Supplementary Information

CO_2 Neutral Energy Security for Switzerland

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A1. CO_2 Emission and Temperature increase

The growth rate of the cumulated CO_2 emissions is[1] decreasing over time and currently around 2.0% (2019). If a continuation of the general trend over the last 40 years is assumed, the growth rate will remain constant at 2.0%.

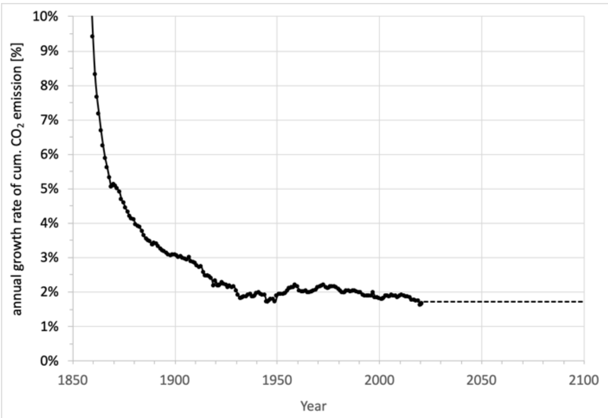

Fig. A1.1 Annual growth rate of the cumulated CO_2 emissions vs. time and extrapolation (dotted line) at a constant growth rate of 2.5%.

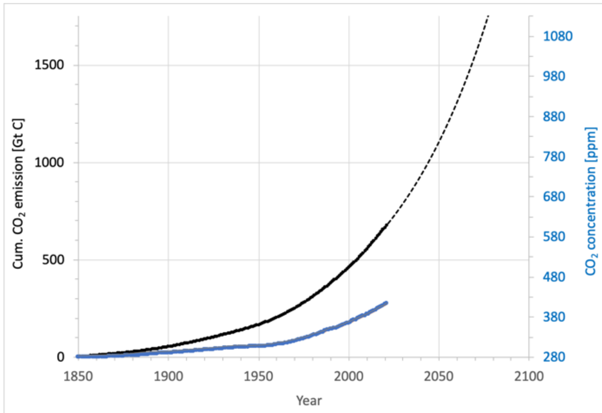

Fig. A1.2 Cumulated CO_2 emissions and CO_2 concentration in the atmosphere vs. time. Extrapolation (dotted line) based on the extrapolated growth rate.

The CO_2 concentration in the atmosphere depends linearly on the cumulated CO_2 emissions (1850 – 2010), but recently it has started to deviate slightly (2010 – 2020). The slope of the CO_2 concentration vs. cumulated emissions was found to be 0.0748 ppm CO_2/Gt CO_2 with an intercept at 0 Gt CO_2 emission (1850) of 292.2 ppm CO_2.

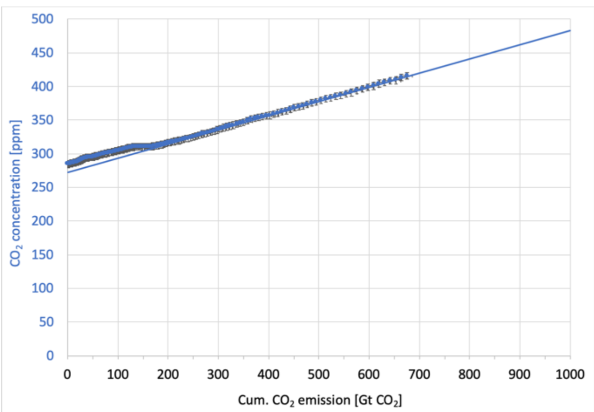

Fig. A1.3 CO_2 concentration vs. cumulated CO_2 emissions (1850 – 2019).

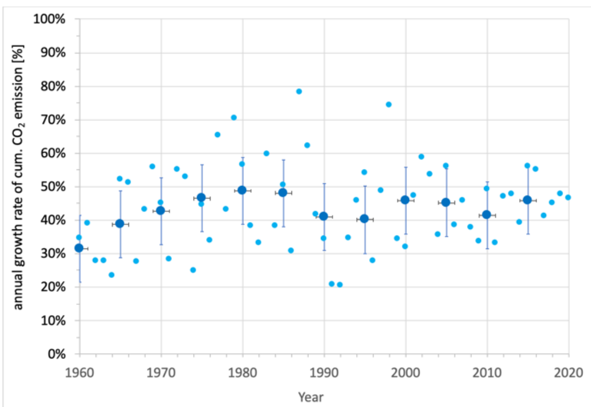

Fig. A1.4 Fraction of the CO_2 increase in the atmosphere divided by the emitted CO_2. Small markers stand for the annual fractions, large markers for the 10 year average.

The mass (m) of the atmosphere can be determined from the atmospheric pressure (p) $p \cdot A = m \cdot g$, the projected surface area of the earth ($A = 510 \cdot 10^6$ km^2), and $g = 9.81$ m·s^{-2}. With the mass of the atmosphere $m = 5.267 \cdot 10^{18}$ kg, and the average molecular mass of 80% N_2 + 20% O_2 is M = 28.8 g/mol results in $1.829 \cdot 10^{20}$ mol molecules. 1 Gt of CO_2 contains $2.273 \cdot 10^{13}$ molecules leading to 0.124 ppm/Gt CO_2.
The empirically determined increase of the CO_2 in the atmosphere based on the concentration measurement corresponds to around 50% of emitted CO_2. The reason for the difference is attributed to natural sinks, i.e., the dissolution of CO_2 in the ocean and the absorption of CO_2 by photosynthesis[2]. The CO_2 emitted from fossil fuels corresponds to about 5% of the natural carbon cycle[3].

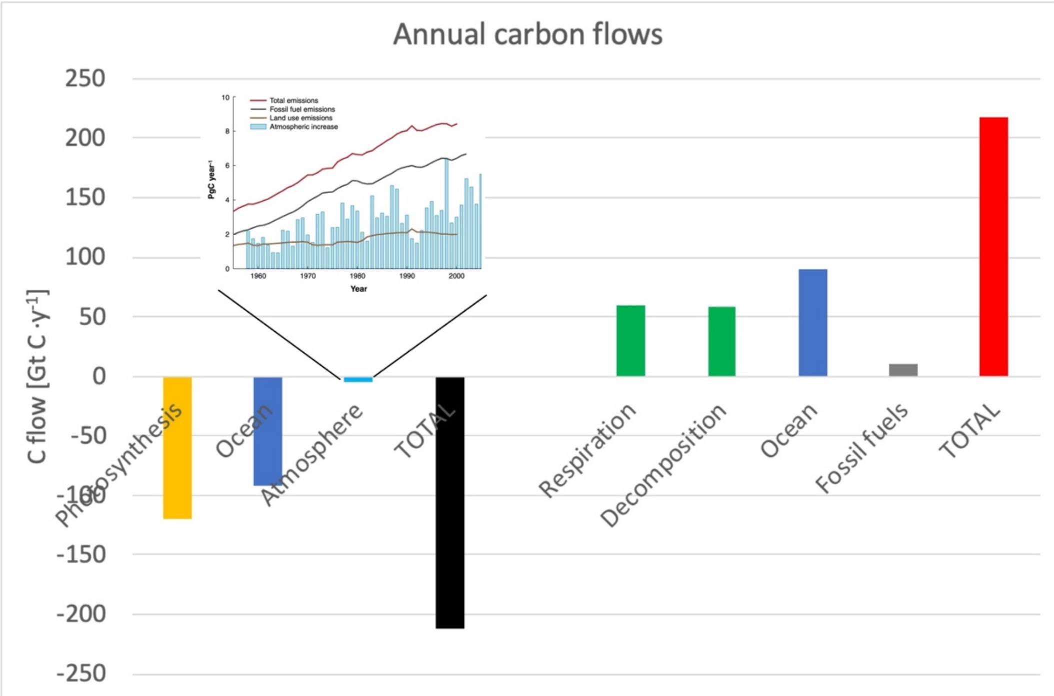

Fig. A1.5 Natural carbon balance, including the estimated surplus of CO_2 remaining each year in the atmosphere.

The CO_2 concentration in the atmosphere leads to radiative forcing (greenhouse effect) due to the absorption of infrared radiation by the CO_2 molecules and re-emission in all directions (also back to the surface of the earth. The radiative forcing[4,5,6] is $\Delta F = 5.35 \cdot W \cdot m^{-2} \cdot \ln(c/c_0)$ and $\Delta T = 0.31 \cdot °C \cdot W^{-1} \cdot m^2 \cdot \Delta F$, leading to $\Delta T = 1.66 \cdot °C \cdot \ln(c/c_0)$. The empirically determined $\Delta T = 2.85 \cdot °C \cdot \ln(c/c_0)$ is explained by the increase of the concentration of water molecules[7], methane, and other greenhouse gas molecules, e.g., N_2O_2, SF_6..., simultaneously with the CO_2 in the atmosphere.

A2. Cost Model

The cost of energy is determined based on the capital cost of the installation (CAPEX), the lifetime (t_L) and the capital interest (Z), the amount of energy transferred (W), and the operation cost (OPEX). The energy input (product + auxiliary energy or electricity) and the efficiency (η) are determined for each component in the energy conversion chain. Together with the cost, the cost per energy unit is calculated at each state of conversion.

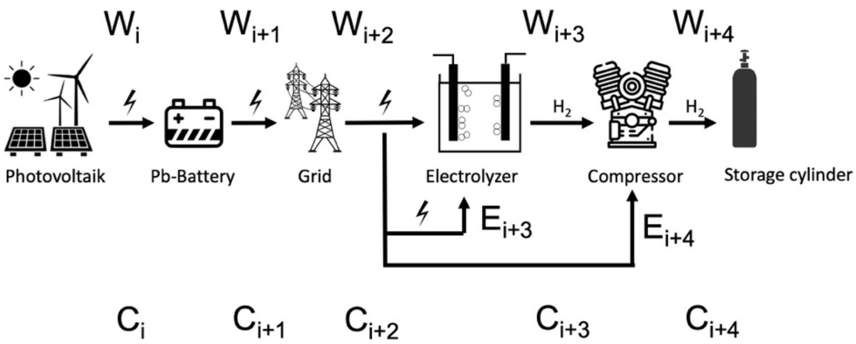

Fig. A2.1. The energy conversion chain distinguishes between the energy transferred through the conversion chain (W_i) and the auxiliary energy (E_i), accounting for additional electricity consumed to run the device.

The energy along the chain is calculated by $W_{i+1} = \eta_i \cdot W_i$ and $W_{i+3} = \eta_i \cdot (W_{i+2} - E_i - E_{i+2})$. The cost of the energy is given by $C_{i+1} = C_i + P_b + OPEX$.

The capital cost (CAPEX or C) is assumed to be amortized during the whole lifetime (n years) and an interest of Z = 2%/year on the capital. The constant annual payback, P_b, can be calculated from the cost series, $0 = (((C\cdot(1+Z)-P_b)\cdot(1+Z))-P_b)\cdot(1+Z))-P_b.... = C\cdot(1+Z)^n-P_b(1+Z)^{n-1}-P_b\cdot(1+Z)^{n-2}....$:

$$P_b = CAPEX \cdot \frac{Z\cdot(1+Z)^n}{(1+Z)^n-1} \qquad \text{(Eq. 1)}$$

where the operating cost (OPEX) is added and, in the case of a storage system, the cost of the energy (C_C) provided to the system. Finally, this sum is divided by the annual energy received from the energy system (E_y), and the result is the cost of the energy per energy unit (C_W).

$$C_W = \frac{P_b+OPEX}{E_y} + \frac{C_C}{E_y} \qquad \text{(Eq. 2)}$$

Example:

Int. [kWh/(y·m2)]:	1100			PeakP [kW] =	18.959							
Efficiency [%]:	20.0%	Area fac.:	1.5	Avg. P [kW] =	2.381							
Area [m2]:	94.80	**Area real [m2]:**	**142.19**	Max. avg P =	7.142							
					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	0.012	536	19'002.34	20'855.07	1'852.73	245.14	0.01	W [kWh·y-1] =	20855.07	10'158	3.0%
Converter AC/DC	95.00%	0	0.022	845	18'052.23	19'812.32	1'760.09	672.45	0.03	Pp [kW] =	7.14	6'036	5.6%
Battery	89.00%	0	0.071	127	16'066.48	17'632.96	1'566.48	1927.00	0.11	C [kWh] =	85.71	10'910	18.9%
Inverter DC/AC	95.00%	0	0.022	845	15'263.16	16'751.32	1'488.16	2288.29	0.14	Pp [kW] =	6.04	5'103	6.9%
Electrolyzer	60.00%	0.02	0.108	2227	9'157.89	9'157.89	0.00	3276.53	0.36	Pp [kW] =	5.23	11'638	55.6%
Compressor	95.00%	0.15	0.021	1223	8'700.00	8'700.00	0.00	3461.42	0.40	Pp [kW] =	3.14	3'836	10.1%
Hydrogen Tank	100.00%	0	0.000	0	8'700.00	8'700.00	0.00	3461.88	0.40	C [kWh] =	35.75	3	0.0%
	45.8%	1488.2	Auxillary power						**0.40**			47'685	100.0%
Efficiency =	**41.7%**							**Fuel [CHF/kgH**	**15.68**		**CAPEX [CHF] =**	**47'685**	

Tab. A2.1. Example of the cost calculation for hydrogen from PV.

A3. Simple Storage Model

The size of the storage required to shift the energy produced by photovoltaics (PV) from summer to winter depends on the shape of the solar intensity curve and the demand curve over the year. In a first-order approximation, the curves are linear between the minimum and maximum, and the size of the storage is calculated:

Electricity production by PV	Consumption (electricity)
$P_{max} = \alpha \cdot P_{min}$ Annual production : $P_a = P_{min} \cdot (1 + (\alpha-1)/2) \cdot t$ Storage : $S = (P_{max} – I_{min}) \cdot t'$ Storage release time: $t'/t = ½ \cdot (C_{max} – P_{min})/(P_{max} - P_{min} + C_{max} - C_{min})$	$C_{max} = \beta \cdot C_{min}$ Annual consumption : $C_a = C_{min} \cdot (1 + (\beta-1)/2) \cdot t$

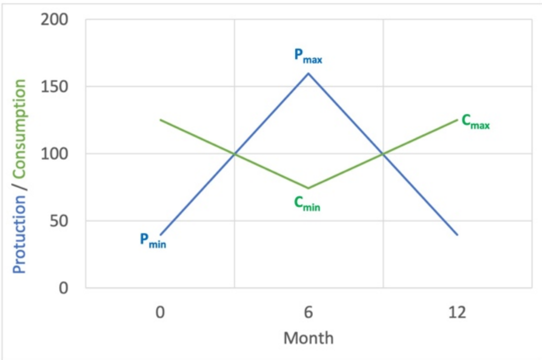

Fig. A3.1. a) Simplified production and consumption profiles.

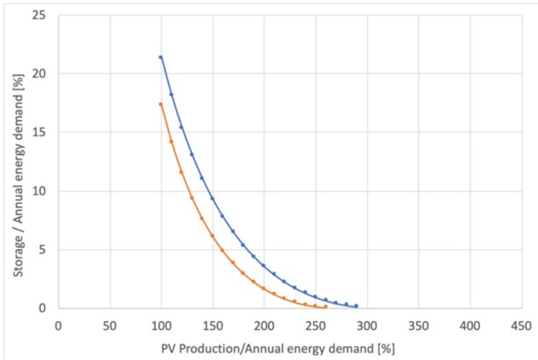

Fig. A3.1.b) Storage size vs. production in relation to the annual energy demand (right).

A4. PV electricity production profile

The PV electricity production is strongly dependent on the location and the meteorological situation. The sizes of the local and seasonal storage facilities are determined based on the monthly solar intensity and the daily intensity profile.

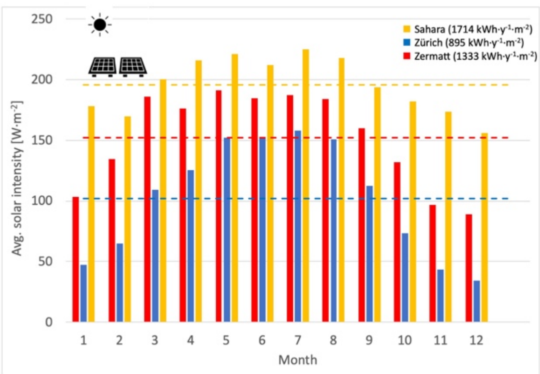

Fig. A4.1 Monthly solar irradiation profile in Zürich, Zermatt and Sahara with an annual solar irradiation of 895, 1333, and 1714 kWh·y^{-1}m^{-2},respectively, and the corresponding seasonal storage size relative to the annual electricity production are 20%, 12%, and 5%, respectively.

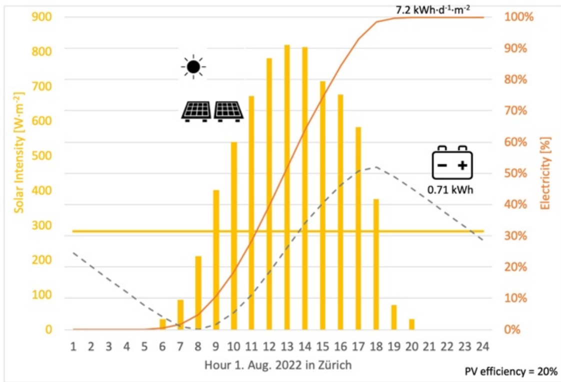

Fig. A4.2 Hourly solar irradiation profile for Zürich on 1. 8. 2020, including the daily average (horizontal line). The sum of the solar irradiation and the day/night storage (dotted black line) are given relative to the daily total irradiation of 6810 Wh·d^{-1}·m^{-2} The required storage size *is 3543 Wh which corresponds to 52% of the daily irradiation and 0.4% of the annual irradiation.*

The annual solar irradiation multiplied with the efficiency of the photovoltaic cells (η) results in the annual energy production of the PV per active area: $W_{el} = \eta \cdot I$. The annual average power is $\langle P_{el.} \rangle = W_{el.}/24h/365$ day. For the dimensioning of the components we assumed the average power in summer is 3 times the annual average power. The peak power is $P_P = \eta \cdot 1000 W \cdot m^{-2}$.

A5. Energy chain modeling

A5.1. PV and hydroelectric power in Switzerland (PV-HYDS)

Int. [kWh/(y·m2)]:	1100			PeakP [kW] =	10.136								
Efficiency [%]:	20.0%	Area fac.:	2.5	Avg. P [kW] =	1.273								
Area [m2]:	50.68	**Area real [m2]:**	**126.70**	Max. avg P =	3.818								
					per year								
Electricity production with PV and seasonal storage with hydroelectric power plant													
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 cont.
PV	100.00%	0	0.071	1607	3358	11150	7792	786	0.07	W [kWh·y-1] =	11149.97	16293	0.0705
Converter AC/DC	97.00%	0	0.022	845	3257	10815	7558	1020	**0.09**	Pp [kW] =	10.14	8566	0.0237
Battery	89.00%	0	0.065	117	2899	9626	6727	1647	0.17	C [kWh] =	45.82	5347	0.0769
Inverter DC/AC	97.00%	0	0.022	845	2812	9337	6525	1849	**0.20**	Pp [kW] =	5.07	4283	0.0269
Grid surface (100 km	99.94%	0	0.015	1342	2810	2810	0	1892	0.21	Pp [kW] =	1.23	1648	0.0154
Hydro pump	88.00%	0	0.020	2446	2473	2473	0	1940	0.26	Pp [kW] =	1.23	3005	0.0488
Lake	100.00%	0	0.000	0	2473	2473	0	1940	0.26	C [kWh] =	2787.49	89	0.0000
Hydro Turb	88.00%	0	0.039	4893	2176	2176	0	2026	0.34	Pp [kW] =	1.27	6227	0.0751
Grid surface (100 km	99.94%	0	0.015	1342	2175	2175	0	2059	0.35	Pp [kW] =	1.27	1708	0.0155
	78.0%	0.0	Auxillary power					Average	**0.25**			47166	0.3527
Efficiency =	**78.0%**							**E [CHF/kWh] =**	**0.35**		**CAPEX [CHF] =**	**47'166**	

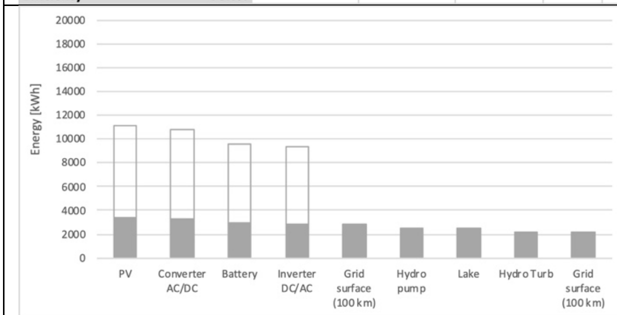

Fig. A5.1.a Energy along the energy conversion chain. Filled bars represent the energy in the product and open bars represent the auxiliary electricity.

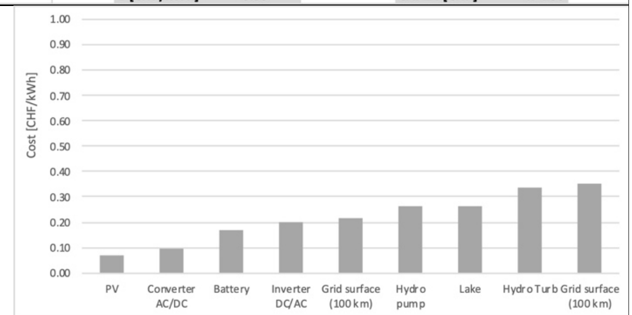

Fig. A5.1.b Cost accumulation for the renewable electricity along the energy conversion chain. Local distribution grid cost is not included.

A5.2. PV and Hydrogen in Switzerland (PV-H_2)

Int. [kWh/(y·m2)]:	1100			PeakP [kW] =	16.666								
Efficiency [%]:	20.0%	Area fac.:	2.5	Avg. P [kW] =	2.093								
Area [m2]:	83.33	**Area real [m2]:**	**208.33**	Max. avg P =	6.278								
					per year								
Electricity production with PV and seasonal storage with hydrogen													
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 cont.
PV	100.00%	0	0.071	1607	9401	18333	8932	1293	0.07	W [kWh·y-1] =	18332.74	26789	0.0705
Converter AC/DC	97.00%	0	0.022	845	9119	17783	8664	1676	0.09	Pp [kW] =	16.67	14085	0.0237
Battery	89.00%	0	0.065	117	8116	15827	7711	2709	0.17	C [kWh] =	75.34	8791	0.0769
Inverter DC/AC	97.00%	0	0.022	845	7872	15352	7480	3040	**0.20**	Pp [kW] =	6.28	5306	0.0269
Electrolyzer	60.00%	0.02	0.108	2227	4723	4723	0	3550	0.48	Pp [kW] =	6.09	8136	0.2800
Compressor	97.00%	0.15	0.011	612	4582	4582	0	3598	0.50	Pp [kW] =	3.65	2235	0.0254
Hydrogen Tank	100.00%	0	0.028	2	4582	4582	0	3729	0.53	C [kWh] =	4352.61	10648	0.0285
Hydrogen Transport	95.00%	0.04	0.010	3182	4353	4353	0	3770	0.57	Pp [kW] =	3.47	11047	0.0375
Hydrogen power pla	50.00%	0	0.023	2561	2176	2176	0	3820	1.16	Pp [kW] =	1.74	4445	0.5925
Grid surface (100 km	0.9994	0	0.015	1342	2175	2175	0	3854	**1.18**	Pp [kW] =	1.73	2328	0.0160
	47.5%	955.8	Auxiliary power						0.44			93808	1.1619
Efficiency =	**47.5%**					0.19	1.49	**H2 [CHF/kg] =**	**22.43**		**CAPEX [CHF] =**	**93'808**	

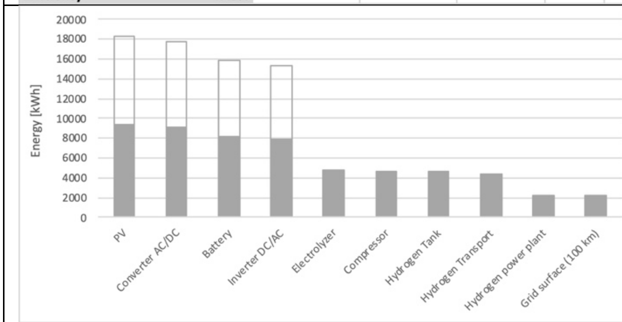

Fig. A5.2.a Energy along the energy conversion chain. Filled bars represent the energy in the product and open bars represent the auxiliary electricity.

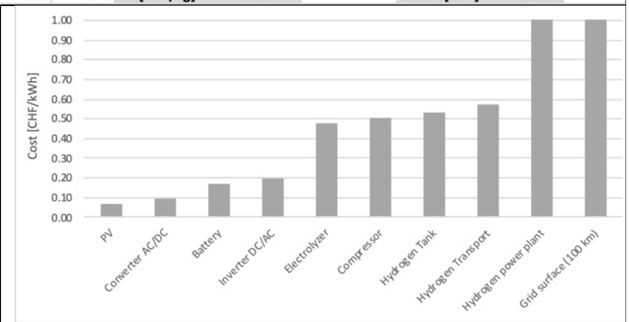

Fig. A5.2.b Cost accumulation for the renewable electricity along the energy conversion chain. Local distribution grid cost is not included.

A5.3. Biomass and hydrogen produced with PV in Switzerland.

Int. [kWh/(y·m2)]:	1100			PeakP [kW] =	17.889		-HCOH-	0.159 kWh		m(Wood) [t]:	4'025'852		1t Holz/0.1
Efficiency [%]:	20.0%	Area fac.:	2.5	Avg. P [kW] =	2.246		H2	0.0788 kWh	0.2378 kWh	A [km2]:	7'448		
Area [m2]:	89.45	**Area real [m2]:**	**223.62**	Max. avg P =	6.739		-CH2	0.14 kWh					
					per year								
PV, Battery, H2, Biomasse, FT													
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 cont.
PV	100.00%	0	0.071	1607	10326	19678	9353	1387.84	0.07	W [kWh·y-1] =	19678.12	28755	0.0705
Converter AC/DC	97.00%	0	0.022	845	10016	19088	9072	1799.53	0.09	Pp [kW] =	6.74	5695	0.0237
Battery	89.00%	0	0.065	117	8914	16988	8074	2907.47	0.17	C [kWh] =	80.87	9436	0.0769
Inverter DC/AC	97.00%	0	0.022	845	8647	16478	7832	3262.88	**0.20**	Pp [kW] =	5.82	4917	0.0269
Electrolyzer	60.00%	0.02	0.108	2227	5188	5188	0	3822.72	0.74	Pp [kW] =	1.78	3956	0.5388
Compressor	97.00%	0.15	0.011	612	5032	5032	0	3876.19	0.77	Pp [kW] =	1.72	1054	0.0334
Hydrogen Tank	100.00%	0	0.028	2	5032	5032	0	4019.42	0.80	C [kWh] =	20.68	51	0.0285
Biomass	100.00%	0	0.095	0	10065	10065	0	4975.56	0.49	Pp [kW] =	1.15	0	0.4944
Pyrolysis	84.00%	0.00	0.015	587	12683	12683	0	5165.80	0.41	Pp [kW] =	1.45	850	-0.0871
FT-Synthesis	70.00%	0.05	0.028	3467	8878	8878	0	5414.05	0.61	Pp [kW] =	0.57	1991	-0.1604
Fuel Taransport	99.00%	0	0.000	4	8789	8789	0	5414.15	0.62	Pp [kW] =	1.01	4	0.0062
Fuel Tank	99.00%	0	0.000	0	8701	8701	0	5414.15	0.62	C [kWh] =	8701.22	1596	0.0062
Hydrogen power pla	50.00%	0	0.023	2561	4351	4351	0	5514.69	1.27	Pp [kW] =	0.50	1285	0.6453
Grid surface (100 km	99.94%	0	0.015	1342	4348	4348	0	5581.09	**1.28**	Pp [kW] =	0.50	673	0.0160
	29.3%	1306.9	Auxillary power						**0.62**			60'263	1.2836
Efficiency =	**29.3%**					29743		**Fuel [CHF/L] =**	**6.22**		**CAPEX [CHF] =**	**60'263**	

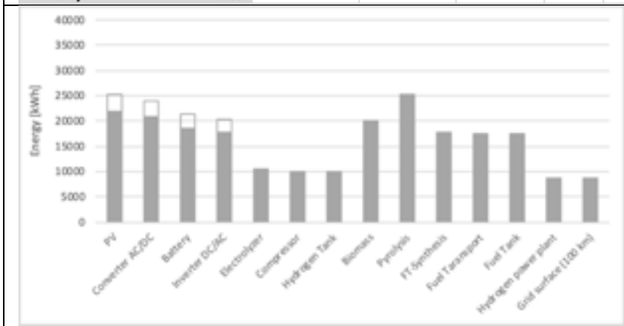

Fig. A5.3.a Energy along the energy conversion chain. Filled bars represent the energy in the product and open bars represent the auxiliary electricity.

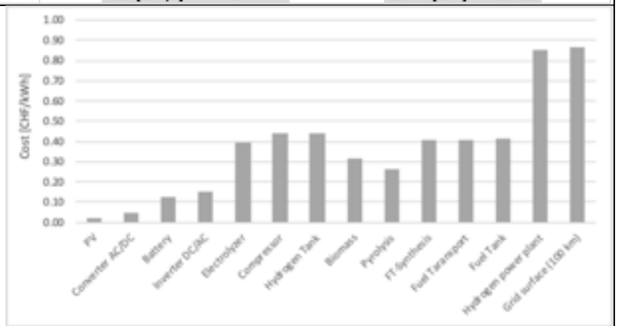

Fig. A5.3.b Cost accumulation for the renewable electricity along the energy conversion chain. Local distribution grid cost is not included.

A5.4. Import of hydrogen produced with PV.

Int. [kWh/(y·m2)]:	2200			PeakP [kW] =	22.697								
Efficiency [%]:	20.0%	Area fac.:	2	Avg. P [kW] =	5.700								
Area [m2]:	113.48	**Area real [m2]:**	**226.97**	Max. avg P =	11.400								
					per year								
Import of hydrogen from Australia													
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 cont.
PV	100.00%	0	0.012	536	42413	49933	7520	587	0.01	W [kWh·y-1] =	49933.30	12161	0.0118
Converter AC/DC	97.00%	0	0.022	845	41141	48435	7294	1632	0.03	Pp [kW] =	22.70	19181	0.0219
Battery	89.00%	0	0.065	117	36615	43107	6492	4443	0.10	C [kWh] =	136.80	15963	0.0694
Inverter DC/AC	97.00%	0	0.022	845	35517	41814	6297	5345	0.13	Pp [kW] =	5.07	4287	0.0248
Electrolyzer	60.00%	0.02	0.108	2227	21310	21310	0	7644	0.36	Pp [kW] =	3.42	7615	0.2309
Hydrogen Transport	95.00%	0.04	0.010	3182	20245	20245	0	7838	0.39	Pp [kW] =	3.25	10340	0.0284
Liquifaction	100.00%	0.25	0.029	6116	20245	20245	0	8424	0.42	Pp [kW] =	3.25	19870	0.0290
Ship transport	86.00%	0	0.008	6	17410	17410	0	8565	0.49	Pp [kW] =	2.79	17	0.0759
Liquid to gas	100.00%	0	0.000	24	17410	17410	0	8568	0.49	Pp [kW] =	2.79	68	0.0002
Liquid storage	100.00%	0	0.000	12	17410	17410	0	8569	0.49	C [kWh] =	938.86	11483	0.0001
Hydrogen power pla	50.00%	0	0.023	2561	8705	8705	0	8771	1.01	Pp [kW] =	1.40	3578	0.5153
Grid surface (100 km	99.94%	0	0.015	1342	8700	8700	0	8903	1.02	Pp [kW] =	1.40	1874	0.0159
	17.4%	6297.2	Auxillary power						**1.02**			106'438	1.0234
Efficiency =	**17.4%**					442		**H2 [CHF/kg] =**	**19.39**		**CAPEX [CHF] =**	**106'438**	

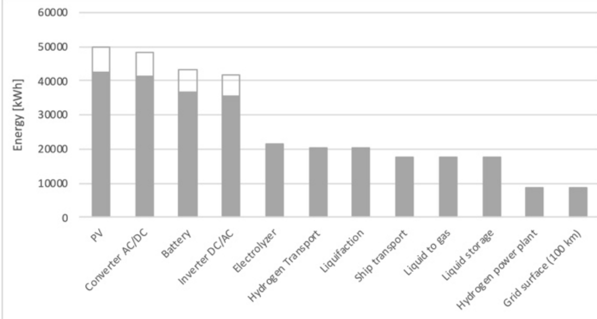

Fig. A5.4.a Energy along the energy conversion chain. Filled bars represent the energy in the product and open bars represent the auxiliary electricity.

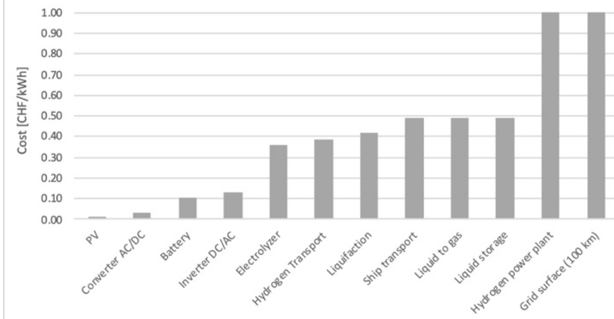

Fig. A5.4.b Cost accumulation for the renewable electricity along the energy conversion chain. Local distribution grid cost is not included.

A5.5. Import of synthetic oil from hydrogen produced with PV and DAC.

Int. [kWh/(y·m2)]:	2200			PeakP [kW] =	12.443		CO2	2.325161865	MtŸ-1				
Efficiency [%]:	20.0%	Area fac.:	2	Avg. P [kW] =	3.125								
Area [m2]:	62.21	**Area real [m2]:**	**124.43**	Max. avg P =	9.375								
					per year								
Import of synthetic oil from hydrogen produced with PV in Australia and DAC													
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 cont.
PV	100.00%	0	0.012	536	24990	27374	2384	322	0.01	W [kWh·y-1] =	27373.79	6667	0.0118
Converter AC/DC	97.00%	0	0.022	845	24240	26553	2313	894	0.03	Pp [kW] =	12.44	10515	0.0219
Battery	89.00%	0	0.065	117	21574	23632	2058	2436	0.10	C [kWh] =	112.50	13127	0.0694
Inverter DC/AC	97.00%	0	0.022	845	20926	22923	1996	2930	0.13	Pp [kW] =	11.07	9359	0.0248
Electrolyzer	60.00%	0.02	0.108	2227	12556	12556	0	4285	0.34	Pp [kW] =	1.87	4175	0.2135
Hydrogen Tank	100.00%	0	0.03	2	12556	12556	0	4642	0.37	Pp [kW] =	1.87	5	0.0285
CO2 Capture 400 ppı	100.00%	0.054	0.36	3404	12556	12556	0	9160	0.73	Pp [kW] =	1.87	6382	0.3598
CO2 Storage	100.00%	0.05	0.00	40	12556	12556	0	9173	0.73	Pp [kW] =	1.87	75	0.0010
FT-Synthesis	70.00%	0.05	0.03	3467	8789	8789	0	9418	1.07	Pp [kW] =	1.31	4550	0.3411
Fuel Tank	99.00%	0	0.00	0	8701	8701	0	9418	1.08	C [kWh] =	436.57	80	0.0108
Hydrogen power pla	50.00%	0	0.023	2561	4351	4351	0	9519	2.19	Pp [kW] =	0.66	1681	1.1055
Grid surface (100 kr	99.94%	0	0.015	1342	4348	4348	0	9585	2.20	Pp [kW] =	0.66	880	0.0166
	15.9%	1996.4	Auxillary power						**2.20**			57'495	2.2046
Efficiency =	**15.9%**							**SF [CHF/kg] =**	**10.82**		**CAPEX [CHF] =**	**57'495**	

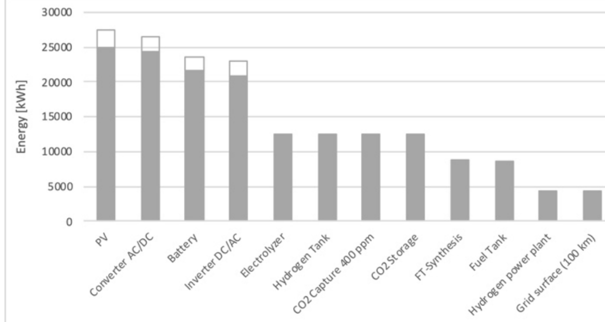

Fig. A5.5.a Energy along the energy conversion chain. Filled bars represent the energy in the product and open bars represent the auxiliary electricity.

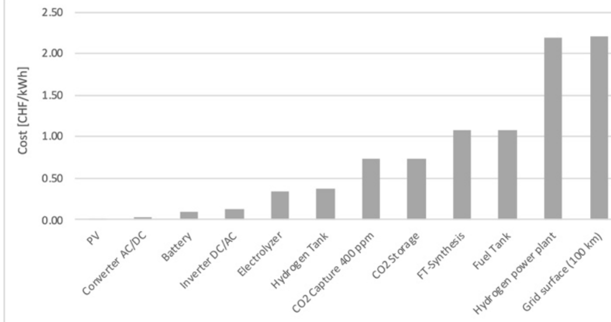

Fig. A5.5.b Cost accumulation for the renewable electricity along the energy conversion chain. Local distribution grid cost is not included.

A5.6. Import of synthetic oil produced from Palm oil and cracked with hydrogen from PV.

Int. [kWh/(y·m2)]:	2200			PeakP [kW] =	1.122		-HCOH-	0.159 kWh		m(Bio oil) [t]:	901'725		1t Palm o
Efficiency [%]:	20.0%	Area fac.:	2.5	Avg. P [kW] =	0.282		H2	0.0788 kWh	0.2378 kWh	A [km2]:	2'344		
Area [m2]:	5.61	**Area real [m2]:**	**14.02**	Max. avg P =	0.845		-CH2	0.14 kWh			6197.193024		
					per year								
Biooil, cracking, refining													
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 cont.
PV	100.00%	0	0.012	536	2245	2468	223	29	0.01	W [kWh·y-1] =	2468.13	601	0.0118
Converter AC/DC	97.00%	0	0.022	845	2178	2394	216	81	0.03	Pp [kW] =	0.85	714	0.0219
Battery	89.00%	0	0.0652	117	1938	2131	192	220	0.10	C [kWh] =	10.14	1184	0.0694
Inverter DC/AC	97.00%	0	0.0216	845	1880	2067	187	264	0.13	Pp [kW] =	0.85	714	0.0248
Electrolyzer	60.00%	0.02	0.108	2227	1128	1128	0	386	0.34	Pp [kW] =	0.39	860	0.0000
Compressor	97.00%	0.15	0.011	612	1094	1094	0	398	0.36	Pp [kW] =	0.37	229	0.0212
Hydrogen Tank	100.00%	0	0.028	2	1094	1094	0	429	0.39	C [kWh] =	4.50	11	0.0285
Biooil	100.00%	0	0.067	0	9739	9739	0	1081	0.11	Pp [kW] =	1.11	0	0.1110
Cracking	95.00%	0	0.015	1741	9252	9252	0	1220	0.13	Pp [kW] =	1.06	1839	0.0208
Refining	95.00%	0	0.015	1741	8789	8789	0	1352	0.15	Pp [kW] =	1.00	1747	0.0219
Fuel Taransport	99.00%	0	0.000	4	8701	8701	0	1352	0.16	Pp [kW] =	0.99	4	0.0016
Hydrogen power pla	50.00%	0	0.023	2561	4351	4351	0	1452	0.33	Pp [kW] =	0.50	1272	0.1785
Grid surface (100 km	99.94%	0	0.015	1342	4348	4348	0	1519	0.35	Pp [kW] =	0.50	666	0.1939
	35.6%	186.7	Auxillary power						**0.35**			9'841	0.3493
Efficiency =	**35.6%**				2344.48	12207		**Fuel [CHF/L] =**	**1.68**		**CAPEX [CHF] =**	**9'841**	

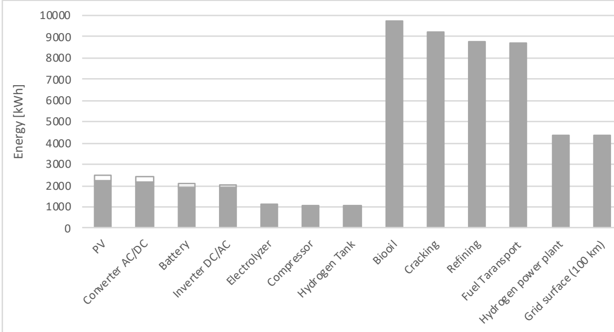

Fig. A5.6.a Energy along the energy conversion chain. Filled bars represent the energy in the product and open bars represent the auxiliary electricity.

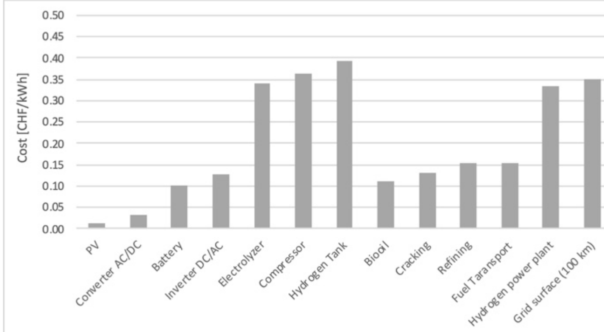

Fig. A5.6.b Cost accumulation for the renewable electricity along the energy conversion chain. Local distribution grid cost is not included.

A6. Crude oil prices vs. oil consumption

The influence of the price of energy on the economy is complex. Considering the crude oil price vs. oil consumption[8] shows that higher prices do not lead to lower consumption (only very a short-term decrease in consumption is observed), nor does it lead to a long-term decrease in the world economy.

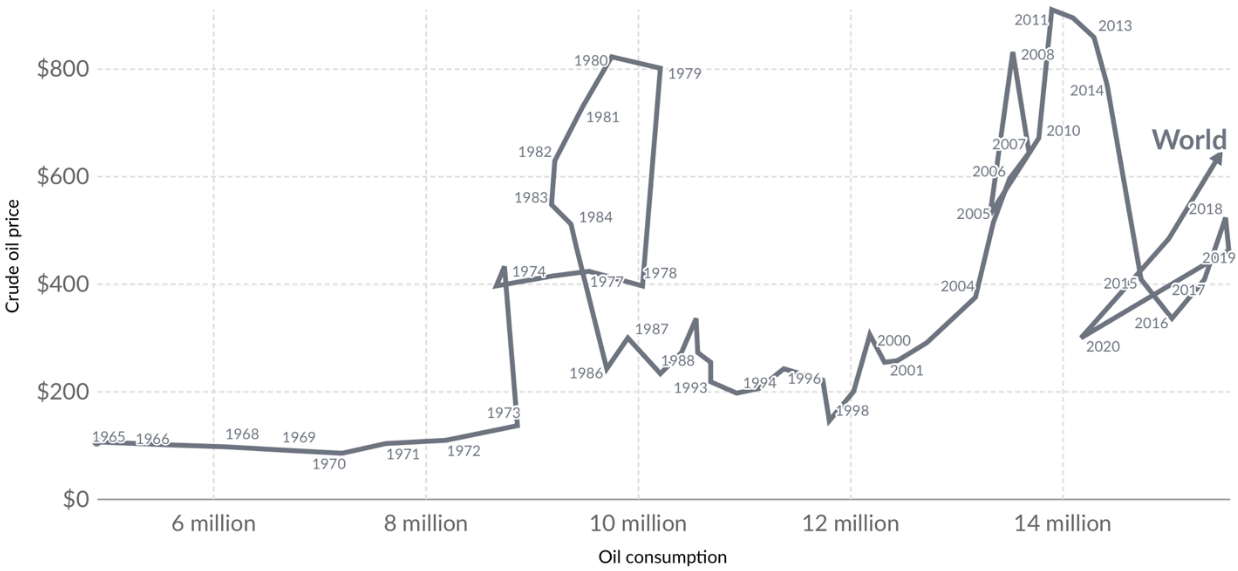

Fig. A6.1 World crude oil price vs. oil consumption. Global crude oil price, measured in US dollars per cubic meter, against total oil consumption, measured in average cubic meters per day. Prices are adjusted for inflation. Data source: Energy Institute Statistical Review of World Energy based on S&P Global Platts (2023) – Learn more about this data. Note: Prices are expressed in constant 2022 US$. OurWorldInData.org/fossil-fuels | CC BY

While the oil price is, with some fluctuations, increasing with time, the oil consumption and the GDP are increasing with time. After a steep increase in the price of crude oil, a short-term decrease in consumption is observed, but the consumption recovers within a few years.

A7 Biomass (wood) in Switzerland

32% of the country area in Switzerland is forest corresponding to 13’100 km^2 (1.31 Mha). The wood reserves correspond to 422 Mm^3 (351 $m^3 \cdot ha^{-1}$) with 33% of hardwood and 67% softwood[9]. The growth rate is about 10 $Mm^3 \cdot y^{-1}$ and 8.2 $Mm^3 \cdot y^{-1}$ are usable wood. The harvested wood in 2022 was 5.1784 $Mm^3 \cdot y^{-1}$ (2.126 $Mm^3 \cdot y^{-1}$ for energy corresponding to 41’270 $TJ \cdot y^{-1}$ = 11.4 $TWh \cdot y^{-1}$). Therefore, the wood growth in Switzerland is 763 $m^3 \cdot y^{-1} \cdot km^{-2}$ or 4.1 $kWh \cdot m^{-2} \cdot y^{-1}$ (5.3 $MWh \cdot m^{-3}$)[10].

A8 Palm oil

Palm oil is a vegetable oil obtained from the pulp of the oil palm. The fat molecules are tri-esters of glycerin and contain 46% saturated palmitic acid, 38% monounsaturated oleic acid, and 8% multiple unsaturated acids. Palm kernel oil is obtained from the kernels of the fruit and consists of more than 80% saturated fats (lauric acid is mainly bound).

Palm oil consists of oleic acid 39% ($C_{18}H_{34}O_2$), linoleic acid 11% ($C_{18}H_{32}O_2$), other fatty acids, i.e., 44%, palmitic acid ($C_{16}H_{32}O_2$), 4% stearic acid ($C_{18}H_{36}O_2$), and 1% myristic acid ($C_{14}H_{28}O_2$). The properties are as follows: density 0.92 kg/l at 15 °C, viscosity 29.4 mm^2/s (at 50 °C), melting temperature 30-37 °C, flash temperature 267 °C, iodine number 34 – 61, octane number 42, higher heating value 10.8 kWh/kg (sat. oil 12.8 kWh/kg). The oil palm has a very high yield of oil, and thus energy per area (4.15 $kWh \cdot m^{-2} \cdot y^{-1}$). One

hectare of a palm oil plantation yields 4 to 6 tons of palm oil per year, depending on the palm variety, weather, and care. Rapeseed only yields 1.5 to 2.5 tons of rapeseed oil per hectare of cultivated area per year. The fuel is made from palm oil after pre-treatment with phosphoric acid (H_3PO_4) and caustic soda (NaOH). Hydrogen (H_2) is added to the oil at temperatures of 320 to 360 °C and up to 80 bar pressure with the addition of a catalyst.
The complete hydriding of palm oil reduces the mass by 15% but conserves the energy in the oil due to the addition of the energy in the hydrogen.

Fraction	C	H	O	M	+H	m(oil)	m(H)	m(H_2O)	m(sat. oil)
0.39	18	34	2	282	8	109.98	3.12	10.92	99.06
0.11	18	32	2	280	10	30.8	1.1	3.08	27.94
0.44	16	32	2	256	6	112.64	2.64	12.32	99.44
0.04	18	36	2	284	6	11.36	0.24	1.12	10.16
0.01	14	28	2	228	6	2.28	0.06	0.28	1.98
0.3333	3	8	3	92	6	30.66	2.00	14.00	14.67
1.3233						**297.72**	**9.16**	**41.72**	**253.25**

Tab. A8.1. Composition of Palm oil[11]

84 Mt·y^{-1} (40% of all bio oil) Palm oil is produced worldwide on 18.7 Mha, an average of 4.5t/ha corresponding to 0.55 W·m^{-2} harvested solar energy and stored in oil. Comparing with the synthetic fuel production based on PV, hydrogen production and CO_2 capture approximately 3 W·m^{-2} solar energy can be harvested and stored in synthetic fuel.
The cultivation of oil palms has been criticized internationally both by environmental protection organizations and politically because of the demand as a raw product for the inexpensive production of biofuels, candles, and detergents and the associated deforestation of large areas of rainforest to create plantations in the growth areas of the oil palm. According to current opinion, the cultivation of oil palms is currently not ecologically sustainable. Various environmental protection organizations in Germany, particularly Greenpeace and Save the rain forest, point out that rain forests are being destroyed on a large scale to establish new oil palm plantations. These statements were backed up by research based on data from the FAO, which found that between 1990 and 2005, 1.87 million hectares of palm oil plantations were newly planted in Malaysia and more than 3 million hectares in Indonesia, more than half of which arose due to deforestation. [Tropical forests axed in favor of palm oil. New Scientist Environment 31. Mai 2008.]
For palm oil and other biogenic energy carriers, a certification system that has been required by law in the Biomass Electricity Sustainability Ordinance since 2007 is intended to guarantee the ecological and social sustainability of cultivation in the future and thus prevent unwanted effects such as deforestation and human rights violations, the production of other palm oil products such as cosmetics and margarine will continue and are not subject to any sustainability criteria. The Roundtable on Sustainable Palm Oil (RSPO), founded in 2003 on the initiative of the WWF, tries, as a central organization, to promote sustainable cultivation methods for palm oil and thus limit environmental damage.[12]

A9 Cost calculation

Type	Cost (day)	Cost (night)	Cost (winter)	Cost El. avg.	Cost fuel	PV_{area} [km^2]/PPU	Bio_{area} [km^2]/PPU	Product [TWh·y^{-1}]
HYD-S	0.05	0.05	0.05	0.05		0	0	Elec. 8.7
HYD-R	0.05	0.05	0.05	0.05		0	0	Elec. 8.7
THERM	0.06	0.06	0.06	0.06		0	0	Elec. 8.7
NUC	0.08	0.08	0.08	0.08		0	0	Elec. 8.7
PV-HYD	0.16	0.17	0.30	0.24		51	0	Elec. 8.7
PV-H2	0.16	0.16	1.01	0.44		83	0	Elec. 8.7
BioSF	0.16	0.16	1.12	0.47	4/L	89	7’448	Fuel 8.7
Imp-H2	1.02	1.02	1.02	1.02	21/kg	(113)	0	Elec. 8.7
Imp-SF	2.20	2.20	2.20	2.20	11/L	(62)	(4.6 Mt·y^{-1})	Fuel 8.7
Imp-PSF	0.35	0.35	0.35	0.35	1.7/L	(6)	(2’344)	Fuel 8.7

Fig. A9.1. Cost estimation [CHF] of the electricity in the various PPU’s based on the system analysis in A5. The El. Cost avg. was determined as 25% cost (day) + 50% cost (night) + 25% cost (winter).

[CHF]	Wel. [TWh·y^{-1}]	2019	$W_{el.}$ [TWh·y^{-1}]	NUC	PV-HYD	PV-H2	BioSF	Imp-H2	Imp-SF	Imp-PSF
Nuclear	23	250	0	0	0	0	0	0	0	0
Fuel/Elec.	122	642	54	693	2’118	3’839	4’068	8’869	19’106	3’027
PV roof			24	324	324	324	324	324	324	324
Grid	40	404	54	546	546	546	546	546	546	546
Renewable	63	1162	55	970	970	970	970	970	970	970
Aviation fuel	23	542	23	439	439	439	439	439	439	439
Total [CHF·y^{-1}] per capita	232	3000	156	2’764	4’397	6’118	6’347	11’148	21’385	5’306
Investment [BCHF]		20		48-72	189	563	362	42 (639)	24 (345)	24 (59)

Fig. A9.2. Total cost of energy in Switzerland for the various PPU’s. Calculation for 6 PPU’s, the minimum necessary energy production.

A10 Future development

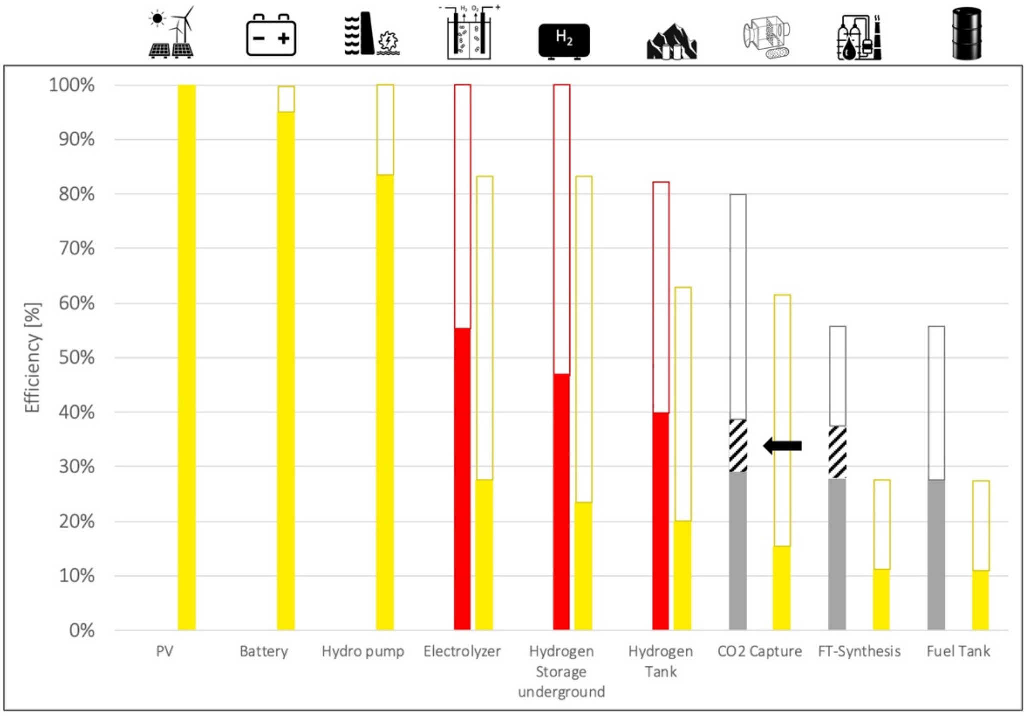

Fig. A9.1. Efficiency of the electricity conversion to in electricity , hydrogen y , and synthetic fuels . Filled bars represent today's technology and open bars the theoretical potential.

A11 Electricity density calculation

	Battery	Hydro	Hydro	H_2	H_2	CH_4	CH_4
Cond.	*Li-ion*	*500 m*	*1800 m*	*200 bar*	*-252°C*	*200 bar*	*-162°C*
Density [kg/m³]	*470*	*1000*	*1000*	*14.94*	*70.8*	*157.2*	*422.8*
Energy density [kWh/m³]	*95*	*1.3*	*4.9*	*549*	*2790*	*2772*	*6511*
Charge eff [%]	*95.0%*	*85.0%*	*85.0%*	*60.0%*	*42.0%*	*47.0%*	*40.0%*
Discharge eff [%]	*95.0%*	*90.0%*	*90.0%*	*50.0%*	*50.0%*	*50.0%*	*50.0%*
Elec. storage density [kWh/m³]	*90.3*	*1.2*	*4.4*	*274.5*	*1395.0*	*1386.0*	*3255.5*
Eff total [%]	*90.3%*	*76.5%*	*76.5%*	*30.0%*	*21.0%*	*23.5%*	*20.0%*
Charge eff [%]	*95.0%*	*85.0%*	*85.0%*	*90.0%*	*63.0%*	*70.5%*	*60.0%*
Discharge eff [%]	*95.0%*	*90.0%*	*90.0%*	*60.0%*	*60.0%*	*60.0%*	*60.0%*
Elec. storage density [kWh/m3]	*90.3*	*1.2*	*4.4*	*329.4*	*1674.0*	*1663.2*	*3906.6*
Eff total [%]	*90.3%*	*76.5%*	*76.5%*	*54.0%*	*37.8%*	*42.3%*	*36.0%*

cont.	Therm H_2O	Therm sand	Therm LiH	Syn. oil	NH_3	NH_3	MH
Cond.	10-80°C	200-800°C	692°C	RT	8 bar	-33.4°C	1 mass%
Density [kg/m^3]	1000	2200	820	820	5.8	681.9	3546
Energy density [kWh/m^3]	100	730	610	10168	27	3200	3140
Charge eff [%]	95.0%	95.0%	95.0%	34.0%	44.0%	44.0%	60.0%
Discharge eff [%]	11.0%	15.0%	67.0%	50.0%	34.0%	34.0%	50.0%
Elec. storage density [kWh/m^3]	11.0	109.5	408.7	5084.0	9.2	1088.0	1570.0
Eff total [%]	10.5%	14.3%	63.7%	17.0%	15.0%	15.0%	30.0%
Charge eff [%]	*95.0%*	*95.0%*	*95.0%*	*51.0%*	*72.0%*	*72.0%*	*90.0%*
Discharge eff [%]	*11.0%*	*15.0%*	*67.0%*	*60.0%*	*45.0%*	*45.0%*	*60.0%*
Elec. storage density [kWh/m^3]	*11.0*	*109.5*	*408.7*	*6100.8*	*12.2*	*1440.0*	*1884.0*
Eff total [%]	*10.5%*	*14.3%*	*63.7%*	*30.6%*	*32.4%*	*32.4%*	*54.0%*

Data used for the electricity storage density calculation (Fig. 8), current values and future values in italics.

A12. References

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