy Research: Process and Energy Systems Engineering, 12:1336016 (2024), https://doi: 10.3389/fenrg.2024.1336016

CO_2 Emissionen und Klimaveränderung









333 W/m² → ΔT = 33°C
0.1°C/(W·m^{-2})

Pferdemist vor 130 Jahren

Pferedemist in 1894

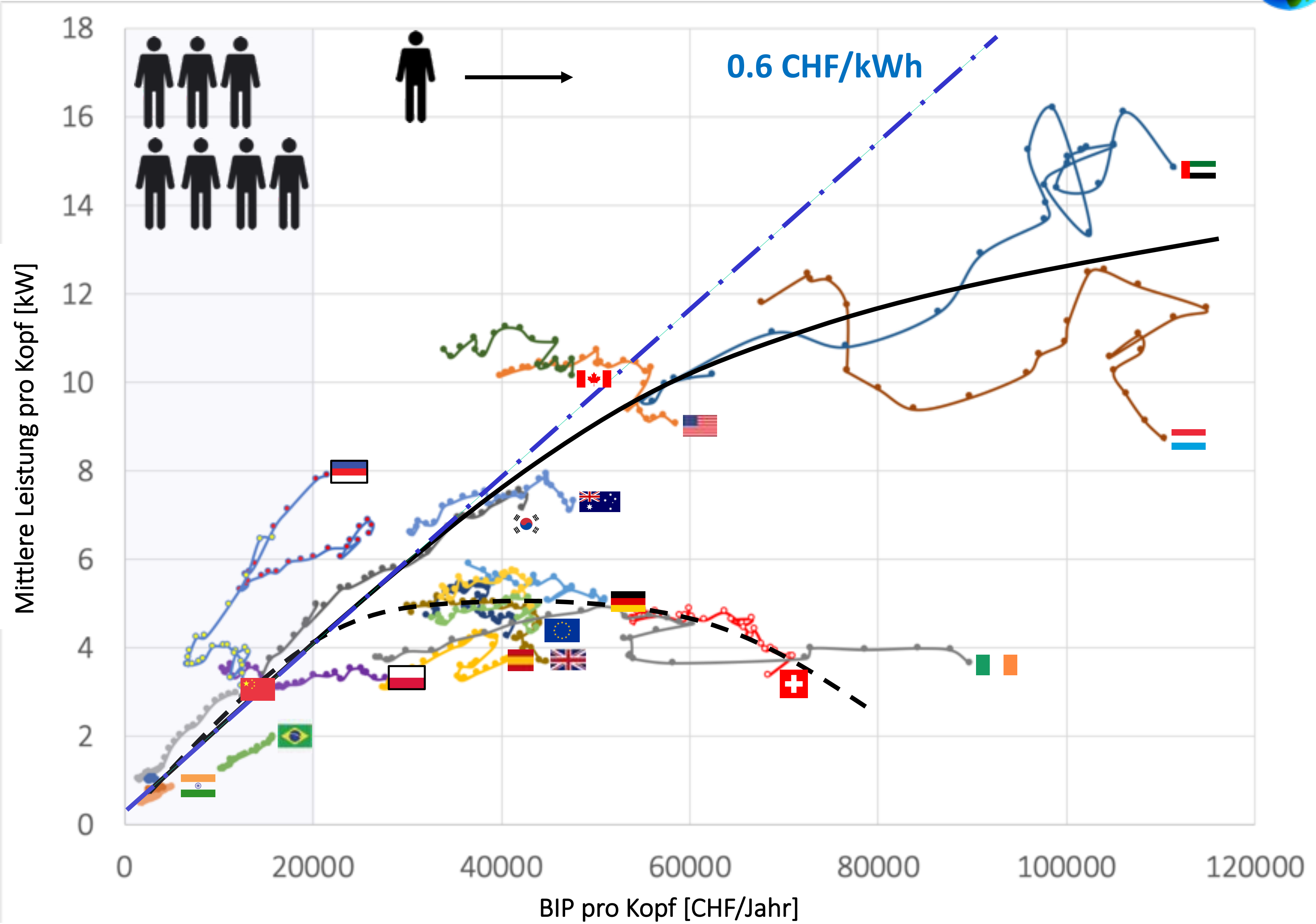
Krise, die Anzahl der Pferde muss reduziert werden!

Pferdemist einsammeln

Pferdemist an der Quelle sammeln

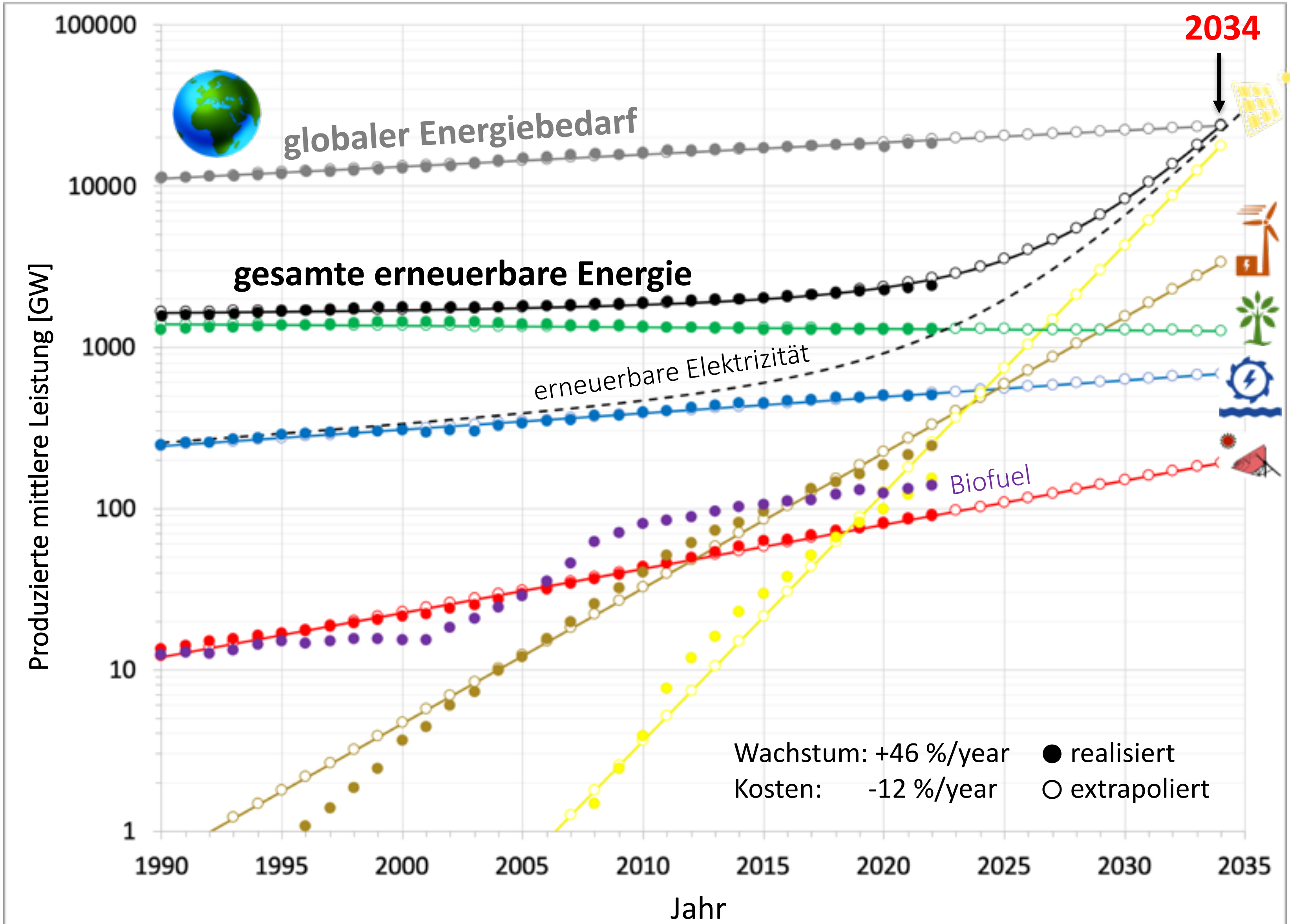
Lösung: neue Technologie!

Energie und Wirtschaft



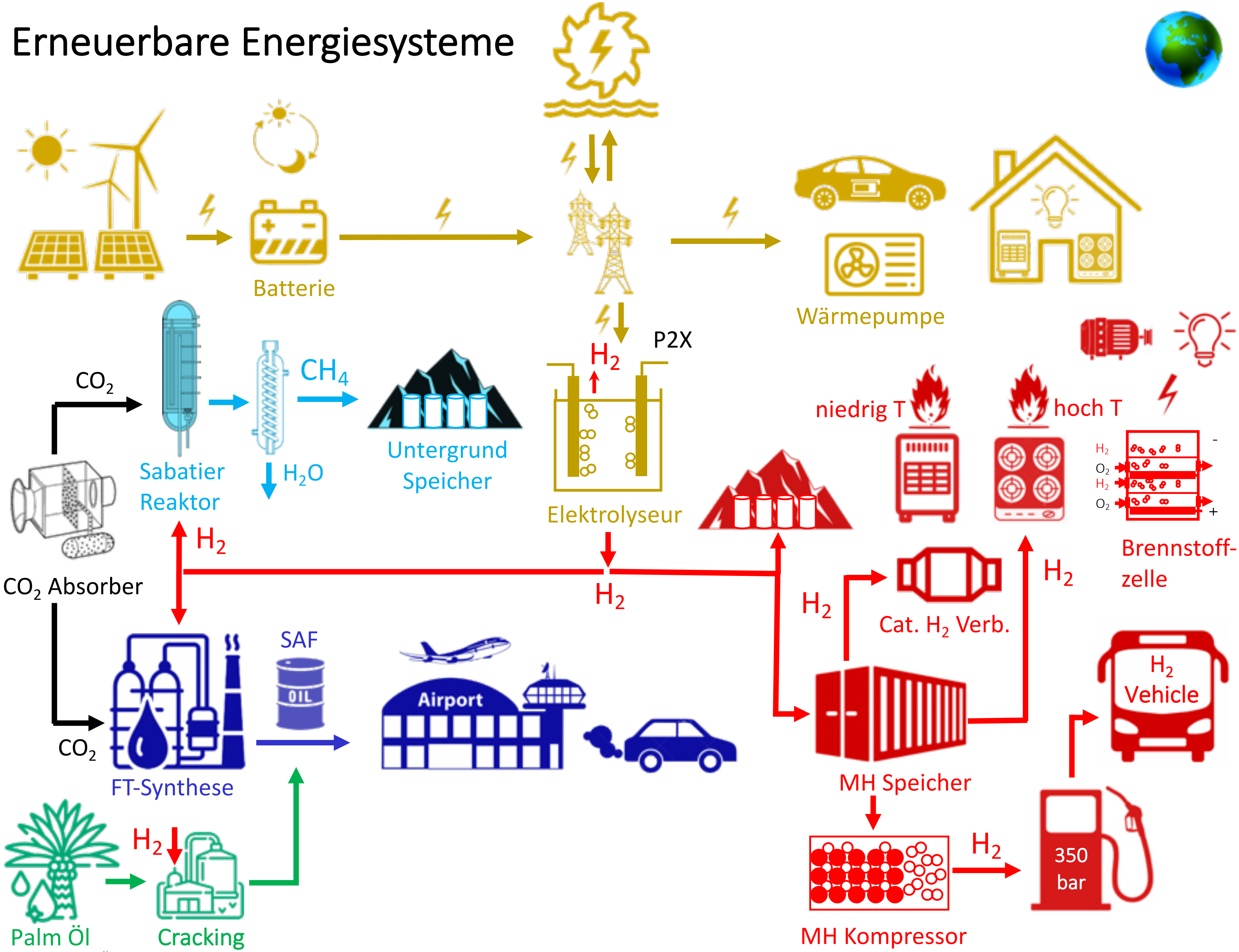
Ref.: https://ourworldindata.org/grapher/energy-use-per-capita-vs-gdp-per-capita

Globale erneuerbare Energieproduktion



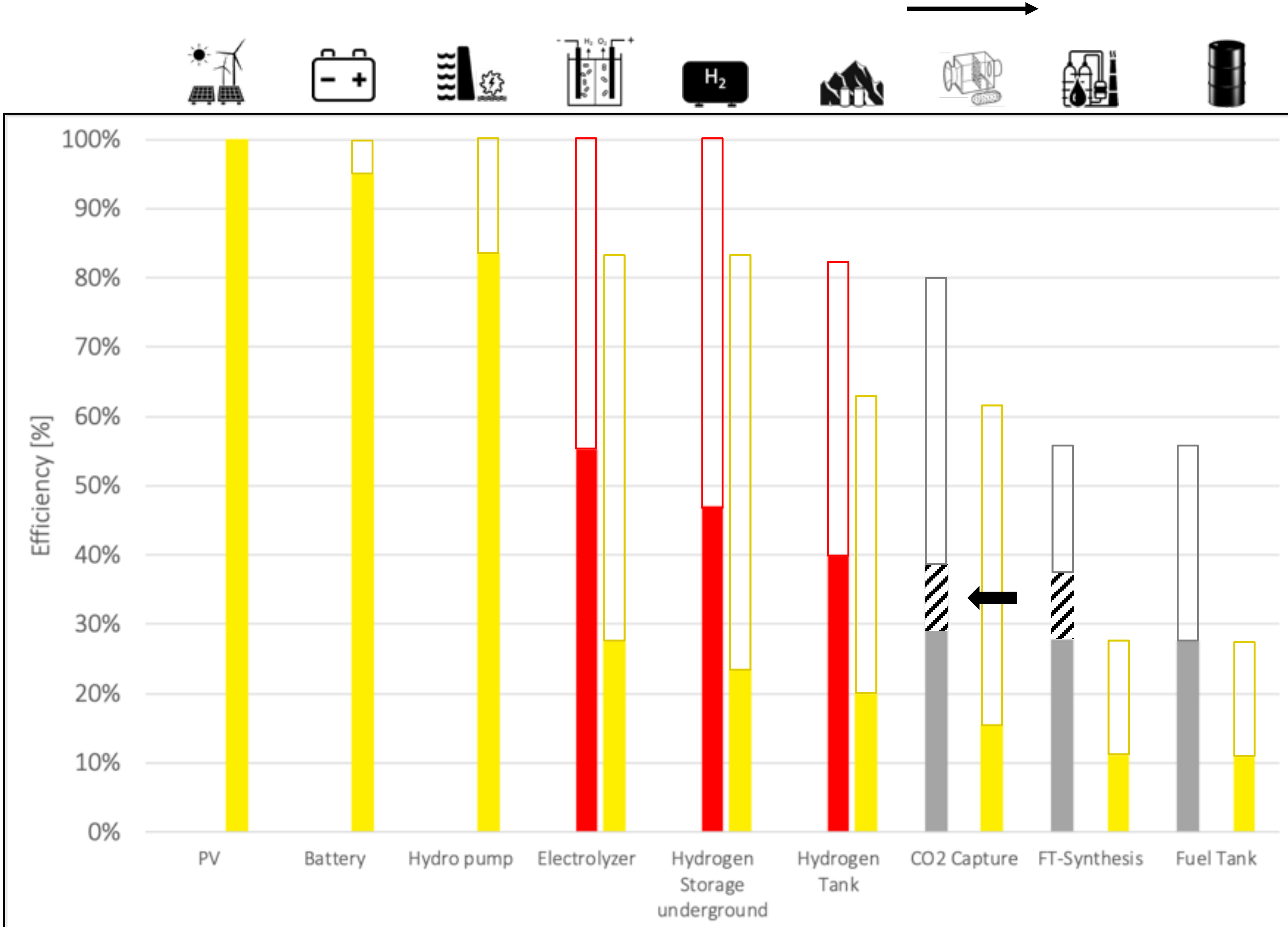
Ref.: https://ourworldindata.org/energy. https://www.pv-magazine.com/2023/02/16/global-solar-installations-may-hit-350-6-gw-in-2023-says-trendforce/#:~:text=2022, and https://ourworldindata.org/energy

Erneuerbare Energiesysteme

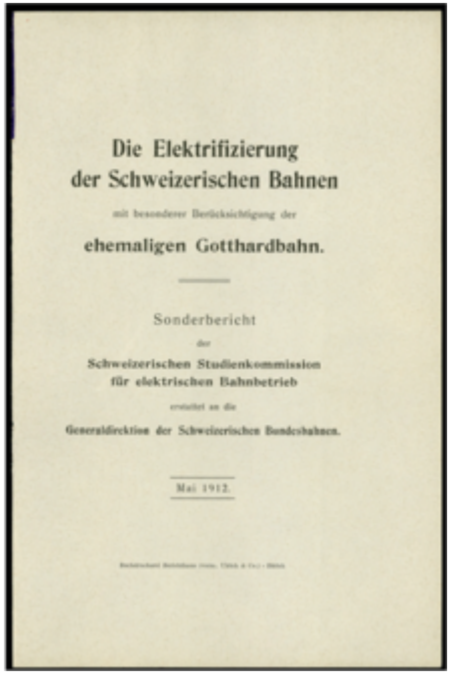


Effizienz entlang der Energiewandlung

Power to X (P2X)



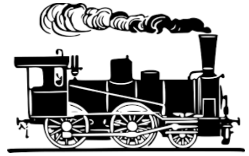
Energiewende in der Schweiz 1912


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.

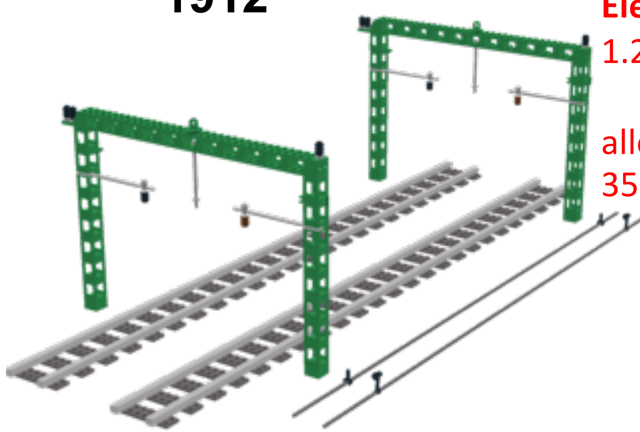
Mai 1912.

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

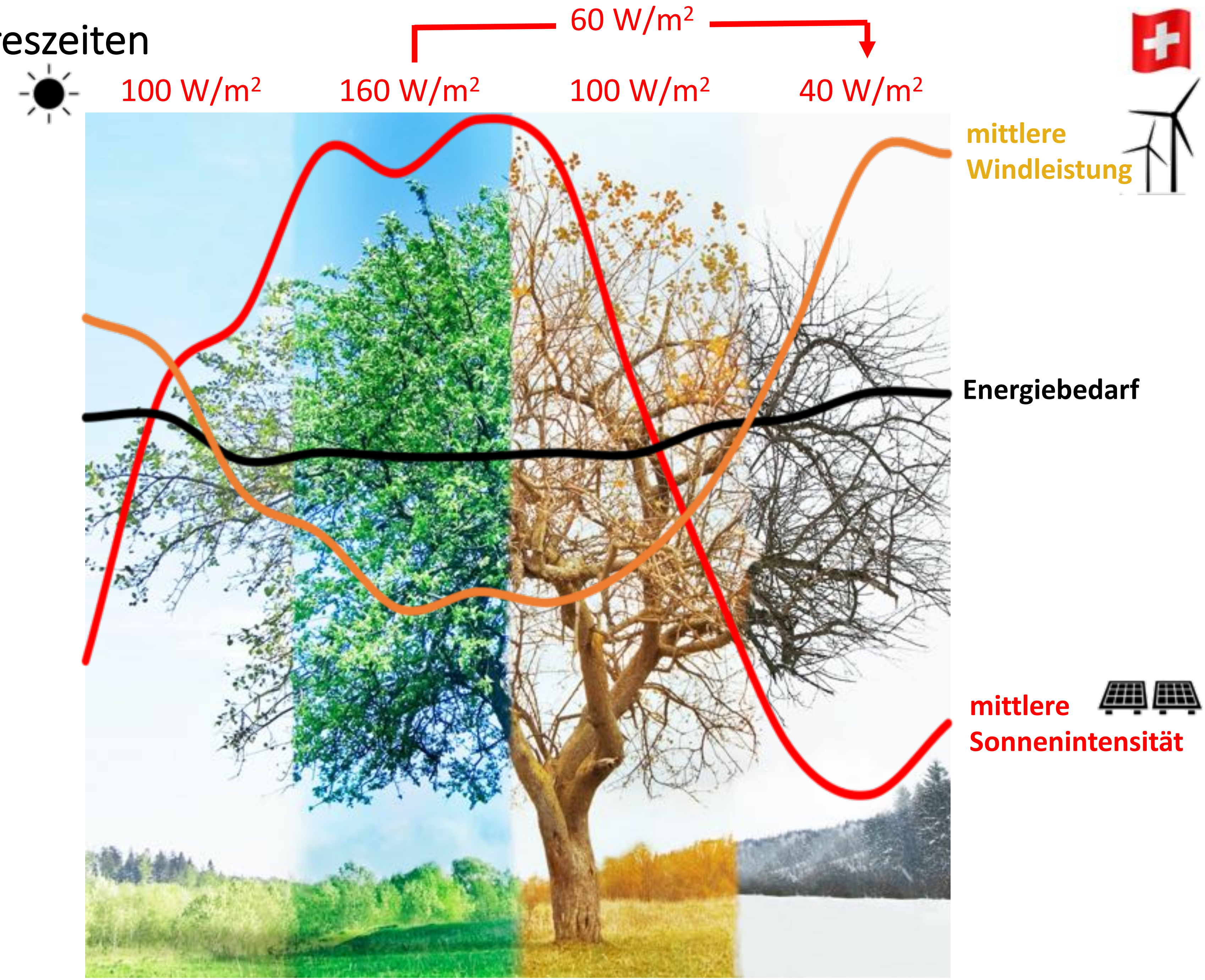
alle 27m ein Mast,
35 – 70 k€ pro Mast

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

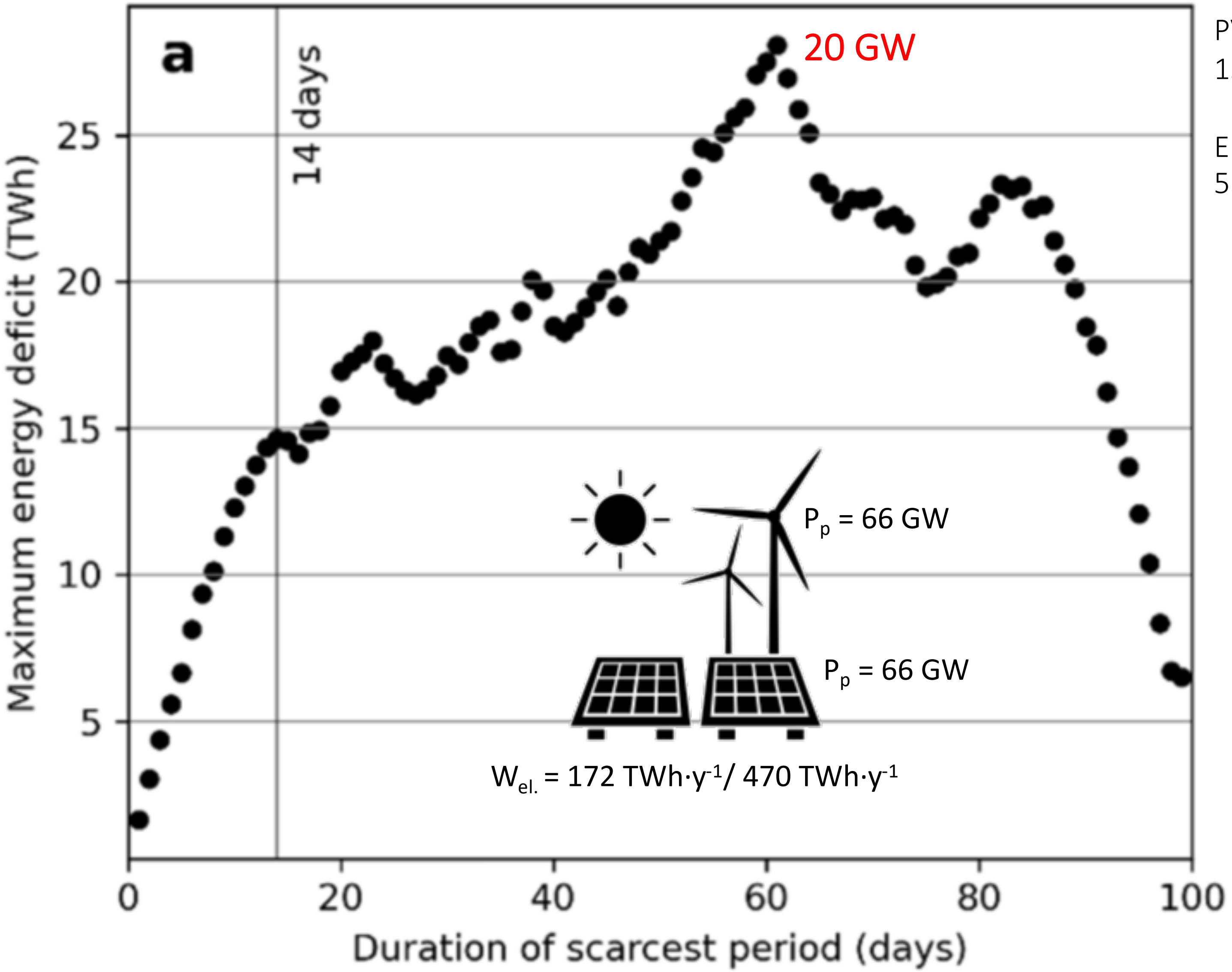
Ref.: Deutschland: Lindau -München 500 Mio.€ für 189 km incl. Lärmschutz und neuem Bahnhof...
Dänemark: Gesamtes Schienennetz 1'600 Mio.€ für 1300 km

Energieautonomie für die Armee

Jahreszeiten



Erneuerbare Energie und Speicherung

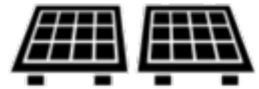


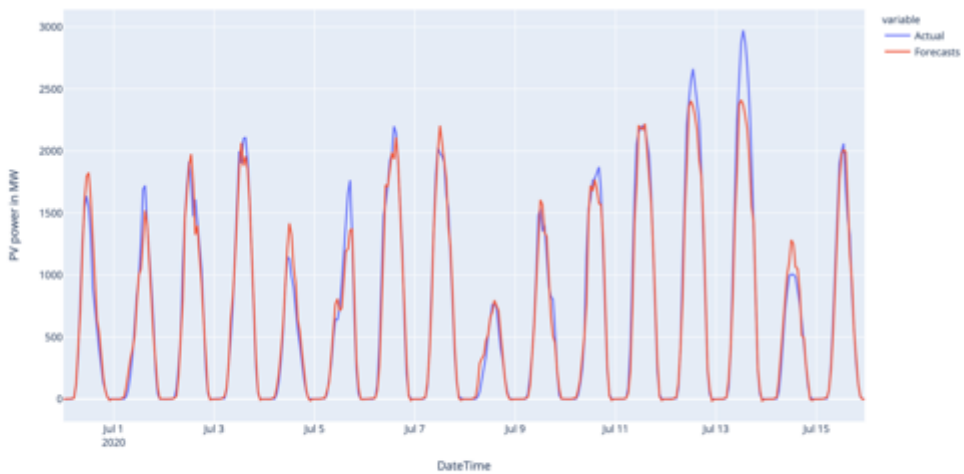
PV & Wind:
150 GW_p installiert

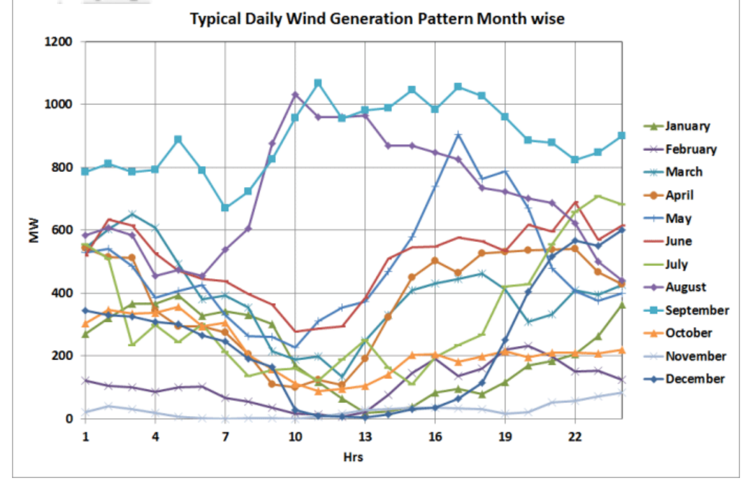
Elektrizität:
53 GW mittlere Leistung

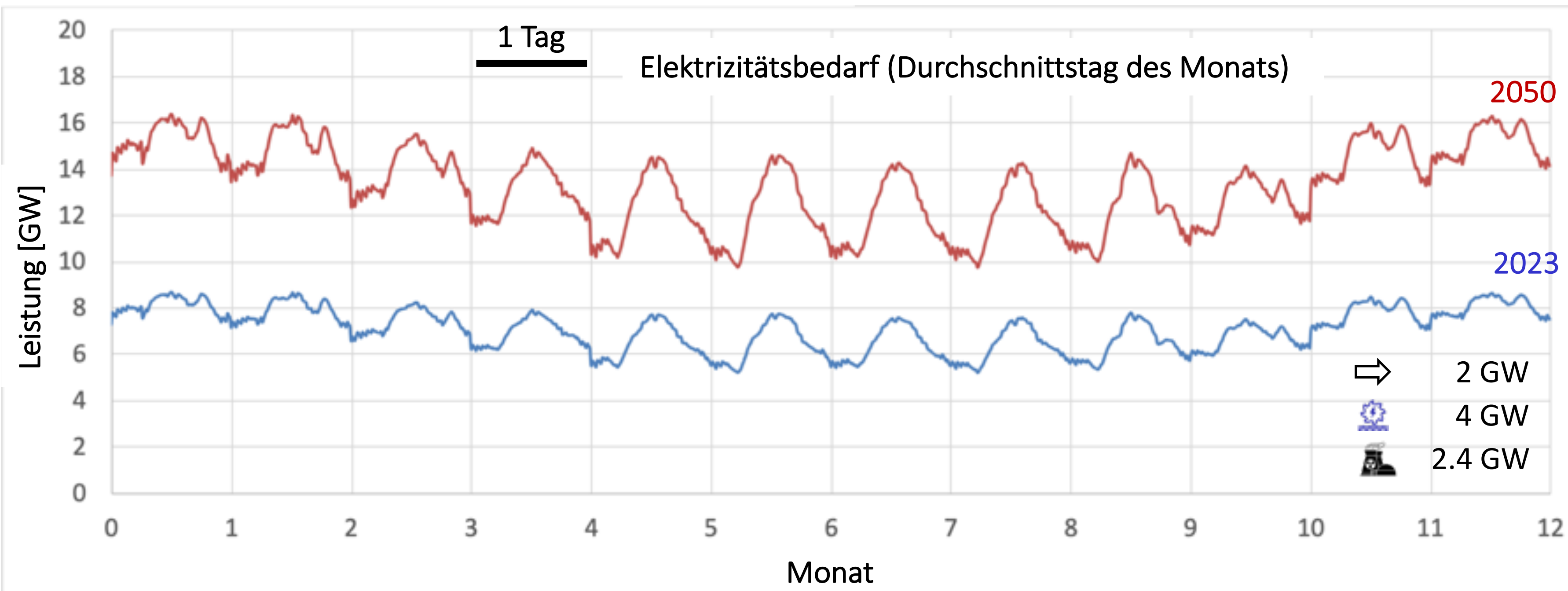
Ref.: Oliver Ruhnau, and Staffan Qvist,"Storage requirements in a 100% renewable electricity system: extreme events and inter-annual variability", Environ. Res. Lett. 17 (2022) 044018, https://doi.org/10.1088/1748-9326/ac4dc8

Erneuerbare Energieproduktion

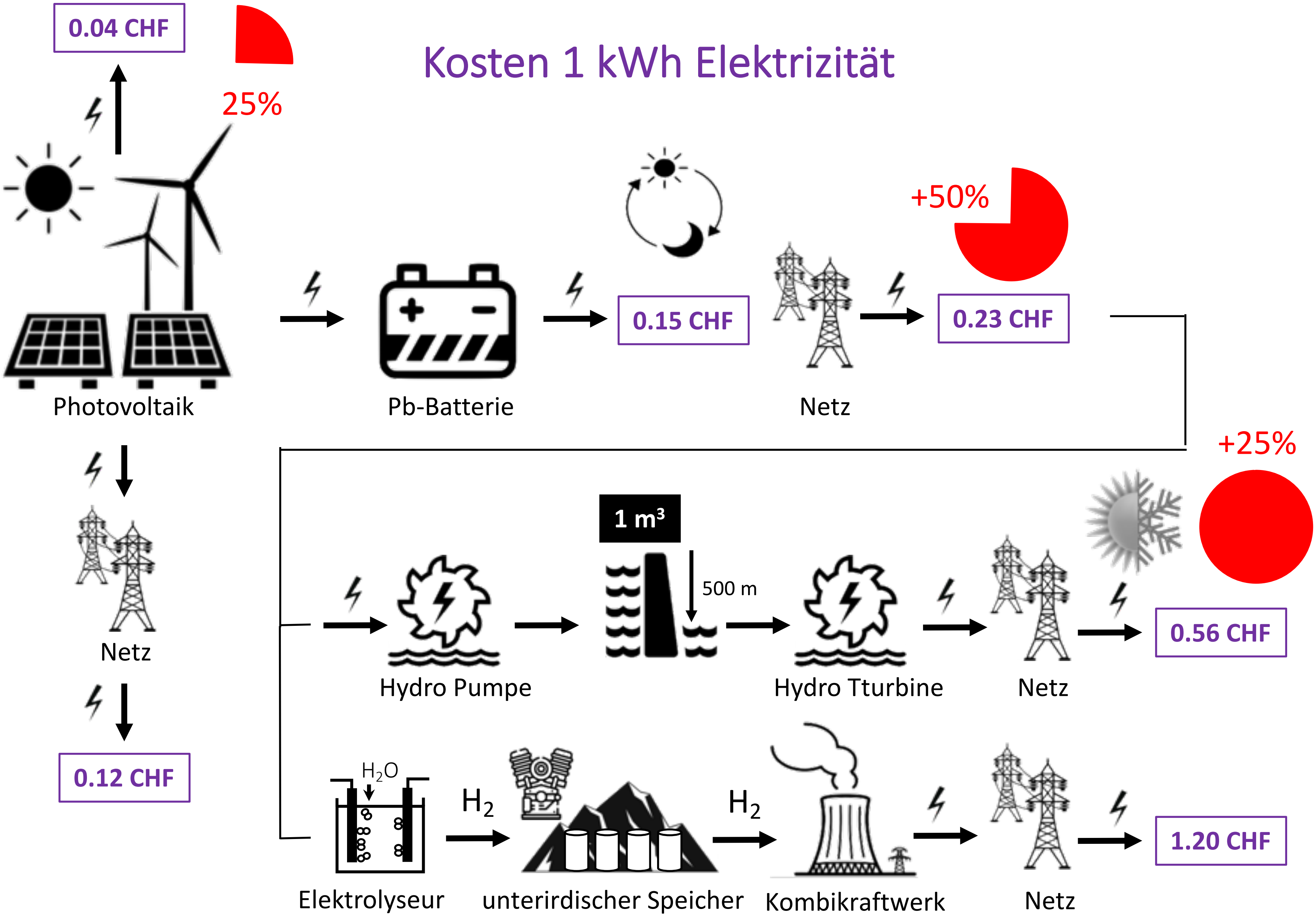




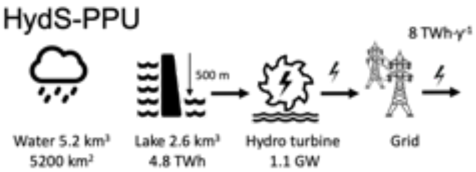


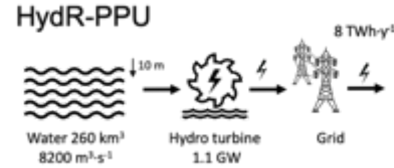


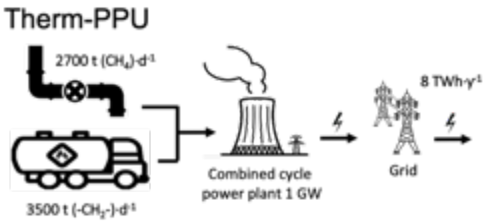
Erneuerbare Energie nach Produktion und nach Bedarf

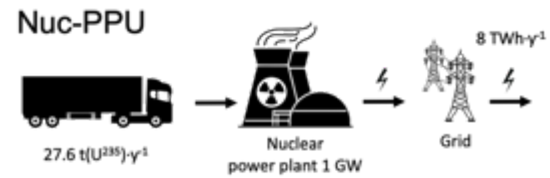


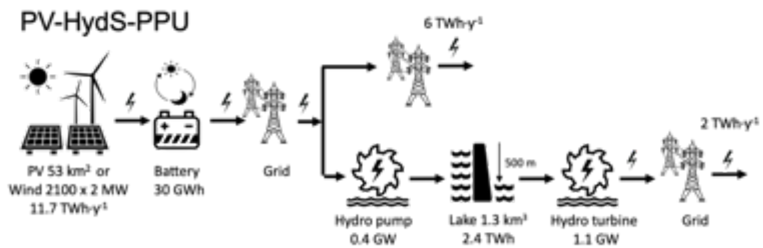
Kraftwerkseinheiten KWE 1/2)

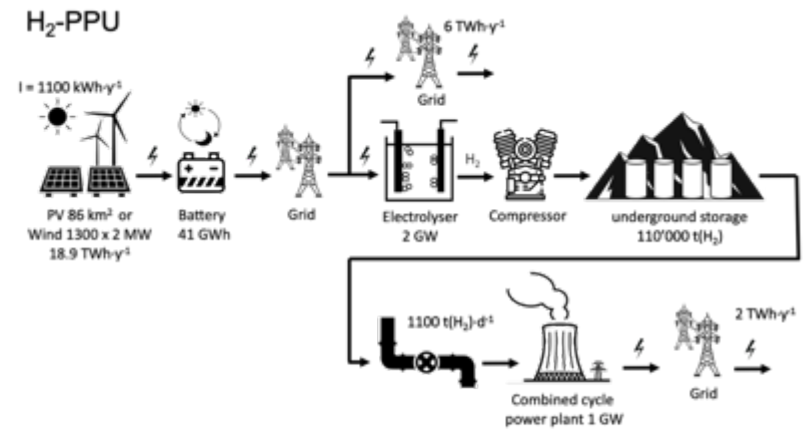


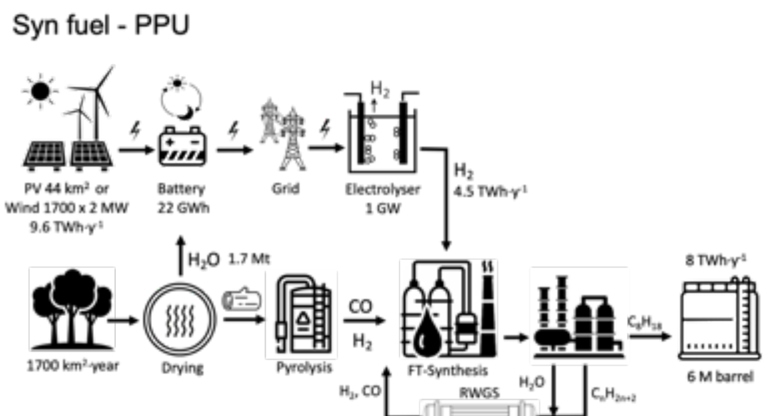








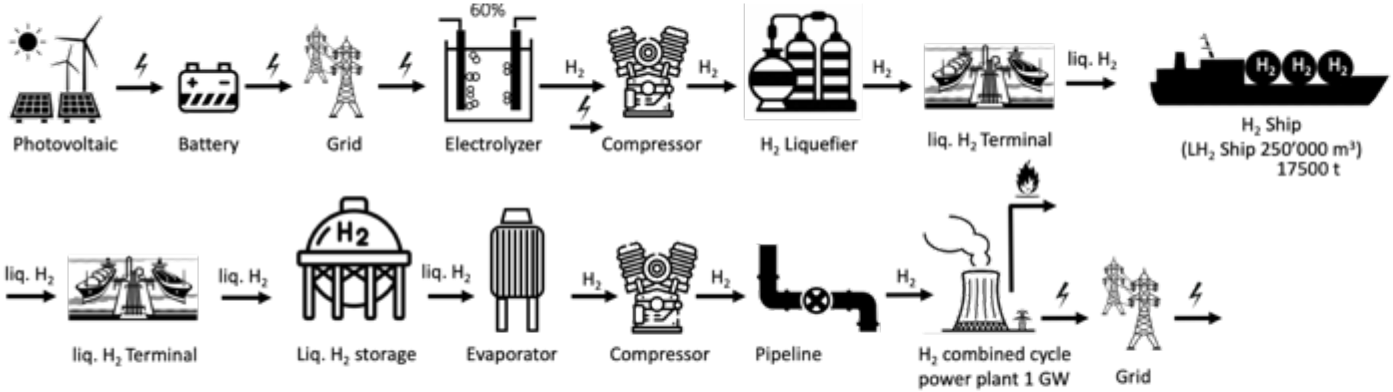




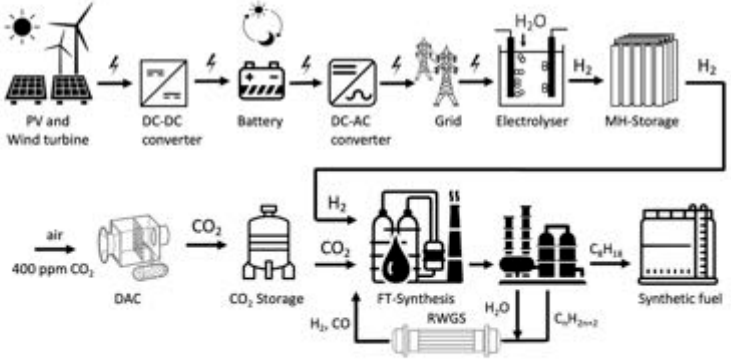
Ref.: Andreas ZÜTTEL, Christoph NÜTZENADEL, Louis SCHLAPBACH, Paul W. GILGEN “Power plant units for CO_2 Neutral Energy Security in Switzerland”, Frontiers in Energy Research: Process and Energy Systems Engineering, 12:1336016 (2024).

Kraftwerkseinheiten (KWE 2/2)

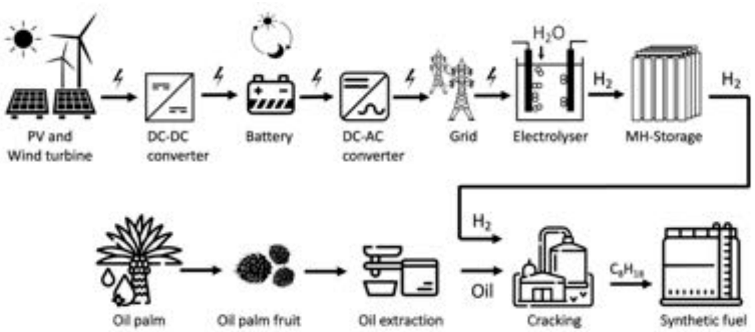
Imp. H_2



Imp. SF or CH_4

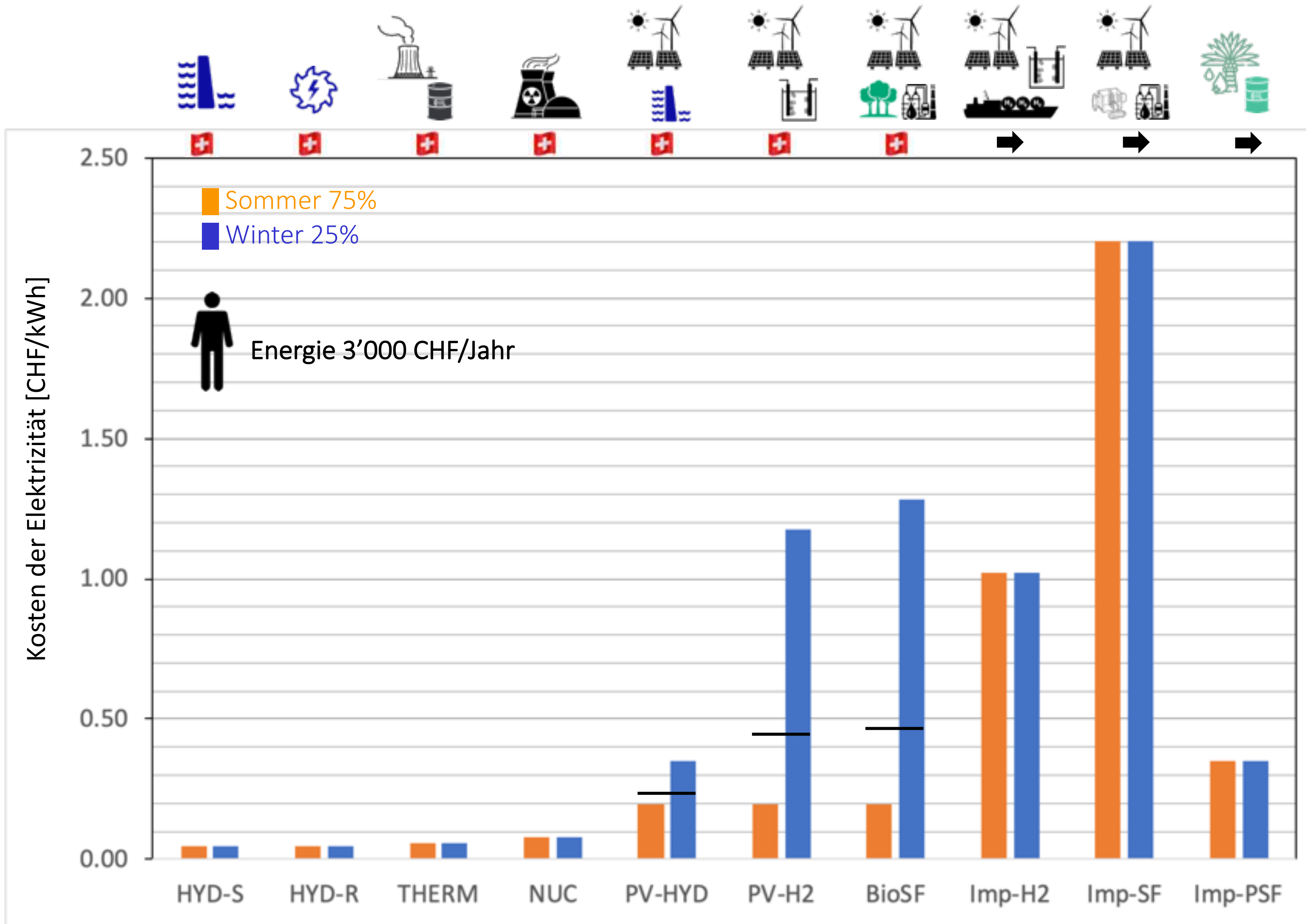


Imp. BSF

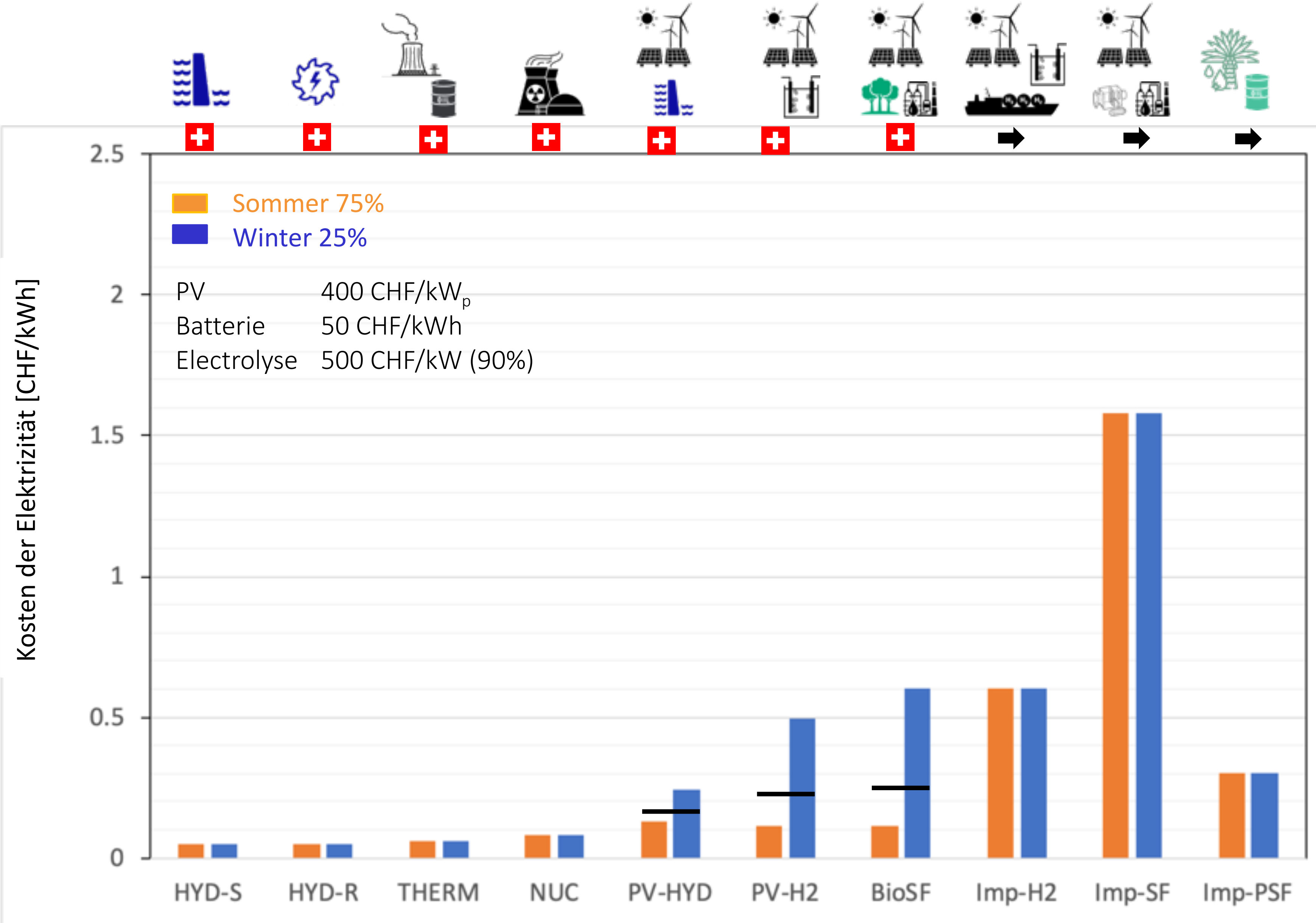


Ref.: Andreas ZÜTTEL, Christoph NÜTZENADEL, Louis SCHLAPBACH, Paul W. GILGEN "Power plant units for CO_2 Neutral Energy Security in Switzerland", Frontiers in Energy Research: Process and Energy Systems Engineering, 12:1336016 (2024).

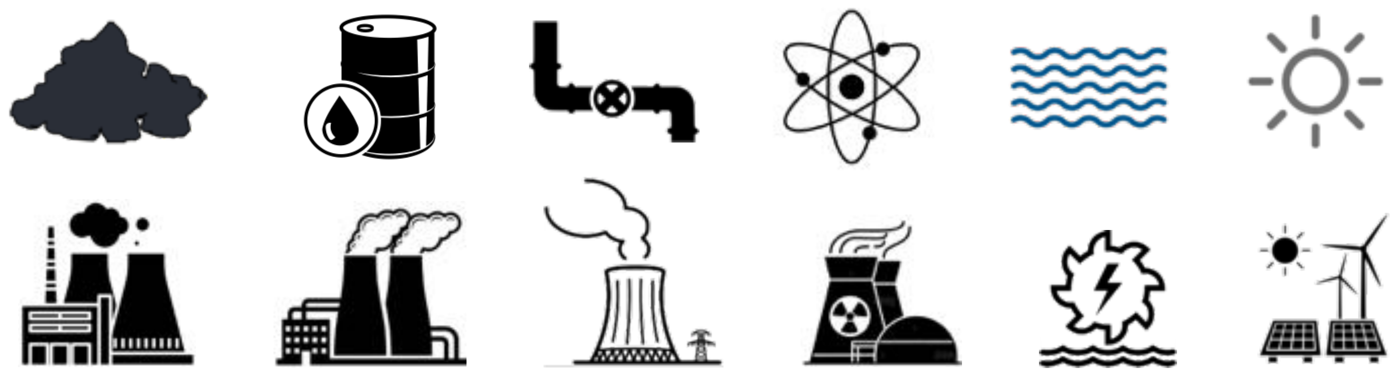
Gestehungskosten der Elektrizität (2023)



Gestehungskosten der Elektrizität (Zukunft)

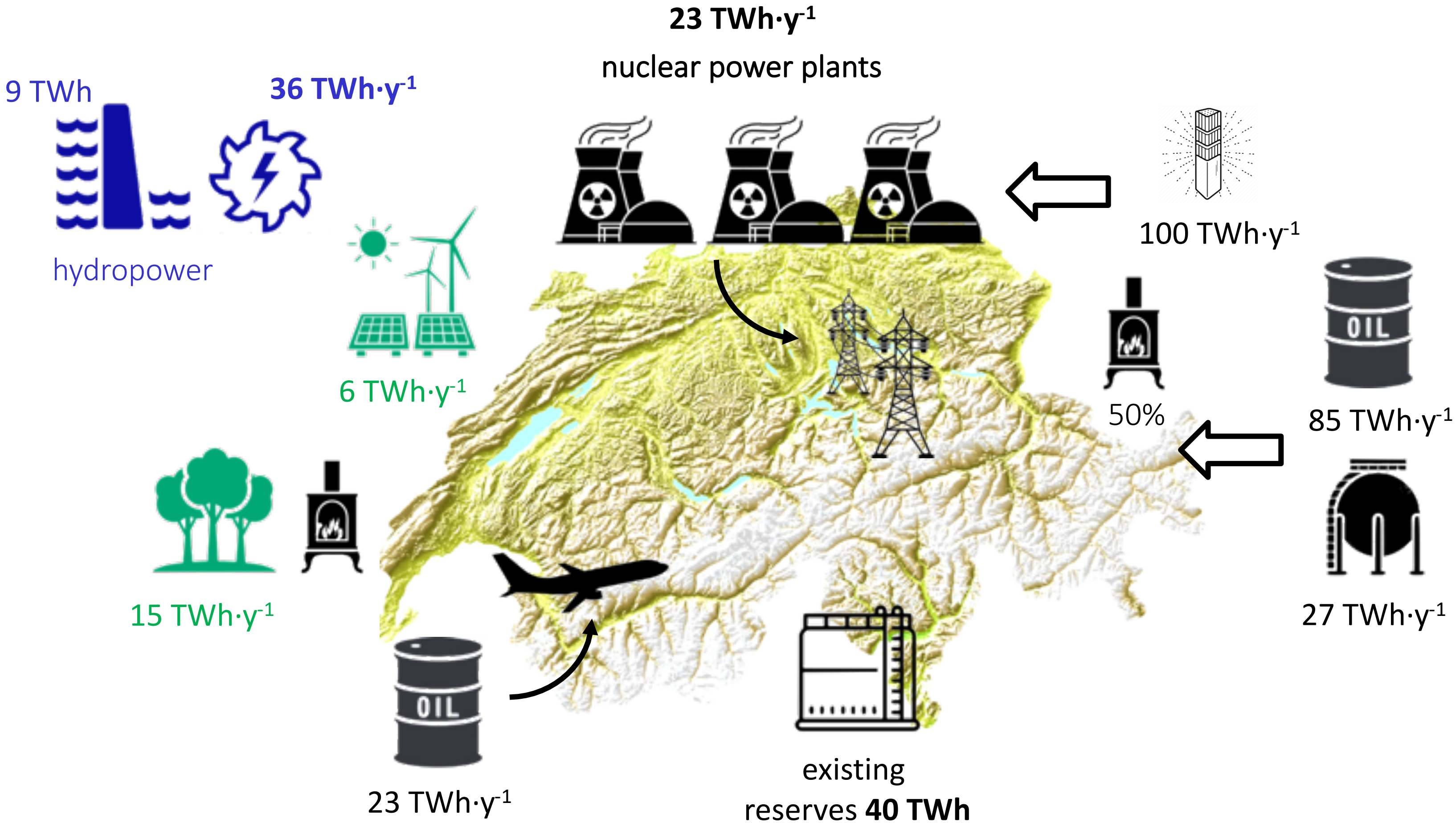


Globale Kraftwerkseinheiten (KWE)

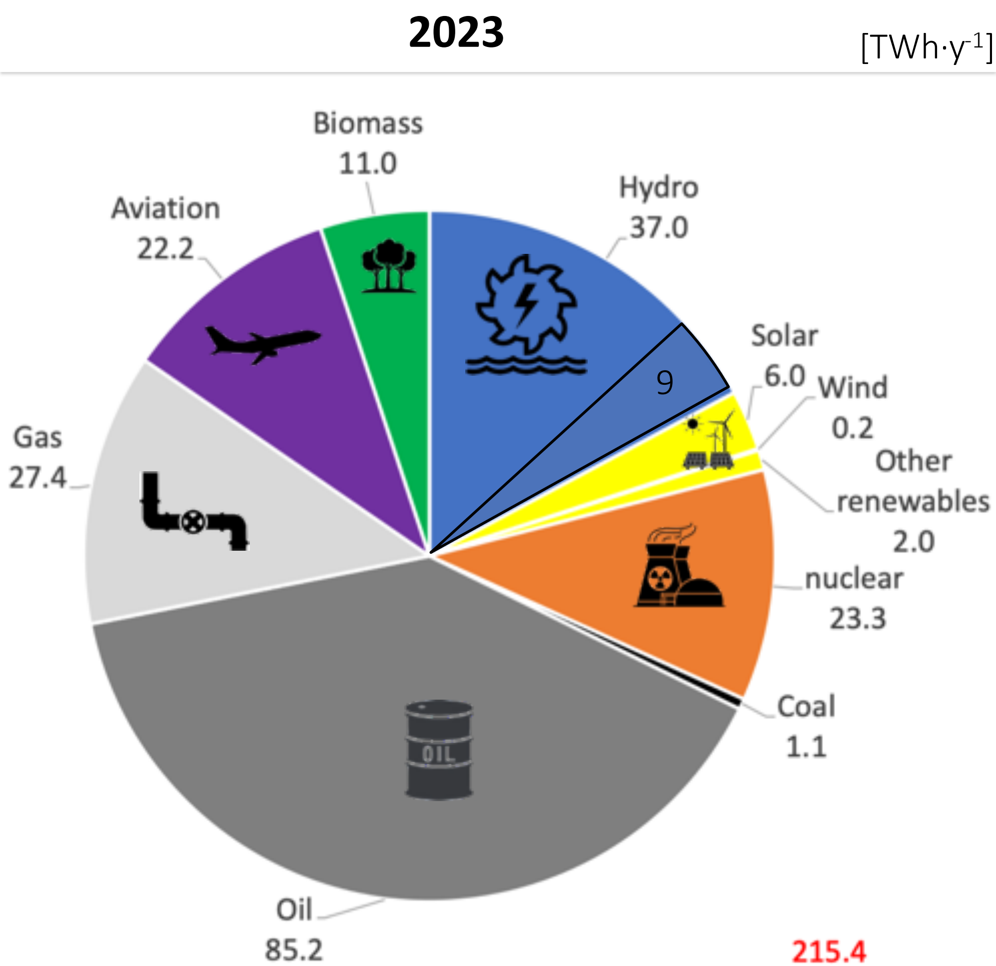


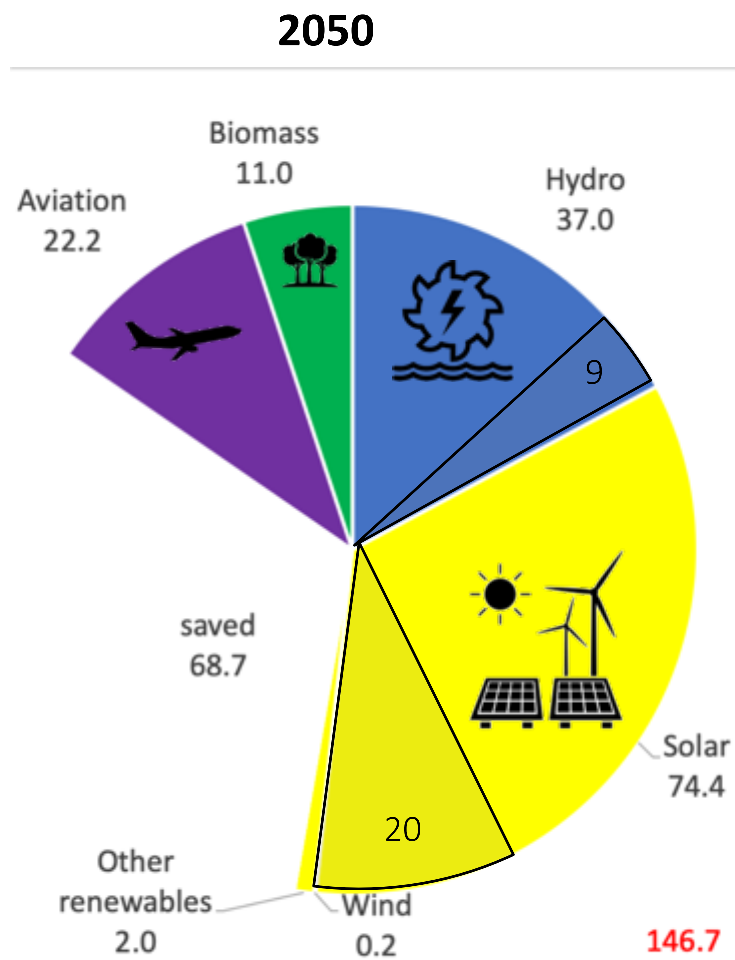
							TOTAL
Elektrizitätsproduktion							
P [TW]:	1.2	0.16	0.64	0.29	0.48	0.4	**3.3**
P [TW]:	4.8	0.48	1.6				6.9
PP:	2400	2281	1000	440	5000		
PPU [1 GW]:	1200	228	640	290	480	420	3258
m C [$Gt \cdot y^{-1}$]	3.9	0.4	0.8	0	0	0	5.1
Direkte Anwendung fossiler Brenn- und Treibstoffe							
P [TW]:	0	4.1 (1.4)	2.8 (1.4)				6.9
m C [$Gt \cdot y^{-1}$]	0	3.4	1.4	0	0	0	4.8
Substitution der fossilen Energie							
PPU [1 GW]:	*1200*	*1598*	*2040*	*290*	*0*	*0*	*5128*

Schweizer Energiebedarf



Energiebedarf nach Quellen (2023 and 2050)



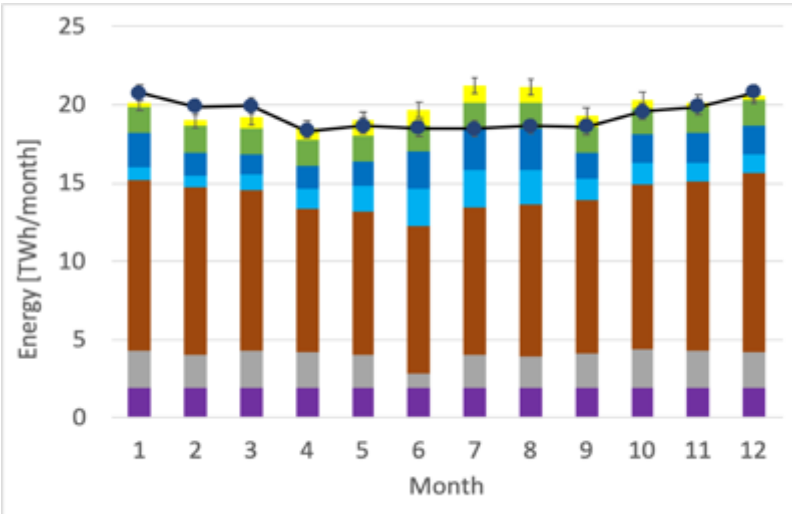


Ref.: Andreas ZÜTTEL, Noris GALLANDAT, Paul J. DYSON, Louis SCHLAPBACH, Paul W. GILGEN, Shin-Ichi ORIMO, "Future Swiss Energy Economy: the challenge of storing renewable energy", Frontiers in Energy Research: Process and Energy Systems Engineering, 9 (2022)

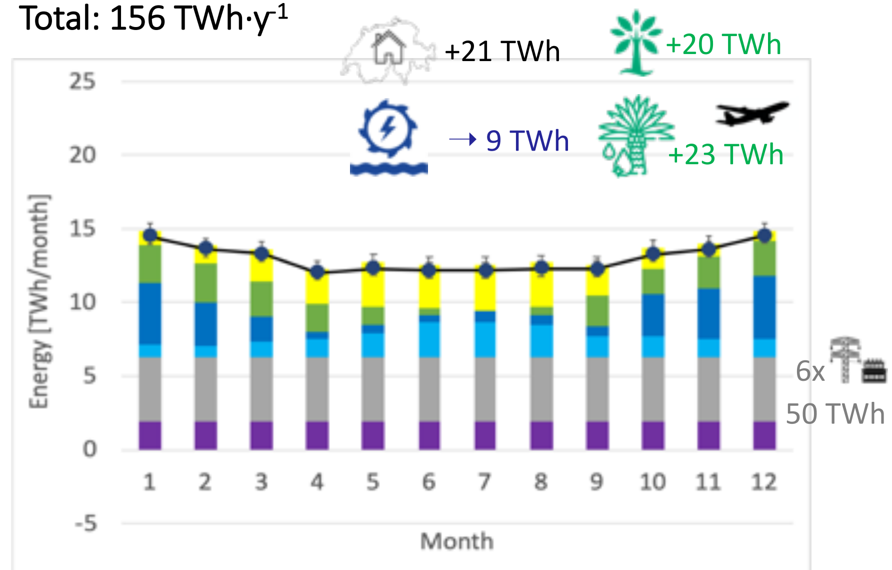
Energieautonomie für die Armee

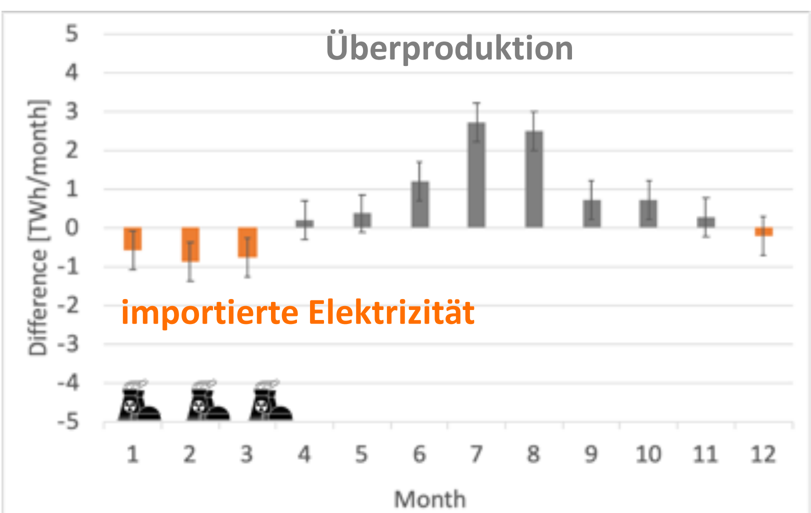
Substitution fossiler mit erneuerbare Energie

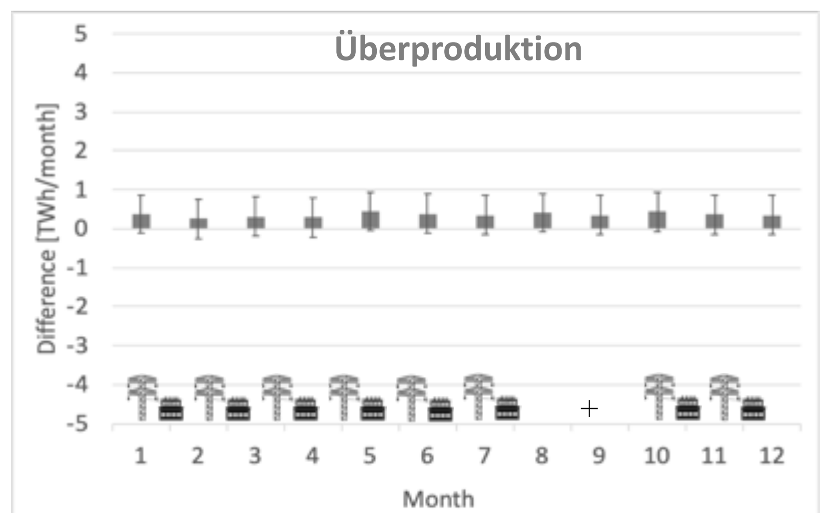
Total: 232 $TWh \cdot y^{-1}$ Fossil: 122 $TWh \cdot y^{-1}$



Total: 156 $TWh \cdot y^{-1}$







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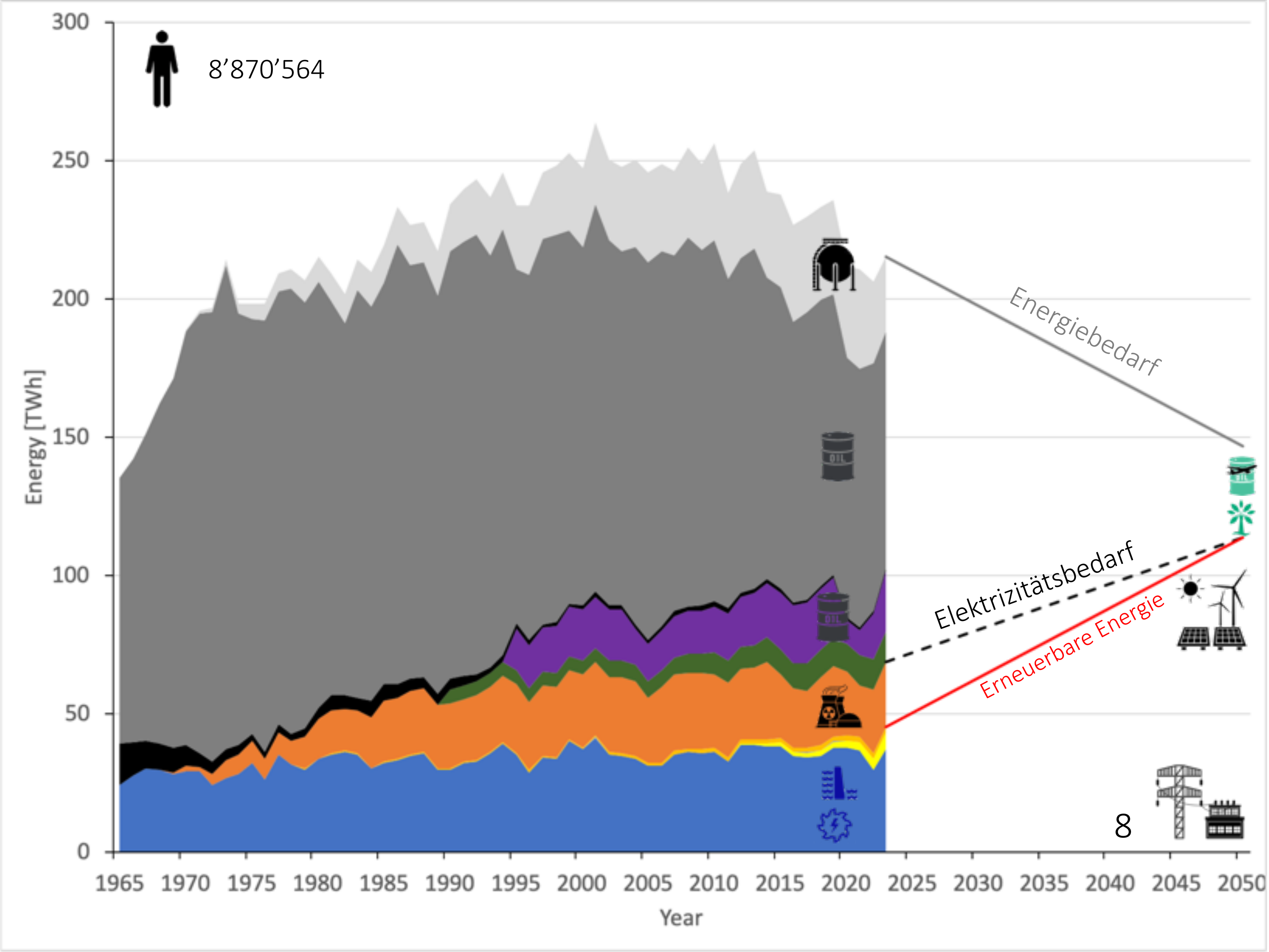
Energiewende (1965 – 2050)



Eigenschaften der Kraftwerkseinheiten

		Gesetz		H_2	
K [CHF·kWh^{-1}]	0.05	0.08	0.25	0.45	0.48
CAPEX [BCHF]	4	8-12	38	71 Speicher	64
Area PV [km^2]	0	0	78	112	82
Area Bio [km^2]		(1'033)	(1'033)	(1'033)	4'900 (1'033)

(….) Import	H_2 →	→	→
K [CHF·kWh^{-1}]	1.00 Kosten	2.20 Kosten	0.35
CAPEX [BCHF]	7 (120)	5 (117)	4 (117)
Area PV [km^2]	0 (120)	0 (1380)	0 (6)
Area Bio [km^2]	0 (1'033)	0 (1'033 + CO_2 2.3 Mt·y^{-1})	(7230)

Kraftwerkseinheiten (KWE), Energie, Kosten Platzbedarf

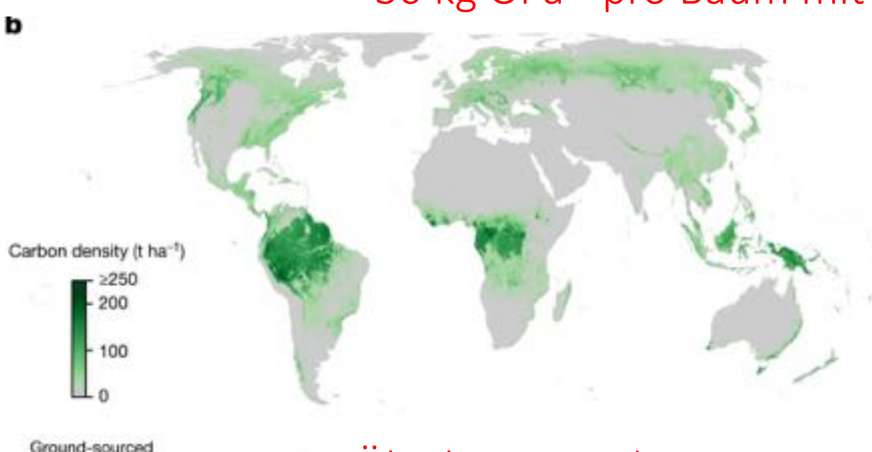
KWE's 	$W_{el.}$ + Q [TWh·y^{-1}]	**LCOE [€·kWh^{-1}]**	CAPEX [G€]	OPEX [G€·y^{-1}]	TCS [G€·y^{-1}]	**Fläche (PV) [km^2]**	Bemerkungen
	8.7 + 17.4	**0.05**	5.5	0.3	0.4	**1**	Energie, Import U, kompakt, billig
	8.7 + 8.7	**0.11**	3	0.9	0.9	**1**	Import Erdgas, fossil, CCS
	*8.7 (75%)*	**0.13**	9.6 + 6	1	1.1	**100**	Energielücke, gross
	8.7 + 2.2	**0.56**	43	1	2.4	**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	0.04	**10**	local, dynamisch billig, Speicher
	8.7	**0.16**	2 + 6	0.5	1.4	**850**	Meeresbucht, Gezeiten

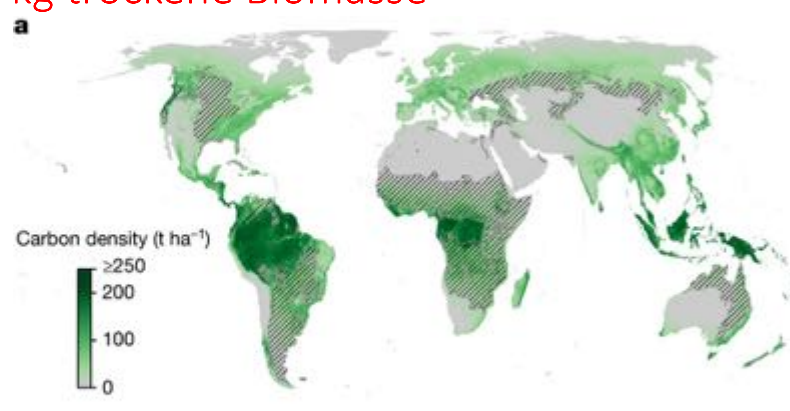
Uran: 200 t Natururan (0,7%) ergeben 20 Tonnen Uran (5%), Natururan kostet 130 €/kg
Batterie kostet 100 €/kWh, Lebensdauer 8 Jahre
PV kostet 1200 €/kWp, produziert 220 kWh·m^{-2}·y^{-1}, Spitzenleistung 1 kW·m^{-2}
Palmöl kostet 0,7 €/L, Energiegehalt syn. Öl 10 kWh/L, Kosten 1.7 €/L
Wasserstoff ist weniger als 6.7 €/kg billiger als Palmölimport und Hydrierung und weniger als 2 €/kg billiger als Wasserkraft.
Wasserkraft braucht Täler und Höhenunterschiede, Kernkraft braucht eine Änderung der Gesetzgebung, PV mit Batterie deckt nur 75% ab, PV mit Batterie und Wasserstoff ist am teuersten, aber am universellsten, Palmöl mit Hydrierung ist ein Import eines umstrittenen Produkts, aber einfach und billig zu speichern.

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·a^{-1} pro Baum mit 524 kg trockene Biomasse



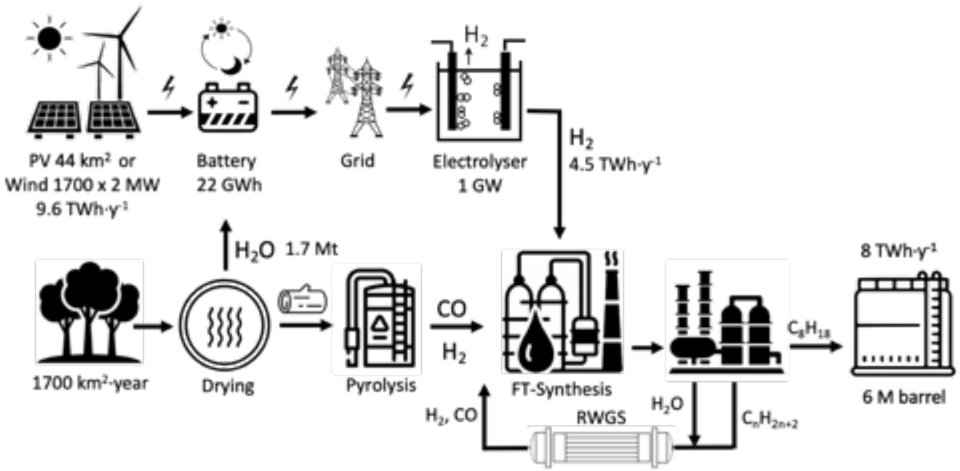


226 Gt Ölpalmen produzieren 13 Gt Öl·a^{-1} mehr als der Weltenergiebedarf an Öl

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

Inländische Synthese von Öl aus Biomasse und CO_2

Syn fuel - PPU



Biomasse

- Heute genutzt 15 $TWh \cdot y^{-1}$
- Nachhaltiges Potential 27 $TWh \cdot y^{-1}$
- Theoretisches Potential: 55 $TWh \cdot y^{-1}$

+ Abfälle, Kunststoffe, CO_2 Absorption

Reserven (Pflichtlager)

Kernenergie	>23 TWh
Wasserkraft	9 TWh
Elektrizitätsspeicher	>32 TWh
Kerosen	4 TWh
Diesel	12 TWh
Benzin	11 TWh
Heizöl	10 TWh
Gas	4 TWh
Kohle	1 TWh

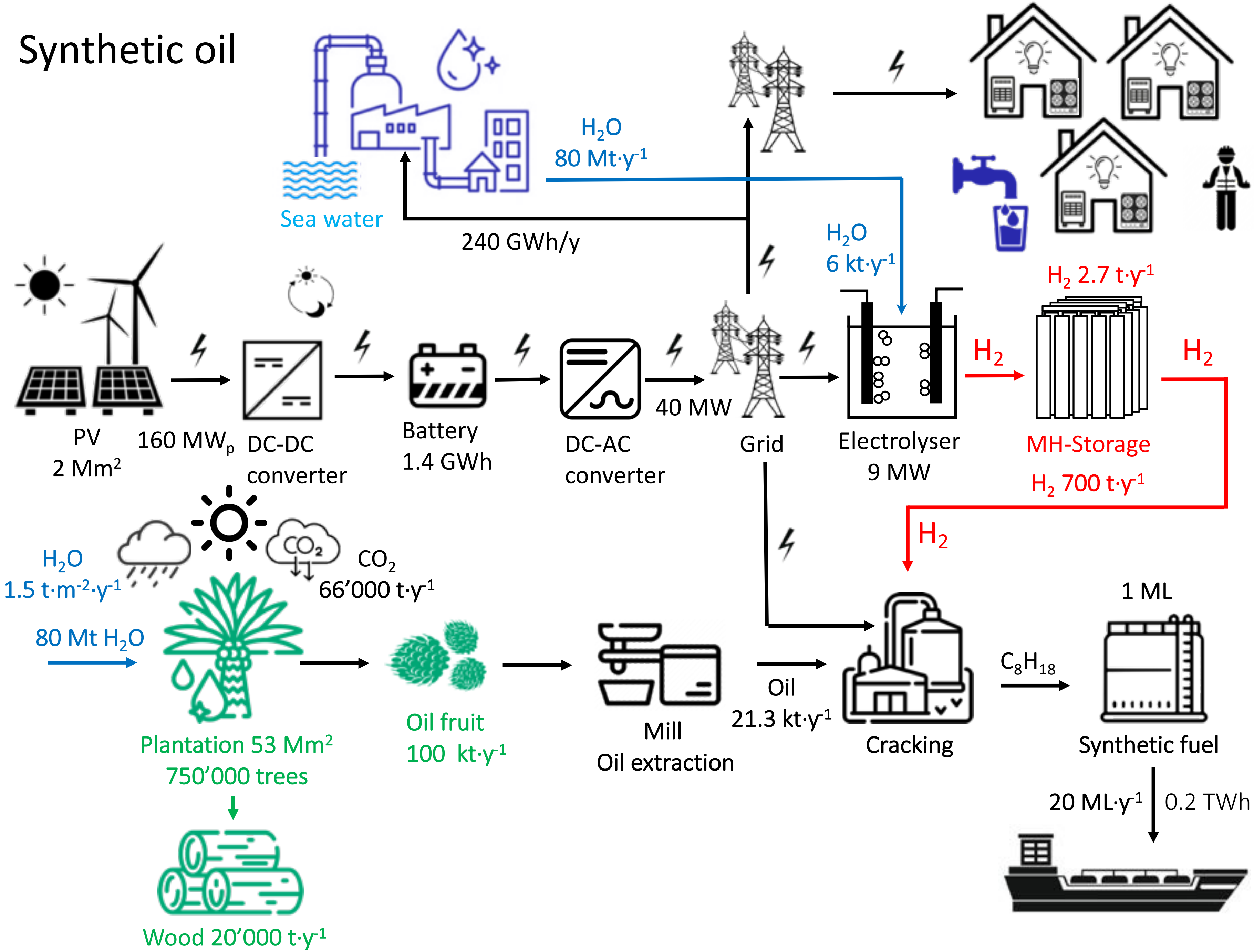
→

Brenn- und Treibstoffe	42 TWh
Biomasse	11 TWh
Nahrung	? TWh

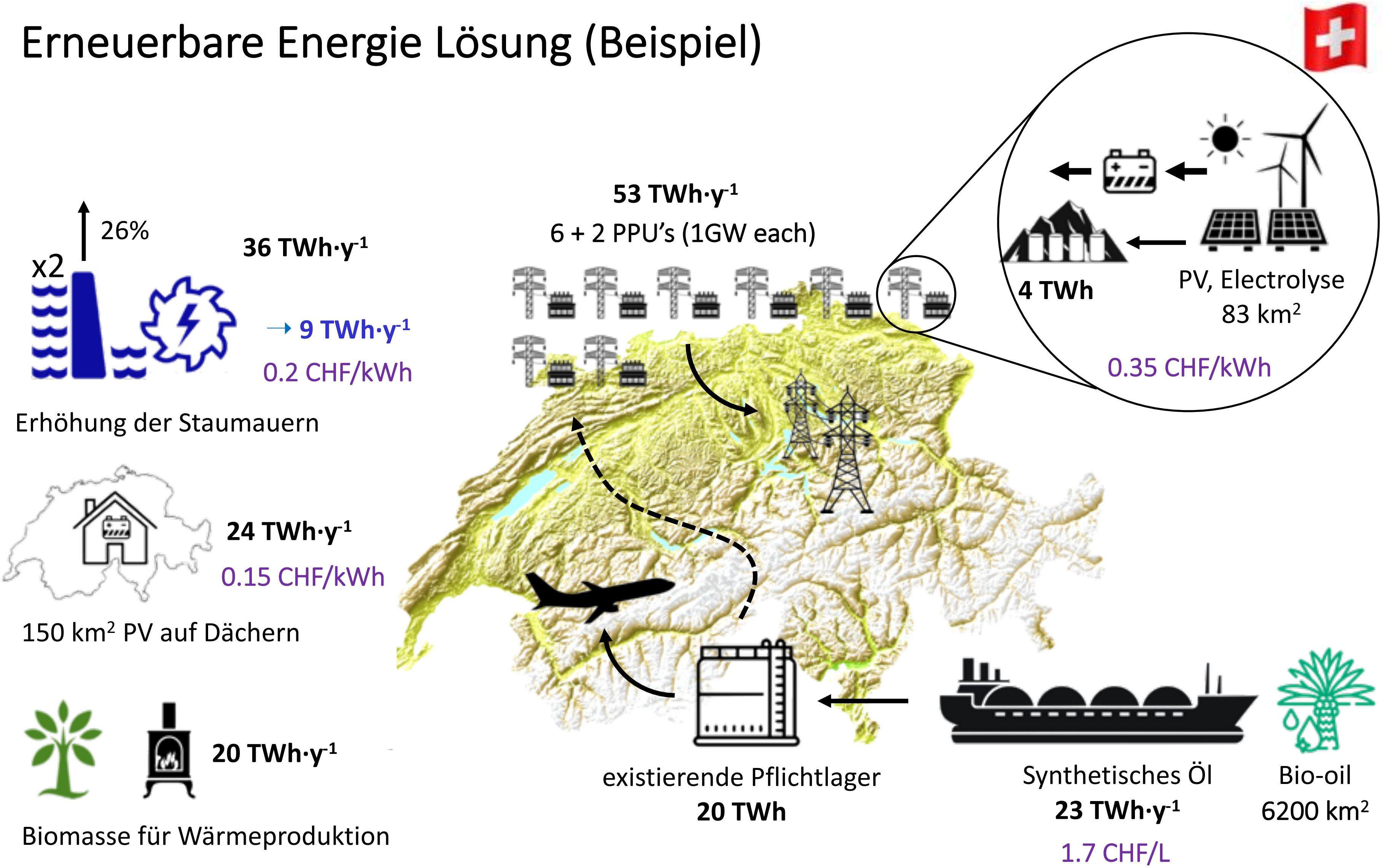
Speicherung von 40 TWh Elektrizität bei einem Verbrauch von 60 TWh/Jahr

Ref.: www.carbura.ch

Synthetic oil



Erneuerbare Energie Lösung (Beispiel)



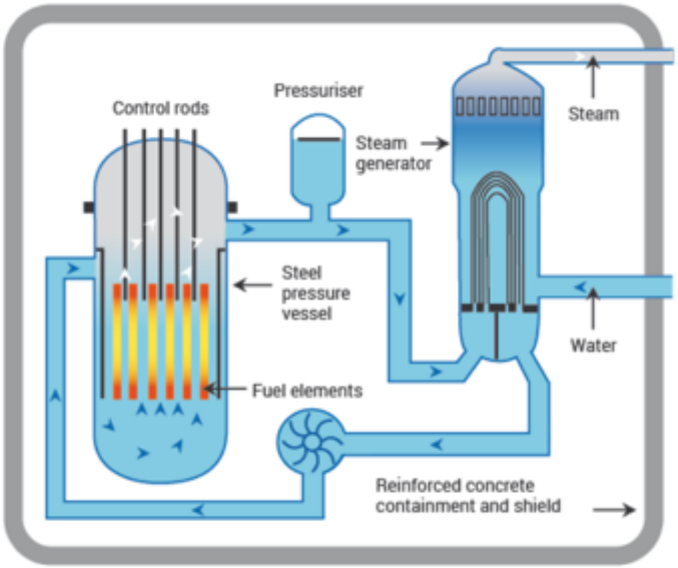
Senken des Energieverbrauchs durch Isolation, Nutzung der Abwärme aus den Kraftwerken zum Heizen.

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).

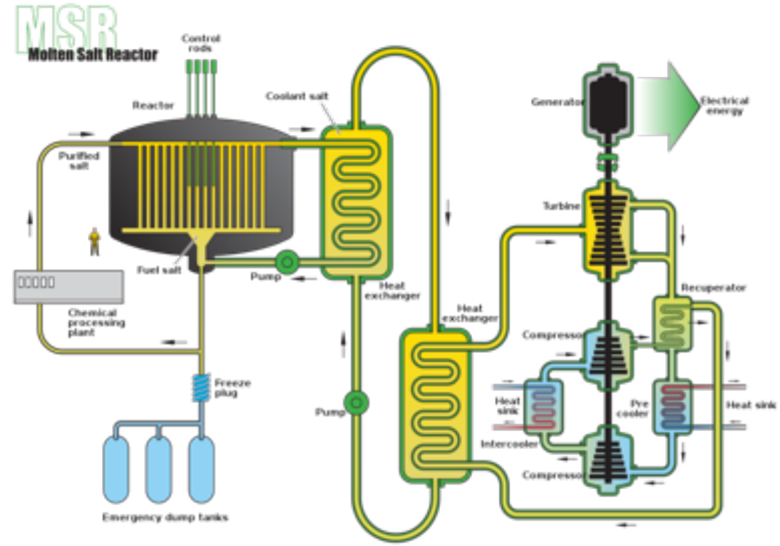
Kernreaktoren

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)

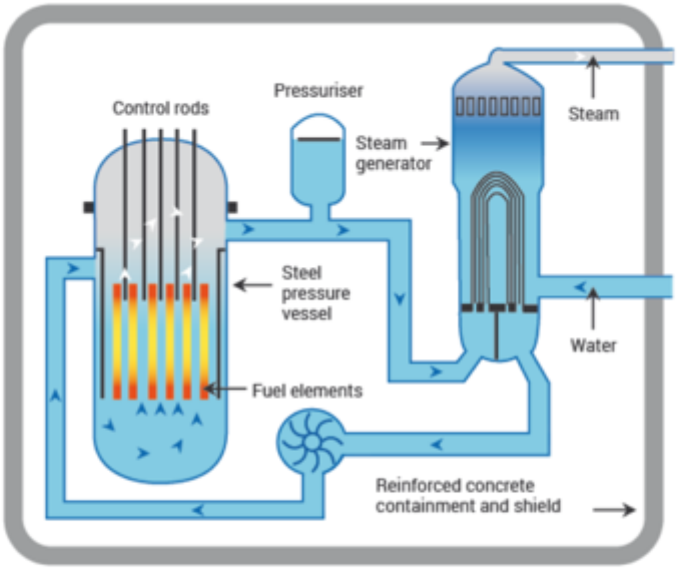
Vorteile:

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



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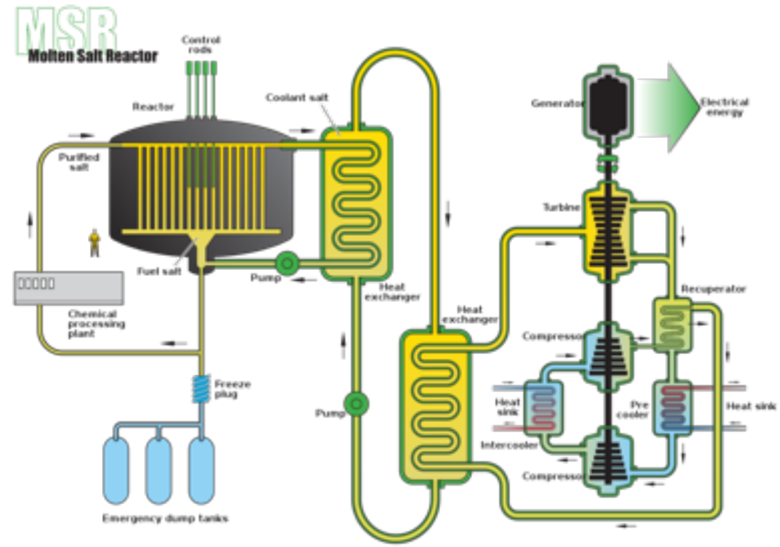
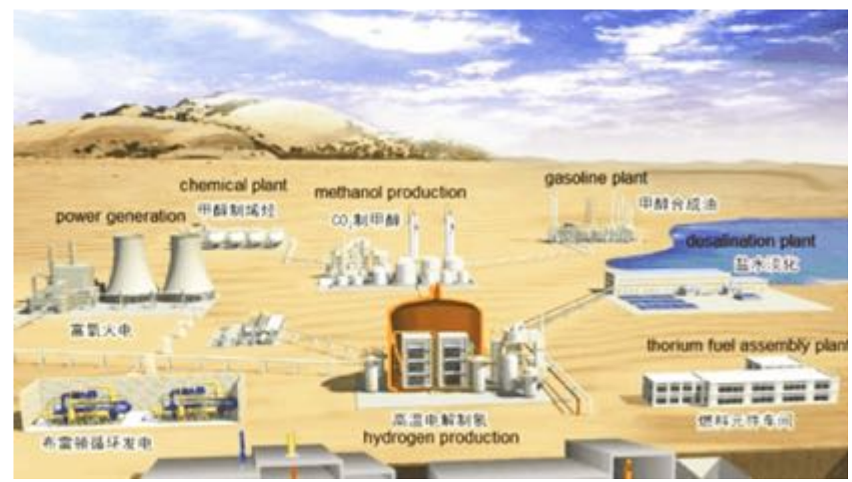
Endlager von Nuc. Abfall
Kleine modulare Reaktoren (SMR)

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

Thorium-Flüssigsalz-Brutreaktoren

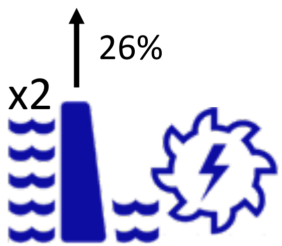


Unterirdisch im Berg, Wärmenutzung



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

CO_2 neutrale Energie Lösung (Beispiel)



36 TWh·y⁻¹

→ **9 TWh·y⁻¹**

0.2 CHF/kWh

Vergrösserung der Wasserspeicher

24 TWh·y⁻¹

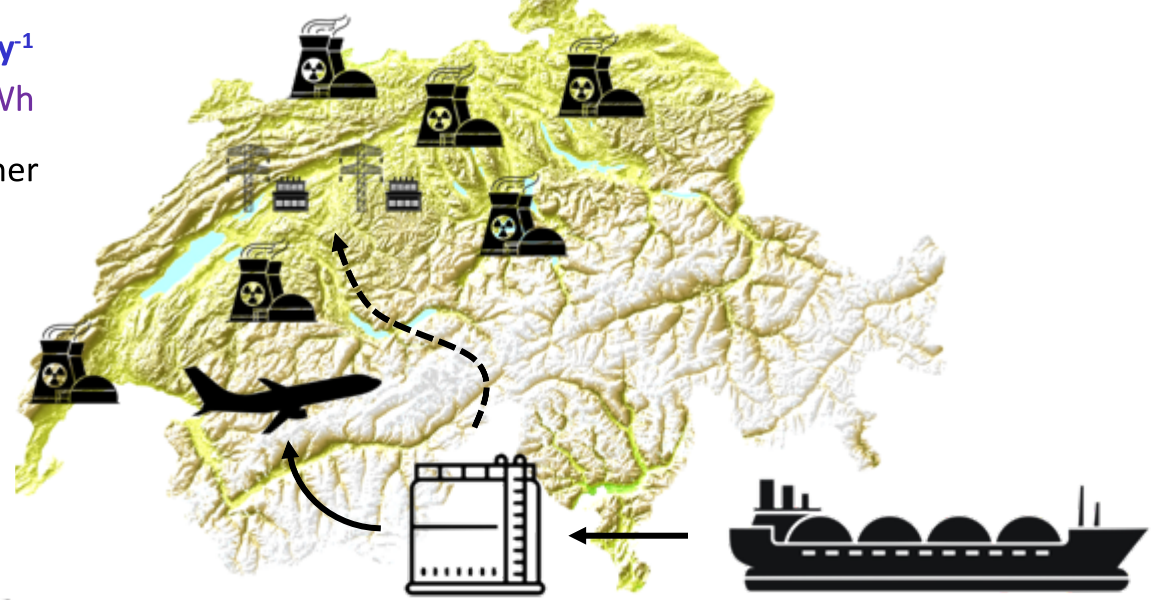
0.15 CHF/kWh

150 km² PV auf Dächern

20 TWh·y⁻¹

Biomasse zum Heizen

6 + 2 PPU's (1GW each) 0.17 CHF/kWh



existierende Reserven **20 TWh**

Öltanker

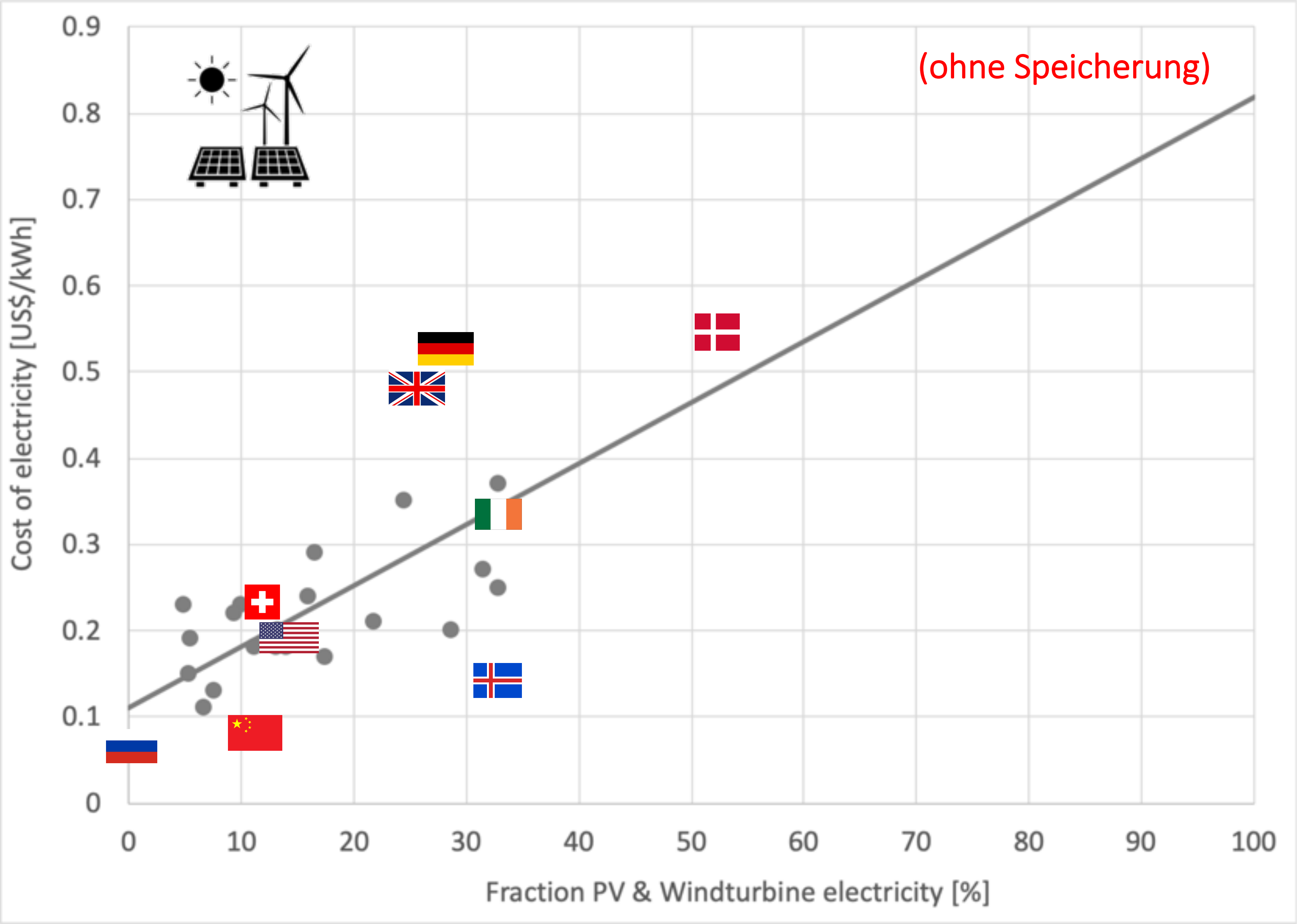
23 TWh·y⁻¹

1.7 CHF/L

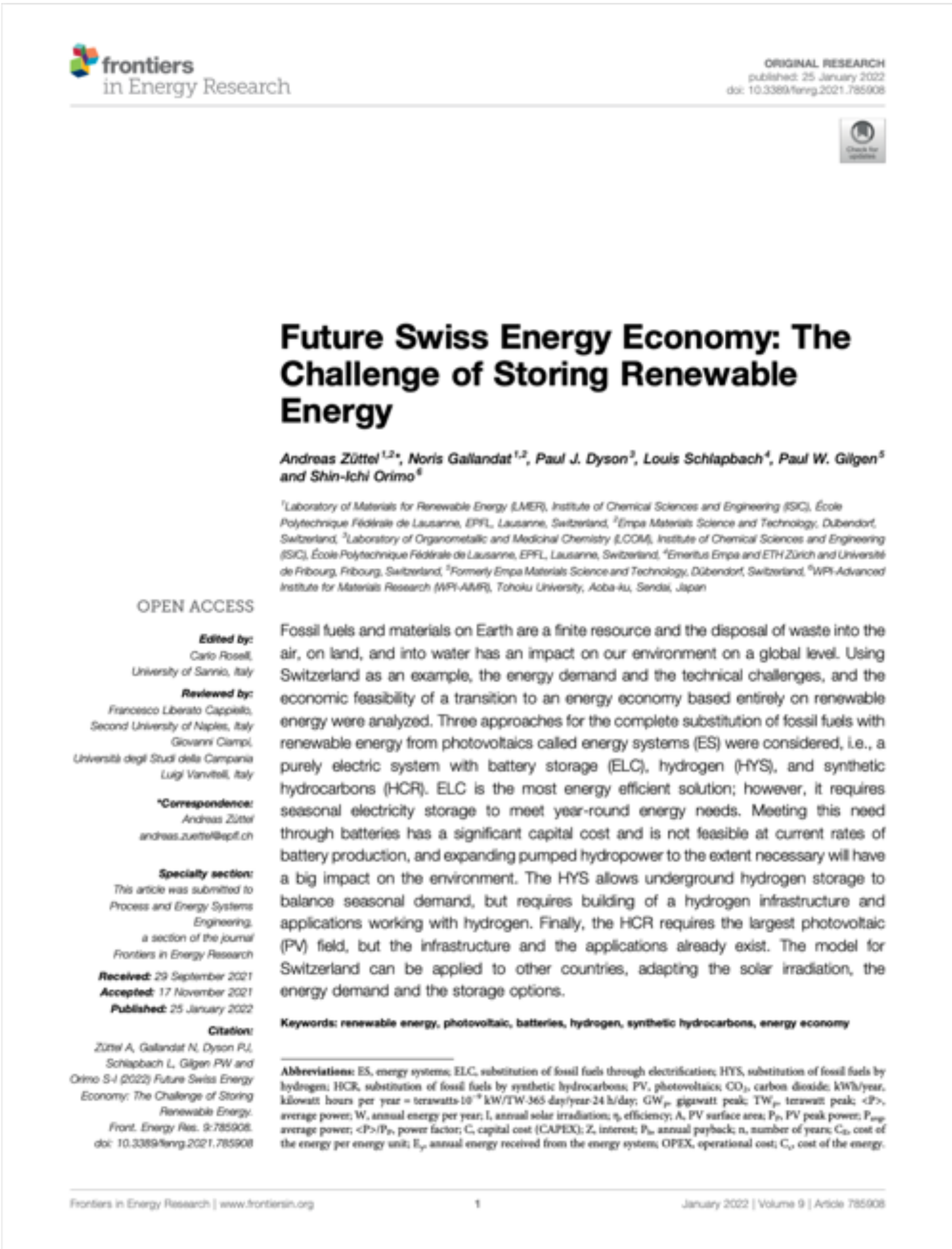
Bio-Oil

<6200 km²

Kosten der Elektrizität (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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Specialty section:
This article was submitted to
Process and Energy Systems
Engineering,
a section of the journal
Frontiers in Energy Research

Received: 29 September 2021
Accepted: 17 November 2021
Published: 25 January 2022

Citation:
Züttel A, Gallandat N, Dyson PJ, Schlapbach L, Gilgen PW and Orimo S-I (2022) Future Swiss Energy Economy: The Challenge of Storing Renewable Energy.
Front. Energy Res. 9:785908.
doi: 10.3389/fenrg.2021.785908

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.

Frontiers in Energy Research | www.frontiersin.org 1 January 2022 | Volume 9 | Article 785908

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Andreas ZÜTTEL, Noris GALLANDAT, Paul J. DYSON, Louis SCHLAPBACH, Paul W. GILGEN, Shin-Ichi ORIMO, “Future Swiss Energy Economy: the challenge of storing renewable energy”, Frontiers in Energy Research: Process and Energy Systems Engineering, 9 (2022), https://doi.org/10.3389/fenrg.2021.785908

Publication 2024

frontiers | Frontiers in Energy Research

TYPE Original Research
PUBLISHED 02 August 2024
DOI 10.3389/fenrg.2024.1336016

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OPEN ACCESS

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RECEIVED 09 November 2023
ACCEPTED 22 May 2024
PUBLISHED 02 August 2024

CITATION
Züttel A, Nützenadel C, Schlapbach L and Gilgen PW (2024), Power plant units for CO_2 neutral energy security in Switzerland.
Front. Energy Res. 12:1336016.
doi: 10.3389/fenrg.2024.1336016

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.

Prof. Dr. Andreas ZÜTTEL

Dr. Christoph NÜTZENADEL

Prof. Dr. Louis SCHLAPBACH

Mr. Paul W. GILGEN

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), https://doi: 10.3389/fenrg.2024.1336016

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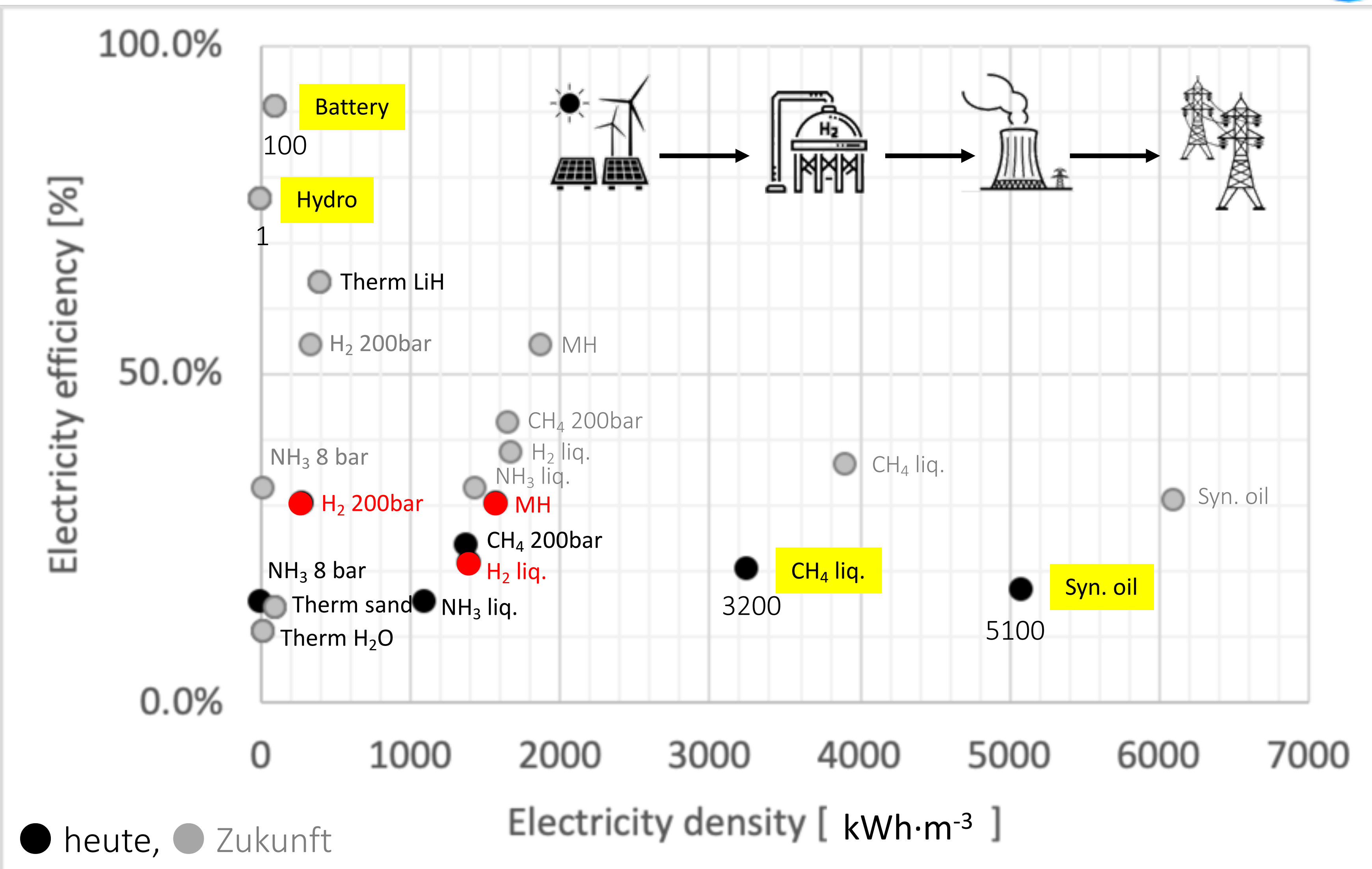
Effizienz und Speicherdichte erneuerbarer Elektrizität



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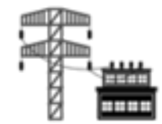
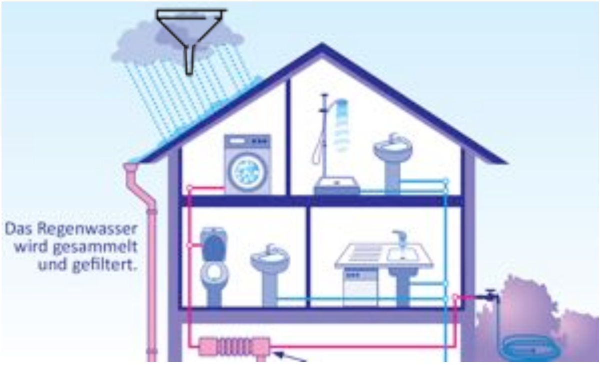
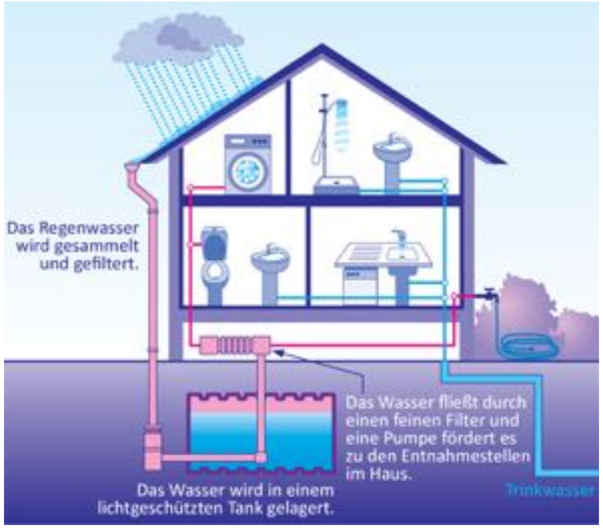
Erneuerbare Energie Produktion zu Energie nach Bedarf

>50 m² PV/Person
20 kWh Batterie/Person
≈1.5 MWh Speicher/Person







1 M Einfamilienhäuser
100 m^2 Dachfläche,
3 Personen/Haus

0.5 M Mehrfamileienhäuser
200 m^2 Dachfläche,
12 Personen/Haus

440 km^2 PV Fläche, 12 TWh Elektrizitäts Speicher
Elektrizität jederzeit nach Bedarf

200 km^2 Dachfläche