“Sécurité énergétique neutre en CO_2 pour la Suisse”

accepté par “Frontiers in Energy Research: Process and Energy Systems Engineering“ (2024)

Frontiers in Energy Research: Process and Energy Systems Engineering MT: final version

CO_2 Neutral Energy Security for Switzerland

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[e)] *Formerly Empa Materials Science and Technology, 8600 Dübendorf, Switzerland.*

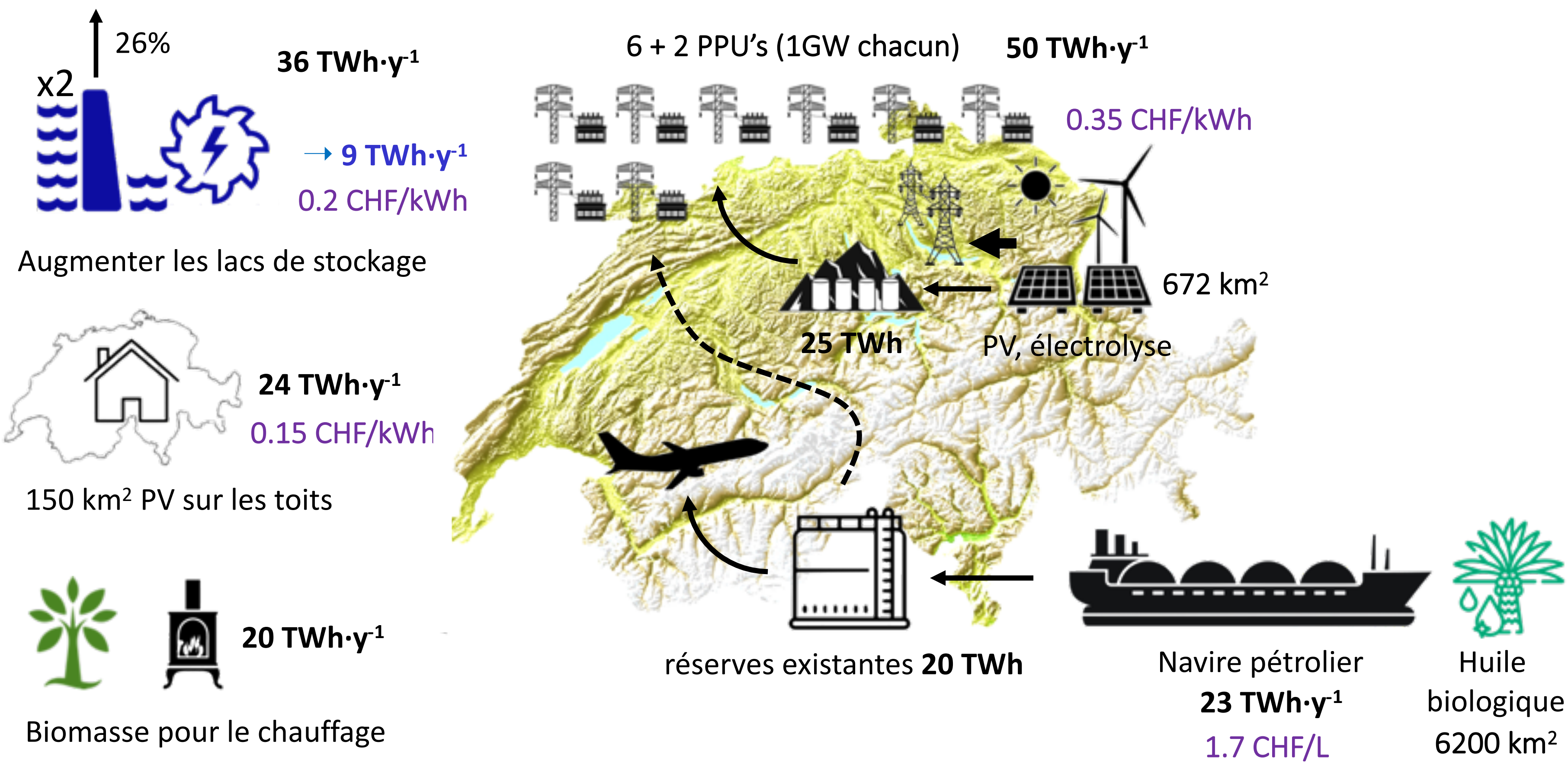
ABSTRACT

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.

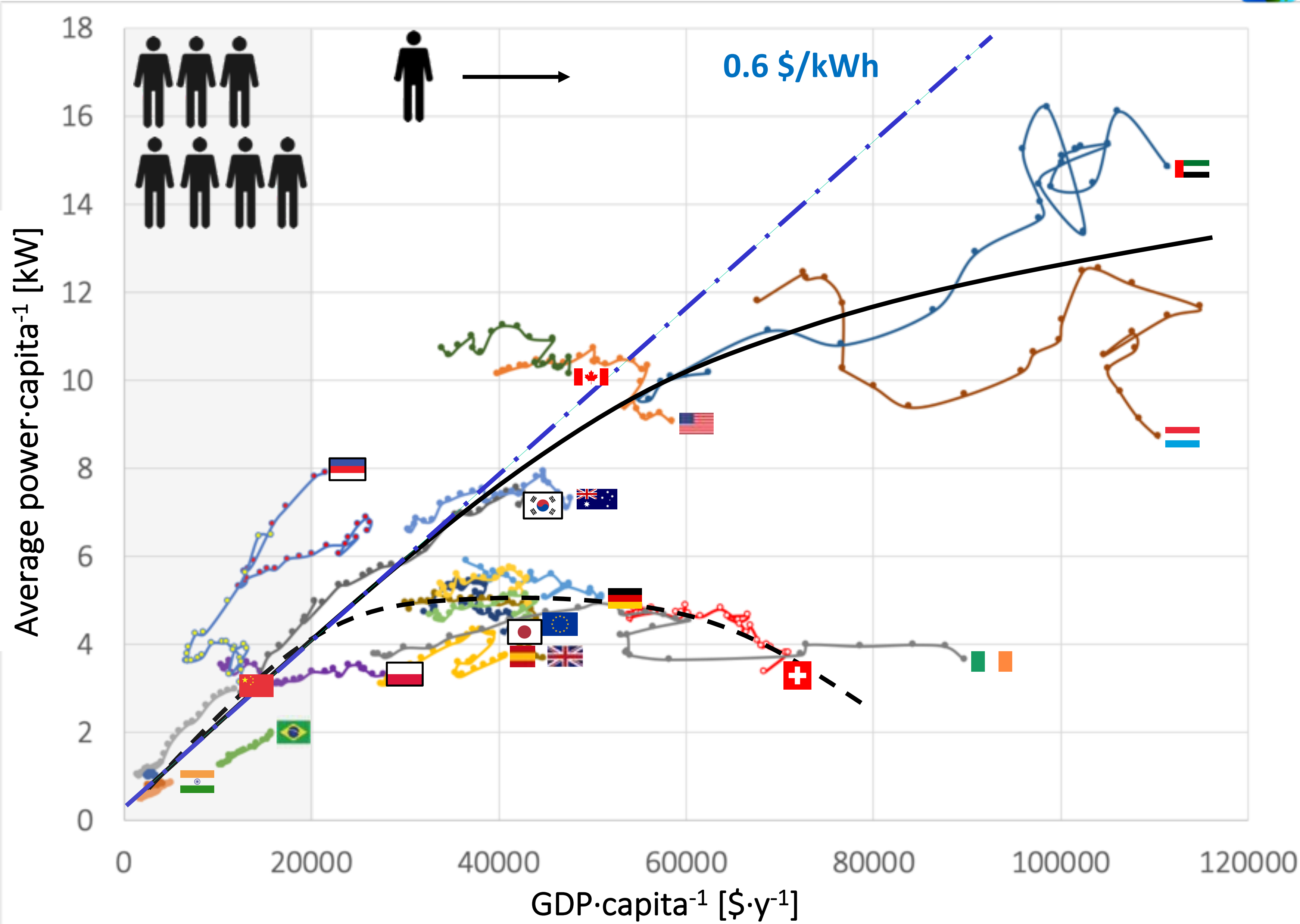
accepted by “Frontiers in Energy Research: Process and Energy Systems Engineering“ (2024)

Solution en matière d'énergie renouvelable (exemple)



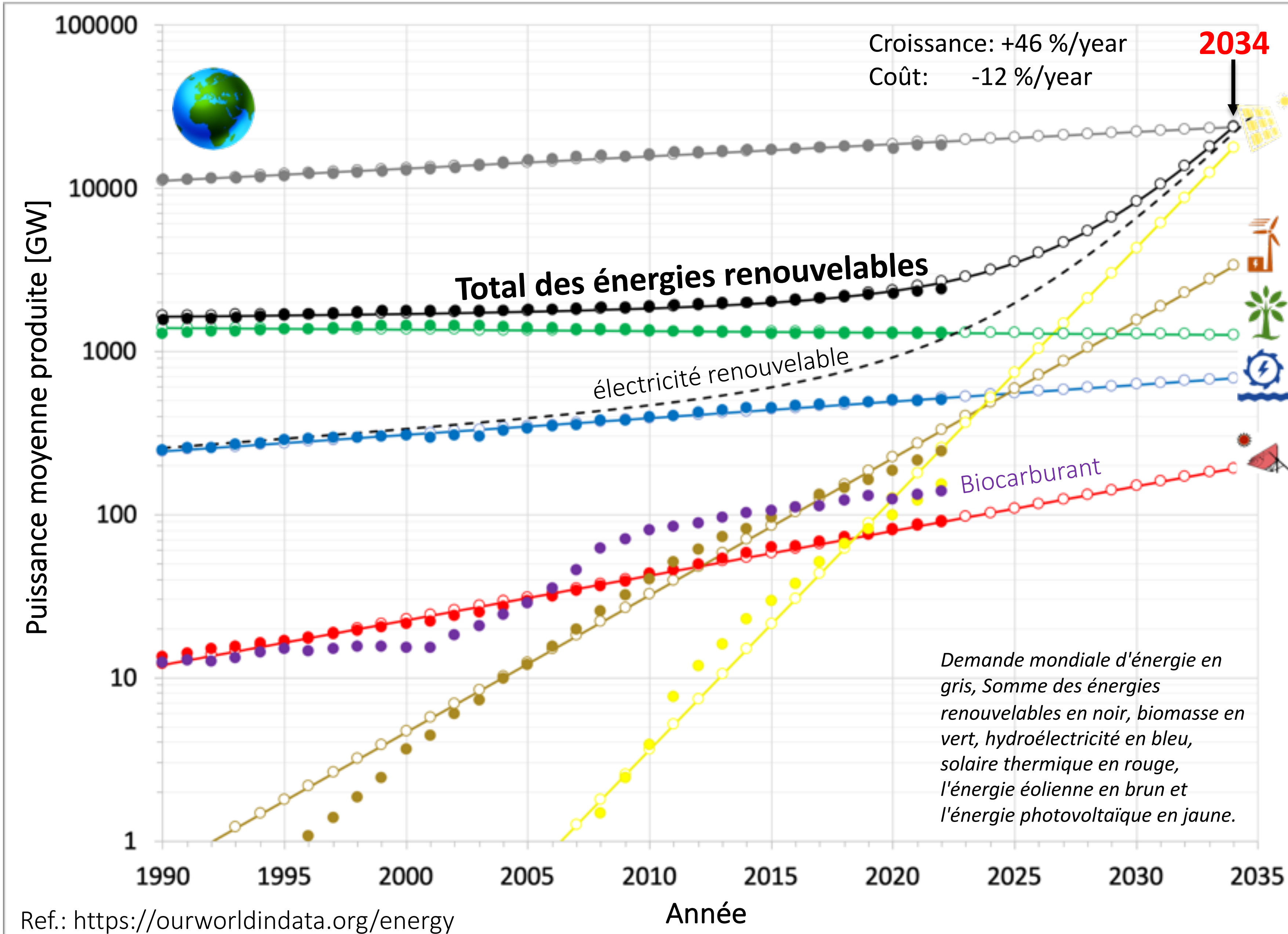
réduire la demande d'énergie par l'utilisation de la chaleur, le stockage de la chaleur, l'isolation

Energie et economie

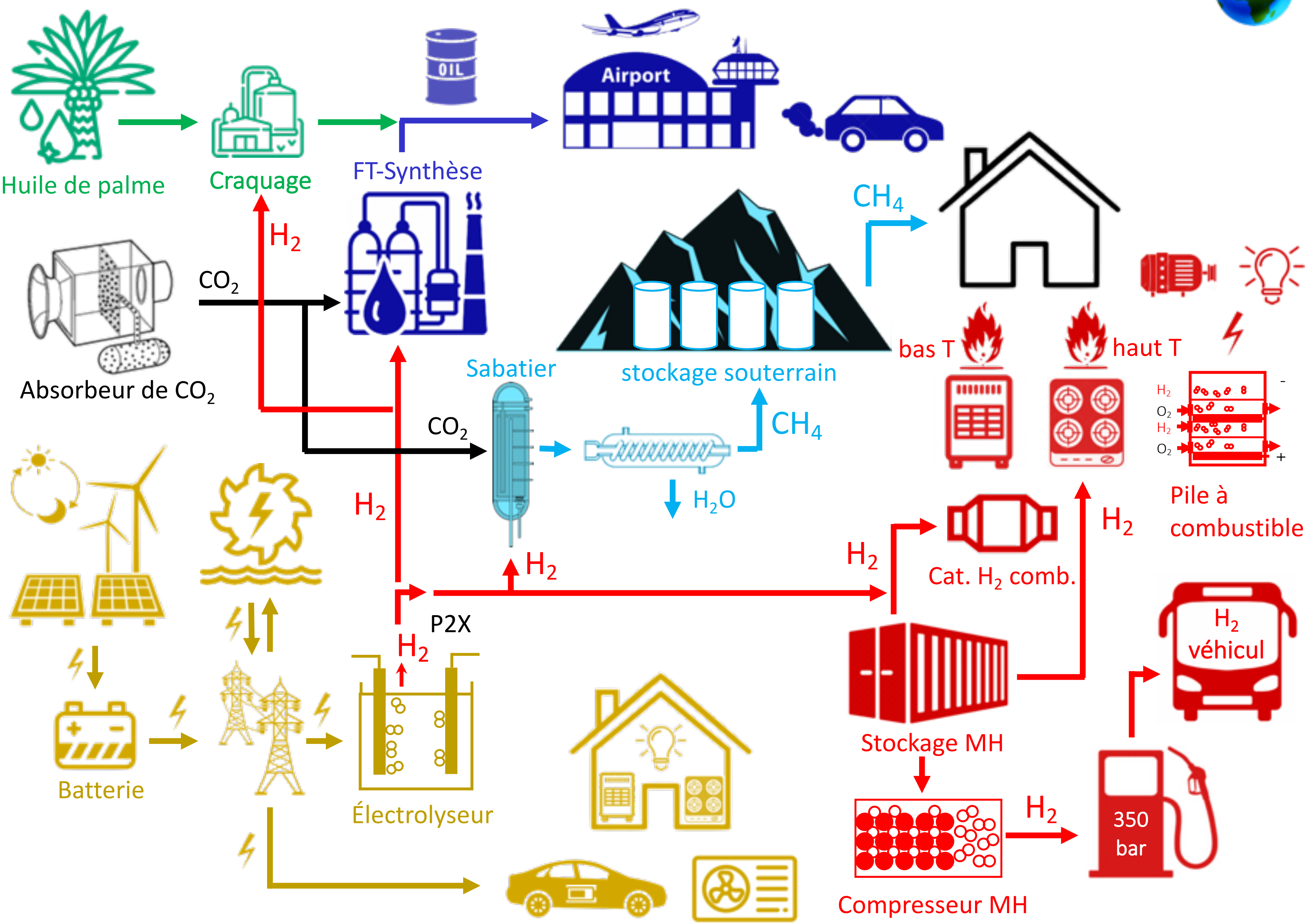


Ref.: https://ourworldindata.org/grapher/energy-use-per-capita-vs-gdp-per-capita

Production mondiale d'énergies renouvelables

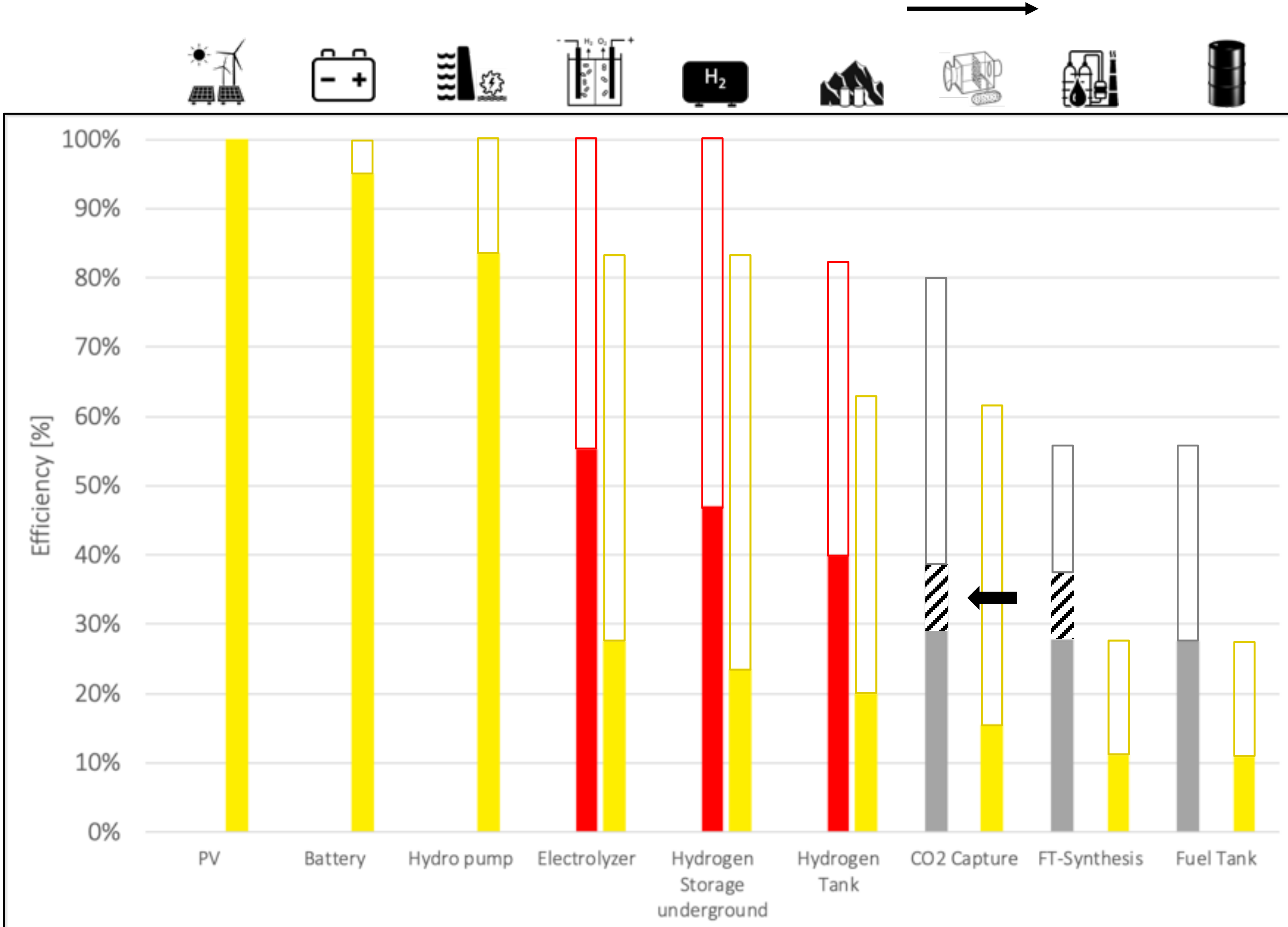


Système d'énergie renouvelable

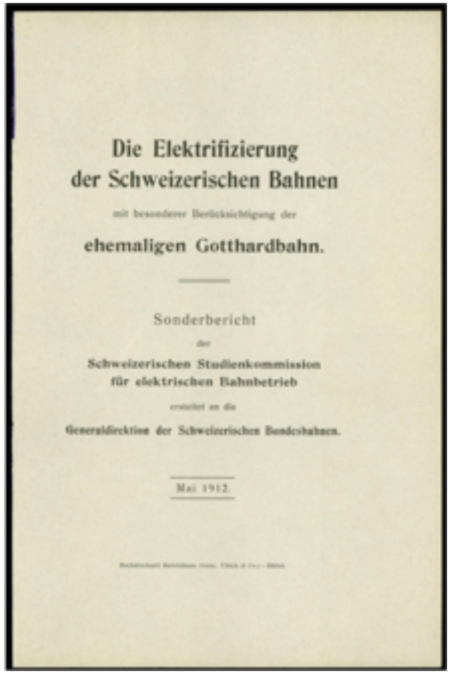


Efficacité de la conversion énergétique

Power to X (P2X)

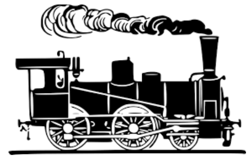


Décision suisse pour l'électricité


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.

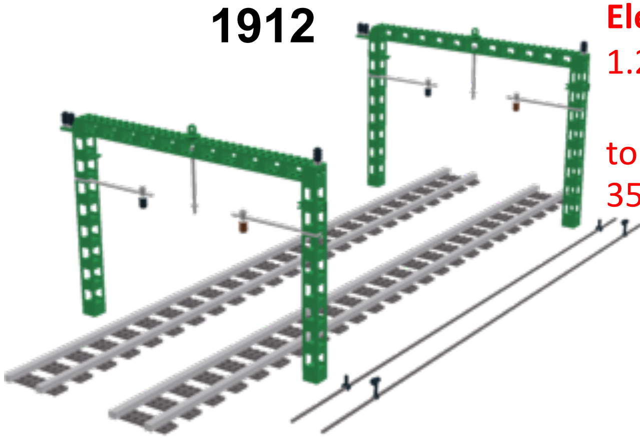
Mai 1912.



1912

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.

1912



Electrifiant
1.23 – 2.6 MCHF/km

tous les 27m est un pôle,
35 – 70 kCHF par pôle

Les voies ferrées coûtent 62 MCHF/km (les autoroutes coûtent entre 150 et 330 MCHF par km)

Ref.: Allemagne : Lindau -München 500 M€ pour 189 km, y compris protection contre le bruit, nouvelle gare...
Danemark : ensemble du chemin de fer 1'600 M€ pour 1300 km

Le changement majeur de l'économie de l'énergie en Suisse

Catastrophe de la centrale nucléaire de Fukushima Dai-ichi

11 mars 2011

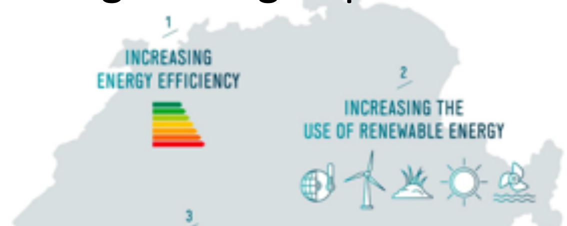
24 mars 2011

Tremblement de terre de 11 mars 2011

25. Mai 2011 Le Conseil fédéral a décidé de ne plus miser sur l'énergie nucléaire à l'avenir. Les centrales nucléaires existantes doivent rester raccordées au réseau tant qu'elles sont sûres. Confirmation par le Parlement le 8 juin 2011.

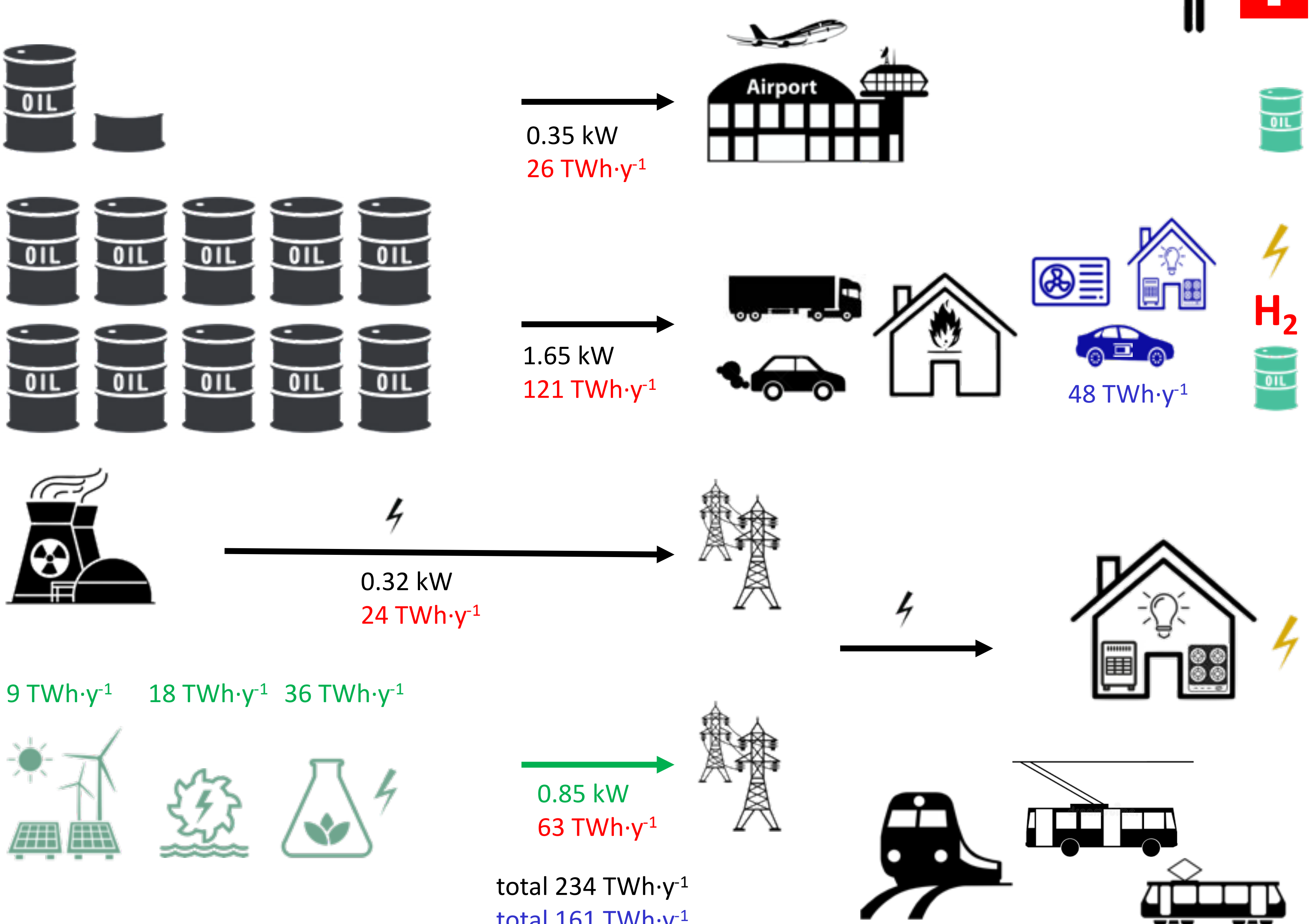
Accord de Paris sur le climat 2014

Stratégie énergétique suisse 2050



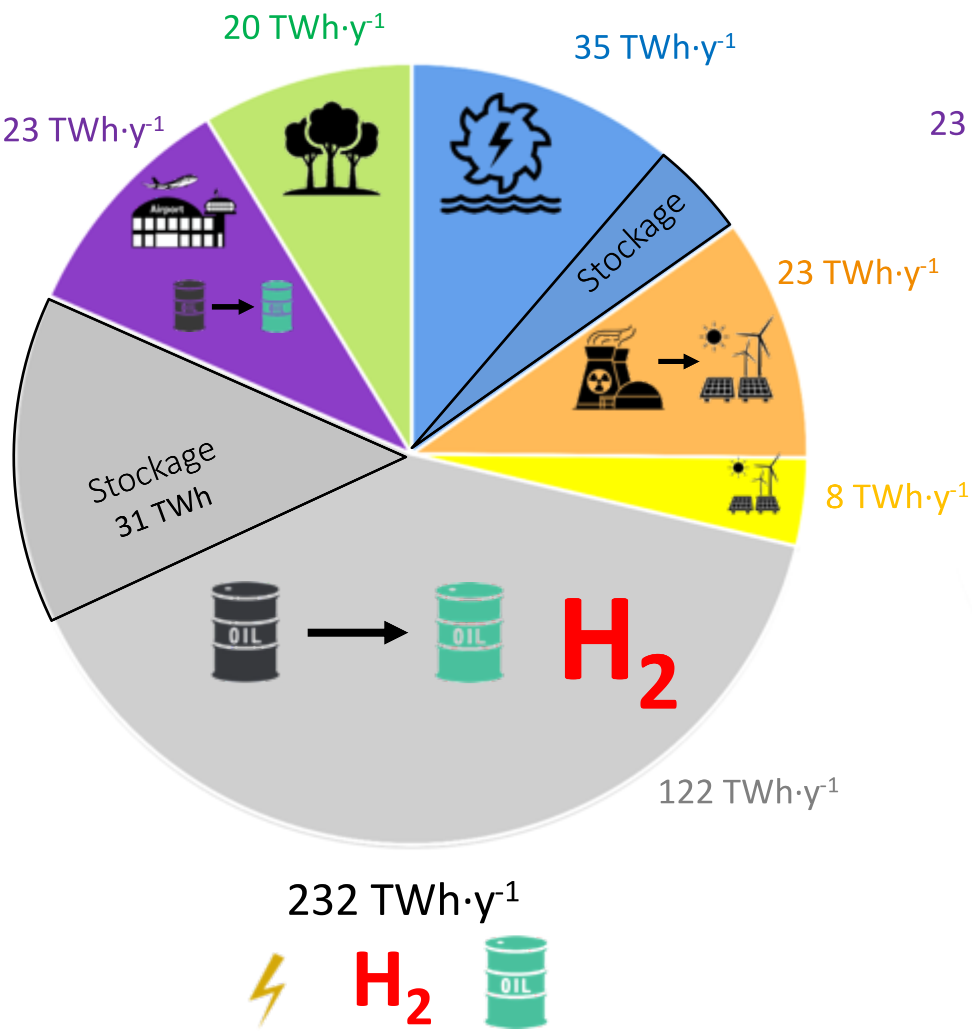
Le 21 mai 2017, le peuple suisse a accepté la révision de la loi fédérale sur l'énergie. Les objectifs de cette révision sont de réduire la consommation d'énergie, d'augmenter l'efficacité énergétique et de promouvoir l'utilisation des énergies renouvelables. En outre, la version révisée interdit la construction de nouvelles centrales nucléaires.

Approvisionnement énergétique actuel de la Suisse (2020)

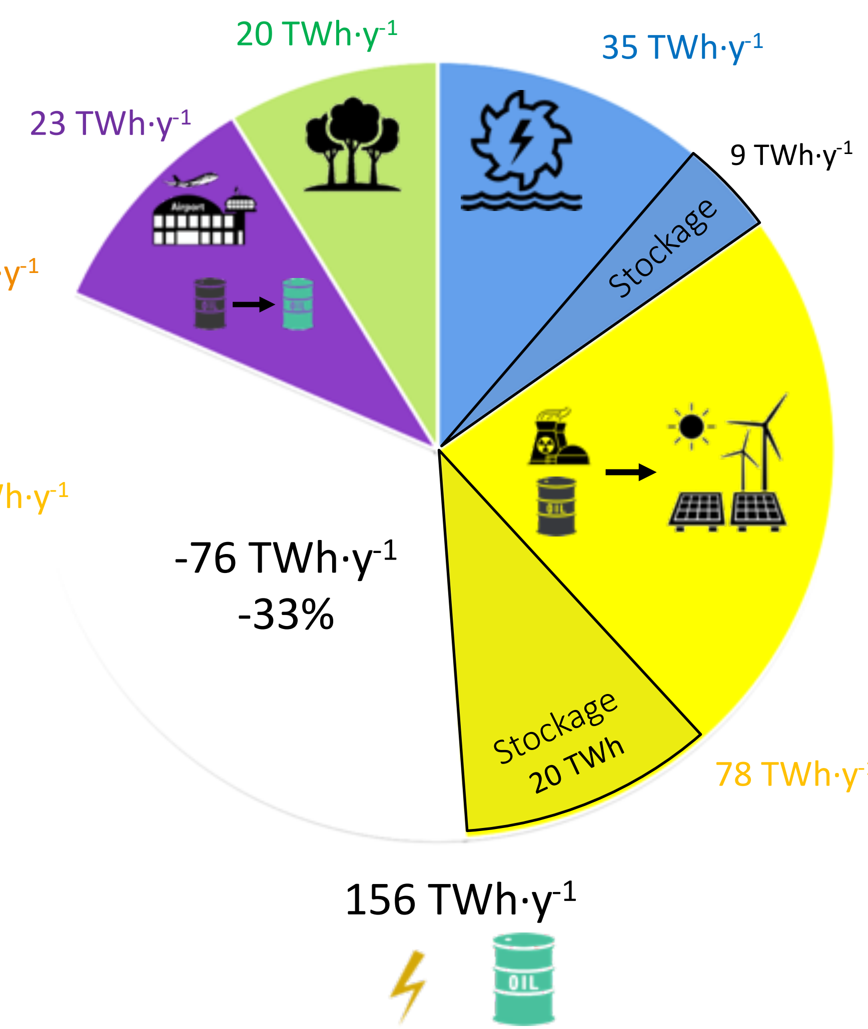


Demande d'énergie par source et électrification

Demande d'énergie (2019)



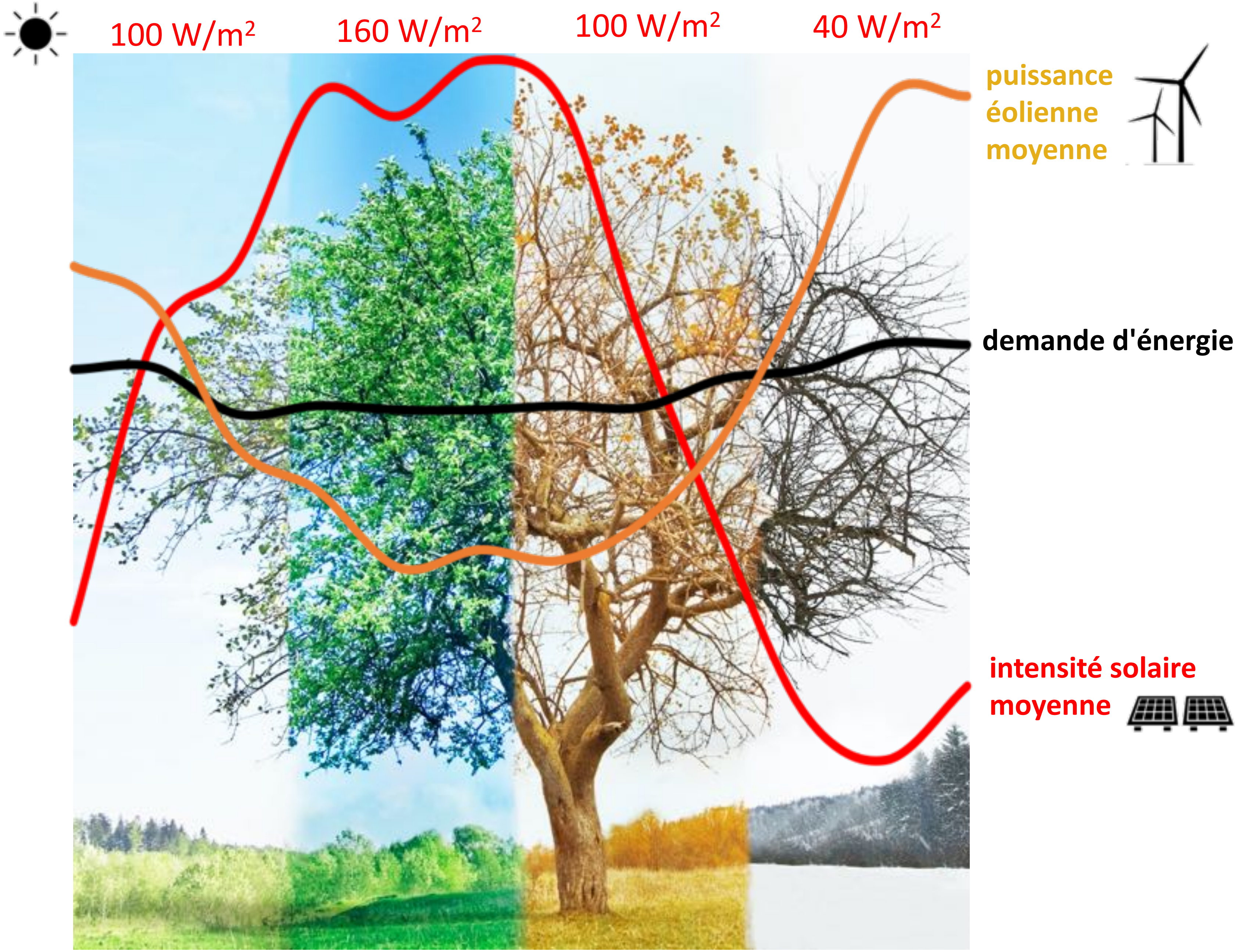
Electrification



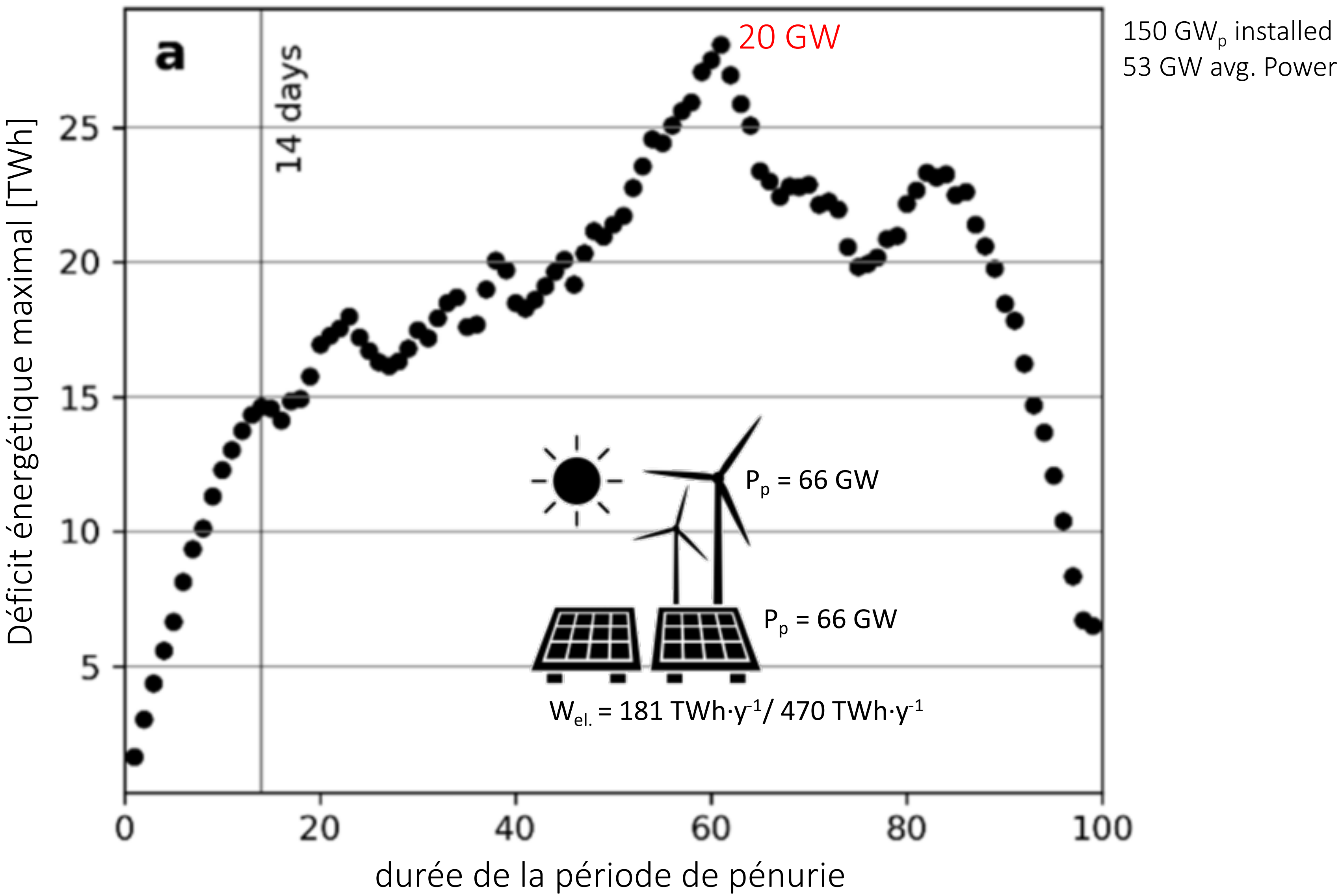
Ref.: SCHWEIZERISCHE GESAMTENERGIE STATISTIK (2019) Art.-Nr. 805.006.19 / 08.20 / 1200 / 860467013, Federal Office of Energy, Switzerland, https://www.bfe.admin.ch/bfe/de/home/versorgung/statistik-und-geodaten/energiestatistiken/gesamtenergiestatistik.exturl.html/

Sécurité énergétique neutre en CO_2 pour la Suisse

SAISONS EN SUISSE



Déficit en énergies renouvelables



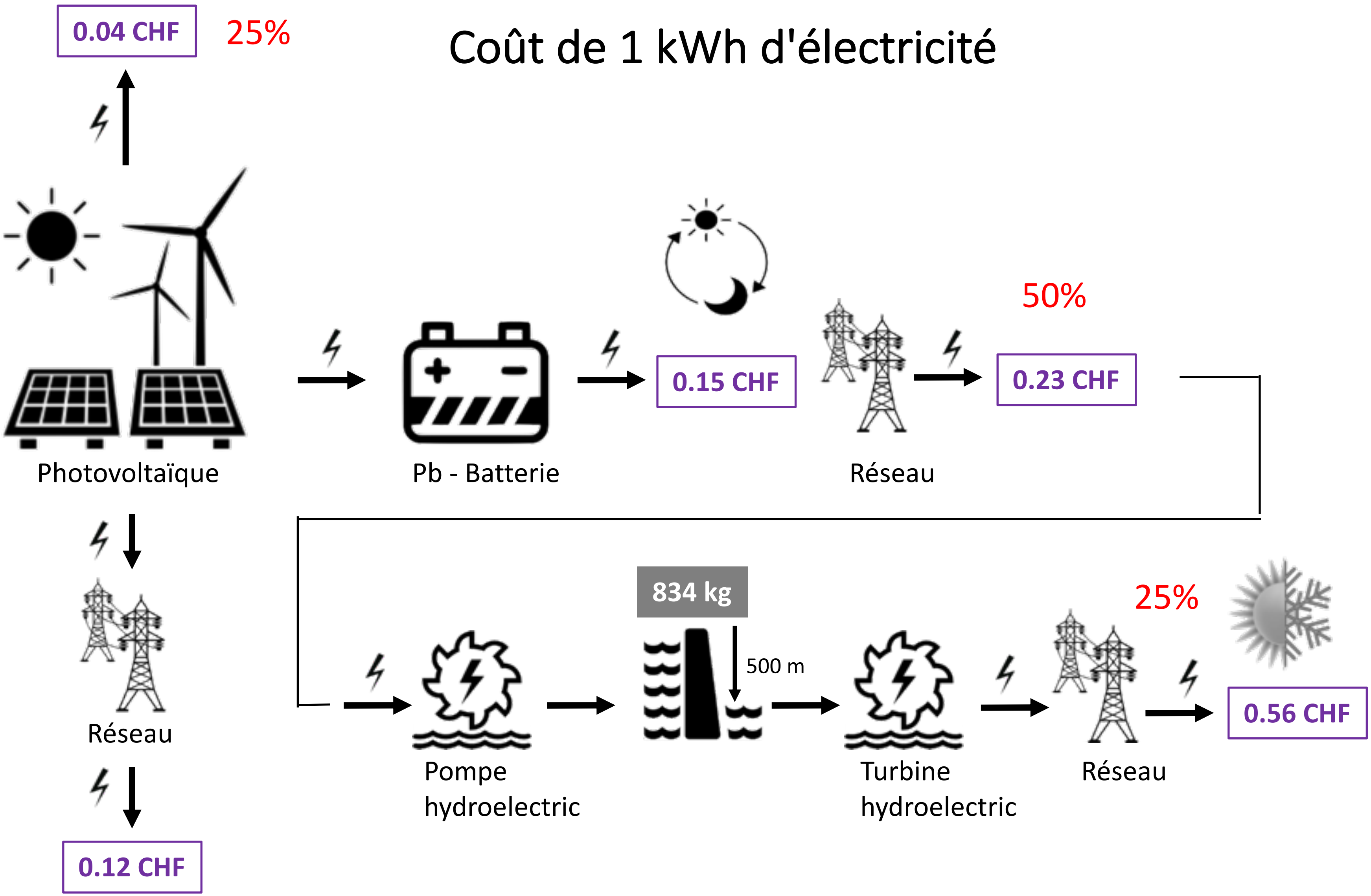
Ref.: Oliver Ruhnau, and Staffan Qvist,"Storage requirements in a 100% renewable electricity system: extreme events and inter-annual variability", Environ. Res. Lett. 17 (2022) 044018, https://doi.org/10.1088/1748-9326/ac4dc8

Sécurité énergétique neutre en CO_2 pour la Suisse

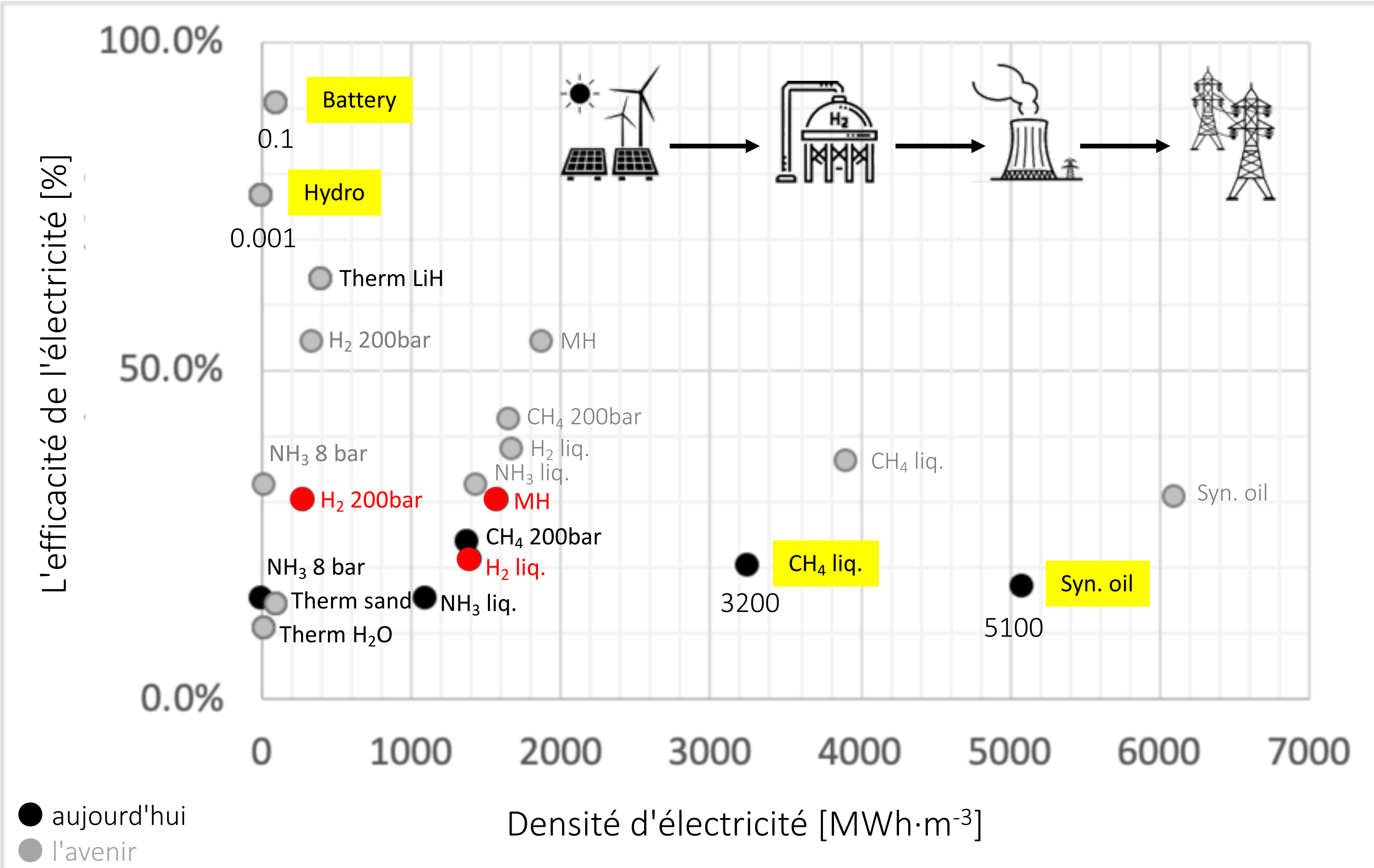
Systèmes d'énergie renouvelable : Résumé

	Electricité 3669.-	Hydrogène 5683.-	Syn. Combustible 9712.-
23 TWh·y^{-1}	1 x 75 GWh 316.- 4 x		
121 TWh·y^{-1}, 47 TWh·y^{-1}	2 x 134 km^2 150 GWh 642.- 9 x 1.5 TWh	6 x 480 GWh 2656.- 2 Mm^3 200 bar 25 x	12 x 920 GWh 6684.- 159 L 94 Mio.
Airport 23 TWh·y^{-1}			2 x 140 GWh 1212.- 14 Mio.
existants 63 TWh·y^{-1} PV, biomasse, hydroélectricité	1500.- 8 TWh·y^{-1} 20 TWh·y^{-1} 35 TWh·y^{-1}		

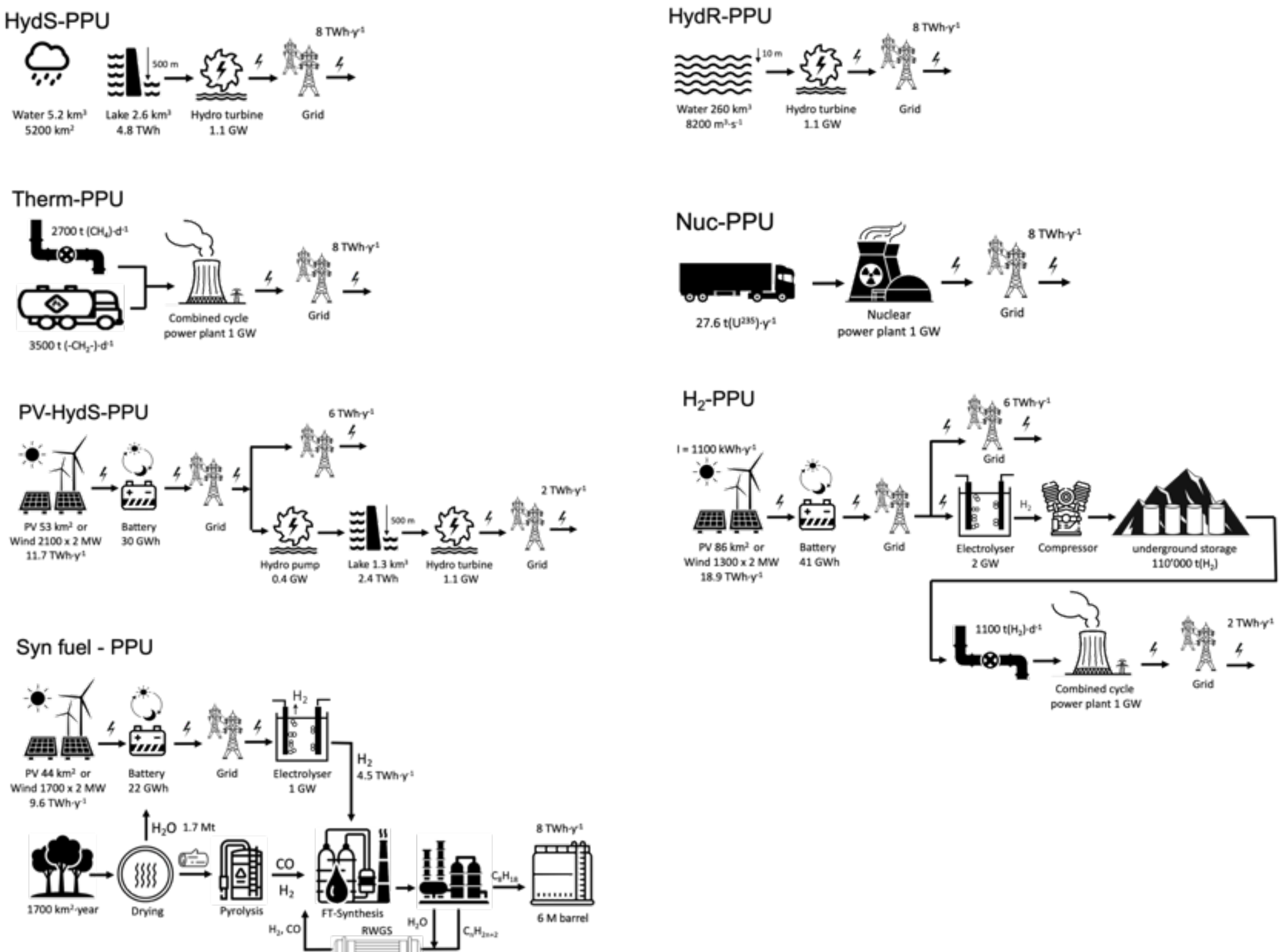
Électricité renouvelable à la demande



Efficacité et densité de stockage de l'électricité renouvelable

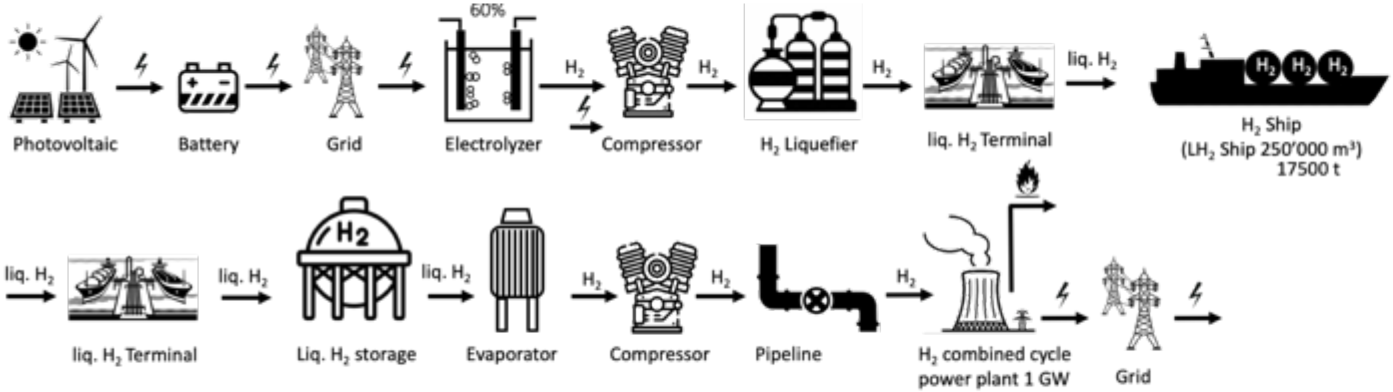


Unités de centrales électriques

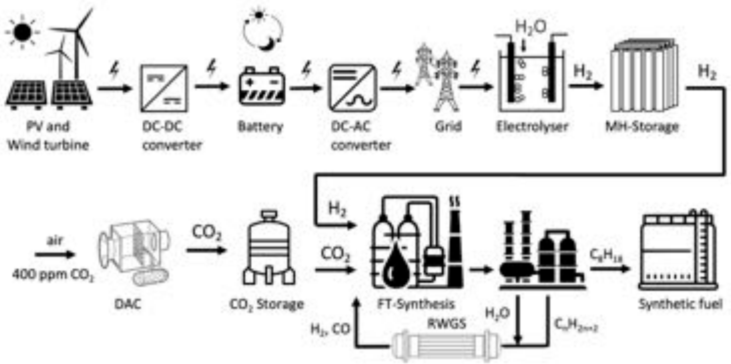


Unités de centrales électriques

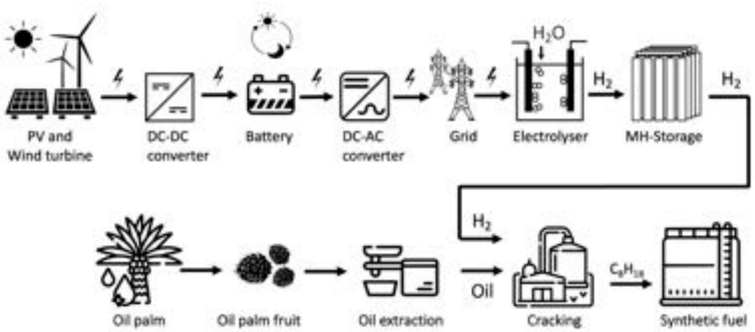
Imp. H_2



Imp. SF

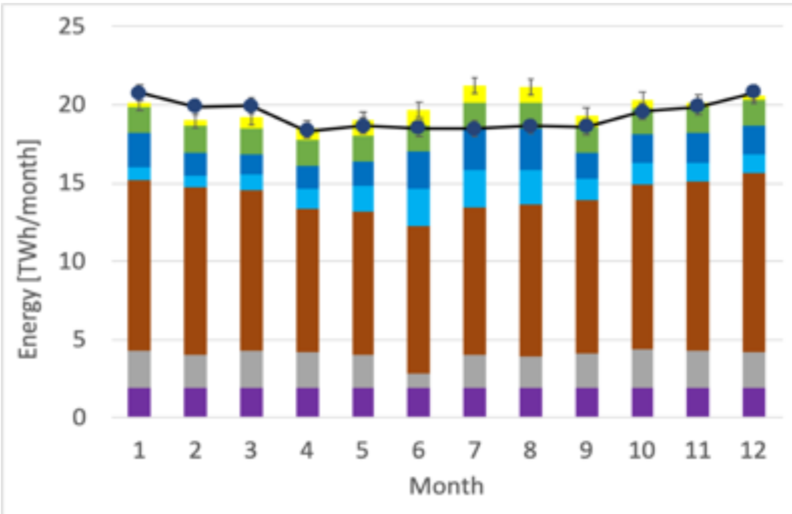


Imp. BSF

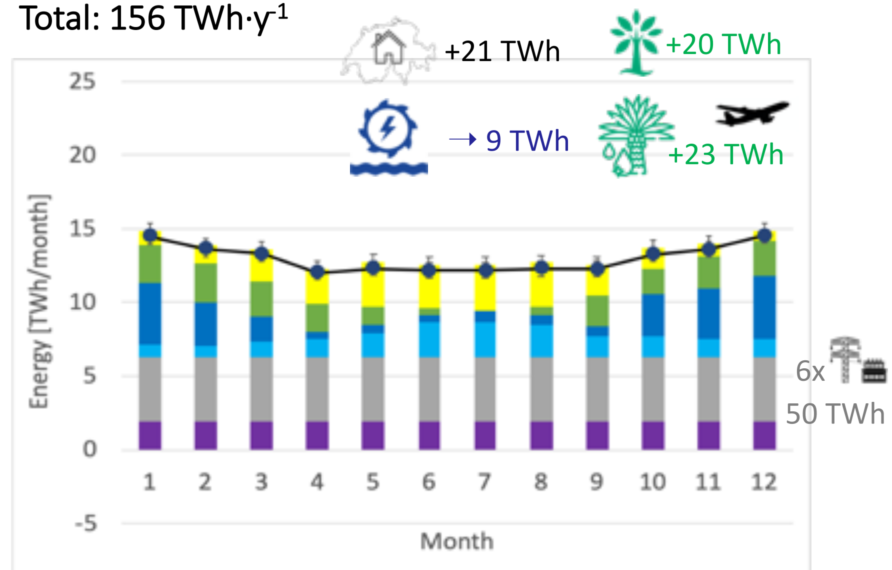


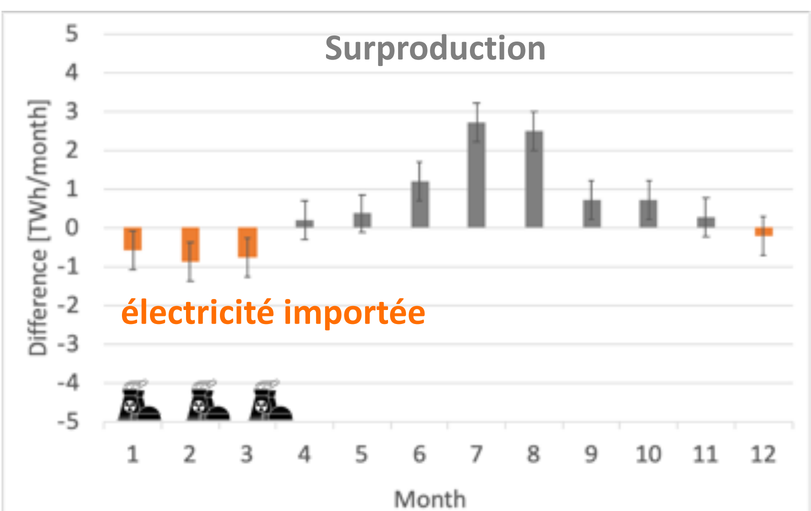
Remplacement des énergies fossiles par des énergies renouvelab

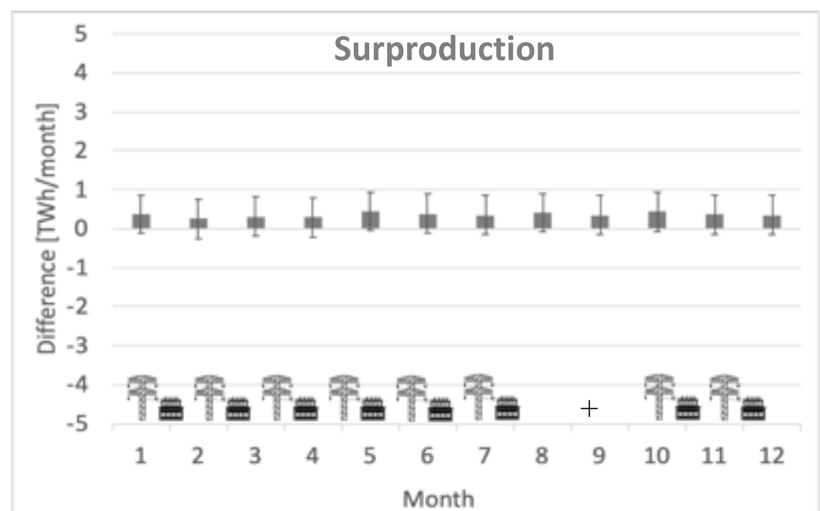
Total: 232 TWh·y-1 Fossil: 122 TWh·y-1



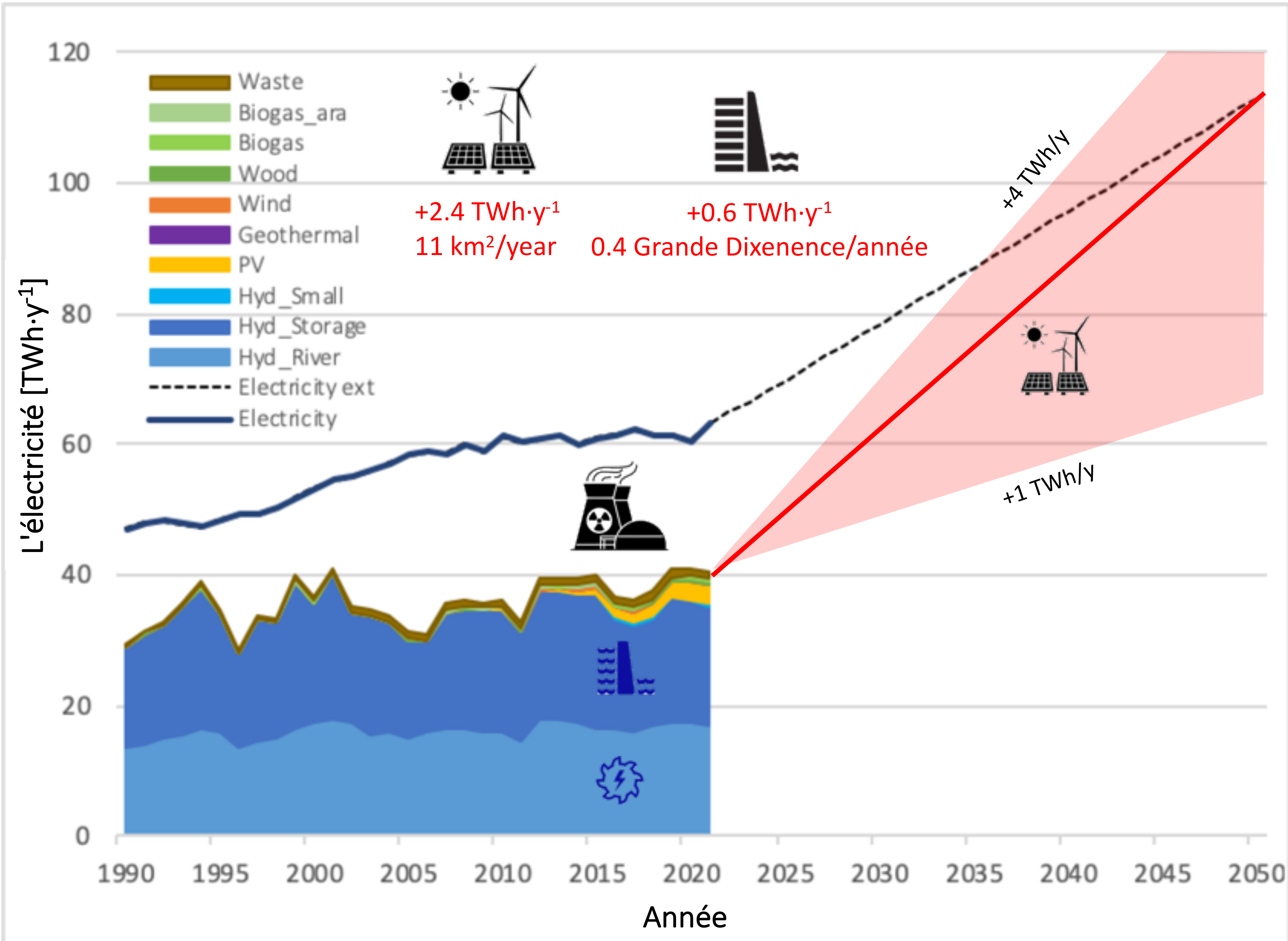
Total: 156 TWh·y-1



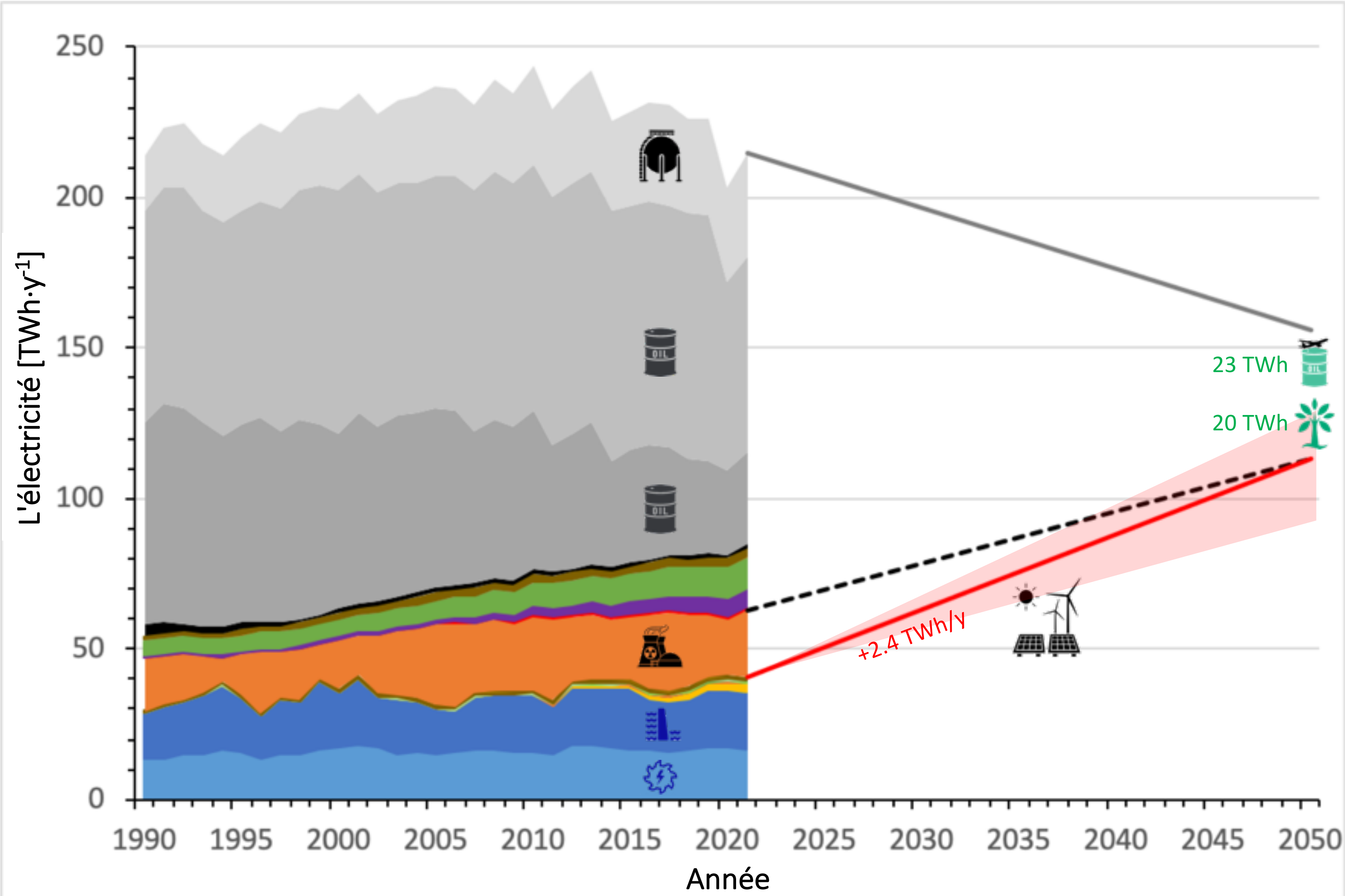




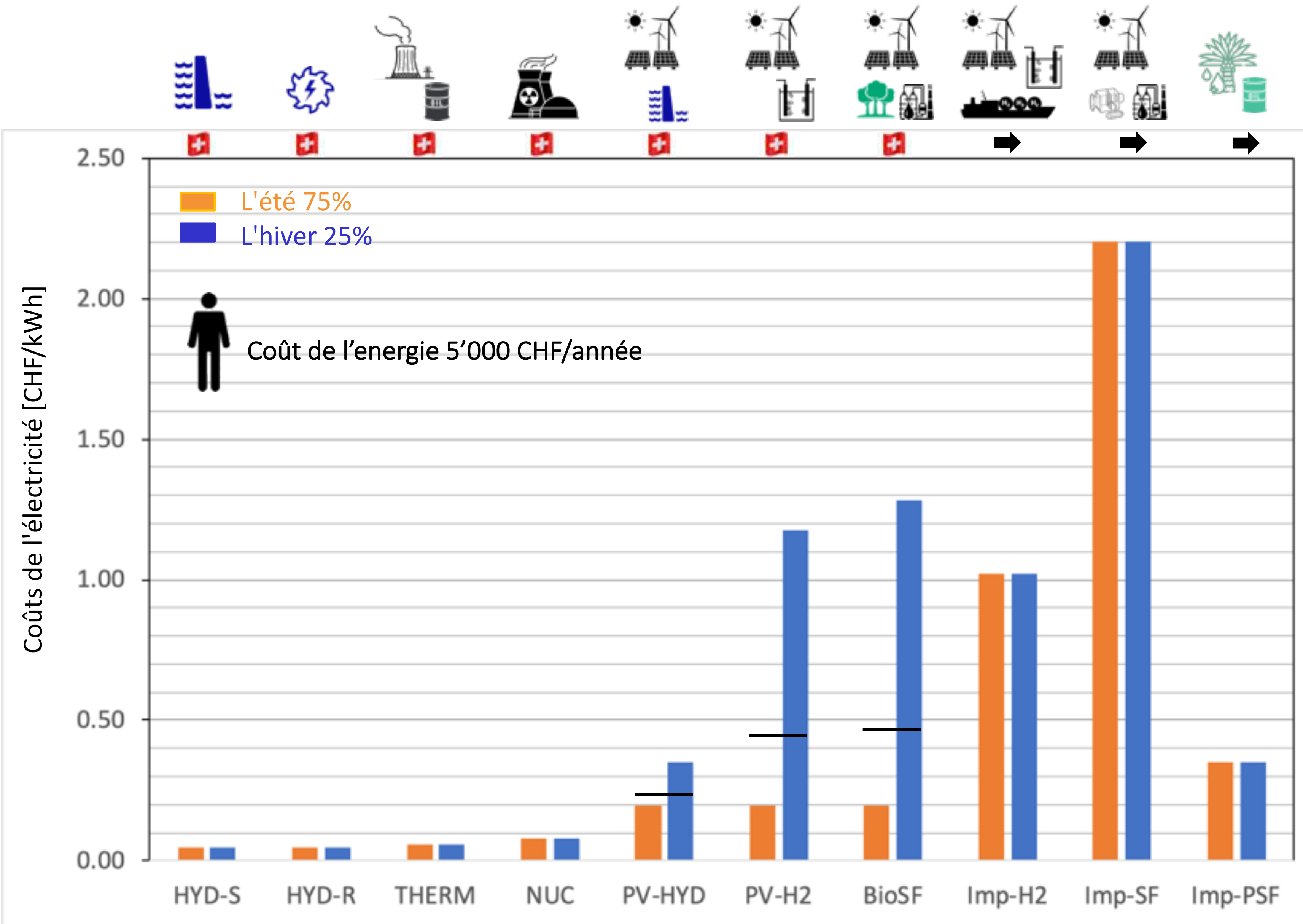
Développement des énergies renouvelables



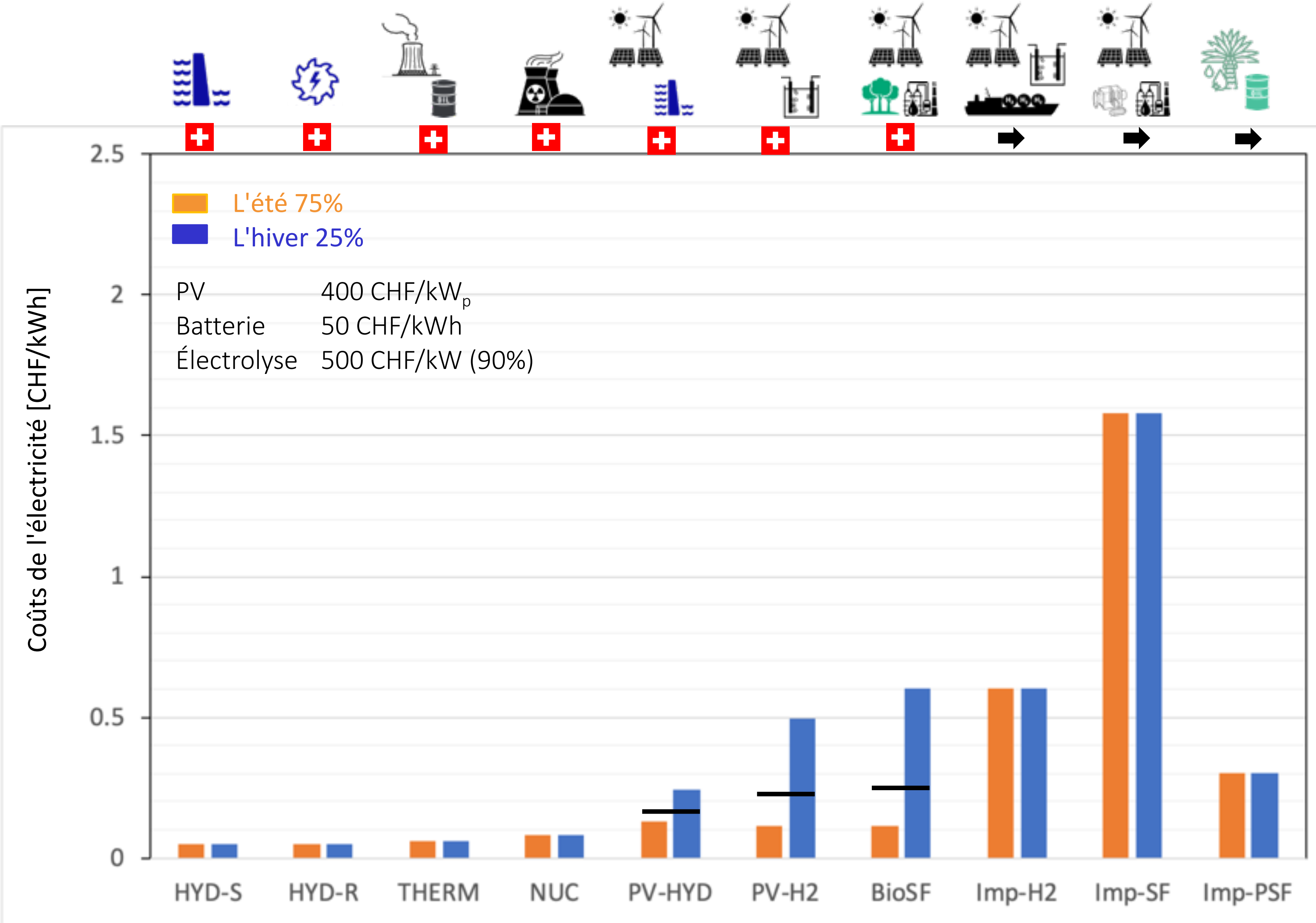
Développement des énergies renouvelables



Coût de l'électricité (2023)



Coût de l'électricité (futur)



50 TWh·y^{-1} par les unités de centrales électriques

	2023	Droit		H_2	
Coût [CHF·y^{-1}]	3'000	2'764	3'402	4'402	4'281
CAPEX [BCHF]	0	48-72	228	426 Stockage	384
Surface PV [km^2]	6	150	468	672	492
Area bio [km^2]		(6'200)	(6'200)	(6'200)	29'400 (6'200)

(....) étranger	H_2 →	→	→
Coût [CHF·y^{-1}]	9'079 Coût	15'445 Coût	4'623
CAPEX [BCHF]	42 (720)	30 (702)	24 (102)
Surface 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)

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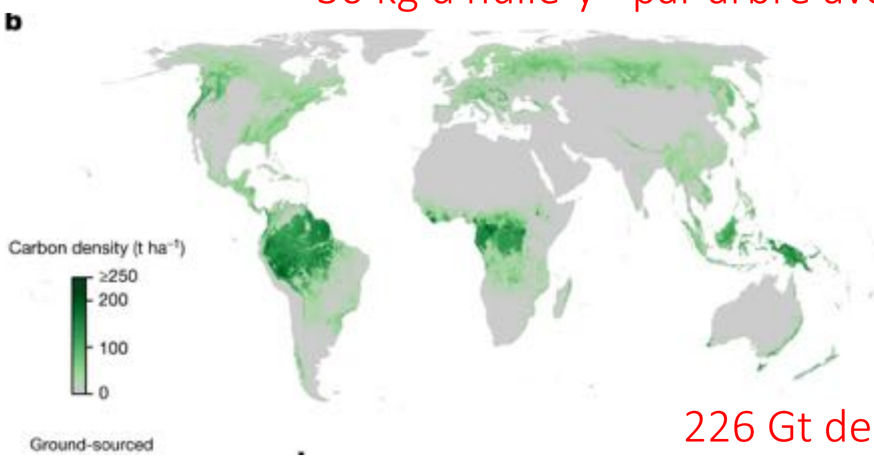
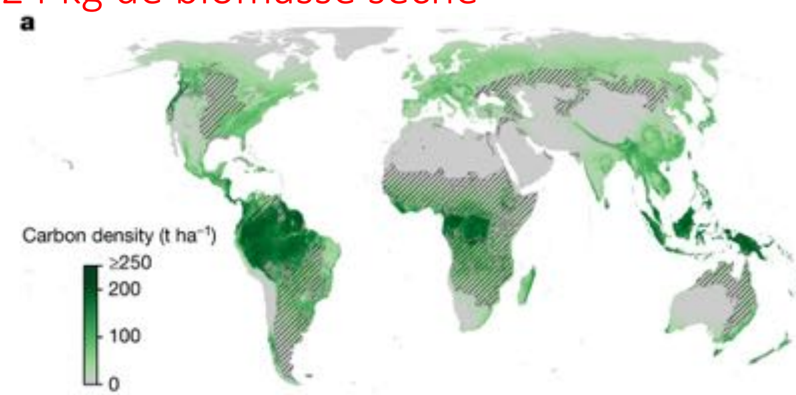
Carbon sinks and palm oil production

À l'heure actuelle, le stockage du carbone forestier mondial est netteme inférieur au potentiel naturel, avec un déficit total de **226 Gt** (fourchette modèle = 151-363 Gt) dans les zones à faible empreinte humaine. [1]
Avec 142 troncs de palmiers à huile (TPO) disponibles par ha de plantatic et une superficie replantée de 100’550 ha en 2017, le poids sec estimé c TPO (74.48 t·ha^{-1}) générés s'élevait à un total de 7.49 Mt [2]. L'huile de palme produite est de 4,0 t·ha^{-1}-y^{-1} et les plantes oléagineuses sont replantées tous les 20 ans.

30 kg d'huile-y^{-1} par arbre avec 524 kg de biomasse sèche





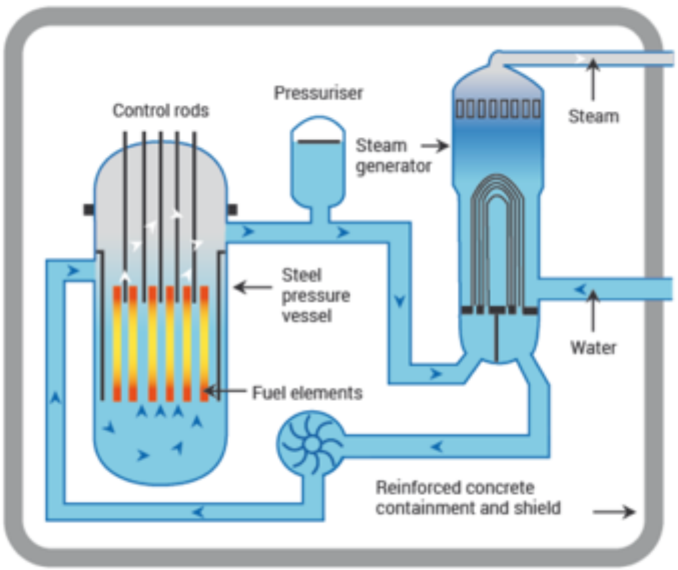
226 Gt de palmiers produisent 13 Gt de pétrole par an, soit la demande mondiale actuelle en énergie fossile.

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

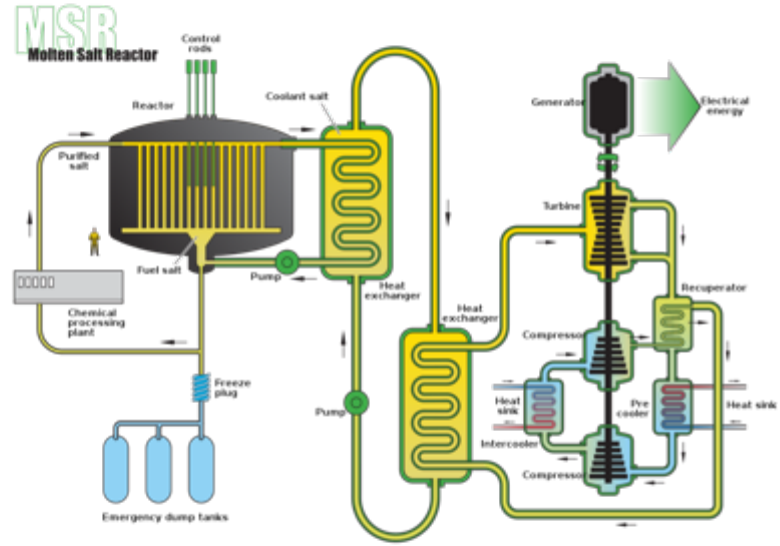
Réacteurs nucléaires

L'avenir

Réacteur à fission à l'uranium



Réacteur à sels fondus au thorium



Inconvénients :

Réserves d'uranium limitées (pour 100 ans)
Risque de fusion du cœur du réacteur
Isotopes à longue durée de vie (Pu)
faible rendement (25 %)
utilisation limitée de la chaleur
Dépôt final de la Nuc. Déchets
Petits réacteurs modulaires (SMR)

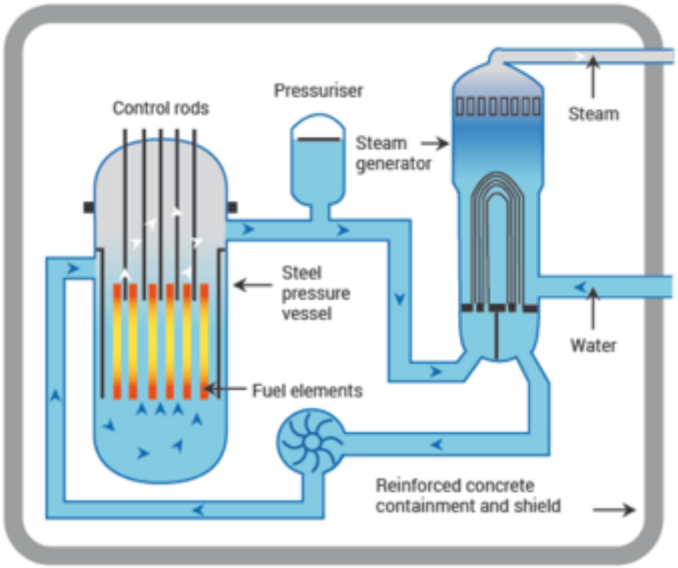
Avantages :

Grandes réserves de thorium (utilisation des déchets nucléaires, 95 % sont des combustibles)
Pas de fusion possible du cœur du réacteur
Pas d'isotopes à longue durée de vie
T plus élevé, rendement plus élevé (> 25 %)
Utilisation de la chaleur pour le chauffage
Réacteur à sels fondus (MSR)

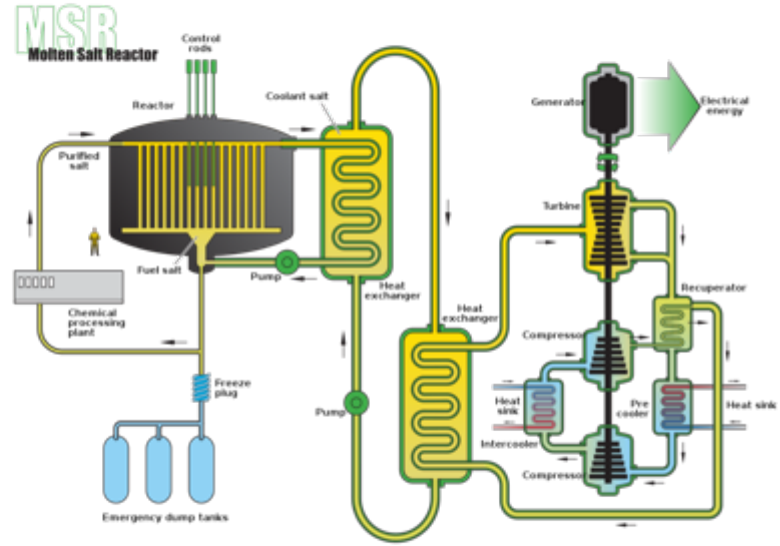
Réacteurs nucléaires

L'avenir

Réacteur à fission à l'uranium



Réacteur à sels fondus au thorium



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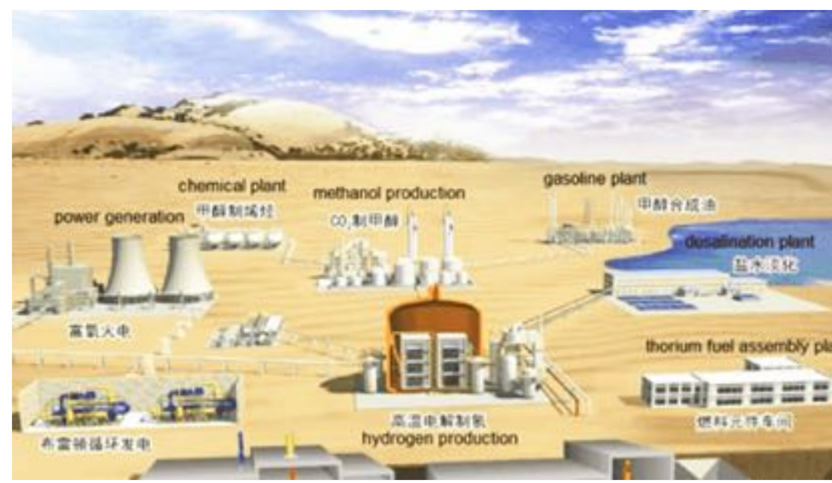
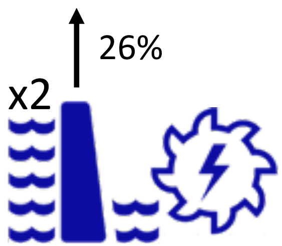


TMSR-LF1 (2 $MW_{therm.}$) construction 2018 - 2023, Wuwei city, Gansu province, China, operated since July 2023

Solution neutre en CO_2 (exemple)



36 TWh·y^{-1}

→ **9 TWh·y^{-1}**

0.2 CHF/kWh

Augmenter les lacs de stockage

24 TWh·y^{-1}

0.15 CHF/kWh

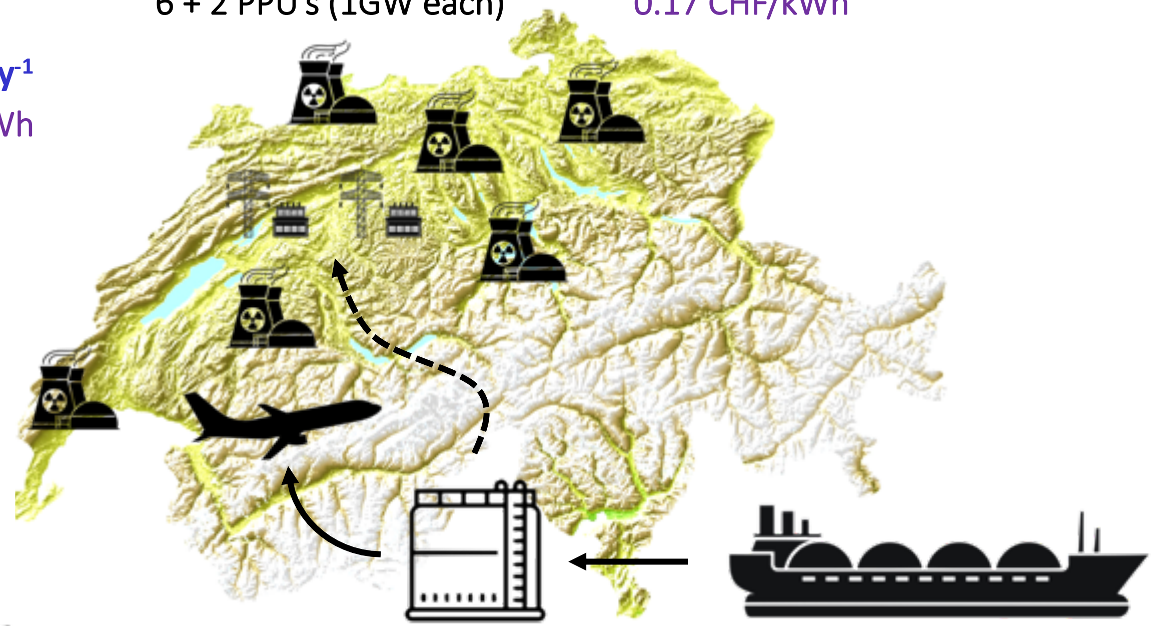
150 km² PV sur les toits

20 TWh·y^{-1}

Biomasse pour le chauffage

6 + 2 PPU's (1GW each)

0.17 CHF/kWh



réserves existantes **20 TWh**

Navire pétrolier

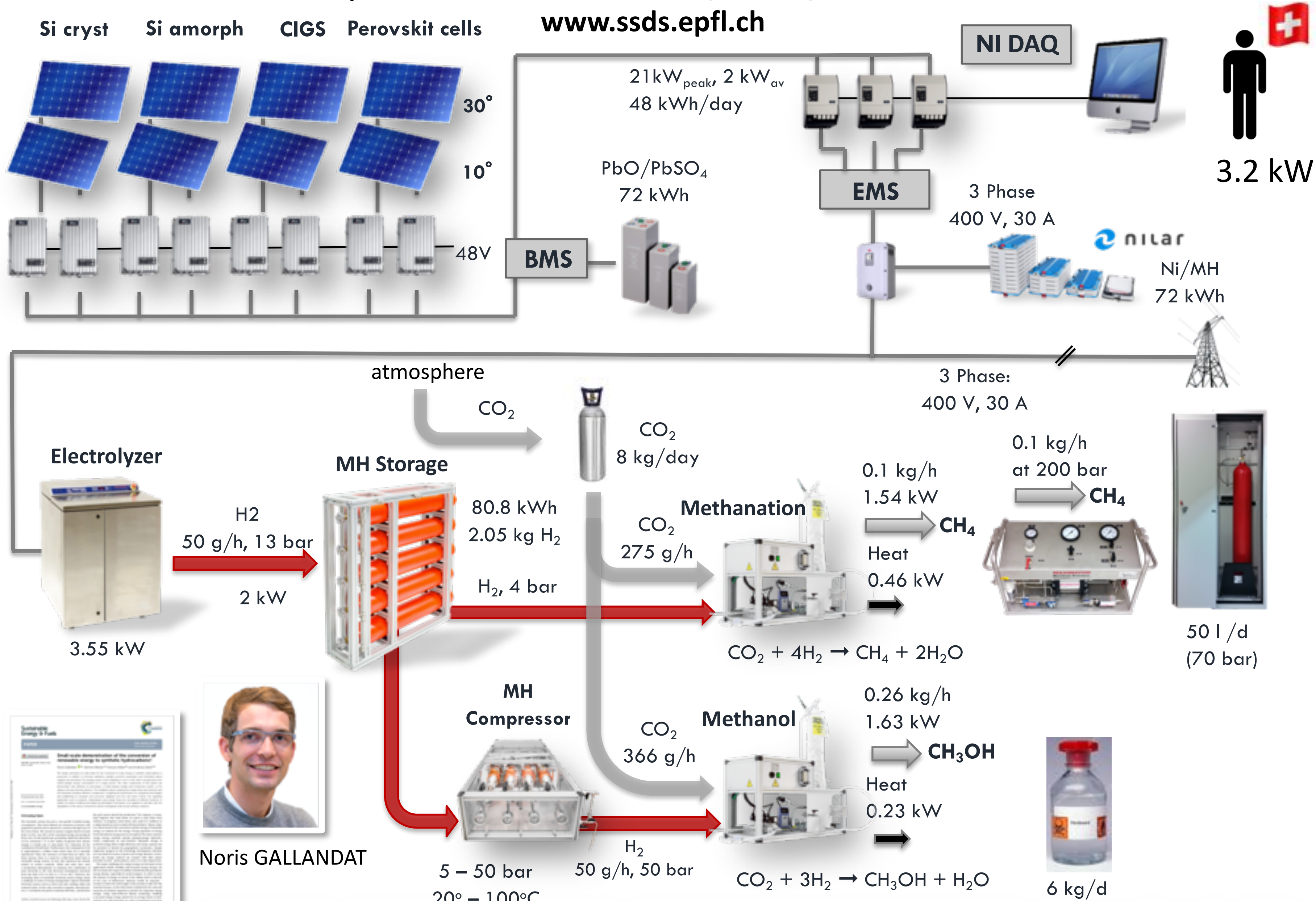
23 TWh·y^{-1}

1.7 CHF/L

Huile biologique <6200 km²

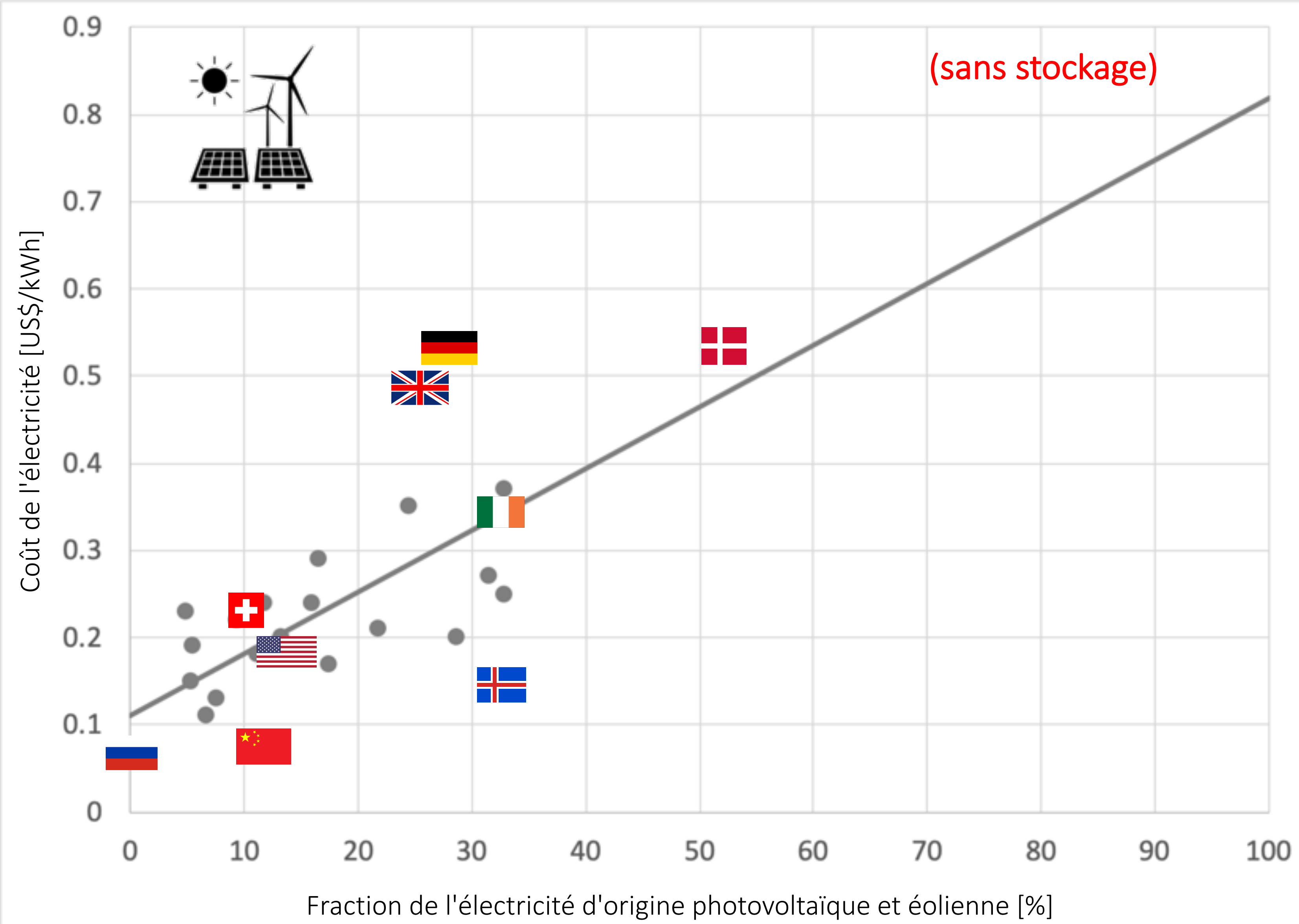
Démonstrateur à petite échelle Sion (SSDS)

www.ssds.epfl.ch



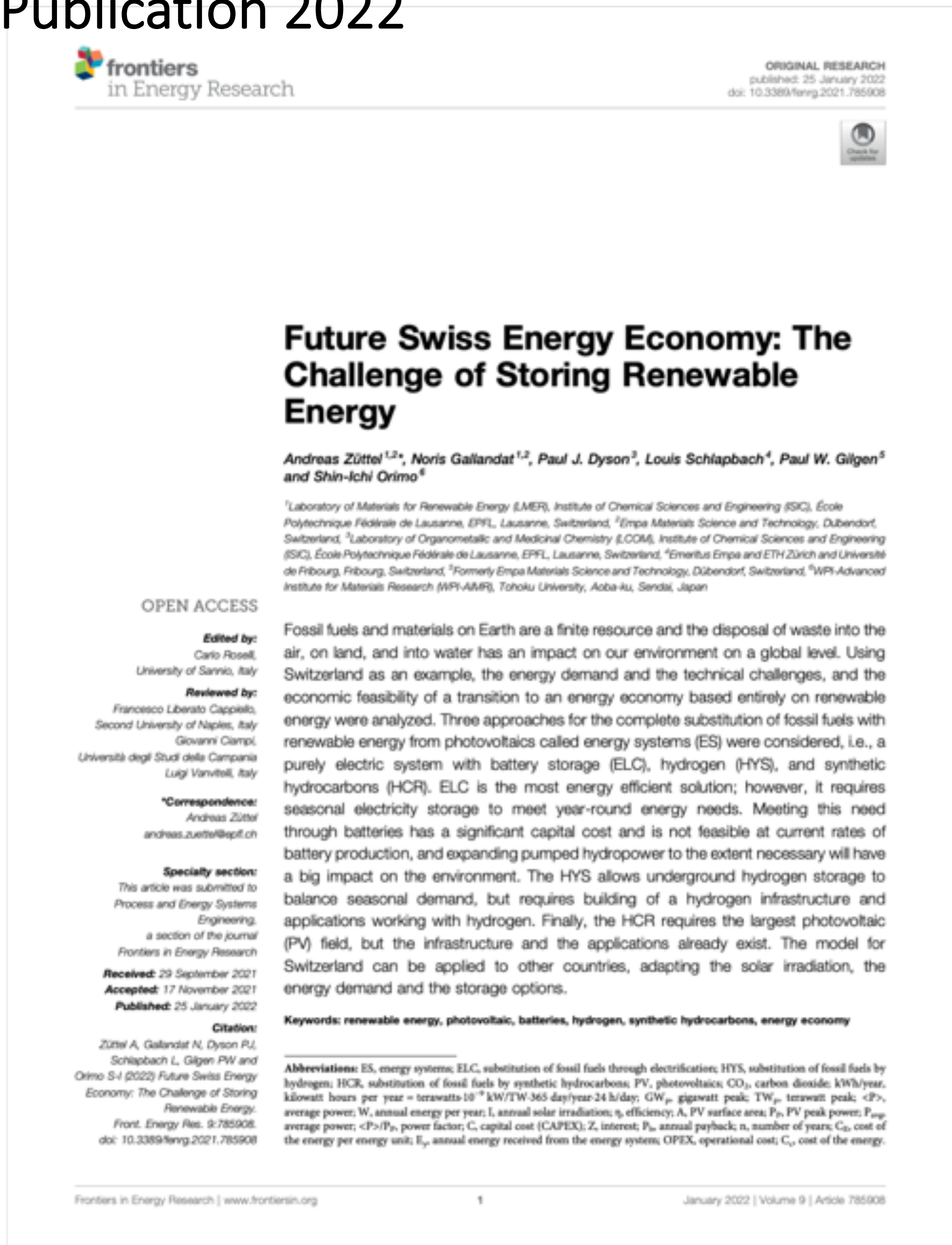
Noris Gallandat, Jérémie Bérard, François Abbet and Andreas Züttel, "Small-scale demonstration of the conversion of renewable energy to synthetic hydrocarbons", Sustainable Energy & Fuels (2017).DOI: 10.1039/c7se00275k, rsc.li/sustainable-energy

Coût de l'électricité photovoltaïque et éolienne (2023)



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

Publication 2022



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

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

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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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