RENEWABLE ENERGY STORAGE IN HYDROGEN AND SYNTHETIC HYDROCARBONS

ANDREAS ZÜTTEL*[a),b)]

[a)]*Laboratory of Materials for Renewable Energy (LMER), Institute of Chemical Sciences and Engineering (ISIC), École Polytechnique Fédérale de Lausanne, EPFL Valais/Wallis, 1950 Sion Switzerland.*

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

Abstract

Renewable energy appears in the form of heat, electricity or biomass. The chemical challenge in the renewable energy economy is to provide the energy in a storable and usable form at the place and time the energy is required. Electricity and heat allow to split water into hydrogen and oxygen, hydrogen can be stored as compressed gas, liquid hydrogen or in metal hydrides. Furthermore, hydrogen reduces CO_2 to hydrocarbons, e.g. synthetic oil, kerosene or diesel, in order to produce the CO_2 neutral fuels. Beside the technical requirements to produce the renewable electricity and heat, the seasonal storage and the production of aviation fuels are the main challenges of an energy economy entirely based on renewable energy.

Renewable Energy

Fossil fuels and materials on Earth in general are a finite resource and the disposal of waste into the air, water and on land has an impact on our environment on a global level[1] (chemical pollution, CO_2 concentration in the atmosphere, radioactive waste).

The combustion of the fossil fuels (currently burning fossil fuels +9.4 $GtC \cdot y^{-1}$ and deforestation +1.6 $GtC \cdot y^{-1}$) leads to an increase of the CO_2 concentration in the atmosphere[2] (Fig. 1). Fortunately natural sinks (Ocean: - 2.5 $GtC \cdot y^{-1}$ (±5%), Forests: -3.4 $GtC \cdot y^{-1}$ (±20%)) lead to the reabsorption of CO_2 of -5.9 $GtC \cdot y^{-1}$ (at 410 ppm) leaving +5.1 $GtC \cdot y^{-1}$ (±50%) increase in the atmosphere. The reserves of fossil fuels are limited[3] and are estimated to be between 900 – 1750 GtC[4]. The anthropic CO_2 emissions[5] grow by 1.5% every year and the cumulated CO_2 emissions double every 27 years. The reserves of fossil fuels are therefore completely consumed between 2047 and 2073. The global renewable energy production is growing more than exponentially[6] and will reach the world energy demand in 2035 (Fig. 2).

However renewable energy appears in the form of heat, electricity or biomass. The chemical challenge in the renewable energy economy is to provide the energy in a storable and usable form at the place and time the energy is required.

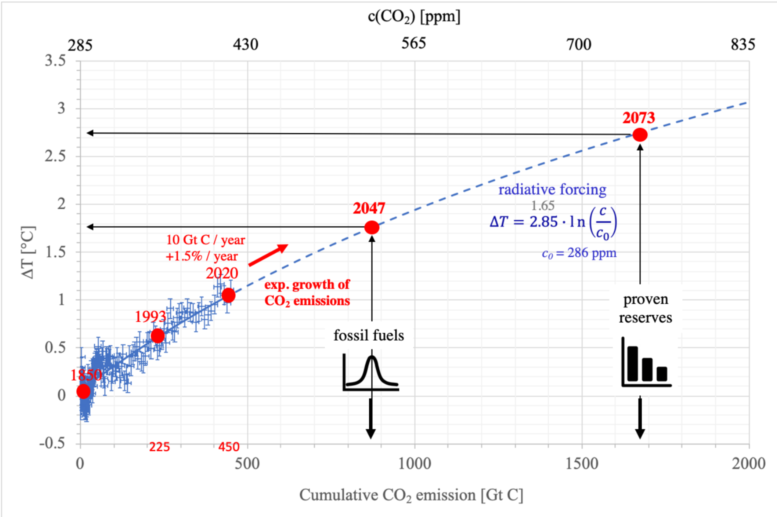

Fig. 1. Observed and extrapolated temperature increase as a function of the cumulated CO_2 emissions. The CO_2 emissions grow by 1.5% every year and the cumulated CO_2 emissions double every 27 years.

The two main challenges in the transition from the current fossil-based energy economy to a future renewable energy based one is the seasonal storage of renewable energy and the synthetic fuels for aviation, because of the large amount of energy to be stored and the high energy density required, respectively. The electricity produced from renewable energy, e.g. photovoltaics, (Fig. 3) is stored for short term locally in batteries or over the seasons in hydroelectric storage lakes. The applications, e.g. mobility and heating are electrified, which reduces the overall energy demand by approximately 33%. However, the seasonal storage of electricity requires large hydroelectric installations, which are not everywhere possible, and the battery electric aviation is limited to small airplanes for short distances. Even if the seasonal storage is lower in some regions closer to the equator or because the renewable energy is imported in the form of hydrogen, storage for the energy demand of approximately 4 months is required for energy security and redundancy of the energy production chain.

Chemical Energy Carriers

The electricity allows to split the water into hydrogen and oxygen, a technology that is called power to X (P2X). Electrolysis[7] exhibits today an efficiency <60% depending on the type, i.e. PEM, alkaline or SOEC, and on the size or power of the electrolyzer. Electrodes of modern electrolyzers work with a power density of >30kW·m^{-2}. The

CAPEX of electrolyzers is >2000 €/kW_{HHV} (HHV: Higher heating value of the hydrogen = 39.4 kWh/kg H_2) leading to an energy cost in hydrogen of +6 €cts./kWh.

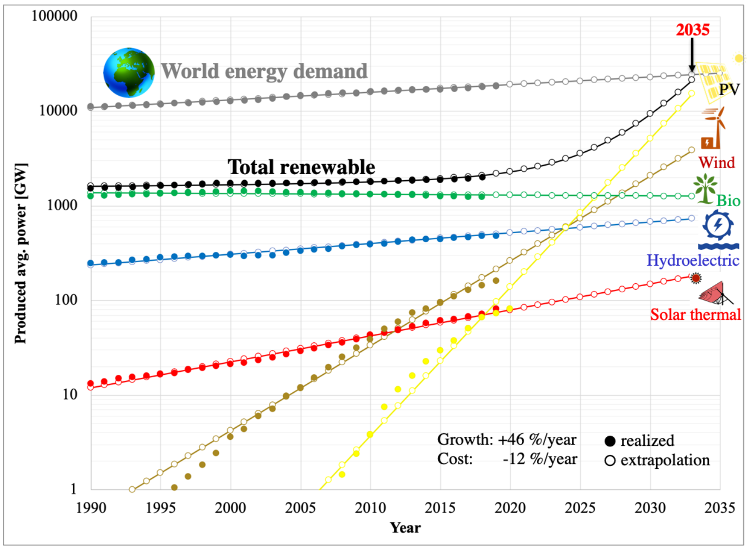

Fig. 2. The development of the renewable energy in comparison with the world energy demand.

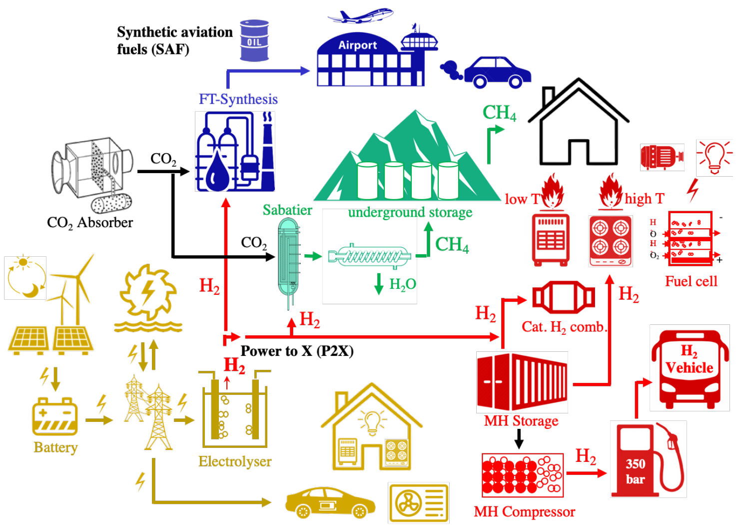

Fig. 3. Renewable energy conversion chain for electricity (yellow), hydrogen (red), synthetic methane (green) and synthetic liquid hydrocarbons (blue). The electrolysis of water allows the transition from power to chemical energy carrier (P2X) and the CO_2 air capture allows the production of synthetic methane and synthetic aviation fuels (kerosene, diesel).

The research topics in electrolysis focus on the increase of the efficiency by reducing the overpotentials on the electrodes with improved electrocatalytic materials, reduce the ohmic losses in the gas separation membrane and develop new water splitting technologies which use the solar energy in photons directly to dissociate water by photoelectrochemical process. Hydrogen is stored as compressed gas, as liquid at low temperature (-252°C) or absorbed in metal hydrides.

Today, hydrogen storage reaches approximately 15% of the volumetric energy density (0.4 - 20 kWh/kg, 0.5 – 1.3 kWh/L) of liquid hydrocarbons, e.g. oil. The storage of hydrogen consumes between 15-30% of the energy in the hydrogen and CAPEX of the storage is between 9 – 2500 €/kgH_2 (+0.4€cts/kWh to +0.12€/kWh). The hydrogen is used in catalytic combustion for heat production or fuel cell to produce electricity with an efficiency of approximately 50%. An energy system based on hydrogen requires the infrastructure for production, storage and distribution of hydrogen and the adaptation of the applications to hydrogen, e.g. hydrogen combustion and fuel cells. Alternatively, hydrogen can be produced as an energy carrier for transport and storage and used in a combined cycle power plant to produce electricity with an efficiency of 50%, while the applications are electrified.

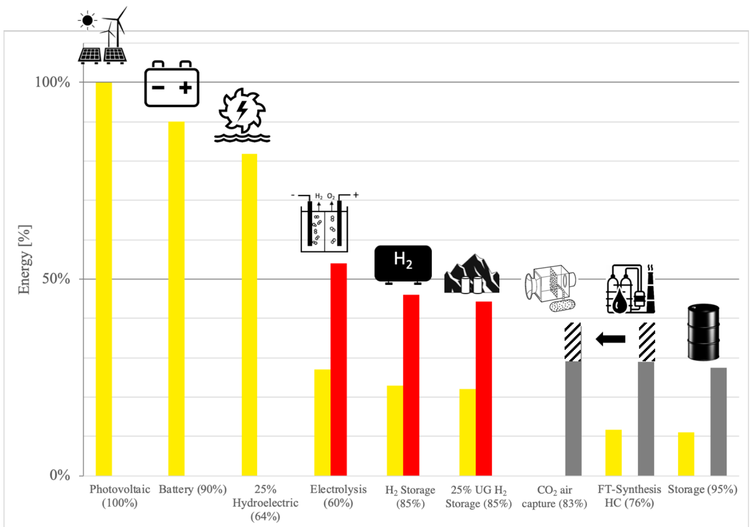

Fig. 4. Conversion efficiencies, from PV and wind to hydrogen and finally hydrocarbons. Energy in electricity (■), hydrogen (■) and hydrocarbons (■)

Hydrogen together with a carbon source e.g. CO_2 from air capture or biomass, allows to synthesize CO_2 neutral hydrocarbons. While selective reactions to methane, methanol and dimethyl-ether are known, the Fischer-Tropsch reaction from syngas (CO, H_2), the product of the reversed water gas shift reaction (RWGS) $CO_2 + H_2 \rightleftarrows CO + H_2O$, leads to a large variety of products described by the Anderson–Schulz–Flory distribution[8]. The

products are refined and the undesired products recycled in the process. The cost of synthetic oil is dominated by the electricity cost and the cost of the CO_2, which is currently between 160 – 830 €/t C, while the biomass is at 800 €/t C. Synthetic hydrocarbons can directly replace the fossil fuels in all applications and the storage and distribution of the synthetic fuel is an established technology and exists already.
Due to the thermodynamic limits and technical conversion limitations described as maximum conversion efficiencies (Fig. 4), energy conversion and storage leads to a partial loss of energy (exothermic reactions) and a reduction of the finally available energy in the product. Therefore, the choice of the energy carrier depends on the energy density required in the application as well as the storage options. The conversion efficiency, the investment for the conversion device and the storage system determine the economics (Fig. 5) of the energy system.

Conclusions

The transition from an energy economy mainly based on fossil fuels to an energy economy based on renewable energy requires the chemical technology to produce the energy carriers selectively and efficiently. Furthermore, economically the cost of energy for the coming 5 – 30 years needs to be invested in order to build up the energy conversion.

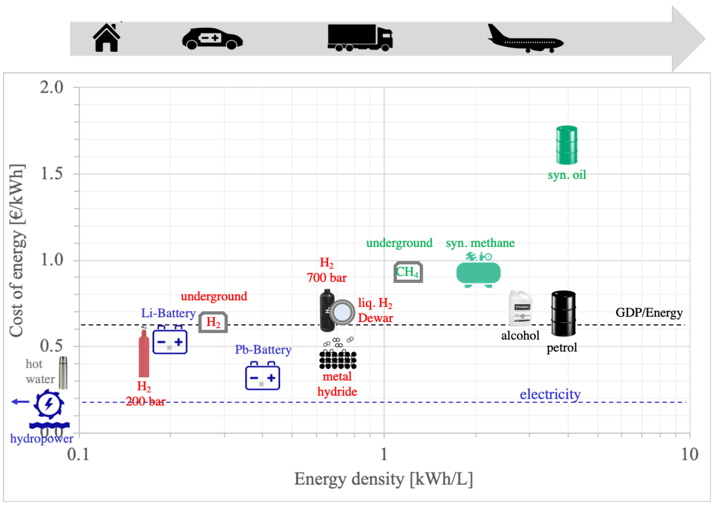

Fig. 5. Cost of energy (electricity) versus volumetric energy density for batteries, hydrogen and synthetic hydrocarbons.

The investment and the final cost of the energy unit are of great importance for the future development of the whole economy. In the industrial countries the energy provided to industry leads to an economic benefit[9] of 0.6€/kWh. Only one billion people live with more than 20000 €/year, 7 billion have less available and are on the linear relationship between energy demand and Grand Domestic Product (GDP). Only the wealthy countries deviate from this linear relationship due to the increasing import of energy rich products and an increasing fraction of the economy is not energy related, e.g. fashion, cosmetics, financial sector. Past developments in Switzerland have demonstrated the feasibility as well as the benefit of long-term investments in technology for a sustainable development, e.g. the Gotthard tunnel[10], the electrification of the railway[11] and the mountain trains[12]. All three examples stand for an enormous investment leading to less pollution and an economic beneficial development, however, the profit arrived a few generations later.

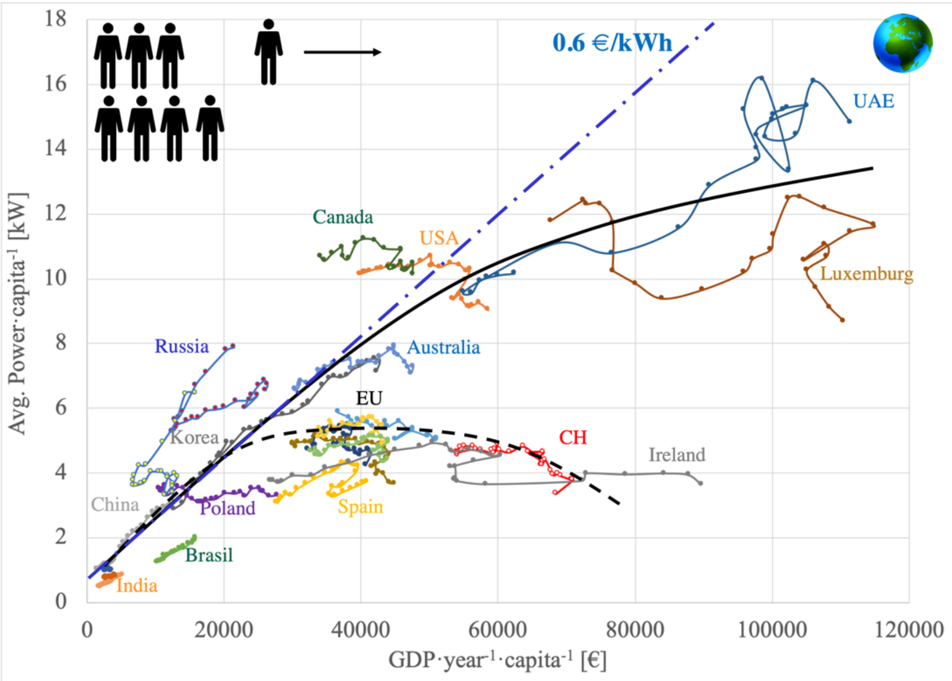

Fig. 6. Average. power per capita versus GDP per year and capacity for selected countries.

References

1 S. Bilgen, *Renewable and Sustainable Energy Reviews* **38**, 890 (2014).
2 P. Friedlingstein *et al.*, *Earth Syst. Sci. Data* **11**, 1783 (2019).
3 H. Ritchie, M. Roser and P. Rosado (2020) - "Energy". Published online at OurWorldInData.org. Retrieved from: 'https://ourworldindata.org/energy' [Online Resource]
4 A. Valero and A. Valero, *Resources, Conservation and Recycling* **68**, 126 (2012).
5 H. Ritchie, M. Roser and P. Rosado (2020) - "CO_2 and Greenhouse Gas Emissions". Published online at OurWorldInData.org. Retrieved from: 'https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions' [Online Resource]
6 A. Züttel, N. Gallandat, P. J. Dyson, L. Schlapbach, P. W. Gilgen, S.-I. Orimo, *Frontiers in Energy Research: Process and Energy Systems Engineering* **9** (2022), https://doi.org/10.3389/fenrg.2021.785908

[7] N. Gallandat, K. Romanowicz, A. Züttel, *Journal of Power and Energy Engineering* **5**, 34 (2017).

[8] P.L. Spath and D.C. Dayton. "Preliminary Screening — Technical and Economic Assessment of Synthesis Gas to Fuels and Chemicals with Emphasis on the Potential for Biomass-Derived Syngas", NREL/TP510-34929 (2003), pp. 95. http://www.fischer-tropsch.org/DOE/DOE_reports/510/510-34929/510-34929.pdf.

[9] https://ourworldindata.org/grapher/energy-use-per-capita-vs-gdp-per-capita

[10] Neue Zürcher Zeitung 1. März 1880

[11] "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.

[12] https://www.jungfrau.ch/de-ch/jungfraujoch-top-of-europe/bau-der-jungfraubahn/