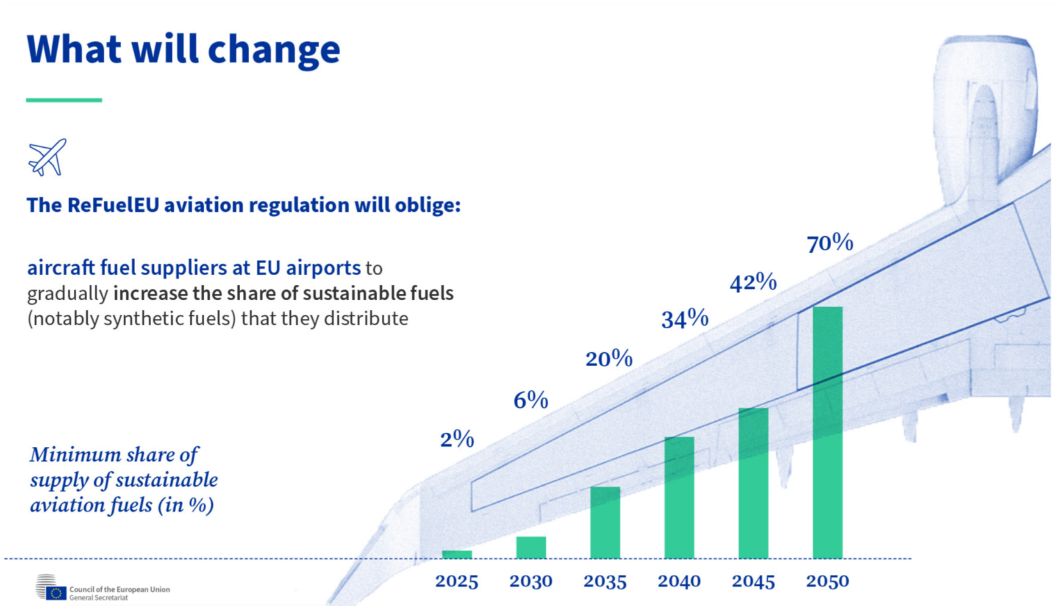
SYNTHETIC AVIATION FUELS (SAF)
A techno-economic analysis of the production pathways



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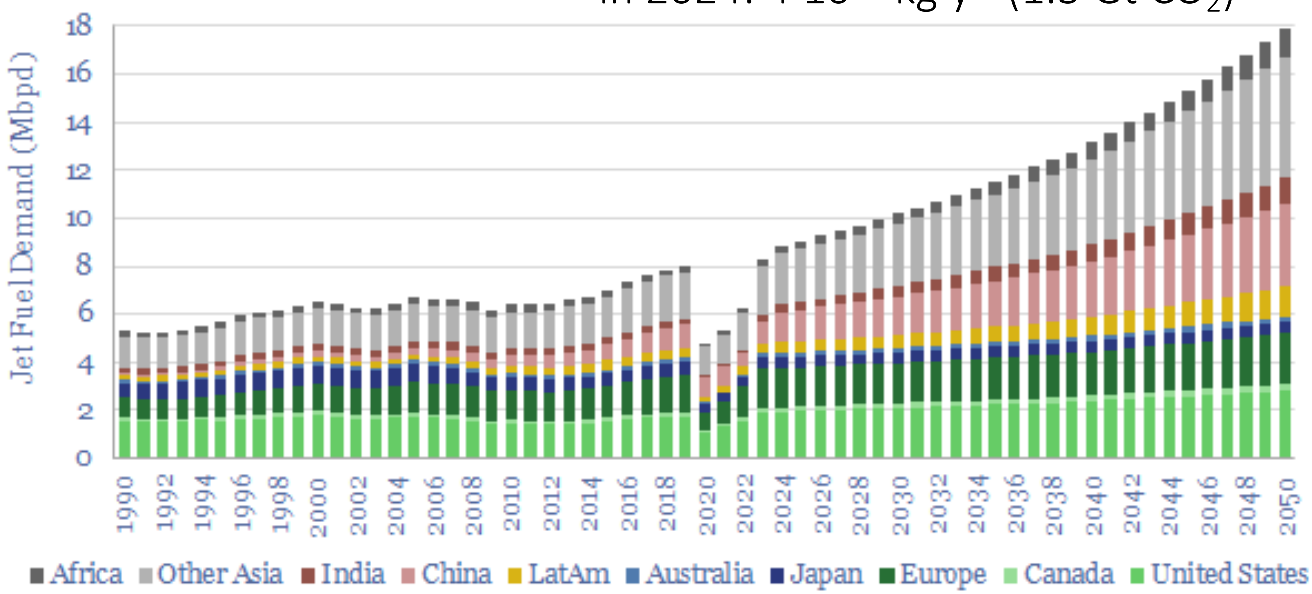
in 2024: $4 \cdot 10^{11}$ kg·y^{-1} (1.3 Gt CO_2)



Horse manure 130 years ago

Horse manure in 1894

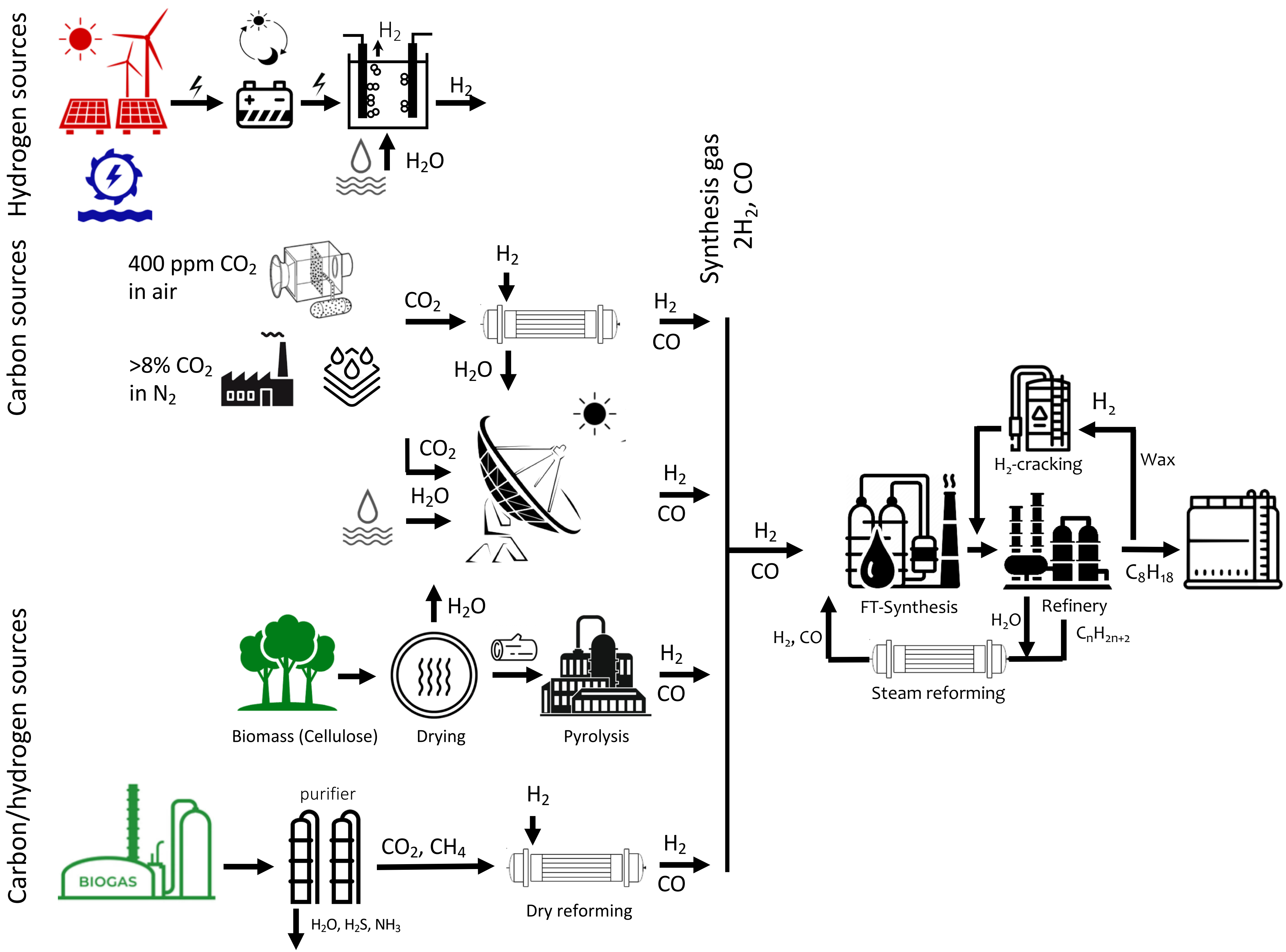
Crisis, we need to reduce the number of horses!

Remove manure

Capture manure at point source

Solution: new technology!

SYNTHETIC AVIATION FUELS (SAF)



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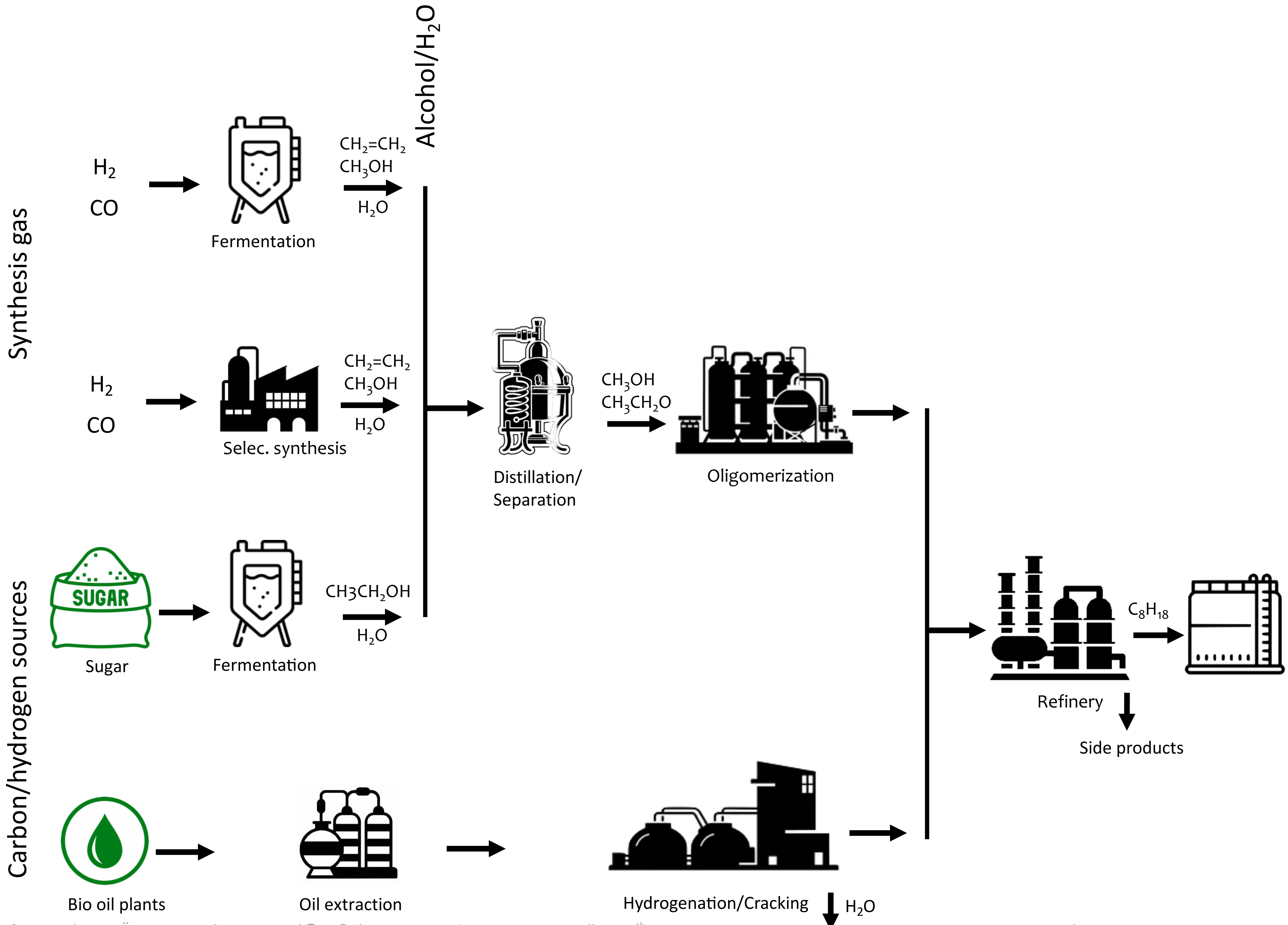
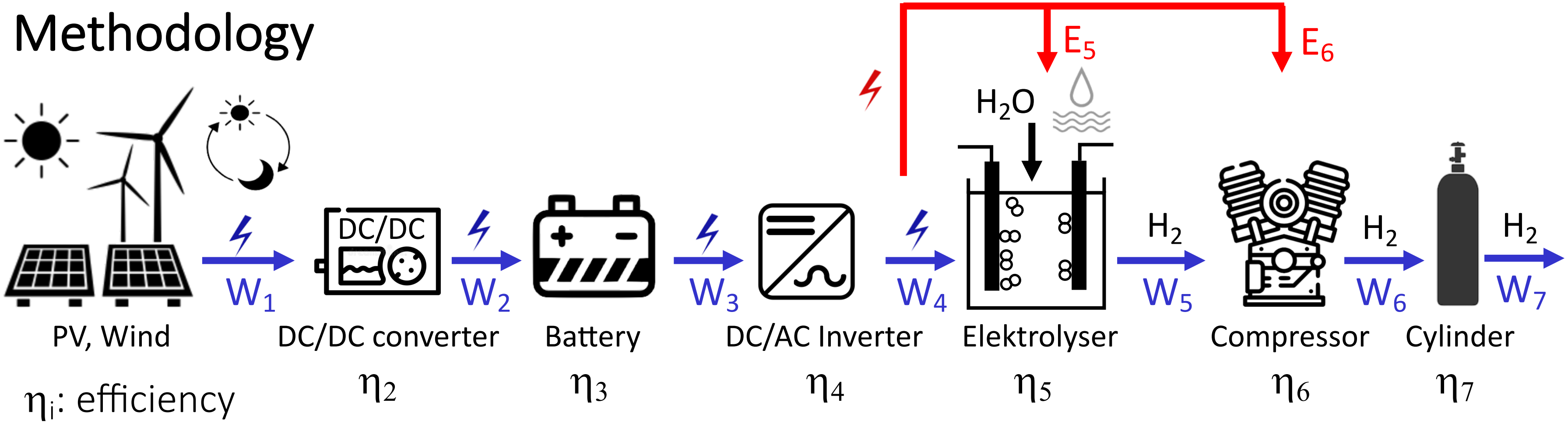


Methodology



Energy transfer: $W_4 = W_5/\eta_5 + E_5 + E_6$

W_i: trans. energy
E_i: electricity

constant annual payback P_b: $P_b = CAPEX \cdot \frac{Z \cdot (1+Z)^n}{(1+Z)^n - 1}$

Z: annual interest
n: lifetime in years

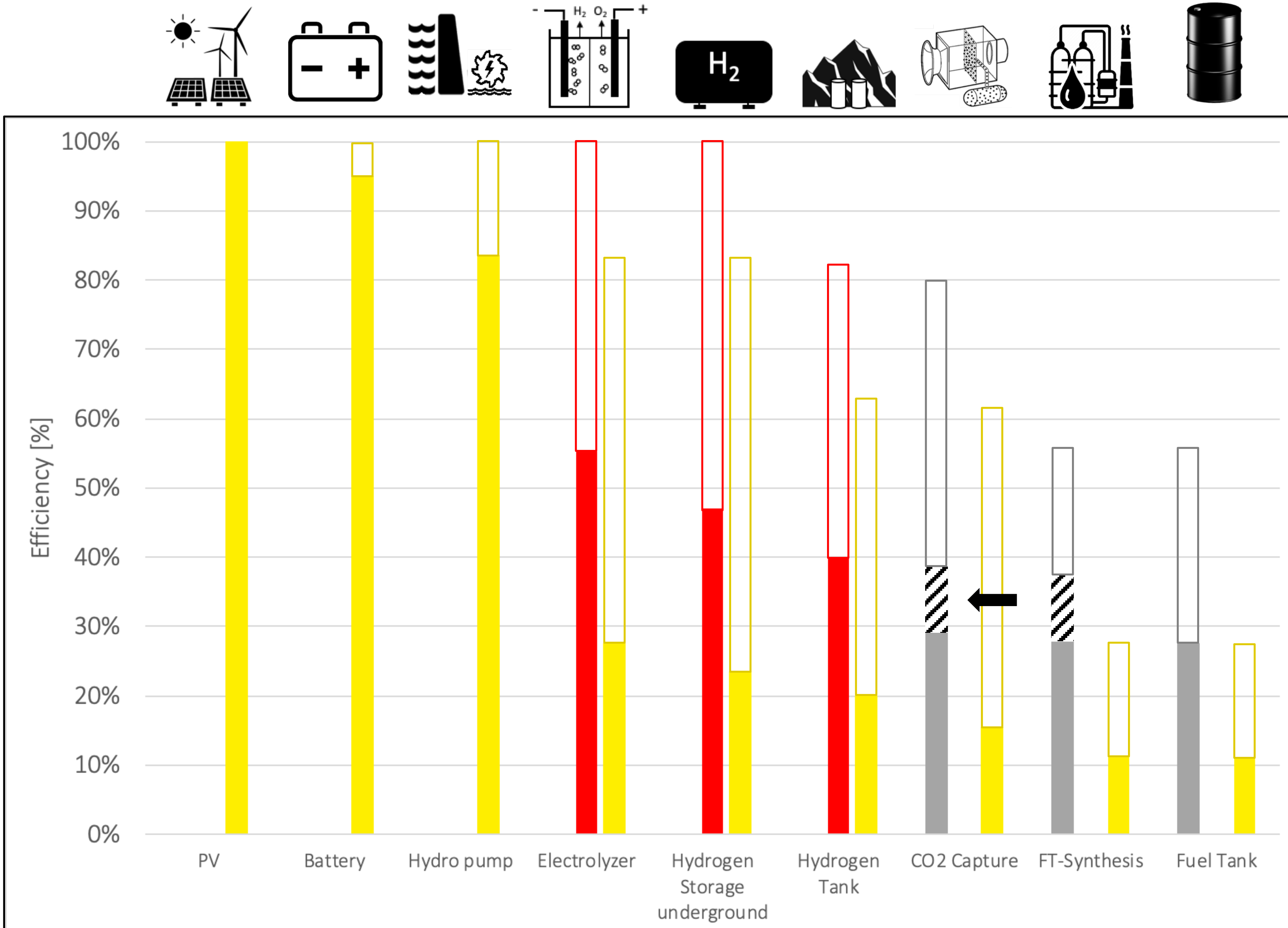
additional energy cost per component = P_b + OPEX

Int. [kWh/(y·m2)]:	1100			PeakP [kW] =	2.179								
Efficiency [%]:	20.0%	Area fac.:	1.5	Avg. P [kW] =	0.274								
Area [m2]:	10.90	**Area real [m2]:**	**16.34**	Max. avg P =	0.821								
					per year								
PV, Battery, Electrolysis, comp. H2													
Converter	*Efficiency [%]*	*W [kWh/kWh]*	*Cost/W [CHF/kWh]*	*Investment [CHF/kW]*	*W [kWh]*	*W [kWh]*	*Wel. [kWh]*	*Cost cum [CHF]*	*Cost/Wcum [CHF/kWh]*	*Size unit*	*Size [kW or kWh]*	CAPEX [CHF]	Cost fraction
PV	100.00%	0	0.071	1607	2184	2397.1	213.0	169.84	0.07	W [kWh·y-1] =	2397.13	3503	11.3%
Converter AC/DC	95.00%	0	0.022	845	2075	2277.3	202.3	218.95	0.10	Pp [kW] =	0.82	694	4.0%
Battery	89.00%	0	0.133	239	1847	2026.8	180.1	489.33	0.24	C [kWh] =	9.85	2351	23.1%
Inverter DC/AC	95.00%	0	0.022	845	1754	1925.4	171.1	530.85	0.28	Pp [kW] =	0.69	587	5.4%
Electrolyzer	60.00%	0.02	0.054	2227	1053	1052.6	0.0	587.65	0.56	Pp [kW] =	0.60	1338	44.9%
Compressor	95.00%	0.15	0.021	1223	1000	1000.0	0.0	608.90	0.61	Pp [kW] =	0.36	441	8.0%
Hydrogen Tank	100.00%	0	0.020	61	1000	1000.0	0.0	629.29	0.63	C [kWh] =	4.11	251	3.2%
	45.8%	171.1	Auxillary power						**0.63**			9164	
Efficiency =	**41.7%**							**Fuel [CHF/kgH**	**24.79**		**CAPEX [CHF] =**	**9164**	

SYNTHETIC AVIATION FUELS (SAF)

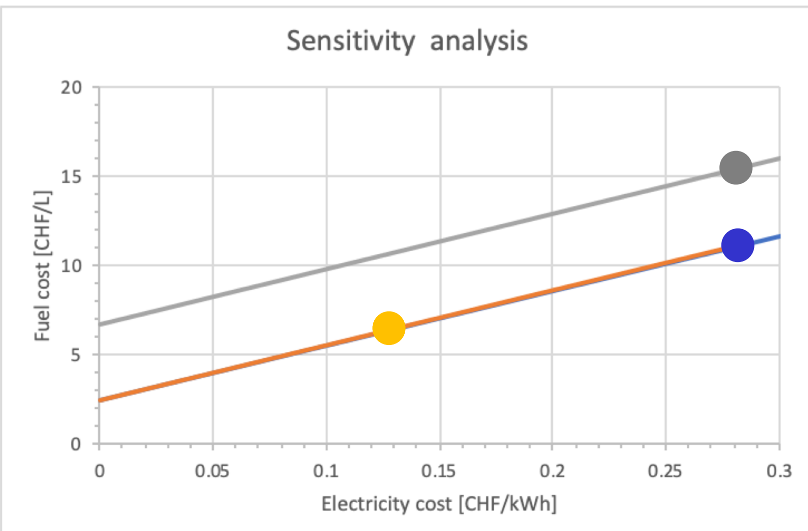
Efficiency of renewable energy conversion

Power to X (P2X)

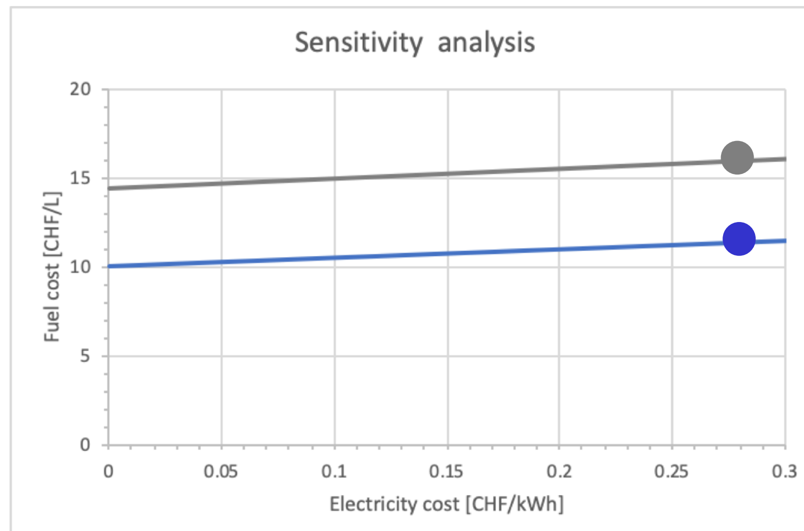


Summary of solar & FT

	PV Land area [km^2]	Efficiency [%]	CAPEX [M CHF]	Cost fuel [CHF/L]
PV, Battery, Hydrogen, conc. CO_2, FT	3.6	27.2	1336	10.8
PV, Hydrogen, conc. CO_2, FT	3.0	32.2	1294	5.5
PV, Battery, Hydrogen, DAC CO_2, FT	3.6 (3.06)	26.7 (31.6)	1461 (1008)	15.3 (9.9)
PV, conc. solar, conc. CO_2, FT	5.6	51.9	999	10.4
PV, conc. solar, DAC CO_2, FT	5.6	51.9	1114	14.8



Cost of fuel as a function of electricity cost for PV, Battery, H_2, conc. CO_2, FT, PV, H_2, conc. CO_2, FT, PV, Battery, H_2, DAC CO_2, FT.



Cost of fuel as a function of electricity cost for PV, conc. CO_2, conc. solar, FT, PV, DAC, conc. solar, CO_2, FT

Scale effect on the cost of fuel

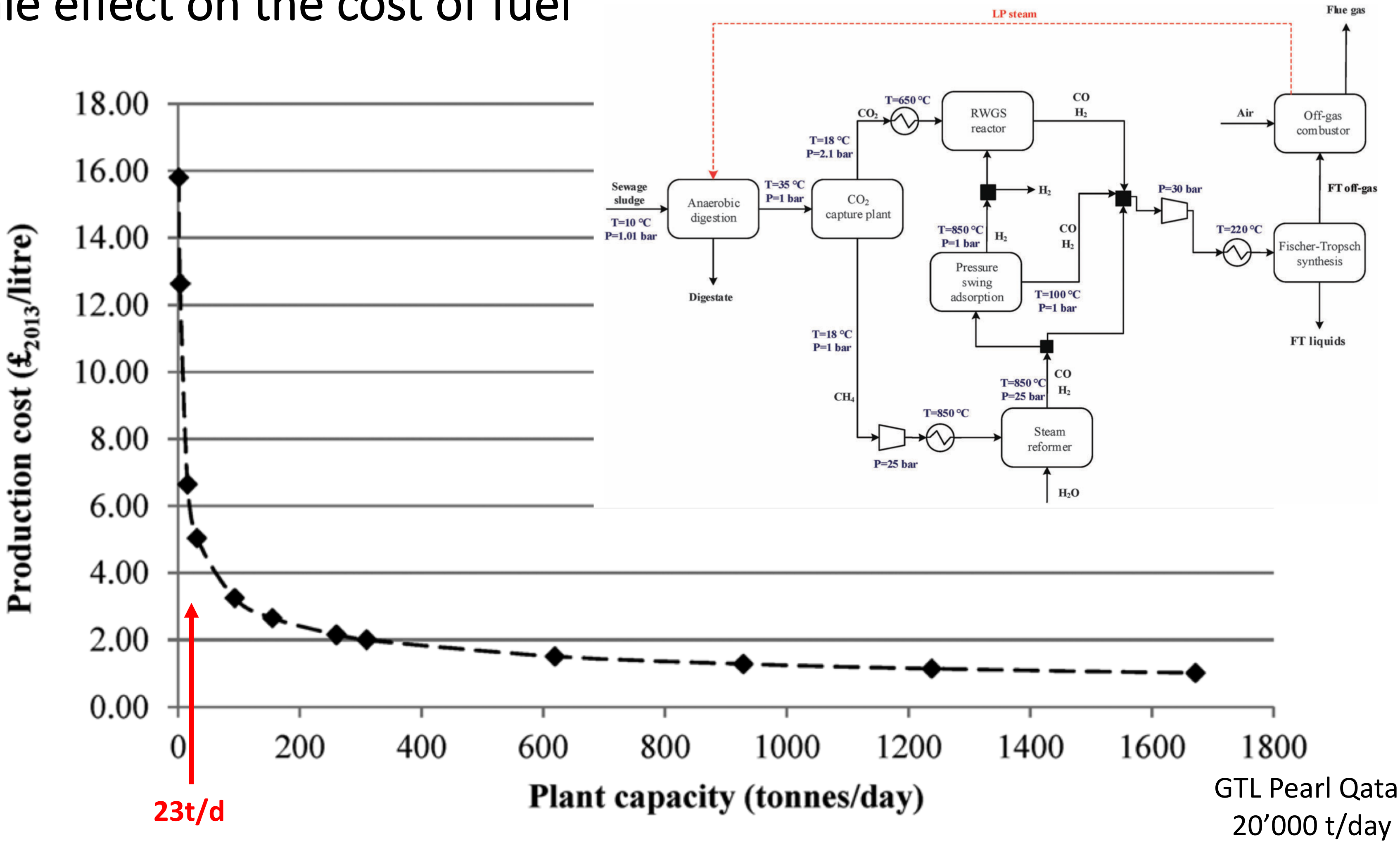
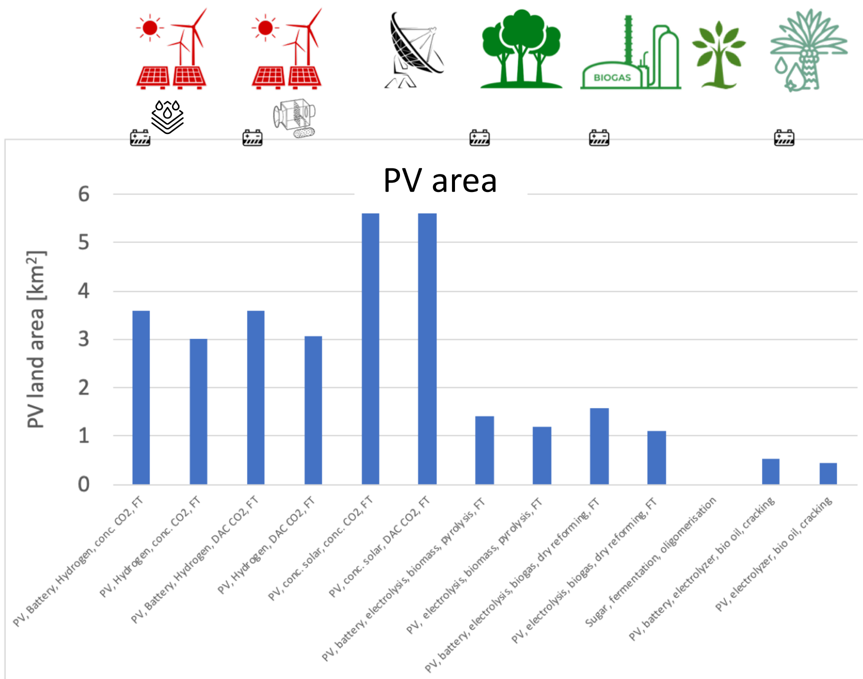
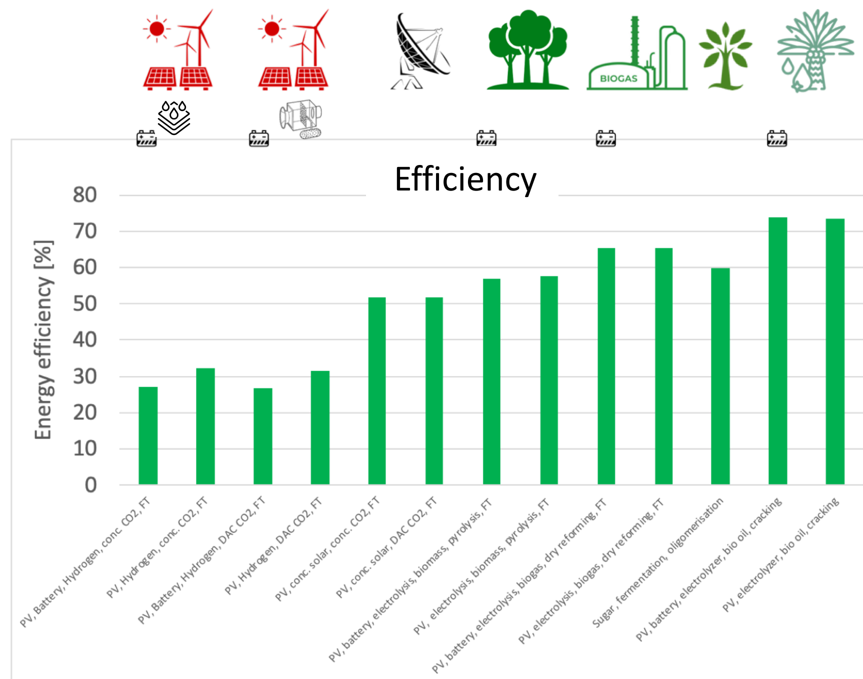


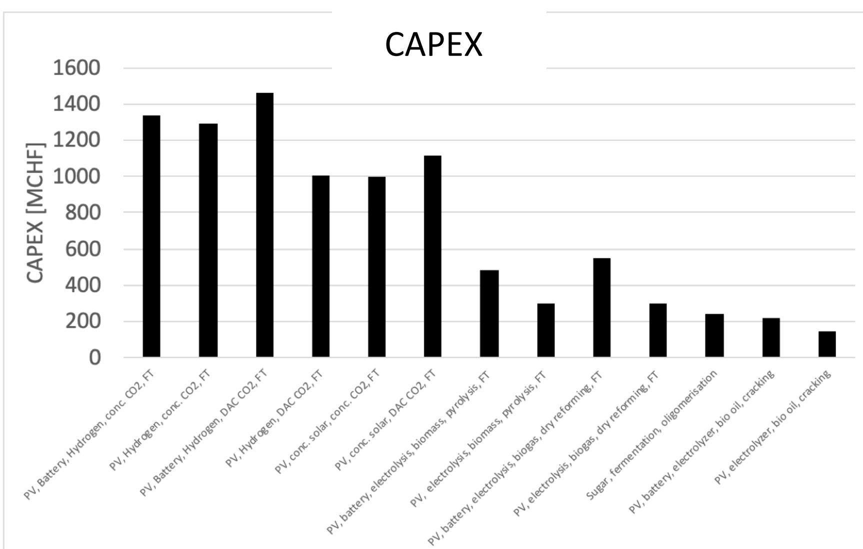
Fig. Cost of liquid fuels in £ per liter for different plant capacities for PD-MEA.

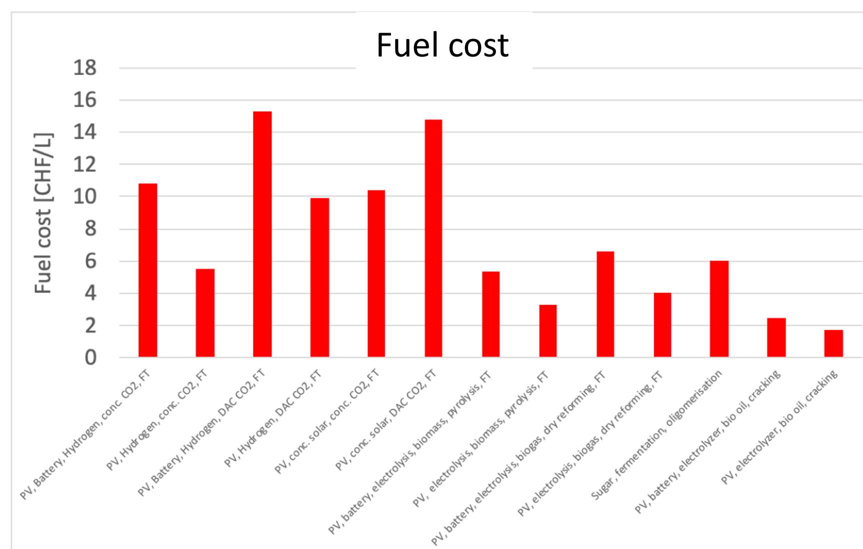
Ref.: Ioanna Dimitriou, Pelayo Garcıa-Gutierrez, Rachael H. Elder,́ Rosa M. Cué llar-Franca,b Adisa Azapagi and Ray W. K. Allen, “Carbon dioxide utilisation for production of transport fuels: process and economic analysis”, Energy Environ. Sci., 2015, 8, 1775

Area, Efficiency, CAPEX and fuel Cost of SAF production paths

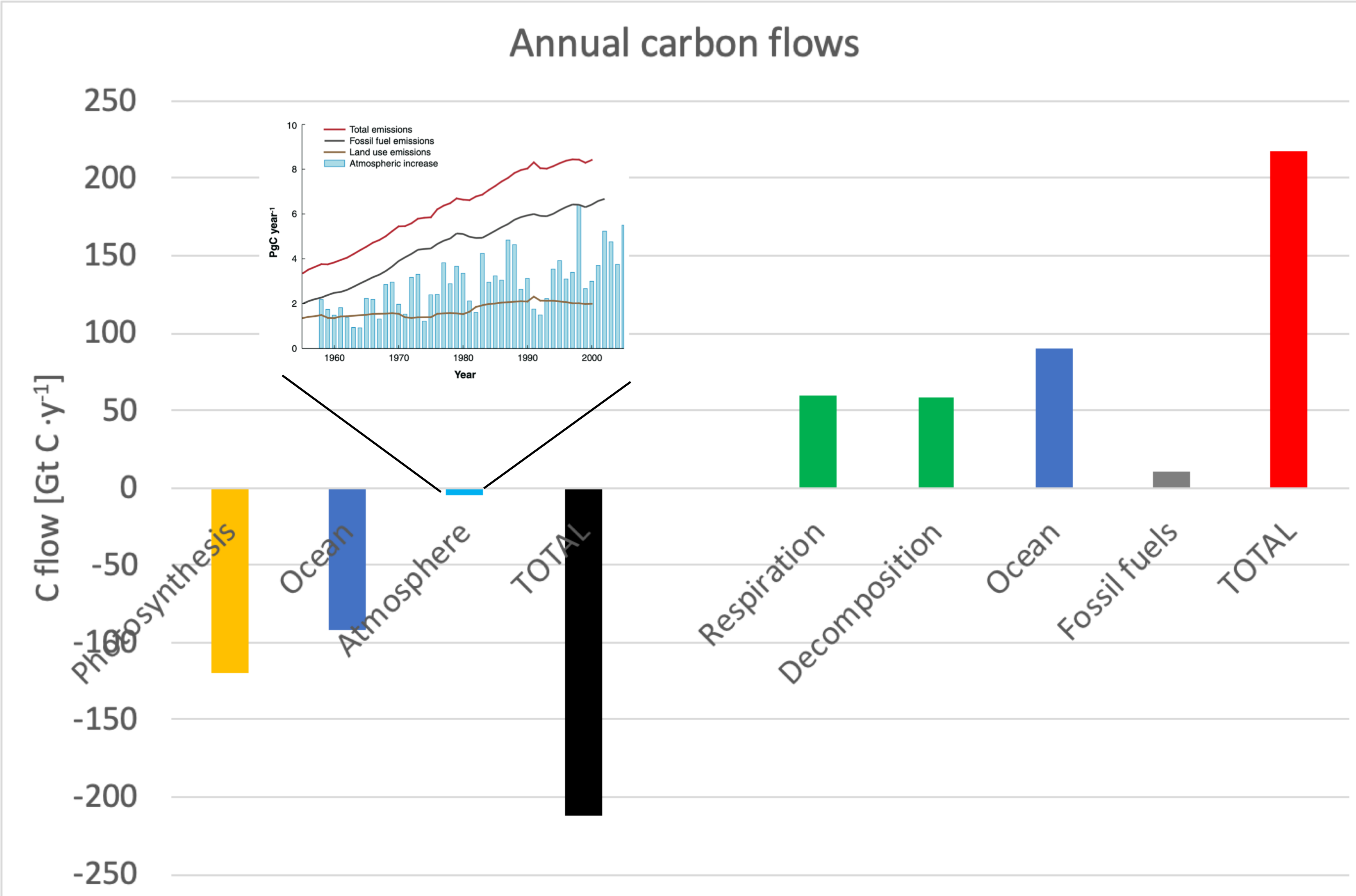








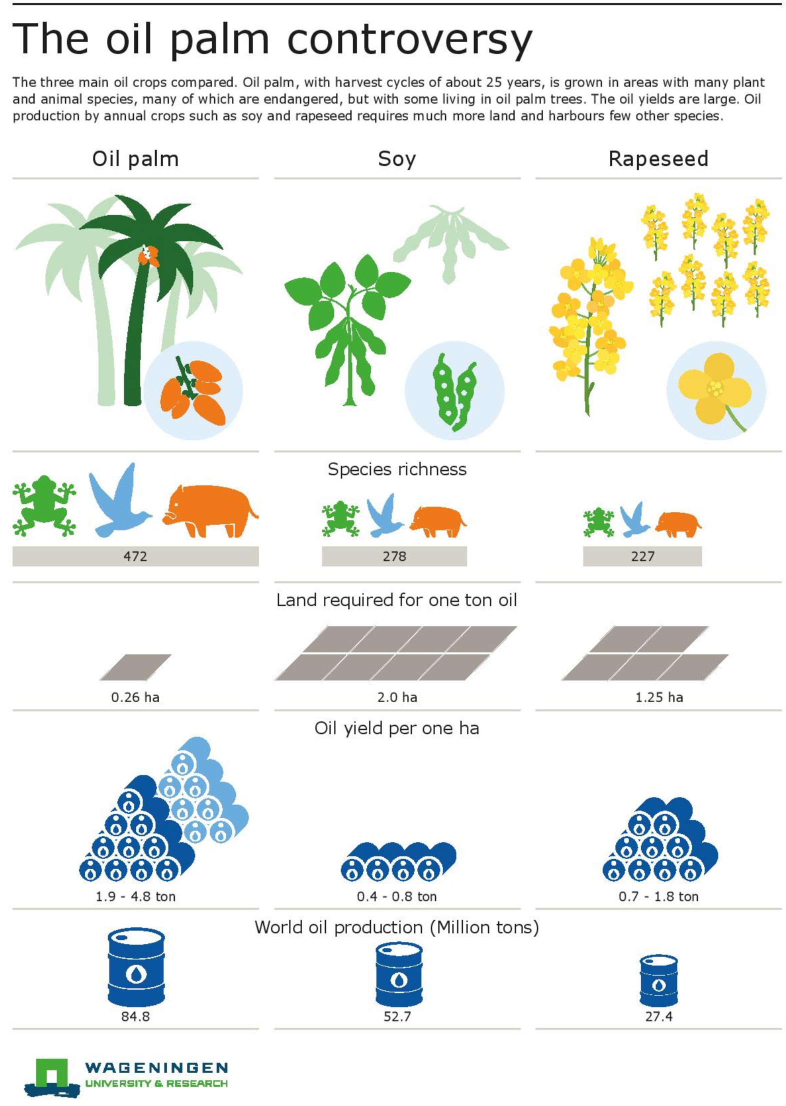
Balancing the Global Carbon Budget



Ref.: R.A. Houghton, “Balancing the Global Carbon Budget”, Annu. Rev. Earth Planet. Sci. 2007. 35:313–47

Biomass production comparaison

Fuel	Moisture	Heating value [kWh/kg]
Green wood	50%	2.64
Seasoned wood	20%	4.31
Dry sawdust	13%	4.50
Wood pellets	10%	4.67
Dry wood (non-resinous)	0%	5.28
Dry wood (resinous)	0%	6.25
Dry stem wood	0%	5.31
Dry bark	0%	5.44
Dry branches	0%	5.58
Dry needles	0%	5.67
Palm oil	0%	10.19
Karoch oil	0%	10.58
Biodiesel	0%	7.42
Bioethanol	0%	6.81

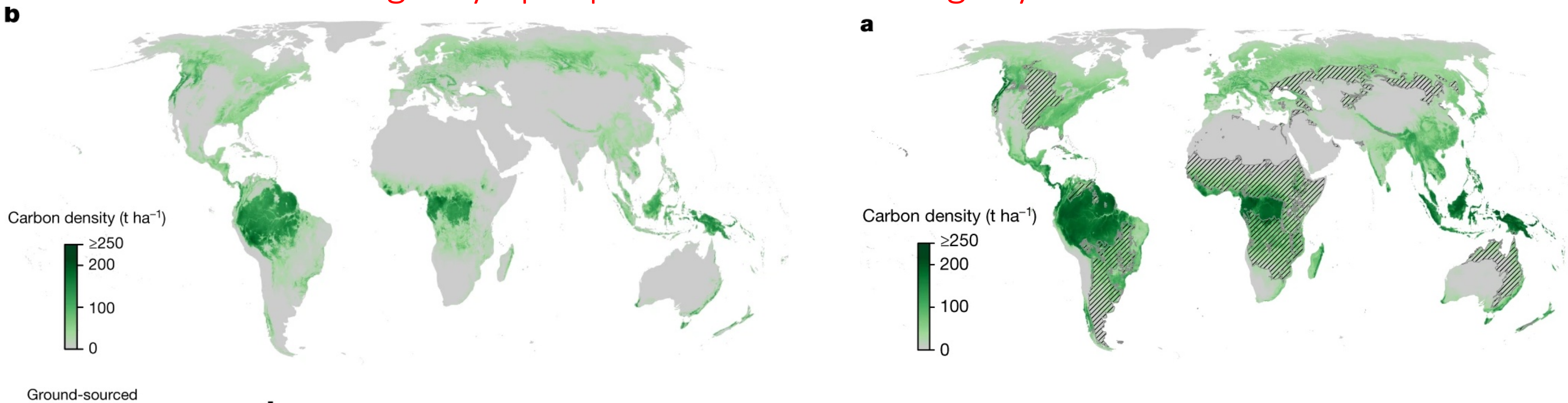


Ref.: https://wood-energy.extension.org/energy-basics/; M.M. Rahman, M Ahiduzzaman, A.K.M. Sadrul Islam and R. Blanchard, "Karoch (Pongamia pinnata)- An alternative source of biofuel in Bangladesh", https://www.researchgate.net/publication/355735059; https://www.wur.nl/en/newsarticle/new-light-on-the-sustainability-of-palm-oil.htm

CO_2 Sinks und 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.

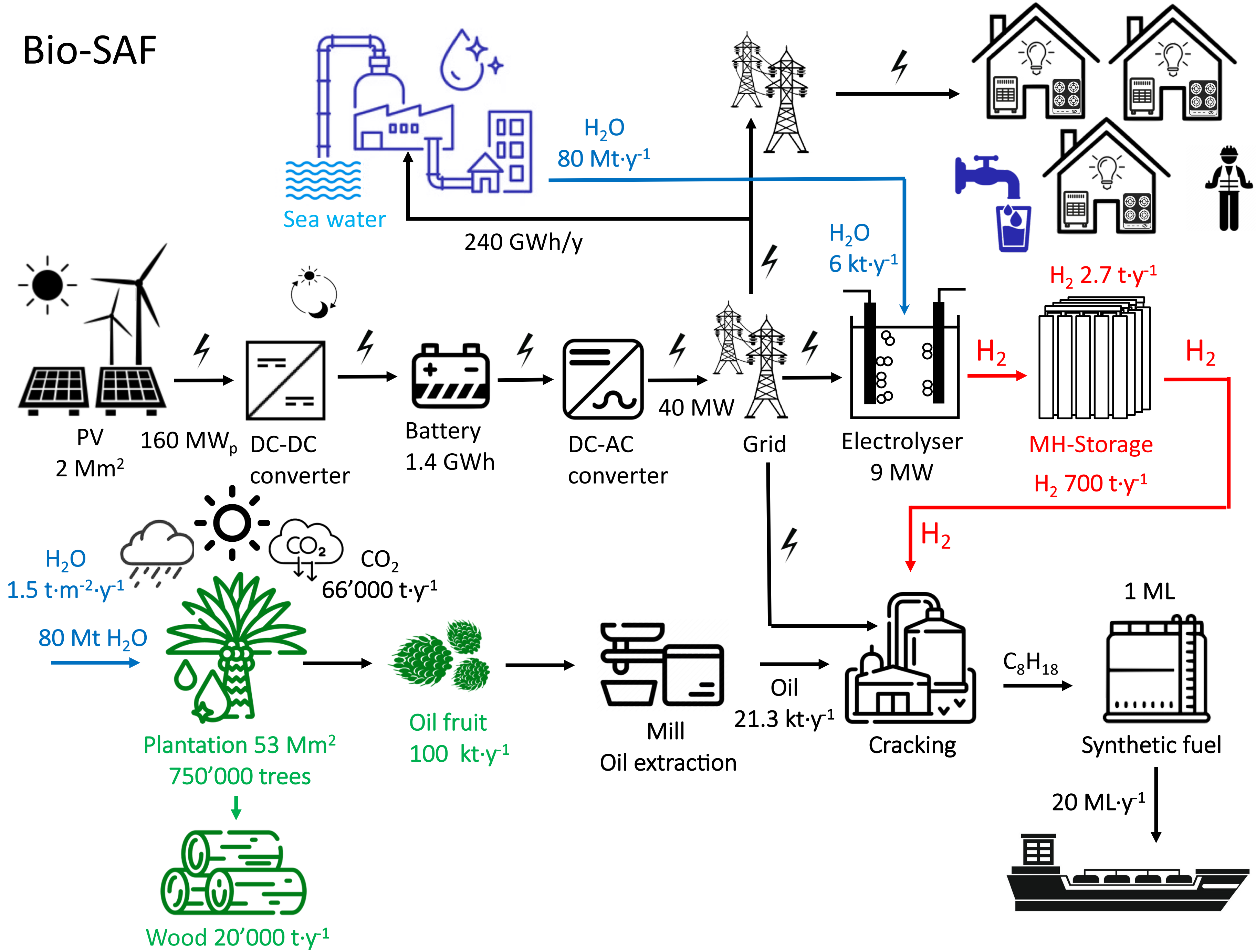
30 kg oil·y^{-1} per palm tree with 524 kg dry biomass



226 Gt oil palm trees produce 13 Gt Oil·y^{-1} more than the global demand of fossil oil.

Ref.: [1] Mo, L., Zohner, C.M., Reich, P.B. et al. Integrated global assessment of the natural forest carbon potential. Nature (2023). https://doi.org/10.1038/s41586-023-06723-z
[2] Thiruchelvi Pulingam, Manoj Lakshmanan, Jo-Ann Chuah, Arthy Surendran, Idris Zainab-La, Parisa Foroozandeh, Ayaka Uked, Akihiko Kosugid, Kumar Sudesh “Oil palm trunk waste: Environmental impacts and management strategies”, Industrial Crops & Products 189 (2022), 115827

Bio-SAF


Sea water
H_2O
80 $Mt \cdot y^{-1}$
240 GWh/y
H_2O
6 $kt \cdot y^{-1}$
H_2 2.7 $t \cdot y^{-1}$
PV
2 Mm^2
160 MW_p
DC-DC
converter
Battery
1.4 GWh
DC-AC
converter
40 MW
Grid
Electrolyser
9 MW
H_2
MH-Storage
H_2 700 $t \cdot y^{-1}$
H_2
H_2
H_2O
1.5 $t \cdot m^{-2} \cdot y^{-1}$
CO_2
CO_2
66'000 $t \cdot y^{-1}$
80 Mt H_2O
1 ML
Plantation 53 Mm^2
750'000 trees
Oil fruit
100 $kt \cdot y^{-1}$
Mill
Oil extraction
Oil
21.3 $kt \cdot y^{-1}$
Cracking
C_8H_{18}
Synthetic fuel
20 $ML \cdot y^{-1}$
Wood 20'000 $t \cdot y^{-1}$

Environmental impact

All considered cycles are closed for carbon (no carbon emissions)

Emissions for the production of:

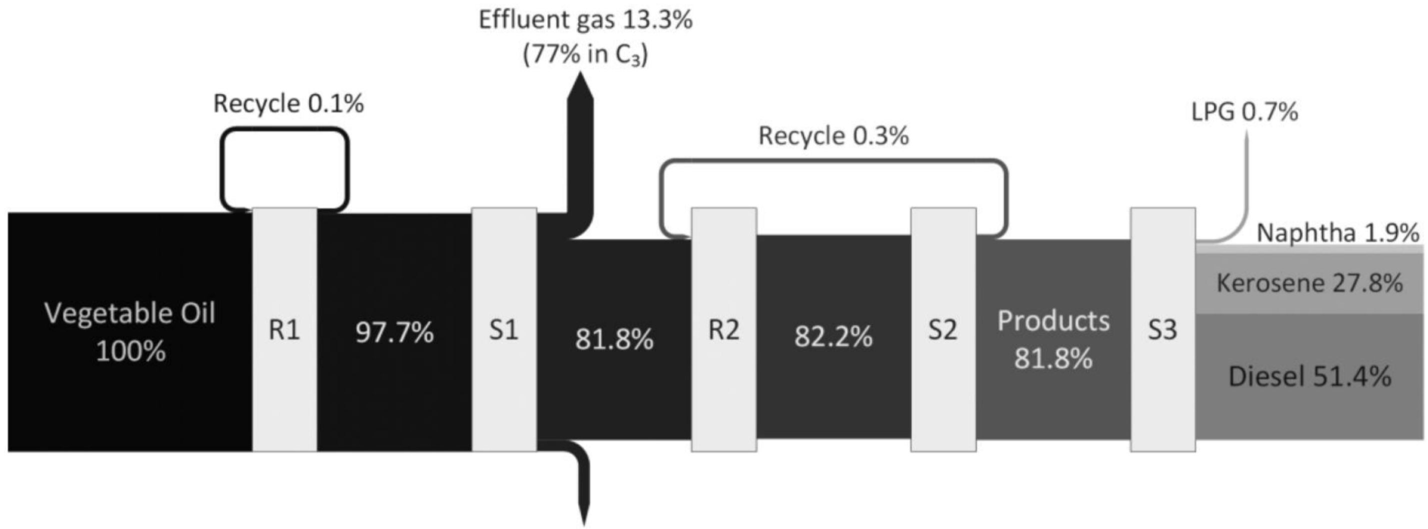
PV (0.15 kWh/kWh)	0- 0.04 kg CO_2 / kWh
Battery	0- 0.05 kg CO_2 / kWh
Electrolyzer	0- 0.02 kg CO_2 / kWh
CO_2 capture	0 – 1.00 kg CO_2 / kWh (DAC)
FT-Synthesis	0- 0.01 kg CO_2 / kWh
Refinery	0- 0.001 kg CO_2 / kWh
Biomass	0.05- 0.1 kg CO_2 / kWh
Use of fuel:	0.27 kg CO_2 / kWh

With increasing amount of renewable energy in the energy mix, the CO_2 emissions of synthetic aviation fuels decreases and vanishes.

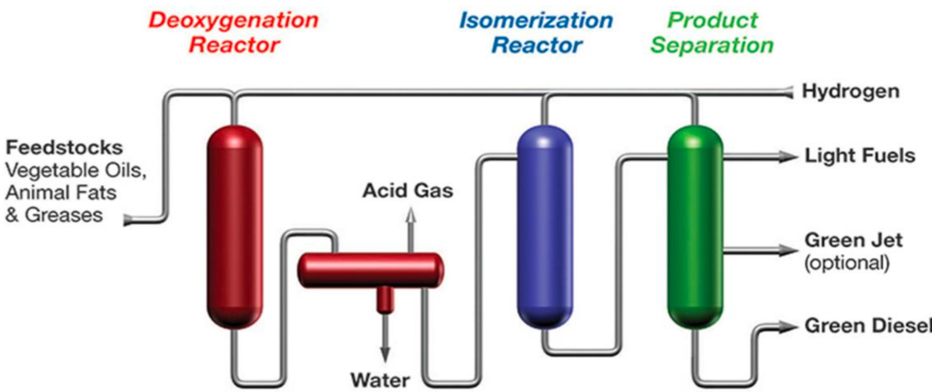
Ref.: Juan D. Medrano-García, Margarita A. Charalambous, and Gonzalo Guillén-Gosálbez, "Economic and Environmental Barriers of CO_2-Based Fischer−Tropsch Electro-Diesel", ACS Sustainable Chem. Eng. 2022, 10, 11751−11759
Ioanna Dimitriou, Pelayo Garcıa-Gutierrez, Rachael H. Elder,́ Rosa M. Cuéllar-Franca,b Adisa Azapagi and Ray W. K. Allen, "Carbon dioxide utilisation for production of transport fuels: process and economic analysis", Energy Environ. Sci., 2015, 8, 1775

Scientific challenges

CONVERSION YIELD & SELECTIVITY



CATALYTIC HYDROGENATION



TRE2021-03-012 "Unidad HDO-HISO de residuos oleaginosos a Green Fuel."
TRANS-ENER+ Alta tecnología clave en la transición en el ciclo energético

HDS Catalysts

Sulfided CoMo/γ-Al_2O_3
Sulfided NiMo/γ-Al_2O_3

- Long experience at industrial scale
- Need of Sulfurization
- Relatively low resistance to water

Metal Catalysts

CoMo, NiMo, Mo, Ni

- Good initial activity
- Quick deactivation
- Need of additives

Noble Metals

Pd, Pt, Rh

- Expensive

Metal Phosphides

Ni_xP, CoP, MoP…

- Alternative, similar electronic structure to noble metals
- Need to development

Ref.: R. Bautz; G. Verdan, K. Agrawal, N. Gallandat, A. Züttel, "Innovation lab of Gaznat", AQUA & GAS No X (2026), to be submitted

Jet fuel consumption by countries

global 8 M barrel / d

Rank	Country	Consumption (Thousand Barrels per Day)
1	United States	1,398.00
2	China	388.00
3	Russian Federation	279.00
4	United Kingdom	242.00
5	Japan	202.00
6	Germany	187.00
7	France	146.00
8	Singapore	140.00
9	Brazil	126.00
10	Australia	125.00
11	India	117.00
12	Hong Kong	115.00
13	Spain	114.00
14	Korea, Republic Of	109.00
15	United Arab Emirates	108.00
16	Canada	92.00
17	Thailand	83.00
18	Italy	82.00
19	Netherlands	72.00
20	Malaysia	69.00
21	Indonesia	64.00
22	Saudi Arabia	63.00
23	Mexico	58.00
24	Taiwan, Province Of China	49.00
25	South Africa	41.00
26	Qatar	39.00
27	Switzerland	34.00

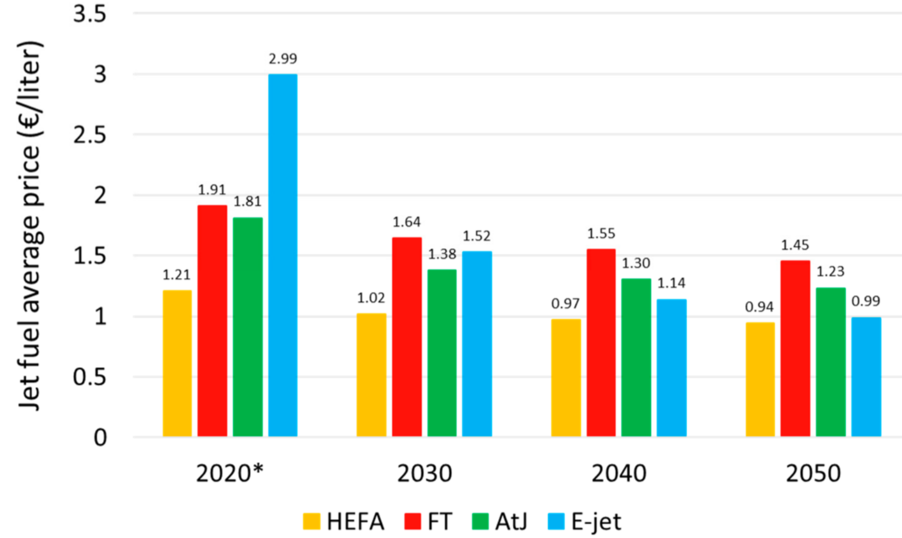
18 %

0.4 %

Ref.: https://www.indexmundi.com/energy/?product=jet-fuel&graph=consumption&display=rank

Cost of SAF production

- Grid electricity
- CO_2 concentrated source
- only electrolysis, CO_2 and synthesis



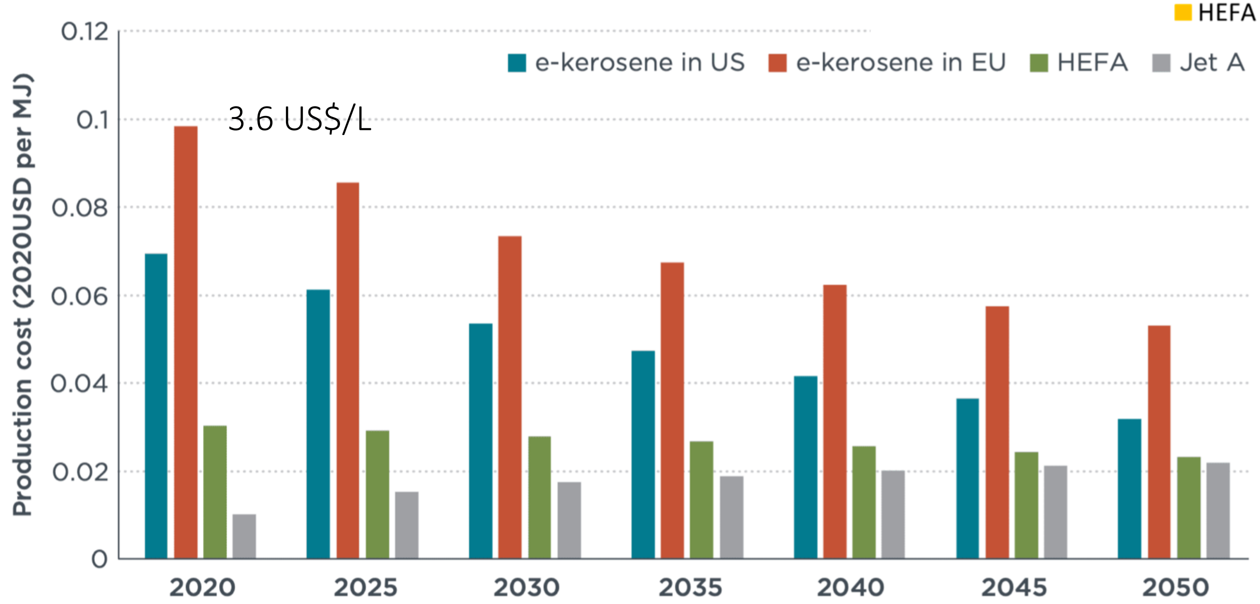


Figure. Estimated e-kerosene production cost in the United States and the EU, compared to hydroprocessed esters and fatty acids (HEFA) and fossil Jet A fuel

Hydrotreated Esters and Fatty Acids (HEFA)

Ref.: https://theicct.org/publication/fuels-us-eu-cost-ekerosene-mar22/

Detsios, N.; Theodoraki, S.; Maragoudaki, L.; Atsonios, K.; Grammelis, P.; Orfanoudakis, N.G. Recent Advances on Alternative Aviation Fuels/Pathways: A Critical Review. Energies 2023, 16, 1904. https://doi.org/10.3390/en16041904

Sustainable Aviation Fuel (SAF)

104 km^2

1 x refuel / day