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Future CO_2-neutral Swiss Energy Economy

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Energy demand

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. The energy demand, the technical challenges, and the economic feasibility of a transition to an energy economy based entirely on renewable energy were analyzed for Switzerland ($8.4 \cdot 10^6$ capita). The approaches, i.e. electricity based, hydrogen based and synthetic fuel-based energy systems were considered, using the current energy demand, considering only the technical efficiencies without any assumption about change of human behavior or reduction of energy demand. Furthermore, photovoltaic and hydroelectric power plants are considered as the sources of renewable energy in order to estimate the size of the necessary electricity production and energy storage [1].

Today in Switzerland, approximately 53 % of the electricity is produced by hydroelectric power plants, 36 % is produced by nuclear power plants (with an average efficiency of 25 % from nuclear fuel to electricity), and the remaining 11 % are obtained from biofuels (< 5.7 %), waste incineration (< 2.7 %), PVs, and wind turbines. Thus, Switzerland's electricity production is almost free of CO_2 emission. As a consequence, Switzerland has a lower overall energy consumption of 6 kW · capita^{-1}, against 8.2 kW · capita^{-1} in Great Britain. In Switzerland, the waste heat produced by nuclear power plants is not used with few exceptions, following the people's political decision to avoid increasing the dependence on nuclear power plants for heat and electricity during the wintertime.

A linear relationship is observed between primary energy consumption per capita and GDP per capita [2], which most countries of the world follow, with a slope of 2.5 kWh / CHF for a GDP < 13 kCHF/ (capita · year). This means, in turn, that the world economy is generating 0.4 CHF / kWh or 4 CHF / liter of fossil oil.

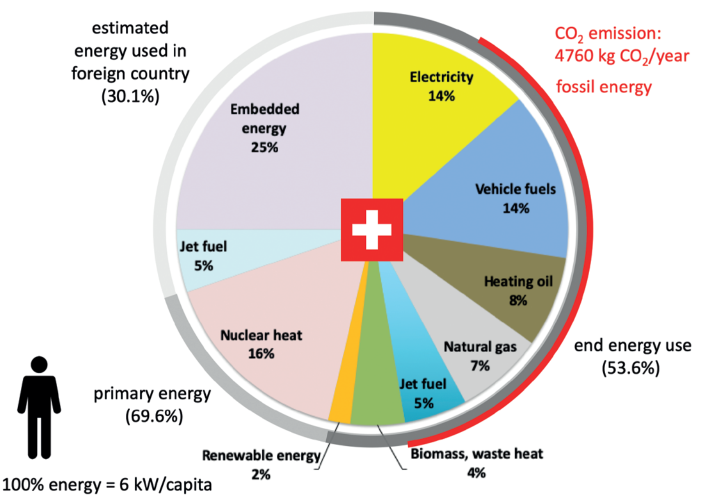

Fig. 1: Energy demand in Switzerland (100 % = 6 kW · capita^{-1}). The dark grey section corresponds to the end energy (3.2 kW · capita^{-1} = 54 % of which 2.4 kW · capita^{-1} = 40 % is non-renewable). Primary energy consumption (4.2 kW · capita^{-1} = 70 %), which includes nuclear waste heat, is (middle grey). The remaining 30 % for embedded energy and jet fuel corresponds to the energy imported in products or used in foreign countries (light grey). The fossil fraction of the end energy use is marked red and amounts to 39.6 % (left).

The end use energy demand in Switzerland reached saturation or even slightly decreased in recent years. The end energy is complemented by nuclear waste heat, leading to the primary energy consumption. All imported embedded energy and the process energy of imported products are additional energy provided to the people in Switzerland. According to McKay [3], the embedded energy amounts to 25 % of the total energy demand in Great Britain. For this analysis, it is assumed that in Switzerland, the embedded energy also amounts to 25 % of the total energy demand. Furthermore, jet fuel represents the jet fuel supplied in Switzerland and not the jet fuel used by Swiss passengers returning to Switzerland.

The energy transition to a fossil-free energy economy requires the generation of the end energy (3.2 kW · capita^{-1}) from renewable energy. Currently, 0.86 kW · capita^{-1} is produced from renewable generation including biomass and the electricity production from nuclear power corresponds to 0.24 kW · capita^{-1}. The nonrenewable end energy is 2.02 kW · capita^{-1}.

Energy [kW · capita^{-1}]	Currently	Form of energy	Renewable
Hydroelectricity	0.48		0.48
other renewables	0.11		0.11
Biomass	0.27		0.27
Nuclear	0.32	PV Electricity	0.32
Vehicle fuel	0.83	PV Electricity	0.65
Heating oil	0.45	H_2 or syn. HC	1.71
Natural gas	0.43		
Jet fuel	0.31	Synthetic HC	0.31
Total Energy	3.20		2.13 3.20

Table 1: End energy use in Switzerland per capita in case of an energy carrier e.g. fossil fuels, hydrogen and synthetic hydrocarbons and in the hypothetic case of complete electrification.

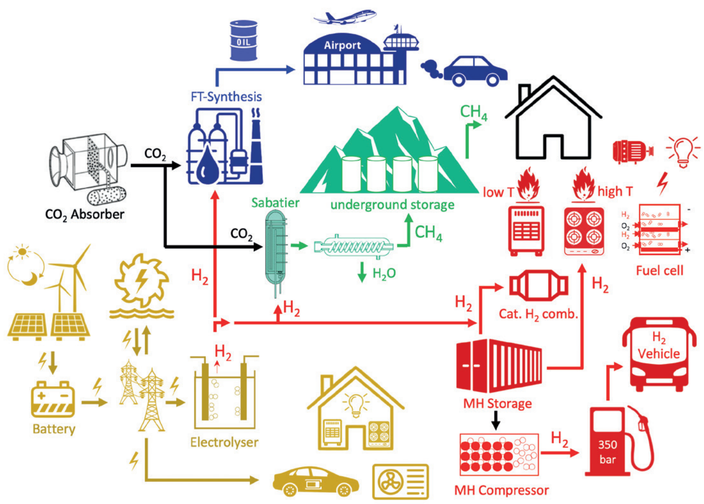

Fig. 2: Renewable energy conversion chain for electricity (yellow), hydrogen (red), synthetic methane (green) and synthetic liquid hydrocarbons (blue).

Electrification

The current monthly average energy demand is 3.2 kW · capita^{-1} with a maximum in winter of 4.1 kW · capita^{-1} (127 %) and a minimum of 2.75 kW · capita^{-1} (86 %) in the summer. The electrification of the vehicles and heating reduces the annual average energy demand by 34 % and the difference between summer and winter from 4 1% to 15 %.

The electrified energy system requires an area of 48 m^2 · capita^{-1} (403 km^2 for CH) of PV, approximately 3 times the roof area in Switzerland [4], for the annual electricity production of 10 MWh · capita^{-1} (87 TWh/year for CH), leading to a peak power of P = 80 GW_p in the Swiss grid. Therefore, local batteries with a capacity of 27 kWh · capita^{-1} (227 GWh for CH ≈ 0.25 % of the annual production) are necessary for peak shaving and to bridge the night. The seasonal storage requires 2.5 MWh · capita^{-1} (20 TWh for CH) storage capacity (≈ 25 % of the annual production), significantly larger than the currently available storage capacity in the hydroelectric storage lakes of 9 TWh and requires an additional 13 hydroelectric power plants of the size of Grand Dixence (1.5 TWh). A seasonal storage of electricity in batteries is very expensive because the battery only charges-discharges once per year. The cost of electricity varies between the direct use from PV of 0.04 – 0.08 CHF/kWh to seasonal storage and distribution through the grid of 0.56 CHF/kWh. Without the seasonal storage 6 power plants with an electric power of 1 GW are necessary to bridge the winter gap. In addition, synthetic fuel has to be produced for aviation which requires an additional 33 m^2 · capita^{-1} of PV, battery, electrolysis, CO_2 capture and Fischer-Tropsch synthesis (s. chapter synthetic hydrocarbons).

Hydrogen

Hydrogen can be produced from electricity and water and used as fuel for heat and mobility. The electricity from nuclear power plants is replaced by electricity from PV and synthetic hydrocarbons are produced for aviation, all other fossil fuels are replaced by hydrogen. The hydrogen-based energy system requires an area of 116 m^2 · capita^{-1} (975 km^2 for CH) of PV, approximately 7 times the roof area in Switzerland, for the annual electricity production of 25 MWh · capita^{-1} (210 TWh/year for CH). Battery capacity of 480 GWh provides constant electric power of 48 GW to the electrolysis. Seasonal storage of hydrogen in underground cavities is safe and most economic. The volume of the storage for almost 33 TWh is 57 Mm^3 corresponding to about 25 times the Gotthard base tunnel. The cost of the hydrogen is between 5.5 and 16.5 CHF/kg.

Synthetic hydrocarbons

Synthetic hydrocarbons can directly replace the fossil fuels in all applications, only the electricity from nuclear power plants is replaced by electricity from PV. The PV area for the synthesis of hydrocarbons is 220 m^2 (1848 km^2 for CH) (producing 330 TWh/year) with 44 Mt CO_2 per year lead to 15 billion Liter of synthetic fuel. The infrastructure as well as the applications for synthetic oil already exist. The cost of syn. oil is > 4.5 CHF/l more expensive than 0.4 CHF/kWh. This may lead to the fundamental problem, that industry is no more able to generate a benefit. Therefore, synthetic oil produced in more sunny regions close to the equator or in Australia significantly reduces the cost of the product (- 35 %).

Conclusions

Approximately 75 % of the energy demand can be covered with renewable electricity at comparable cost to todays energy cost. The remaining 25 %, i.e. the winter months, are technically challenging and very expensive. The complete electrification is only possible if the electricity can be moved from summer to winter or produced in winter from hydrogen. The PV area for the electricity-based system incl. aviation fuels is around 80 m^2 · capita^{-1}, for the hydrogen-based energy system this area becomes twice as large and for the synthetic hydrocarbon-based energy system the PV area again almost doubles. However, building 13 hydroelectric power plants like Grand Dixence or 25 times the Gotthard base tunnel for hydrogen storage are constructions beyond everything Switzerland built so far. Investing in hydrogen and synthetic fuel production close to the equator, e.g. in the desert, or in Australia is the most economic and feasible strategy in order to enable the transition to renewable energy. The hydrogen can then be used directly to produce heat or efficiently converted into electricity in a combined cycle power plant (with an H_2 steam generator) to produce the electricity during the winter months. The synthetic fuels will be used mainly for aviation. Approx. 1 Mio. km^2 in Australia (1/8 of the country area) could provide renewable energy to the whole world and replace all fossil fuels.

References

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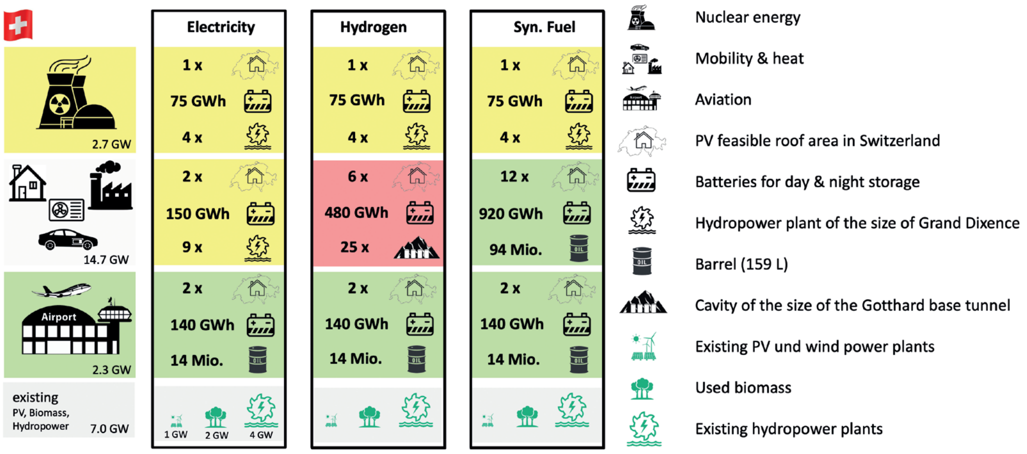

Fig. 3: The four energy sectors: nuclear power plants, road mobility and heat, aviation and already existing renewable energy with the three energy systems including the size of PV and storage