“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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[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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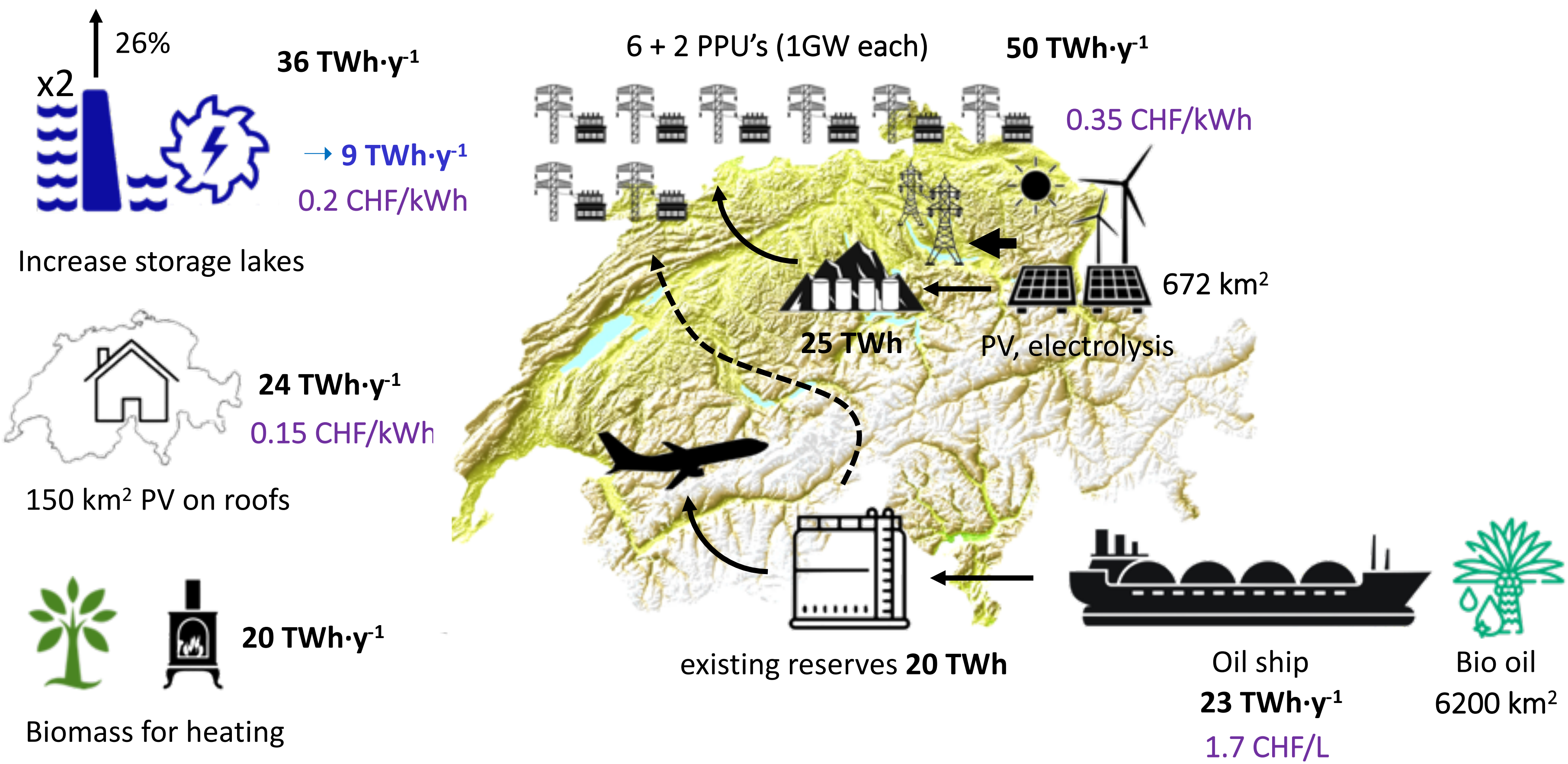
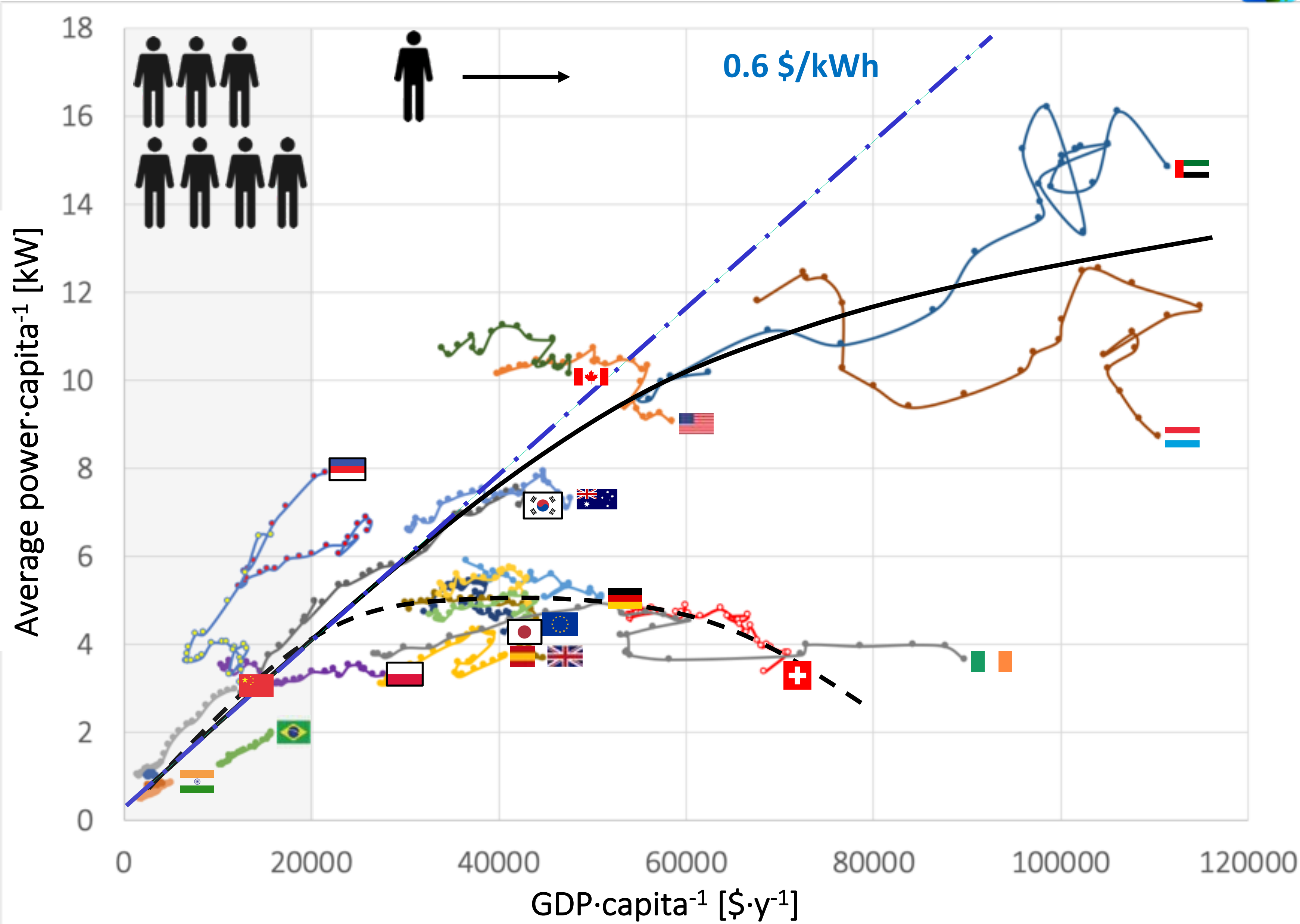
Renewable energy solution (example)



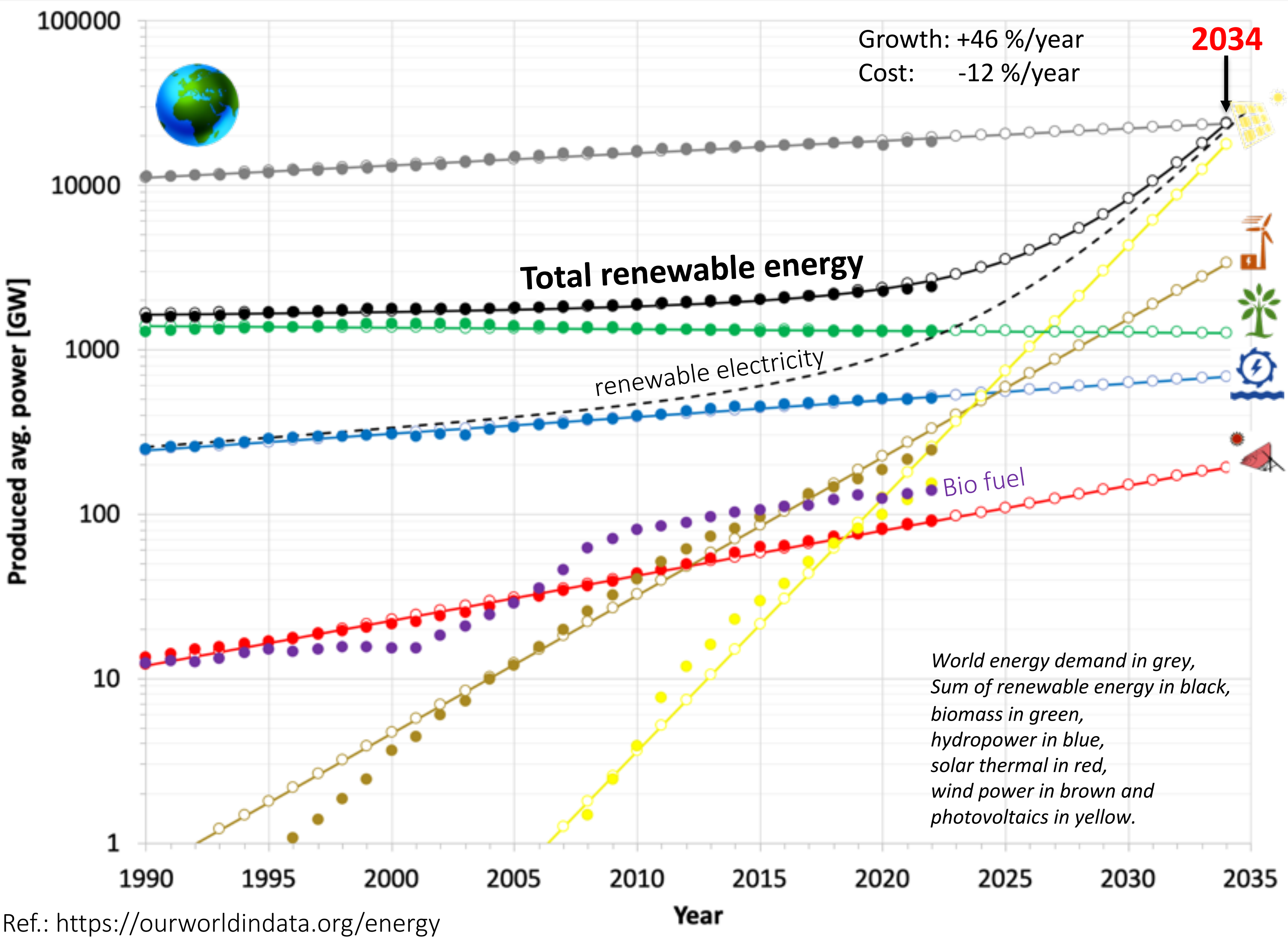
lower energy demand by heat use, heat storage, Insulation

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

Renewable energy system

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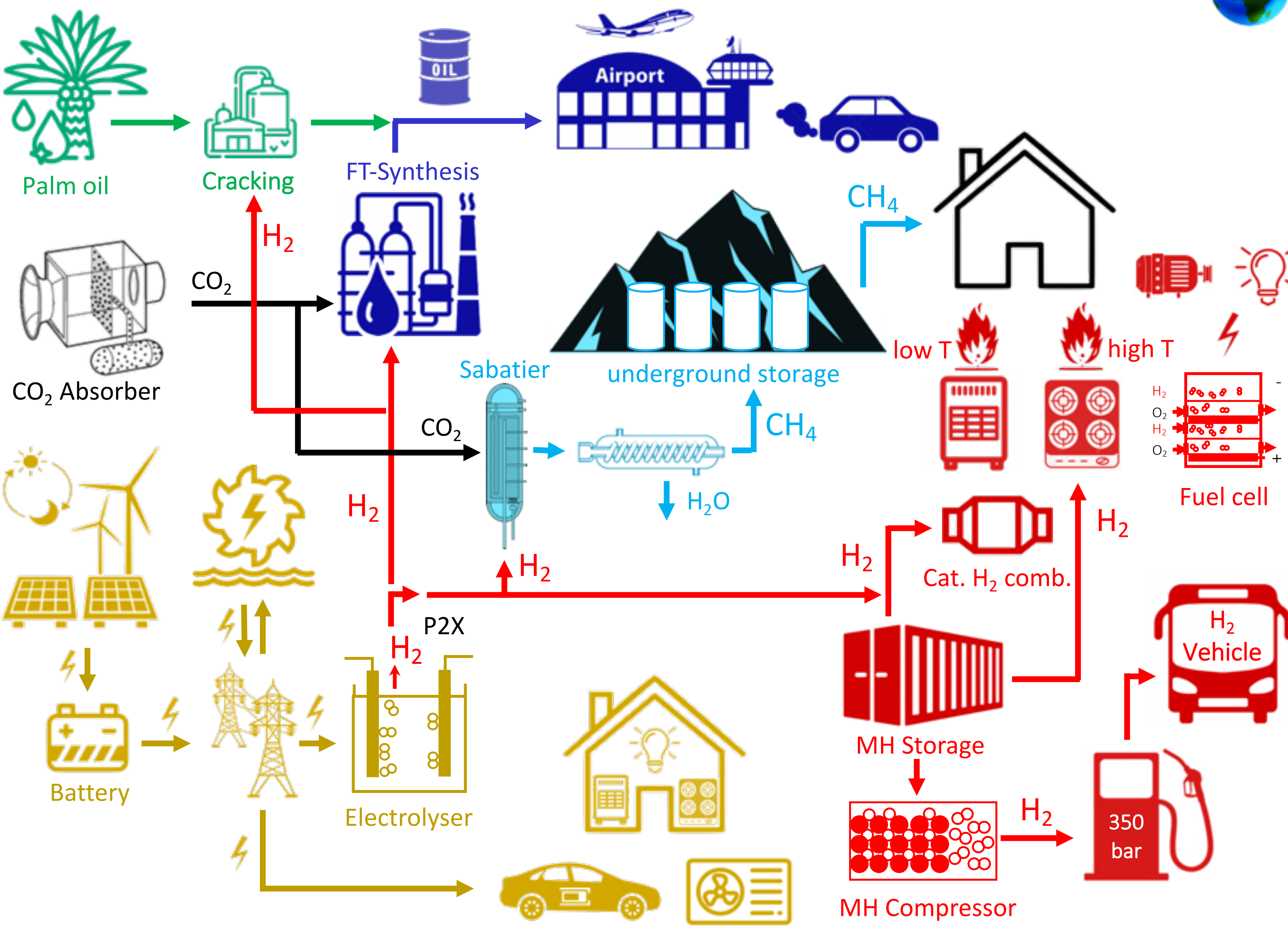
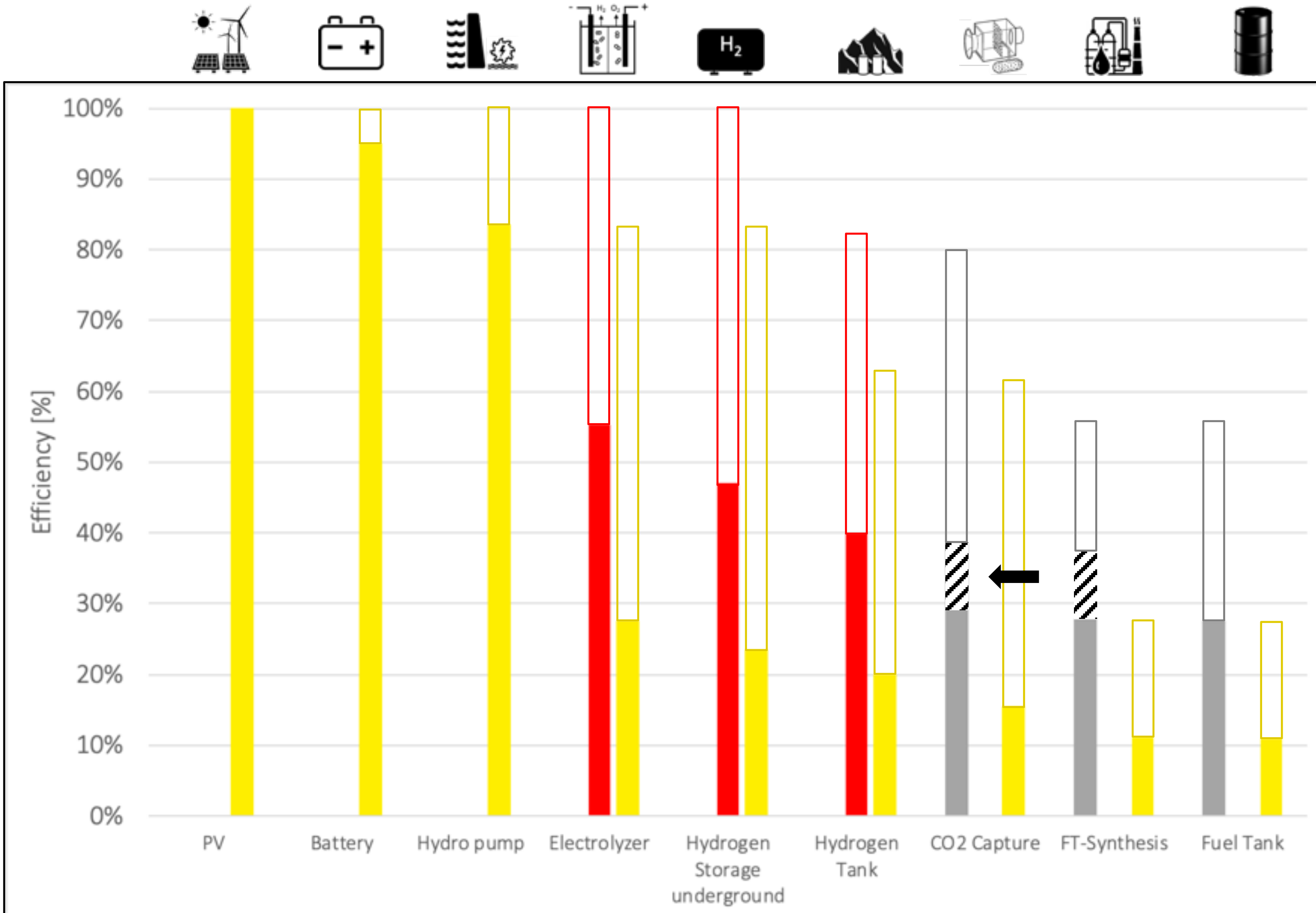
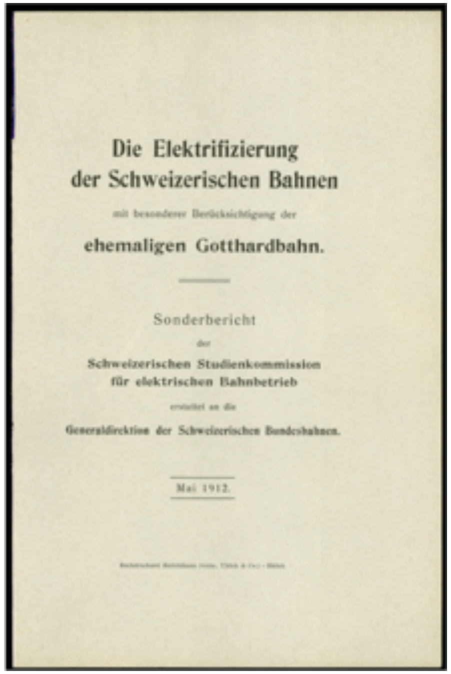


Efficiency of energy conversion

Power to X (P2X)



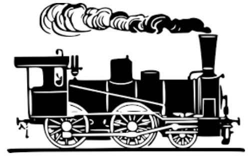
Swiss Decision for Electricity


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.

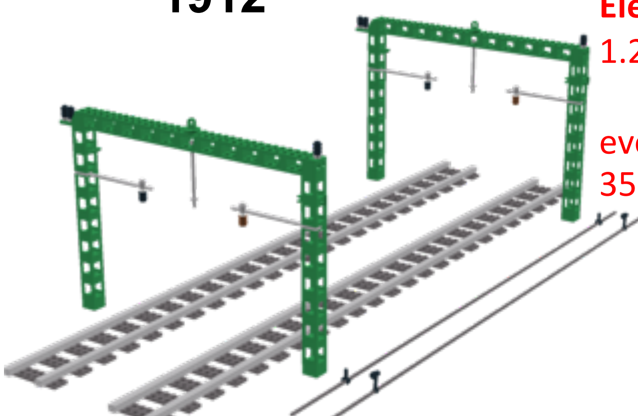
Mai 1912.

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.



Electrifying
1.23 – 2.6 Mio.€/km

every 27m is a pole,
35 – 70 k€ per pole

Railway track costs 62 Mio. CHF/km
(Highway costs 150 - 330 Mio.CHF/km)

Ref.: Germany: Lindau -München 500 Mio.€ for 189km incl. noise protection, new train station...
Denmark: whole railway 1'600 Mio.€ for 1300 km

The major change of energy economy in Switzerland

Fukushima Dai-ichi nuclear-plant disaster

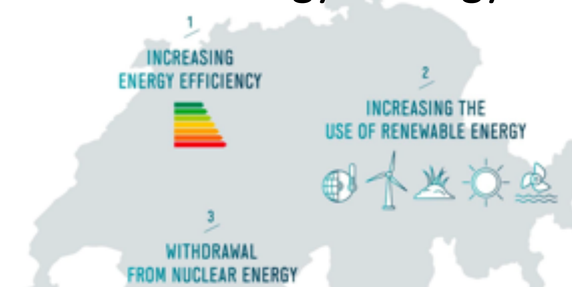

11. March 2011 24. March 2011

11. March 2011 earthquake

25. May 2011 The Federal Council has decided **not to rely on nuclear power** in the future. The existing nuclear power plants should remain connected to the grid for as long as they are safe. Confirmed by the national parliament on 8. June 2011.

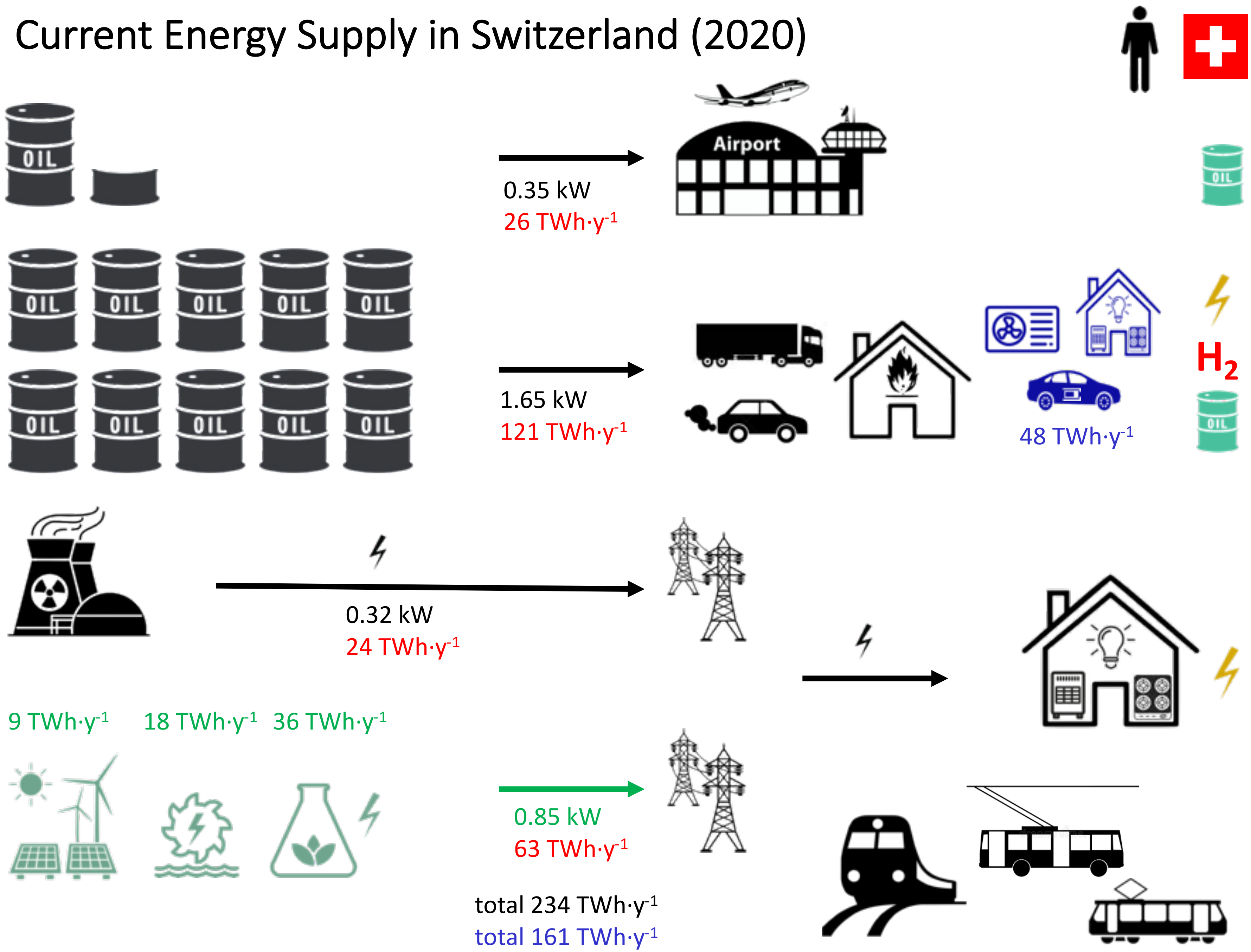
Paris climate agreement 2014

Swiss Energy Strategy 2050

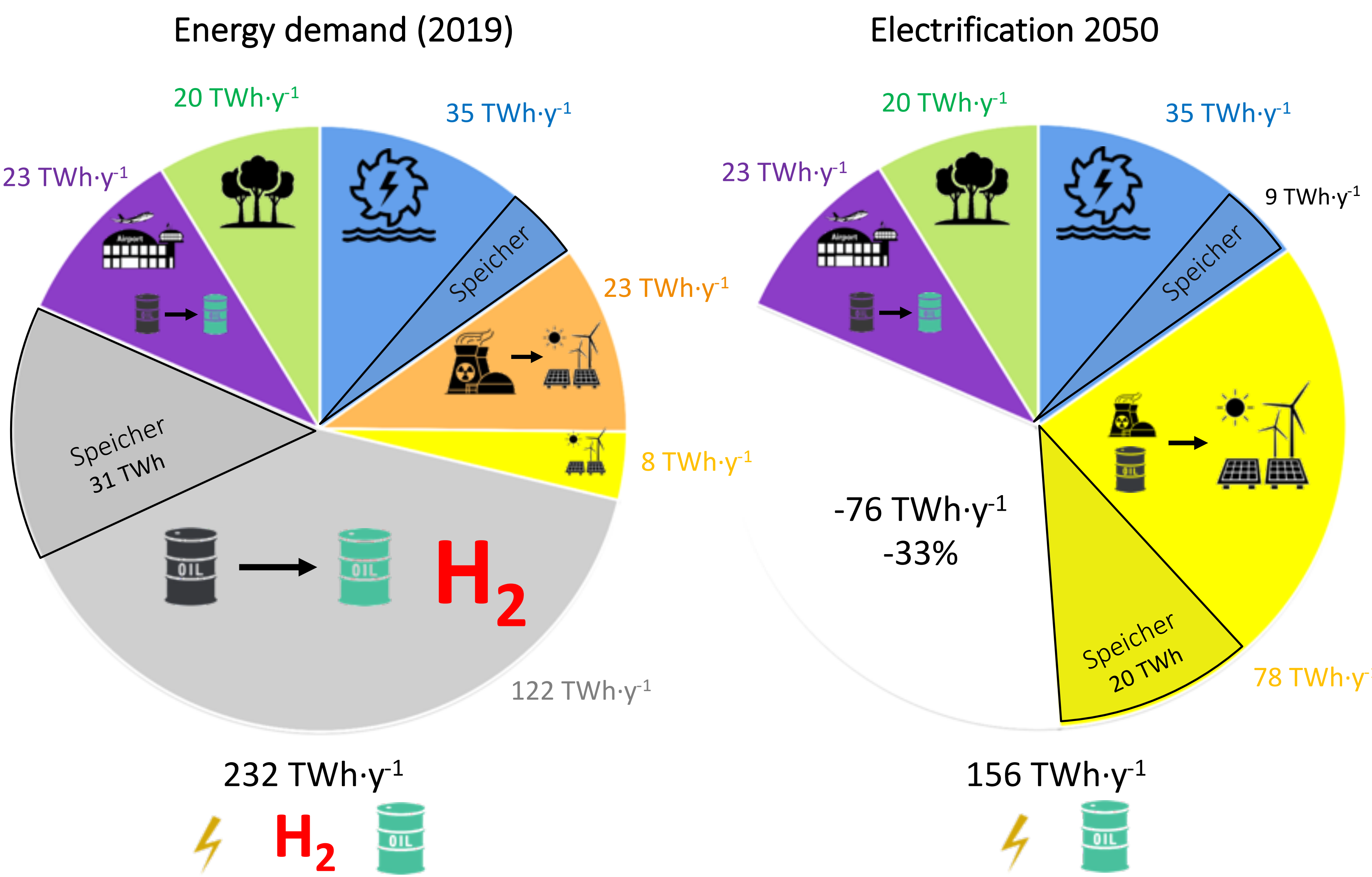


On 21 May 2017 the Swiss electorate accepted the revised Federal Energy Act. The aims behind the revision are to **reduce energy consumption, increase energy efficiency and promote the use of renewable energy**. In addition, the revised version prohibits the construction of new nuclear power plants.

Current Energy Supply in Switzerland (2020)

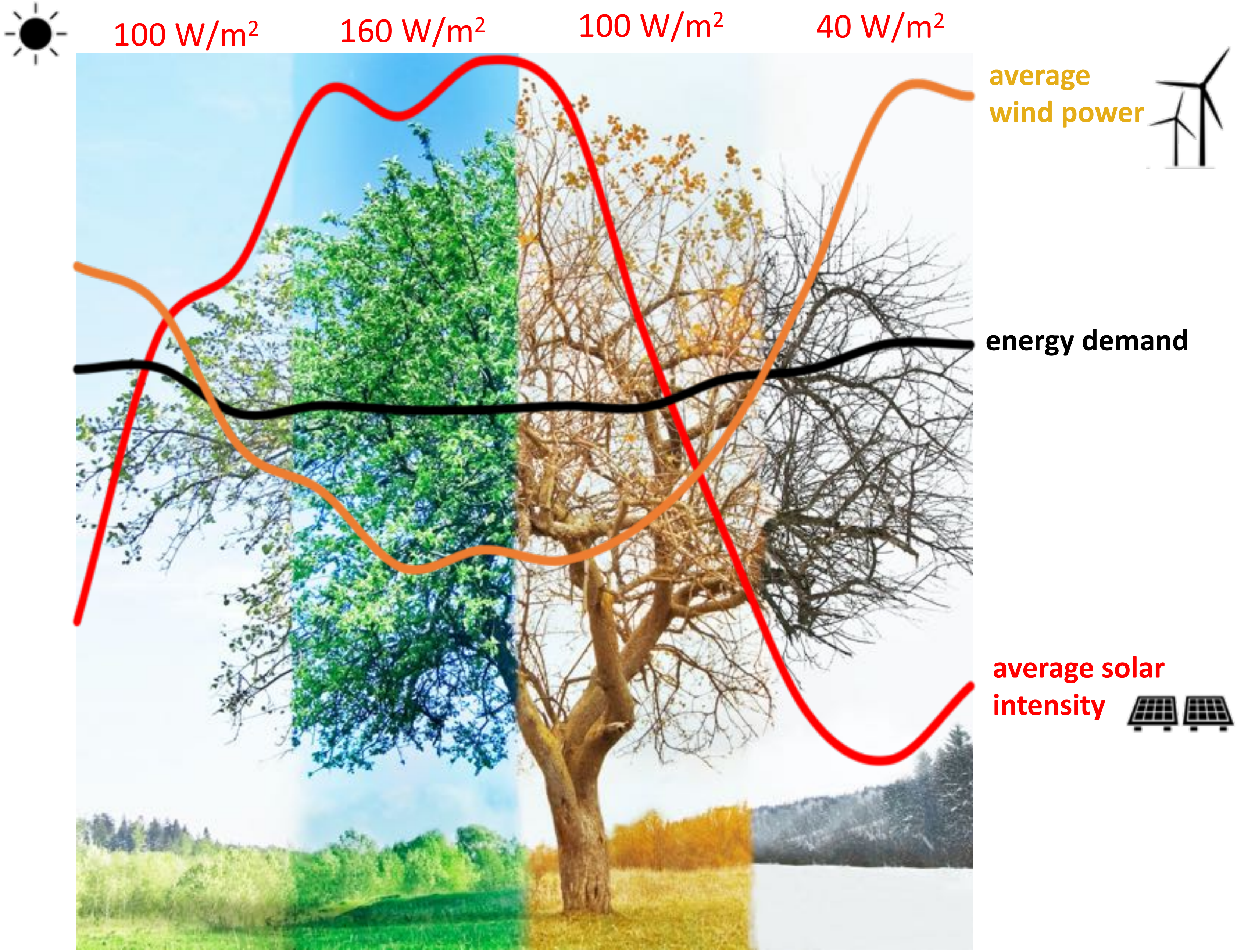


Energy demand by source and electrification

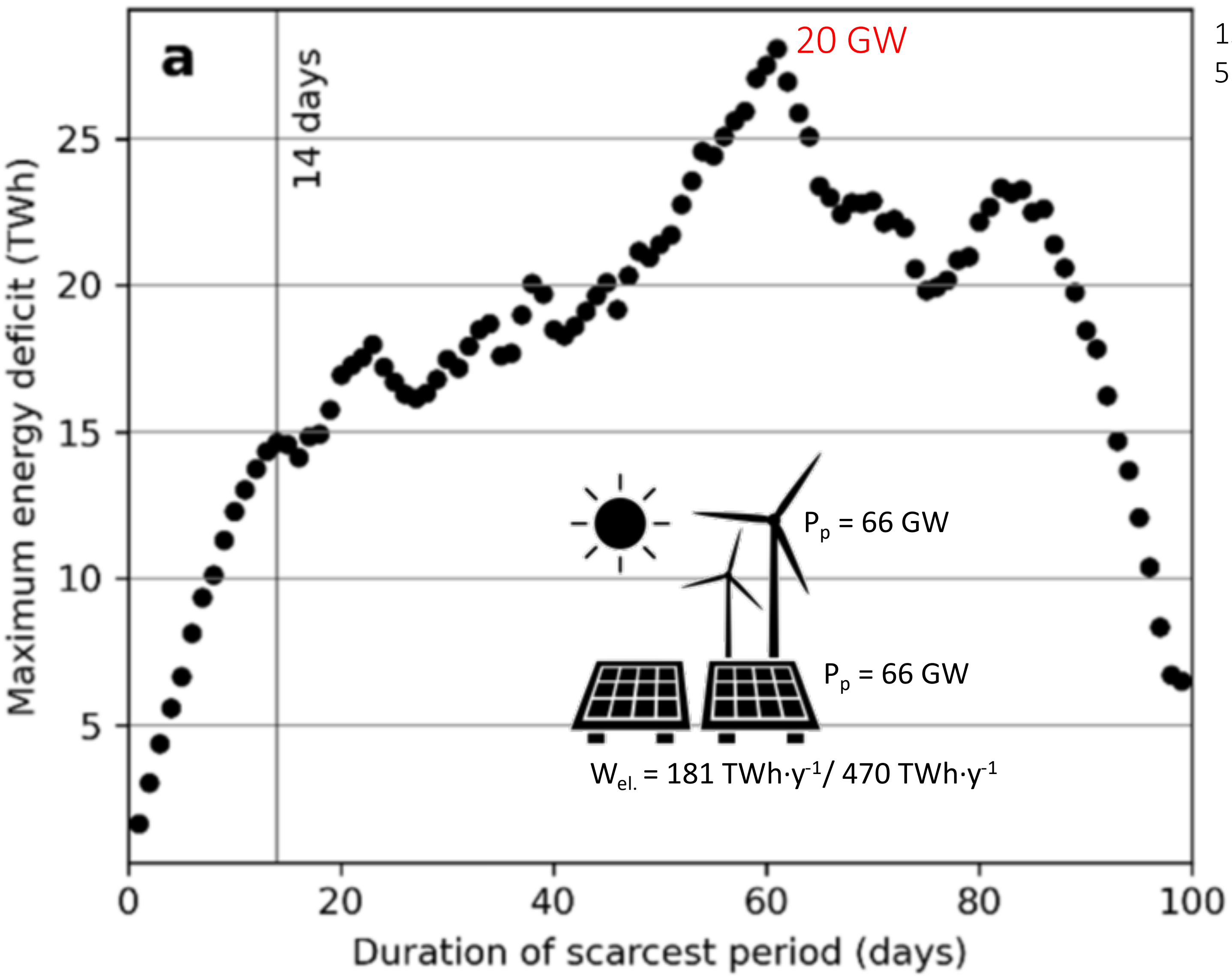


Ref.: SCHWEIZERISCHE GESAMTENERGIE STATISTIK (2019) Art.-Nr. 805.006.19 / 08.20 / 1200 / 860467013, Federal Office of Energy, Switzerland, https://www.bfe.admin.ch/bfe/de/home/versorgung/statistik-und-geodaten/energiestatistiken/gesamtenergiestatistik.exturl.html/

Seasons in Switzerland



Renewable energy storage



150 GW_p installed
53 GW avg. 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

Renewable Energy Systems: Summary

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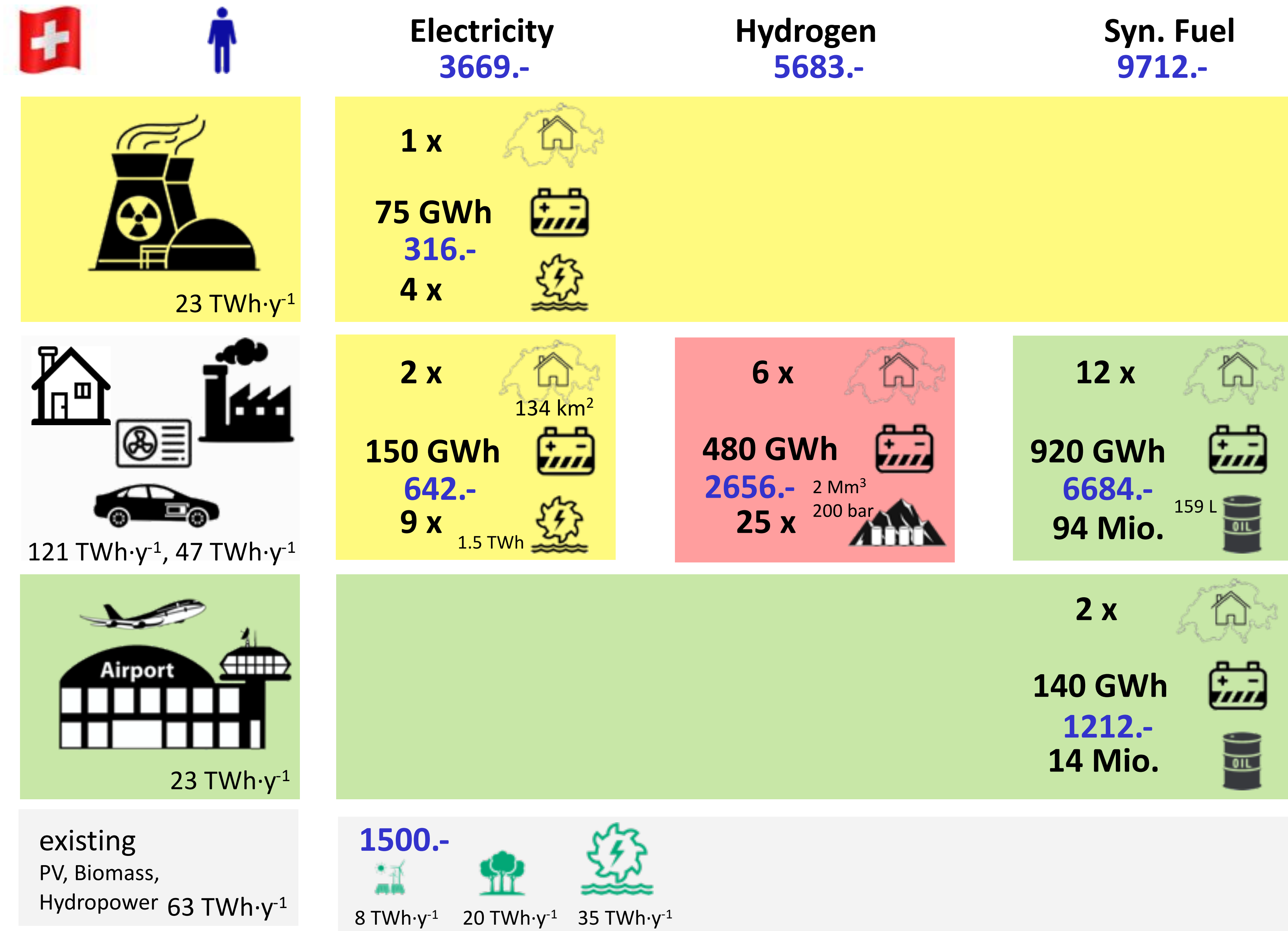
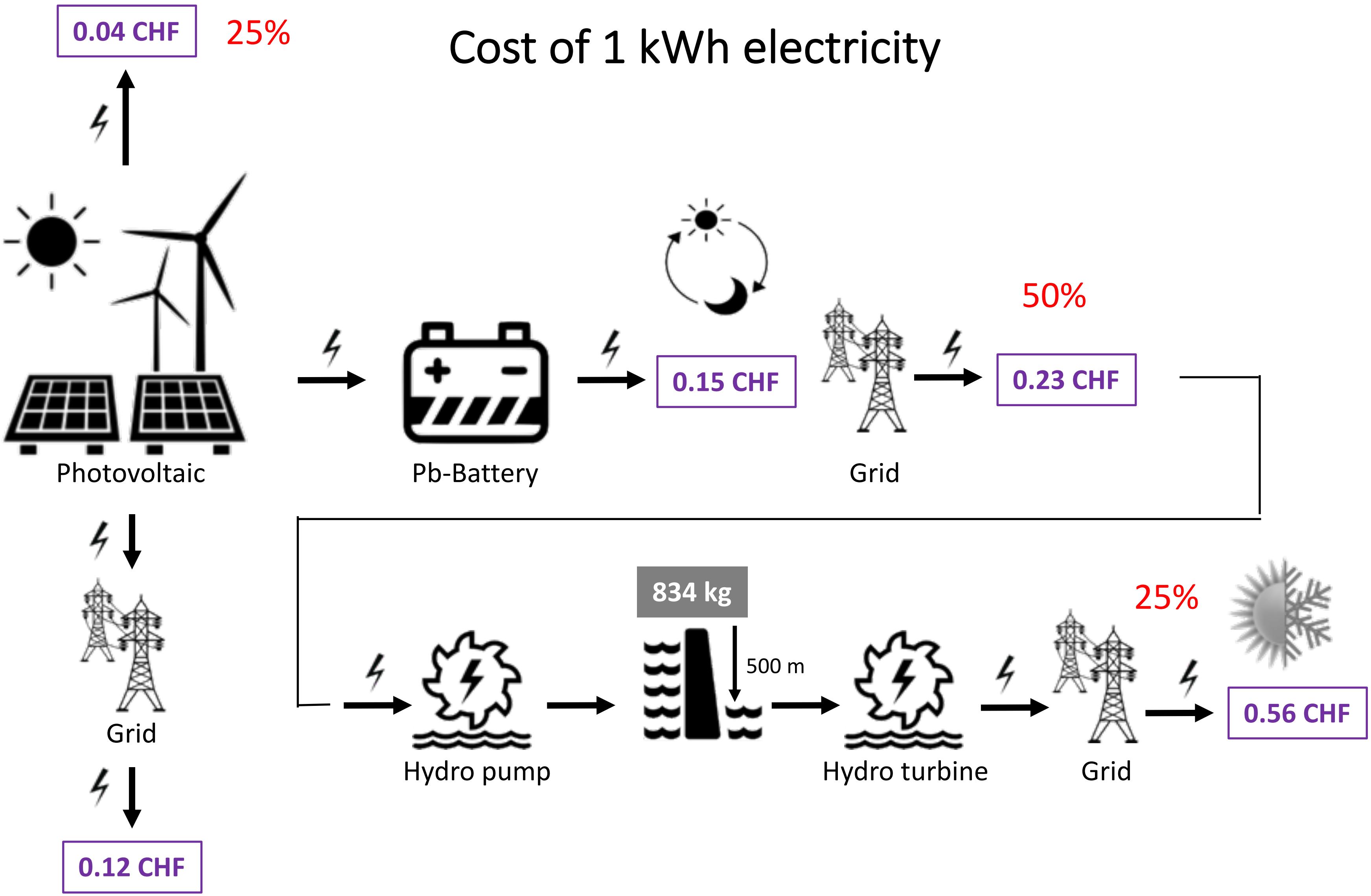
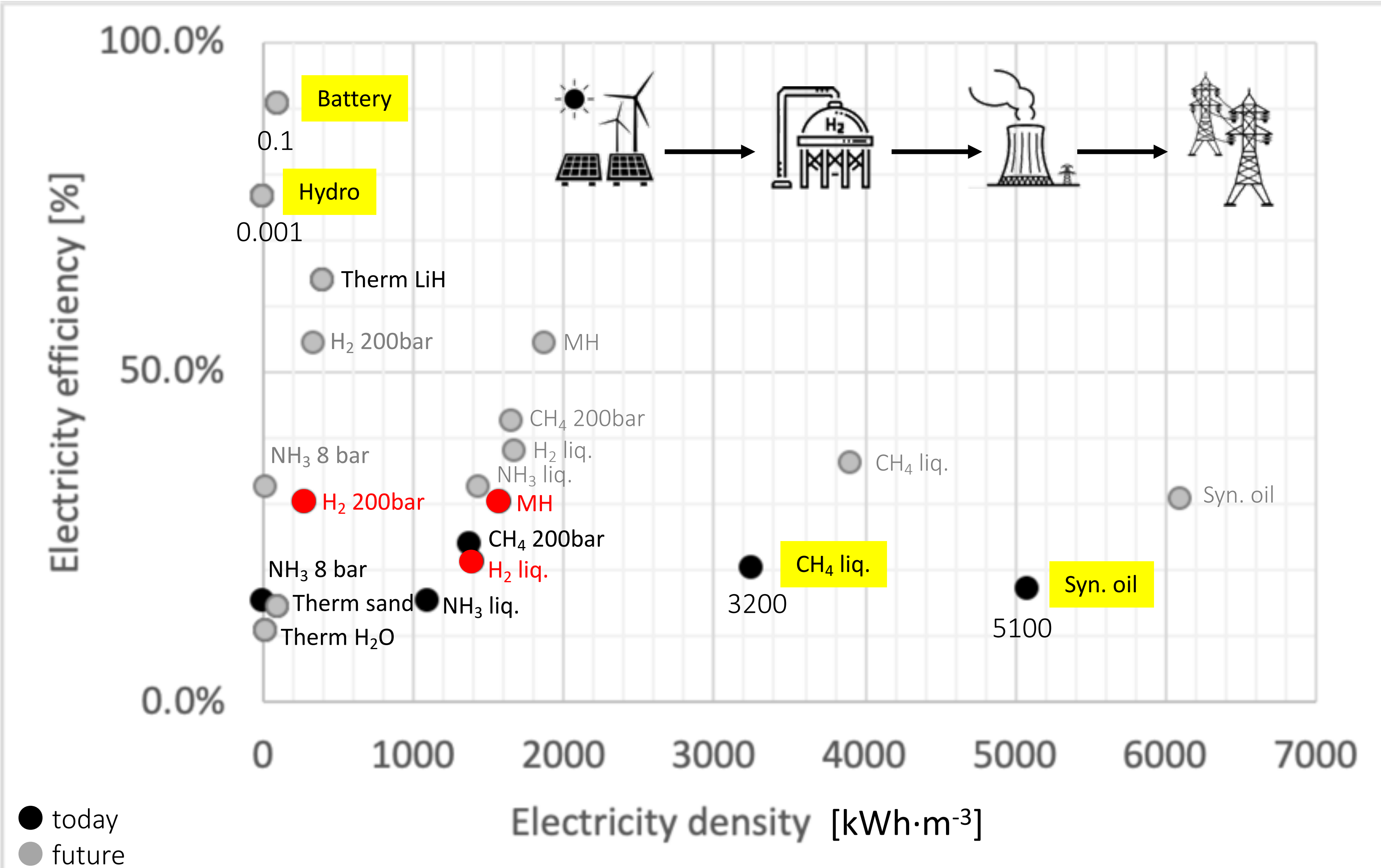


Renewable electricity on demand

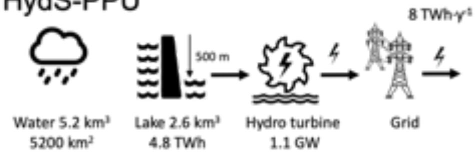


Efficiency and storage density of renewable electricity

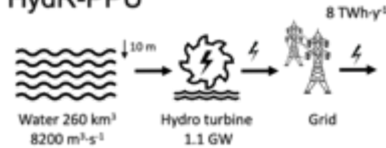


Power plant units

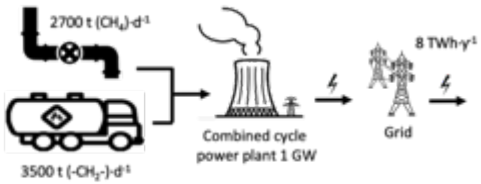
HydS-PPU



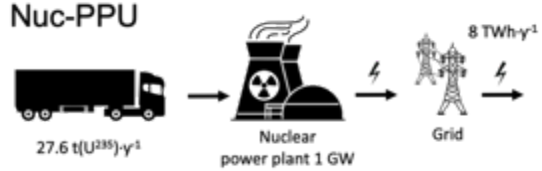
HydR-PPU



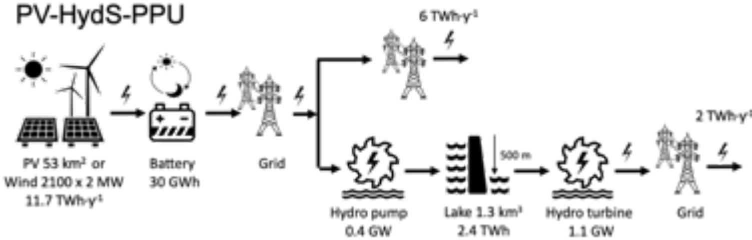
Therm-PPU



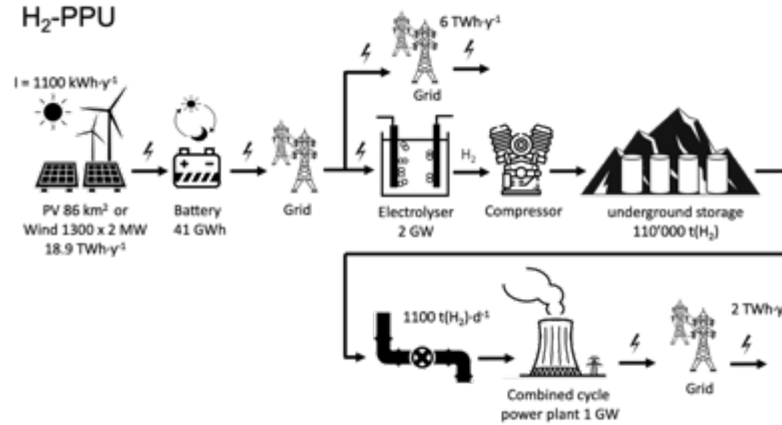
Nuc-PPU



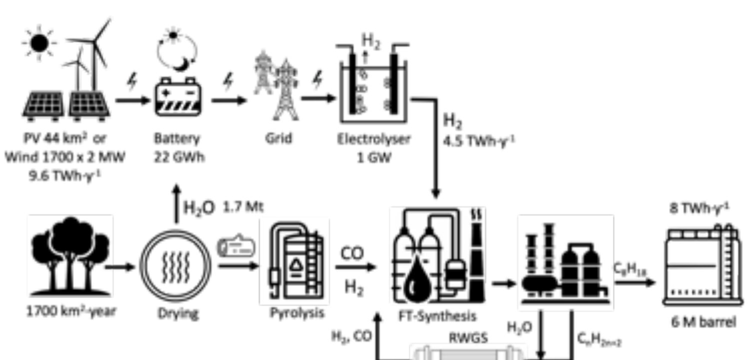
PV-HydS-PPU



H2-PPU

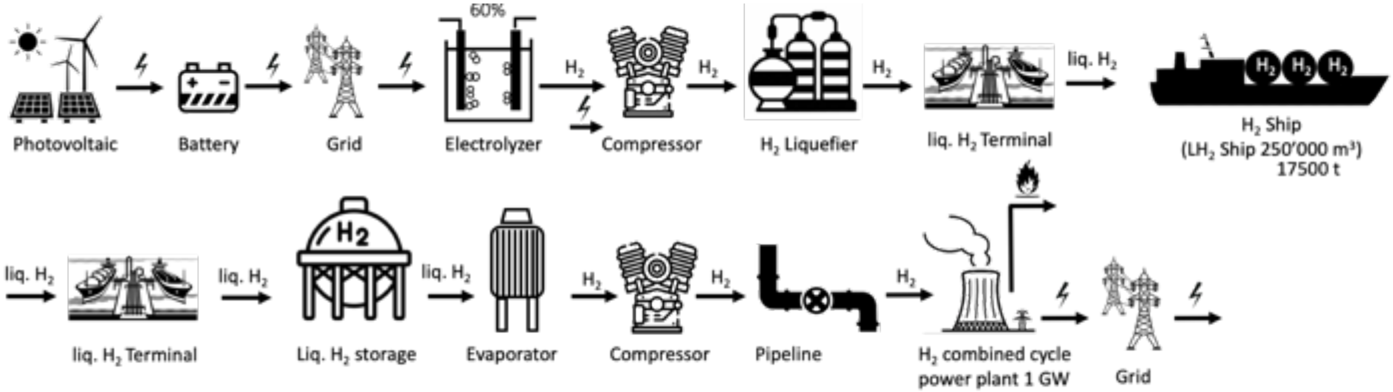


Syn fuel - PPU

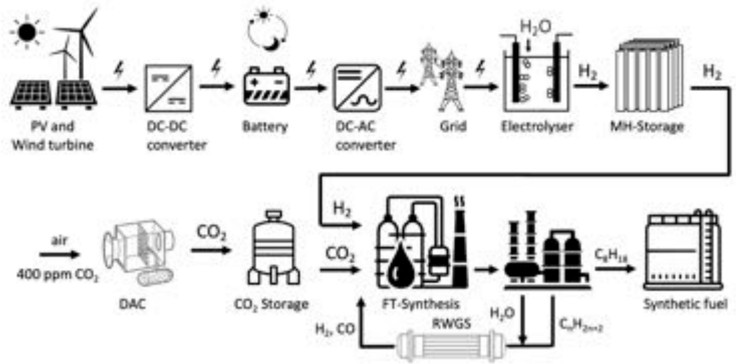


Power plant units

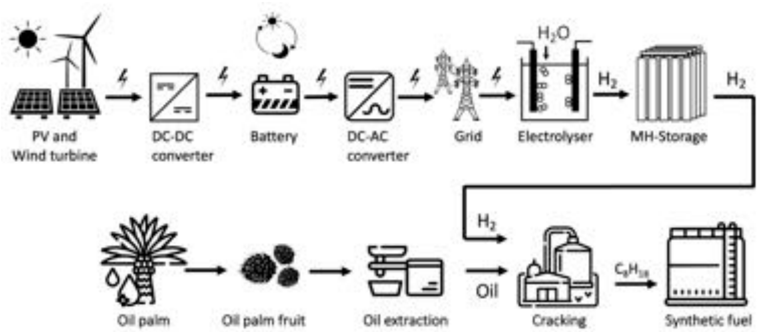
Imp. H_2



Imp. SF

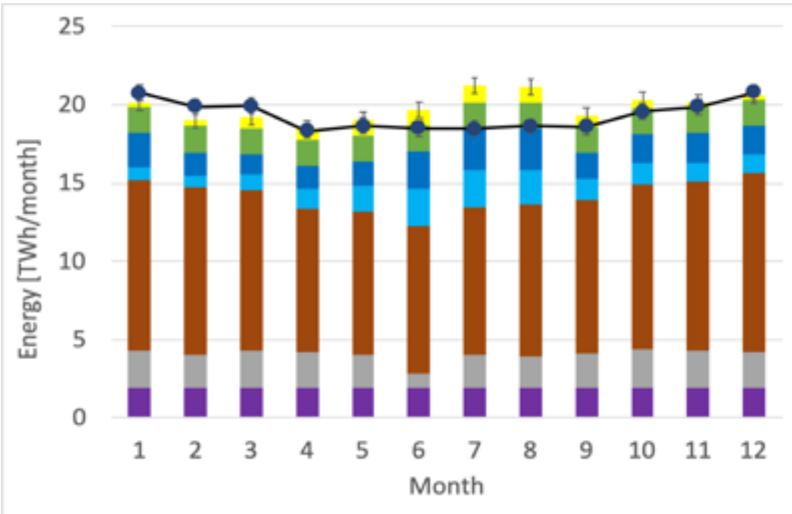


Imp. BSF

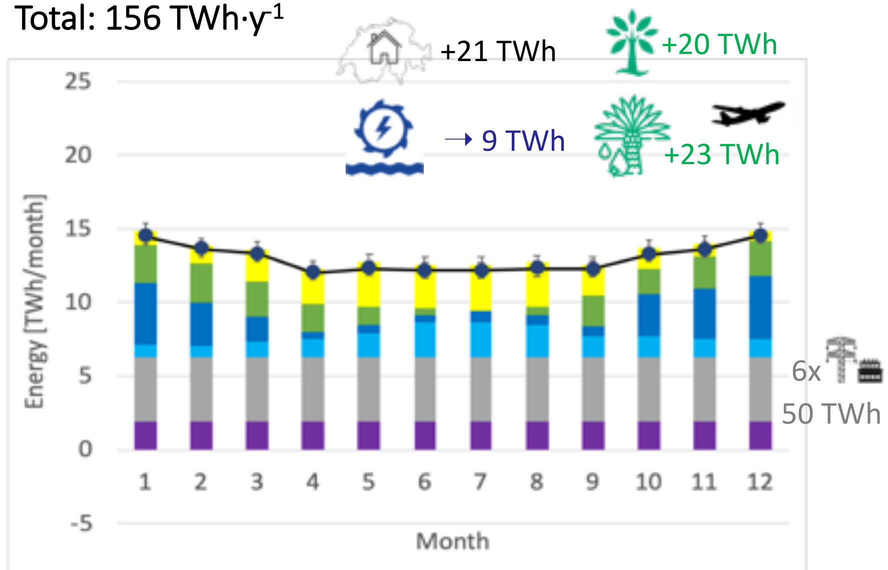


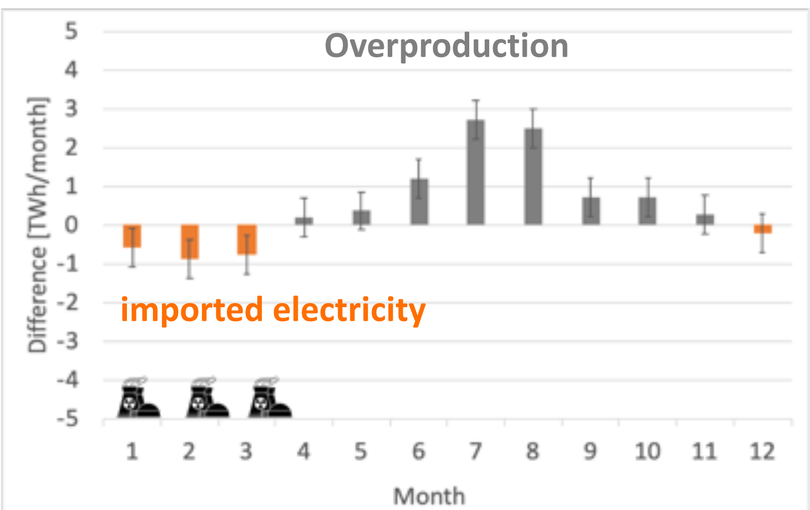
Substitution of fossil with renewable energy

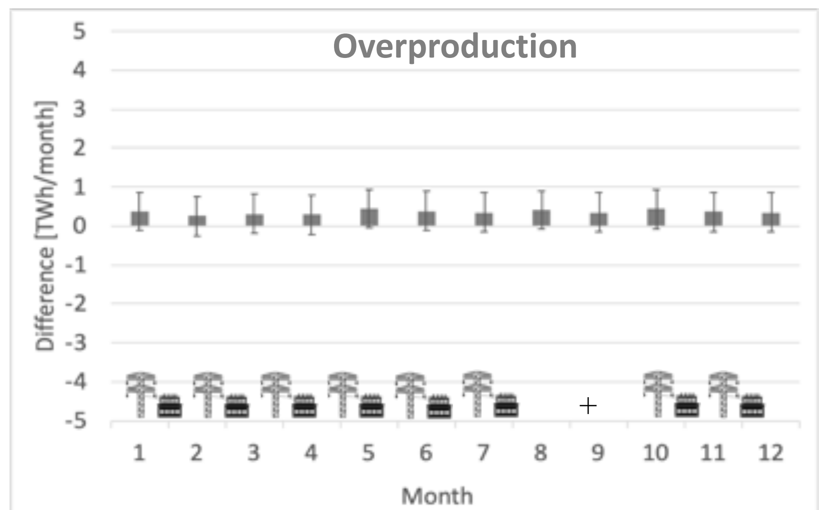
Total: 232 TWh·y^{-1} Fossil: 122 TWh·y^{-1}



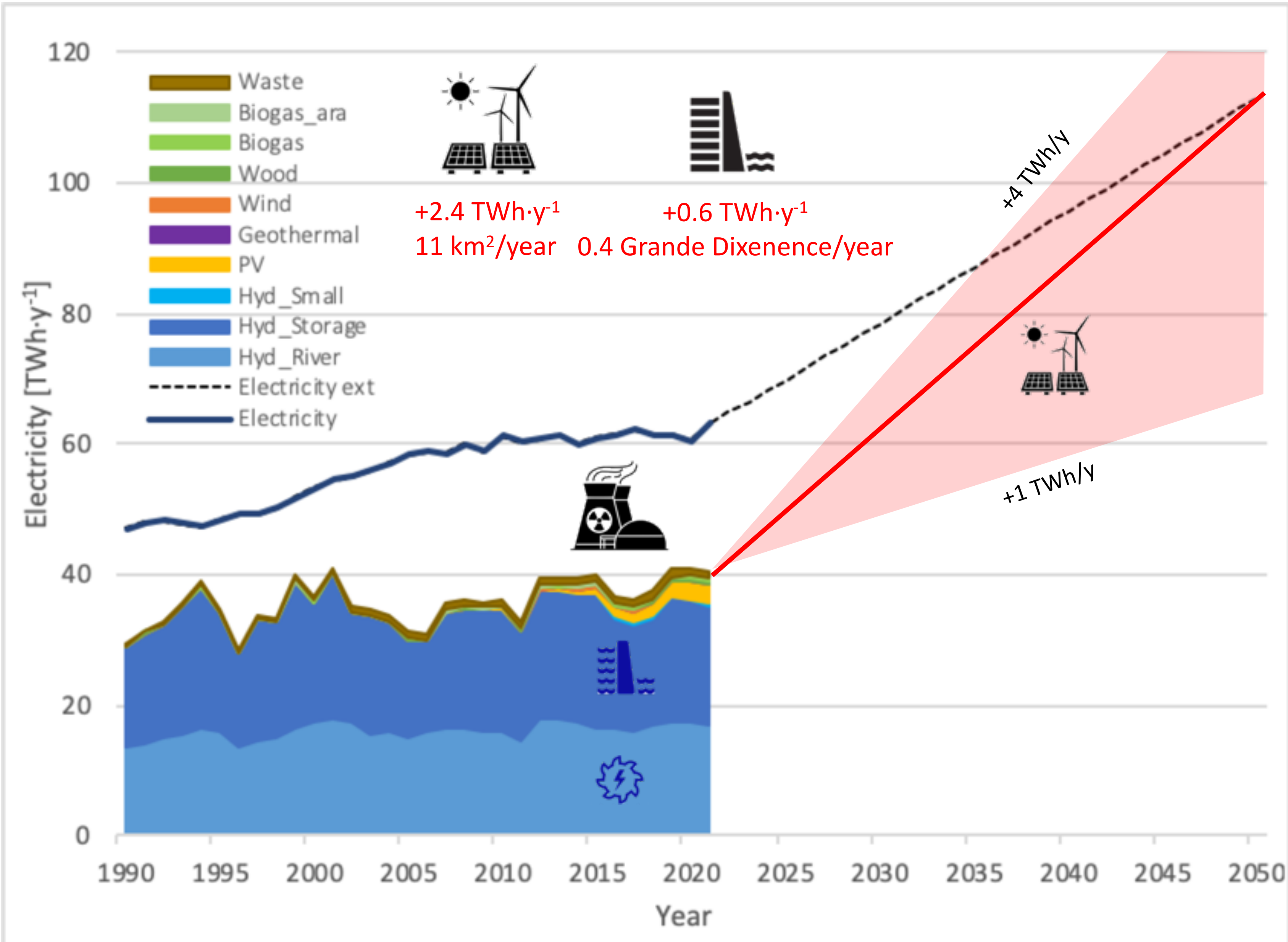
Total: 156 TWh·y^{-1}



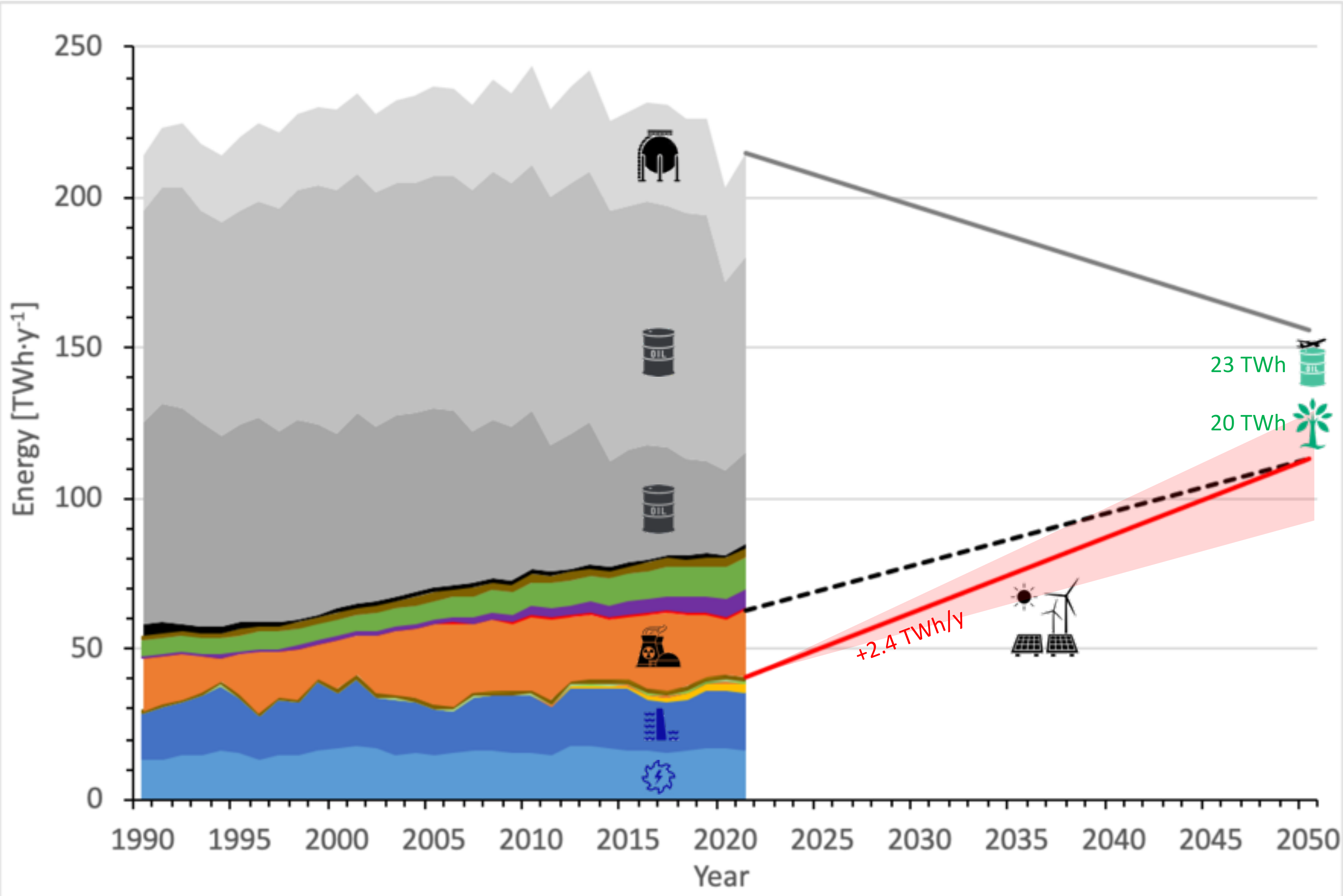




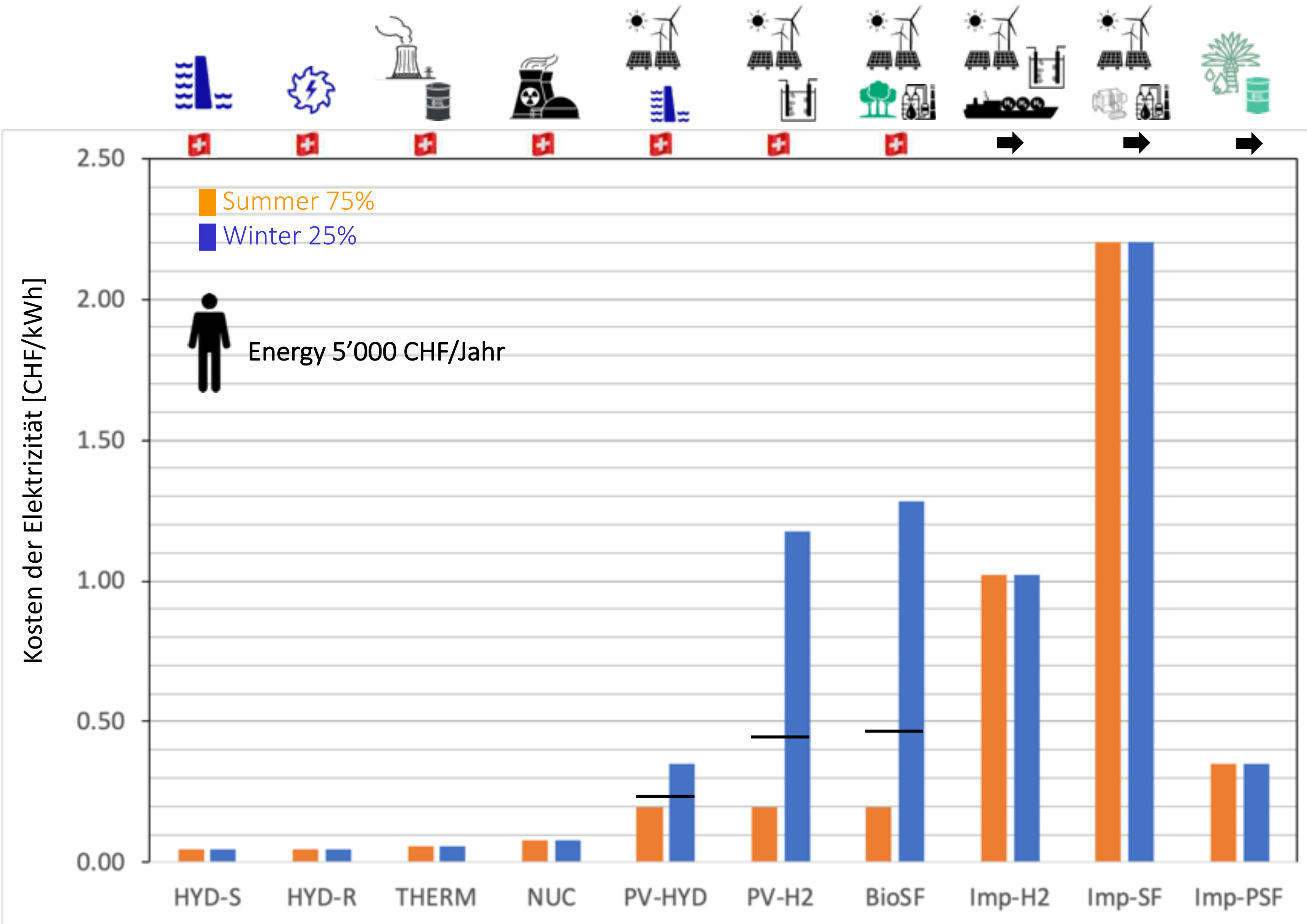
Renewable energy development



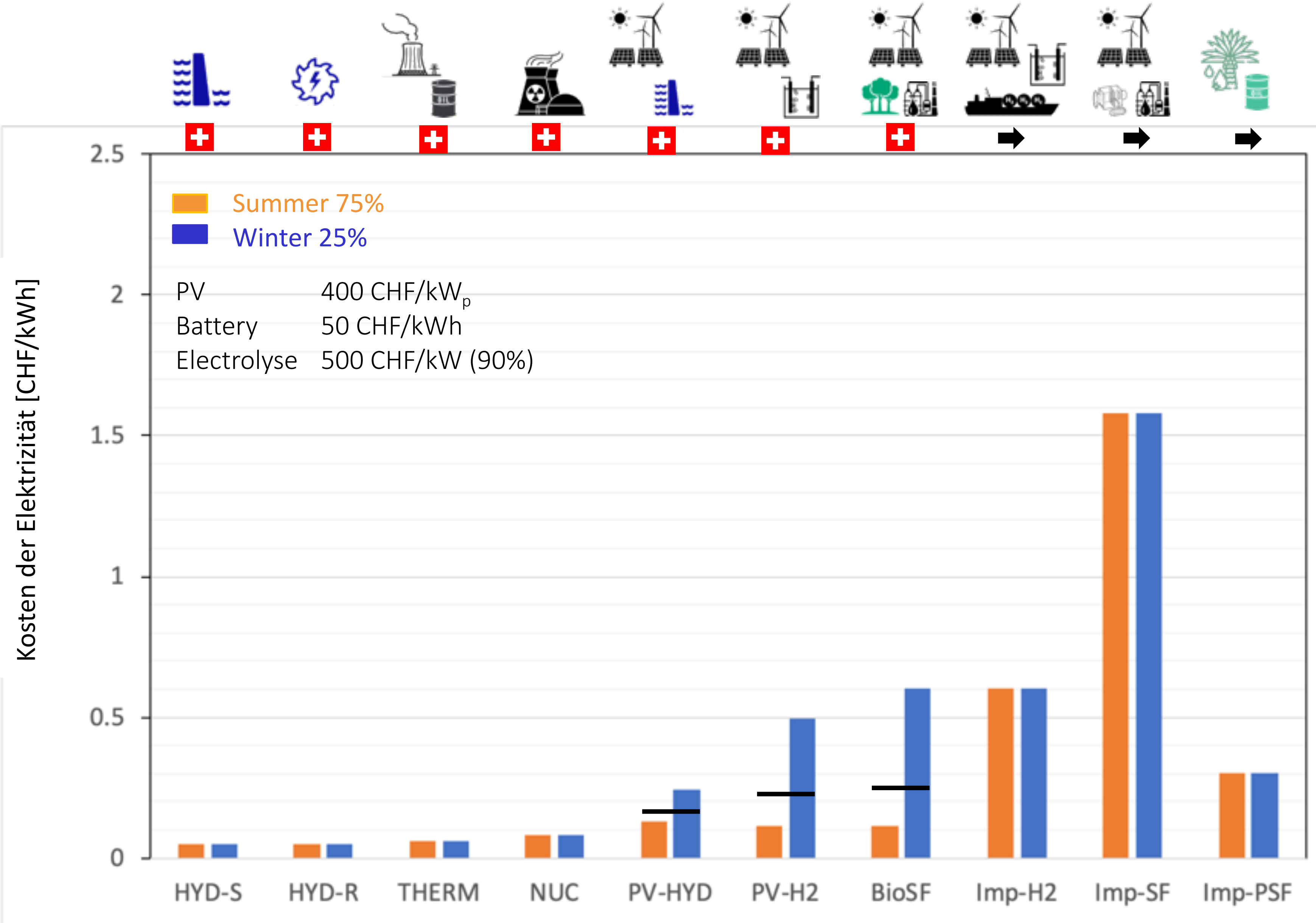
Renewable energy development



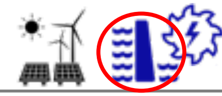
Cost of electricity (2023)

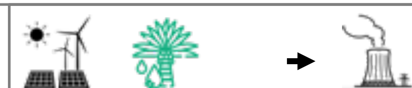


Cost of electricity (future)



Renewable energy power plant units

	2023	 Law		 H$_2$ 	
Cost [CHF·y^{-1}]	3’000	2’764	3’402	4’402	4’281
CAPEX [BCHF]	0	48-72	228	Storage 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)

(....) foreign c.	 H$_2$ → 		
Cost [CHF·y^{-1}]	9’079 Cost	15’445 Cost	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·y^{-1})	(43’400)

Renewable energy power plant units

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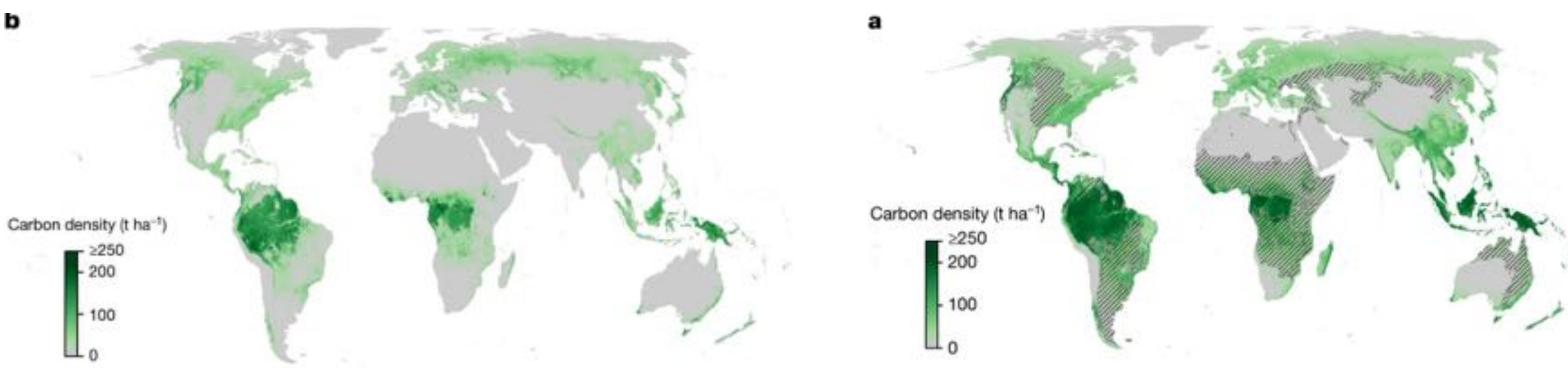
Carbon sinks and palm oil production

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



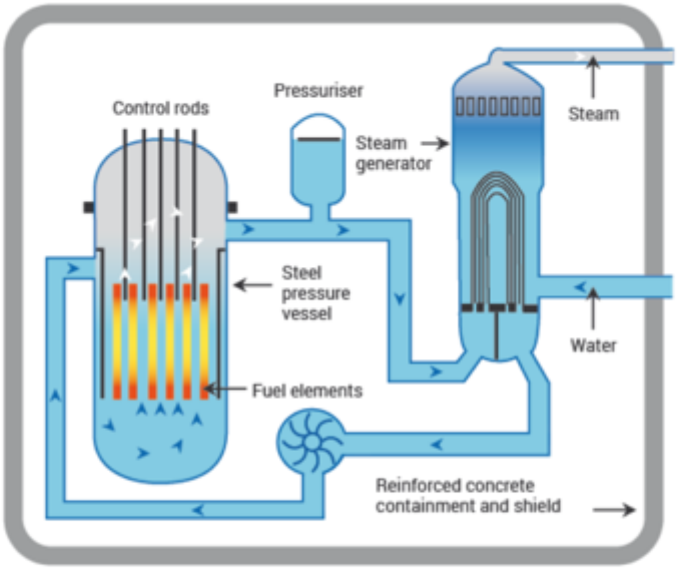
226 Gt palm tree produce 13 Gt oil·y^{-1} the current world fossil energy demand

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

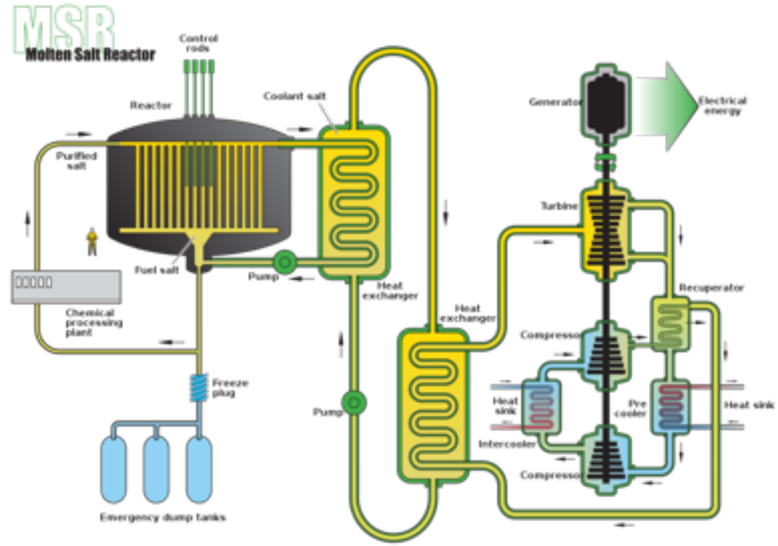
Nuclear reactors

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)

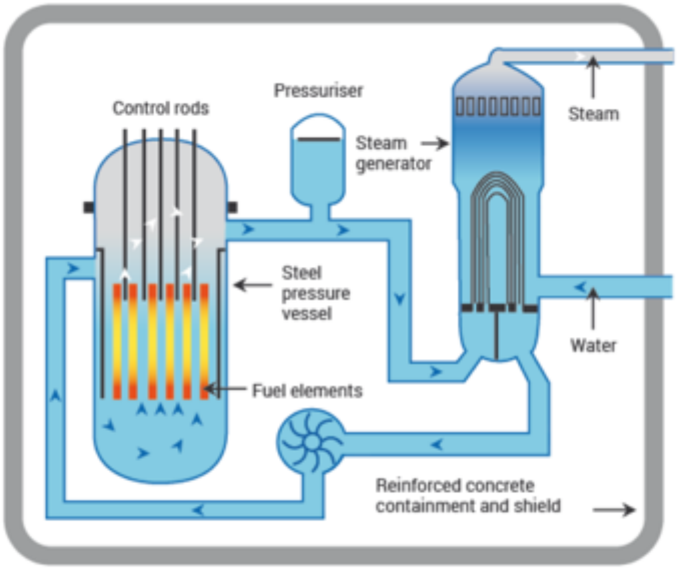
Advantages:

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)

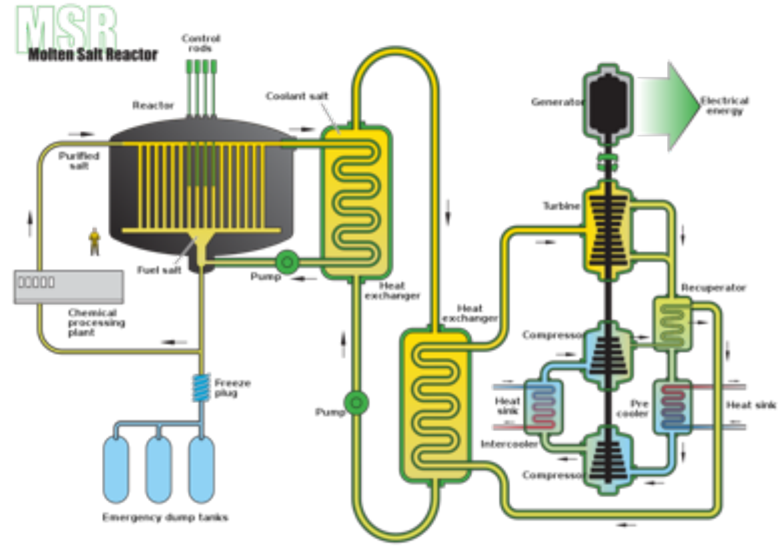
Nuclear reactors

Future

Uranium fission reactor



Thorium molten salt breading reactor



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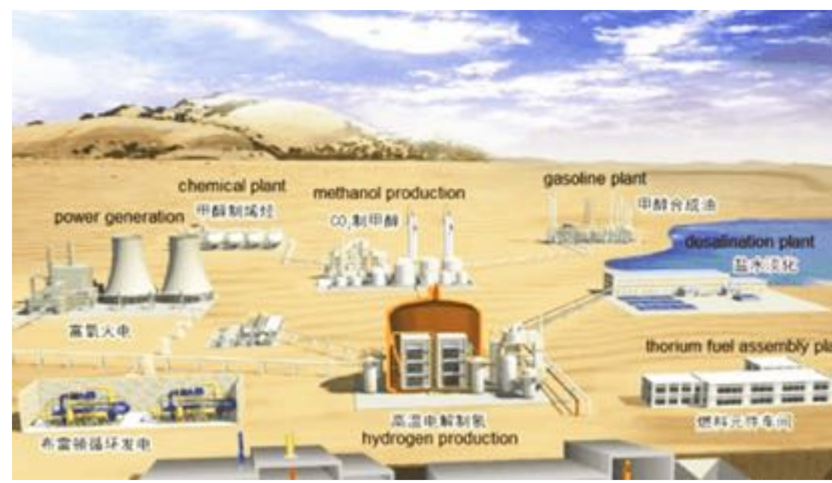
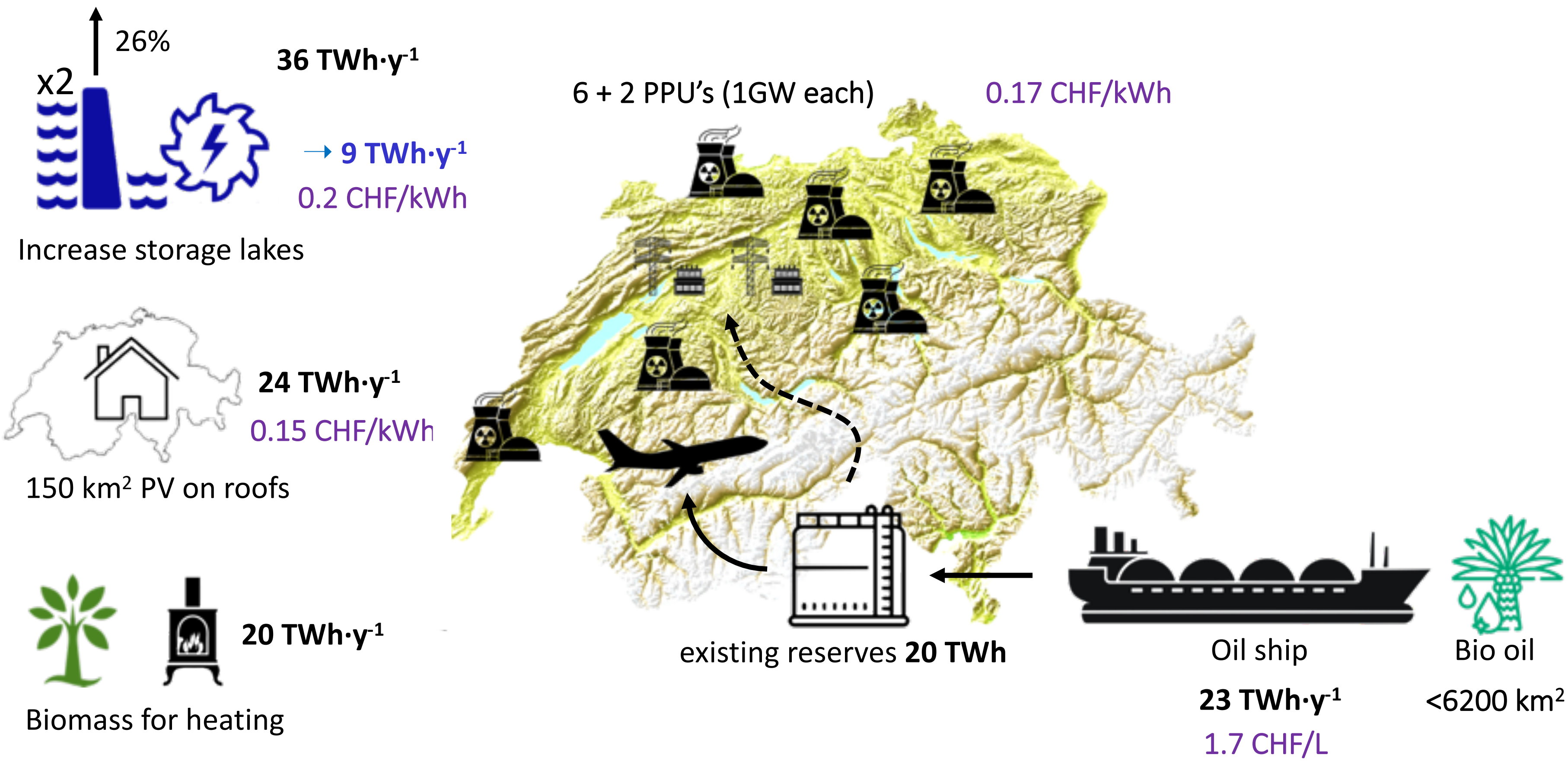
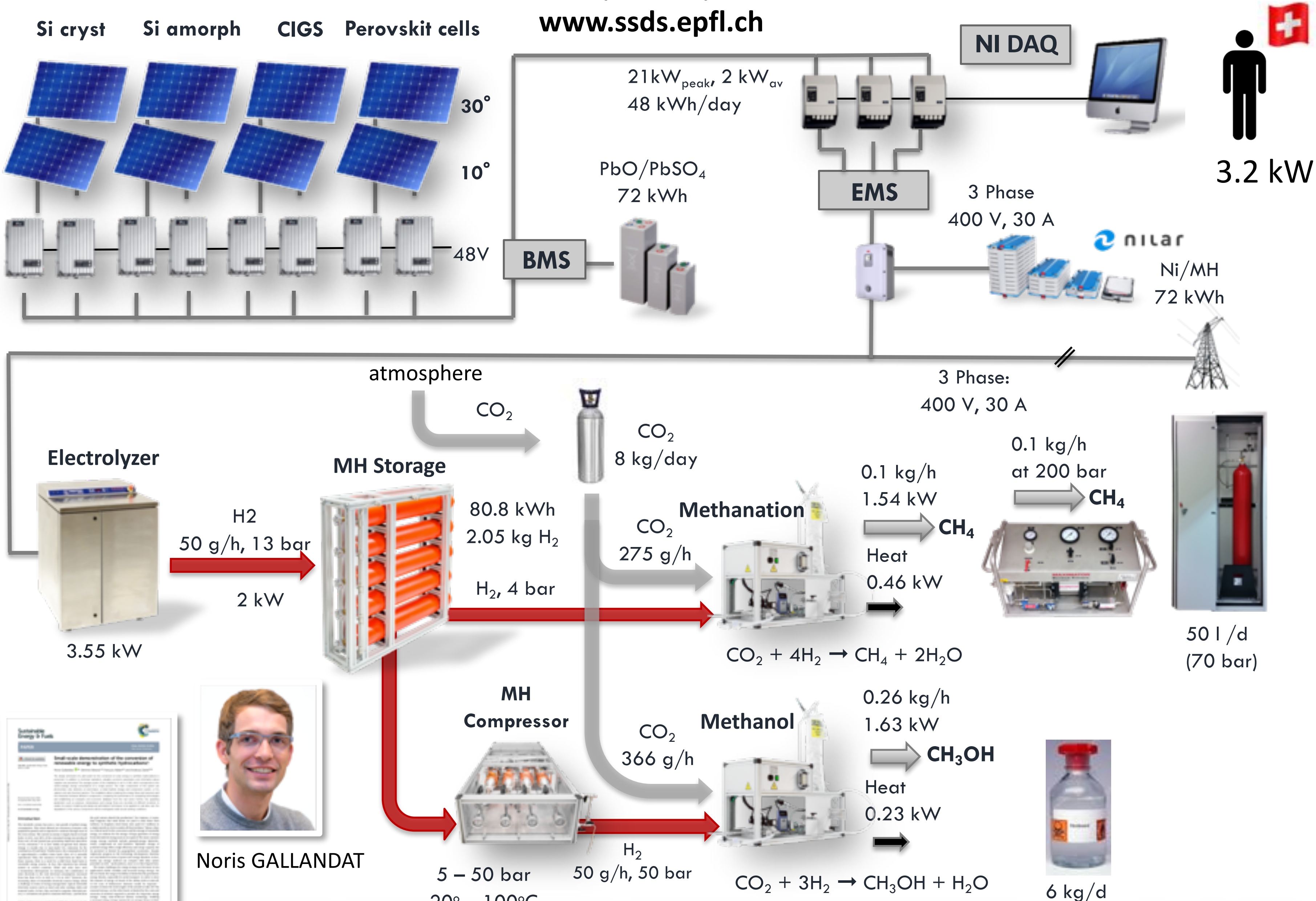


TMSR-LF1 (2 $MW_{therm.}$) construction 2018 - 2023, Wuwei city, Gansu province, China, operated since July 2023

CO_2 neutral solution (example)

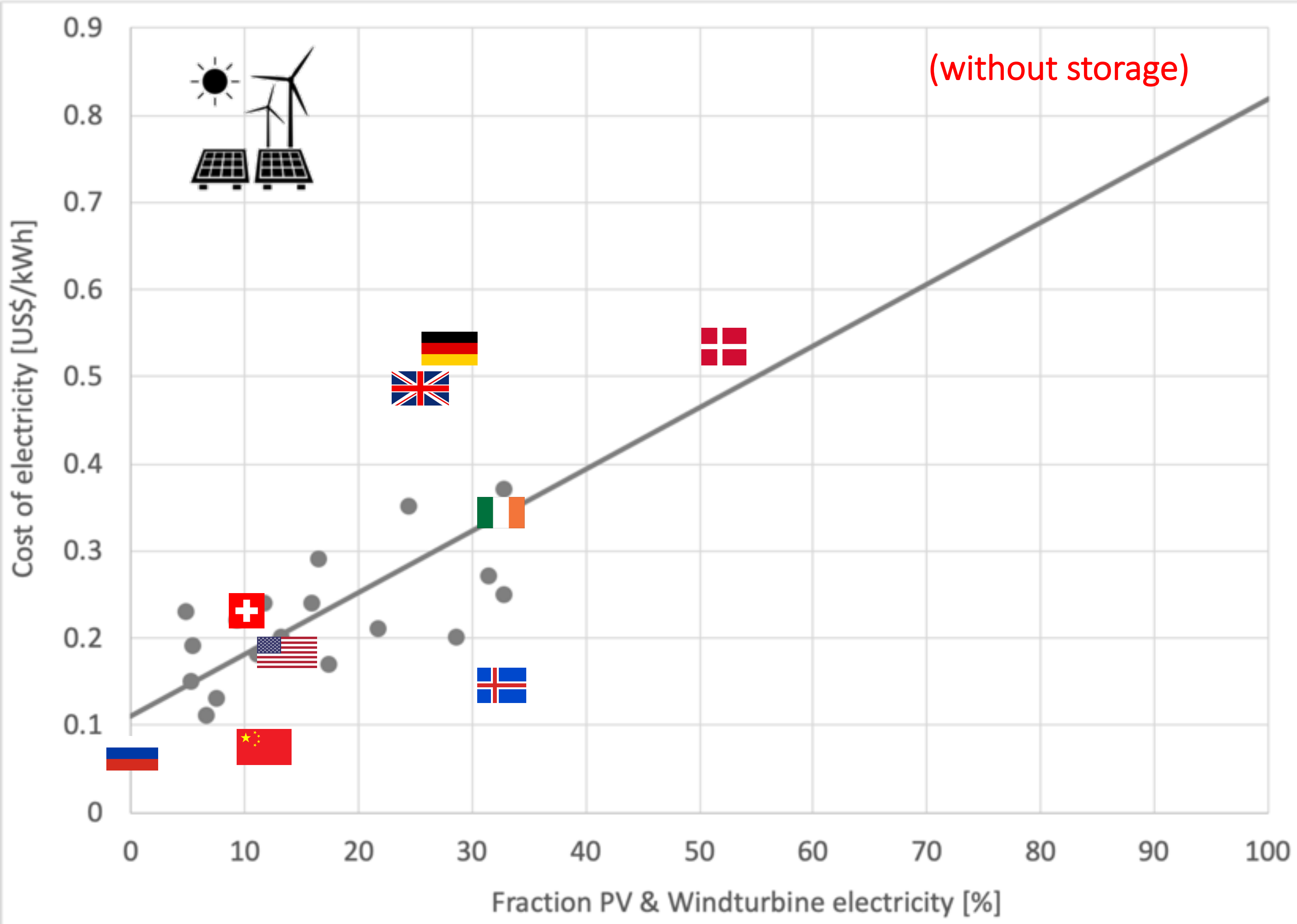


Small Scale Demonstrator Sion (SSDS)



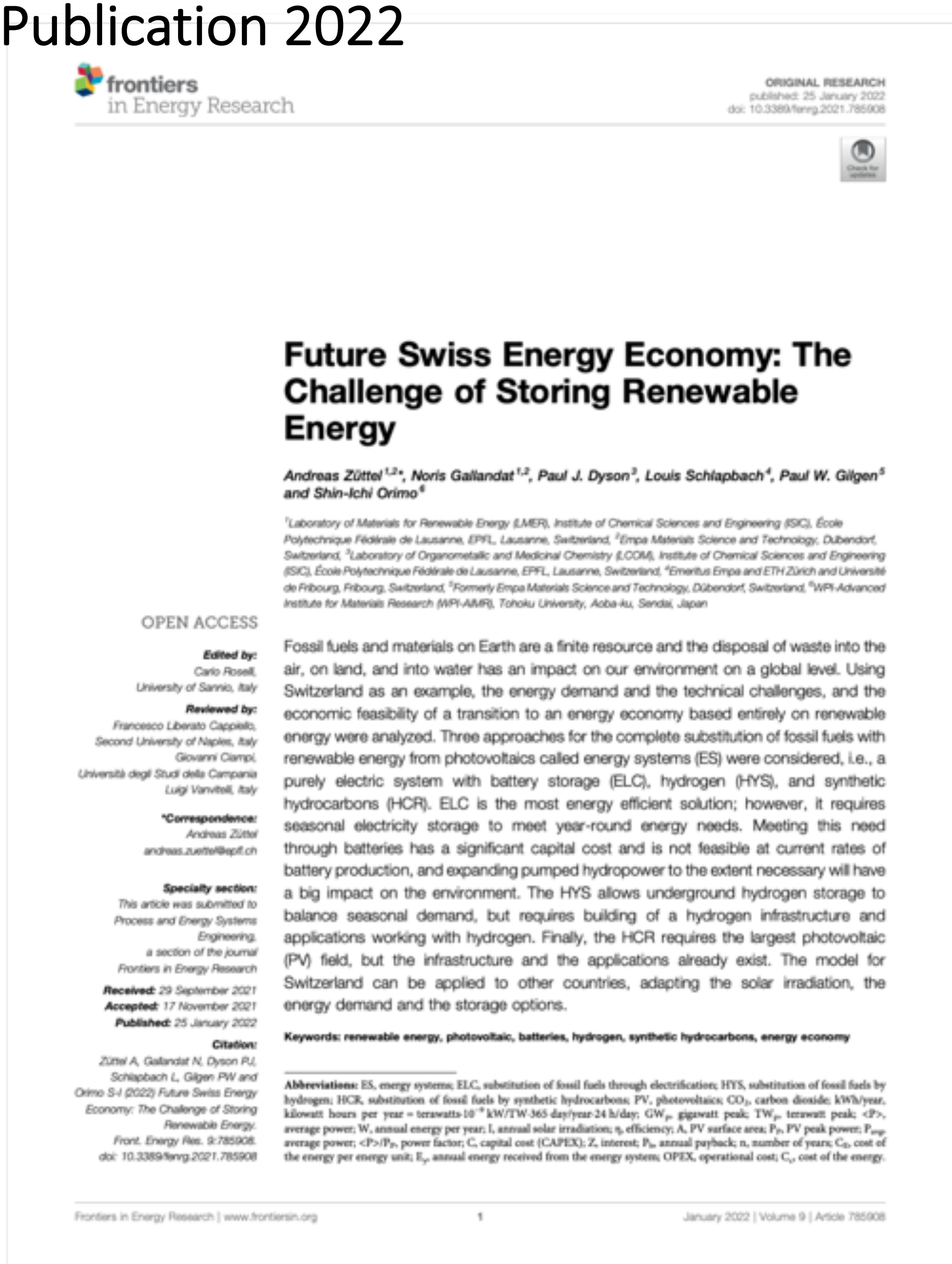
Noris Gallandat, Jérémie Bérard, François Abbet and Andreas Züttel, "Small-scale demonstration of the conversion of renewable energy to synthetic hydrocarbons", Sustainable Energy & Fuels (2017).DOI: 10.1039/c7se00275k, rsc.li/sustainable-energy

Cost of electricity with PV and wind (2023)



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

Publication 2022



frontiers in Energy Research

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Future Swiss Energy Economy: The Challenge of Storing Renewable Energy

Andreas Züttel[1,2], Noris Gallandat[1,2], Paul J. Dyson[3], Louis Schlapbach[4], Paul W. Gilgen[5] and Shin-Ichi Orimo[6]*

[1]Laboratory of Materials for Renewable Energy (LMER), Institute of Chemical Sciences and Engineering (ISIC), École Polytechnique Fédérale de Lausanne, EPFL, Lausanne, Switzerland, [2]Empa Materials Science and Technology, Dübendorf, Switzerland, [3]Laboratory of Organometallic and Medicinal Chemistry (LCOM), Institute of Chemical Sciences and Engineering (ISIC), École Polytechnique Fédérale de Lausanne, EPFL, Lausanne, Switzerland, [4]Emeritus Empa and ETH Zürich and Université de Fribourg, Fribourg, Switzerland, [5]Formerly Empa Materials Science and Technology, Dübendorf, Switzerland, [6]WPI-Advanced Institute for Materials Research (WPI-AIMR), Tohoku University, Aoba-ku, Sendai, Japan

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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_y, 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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