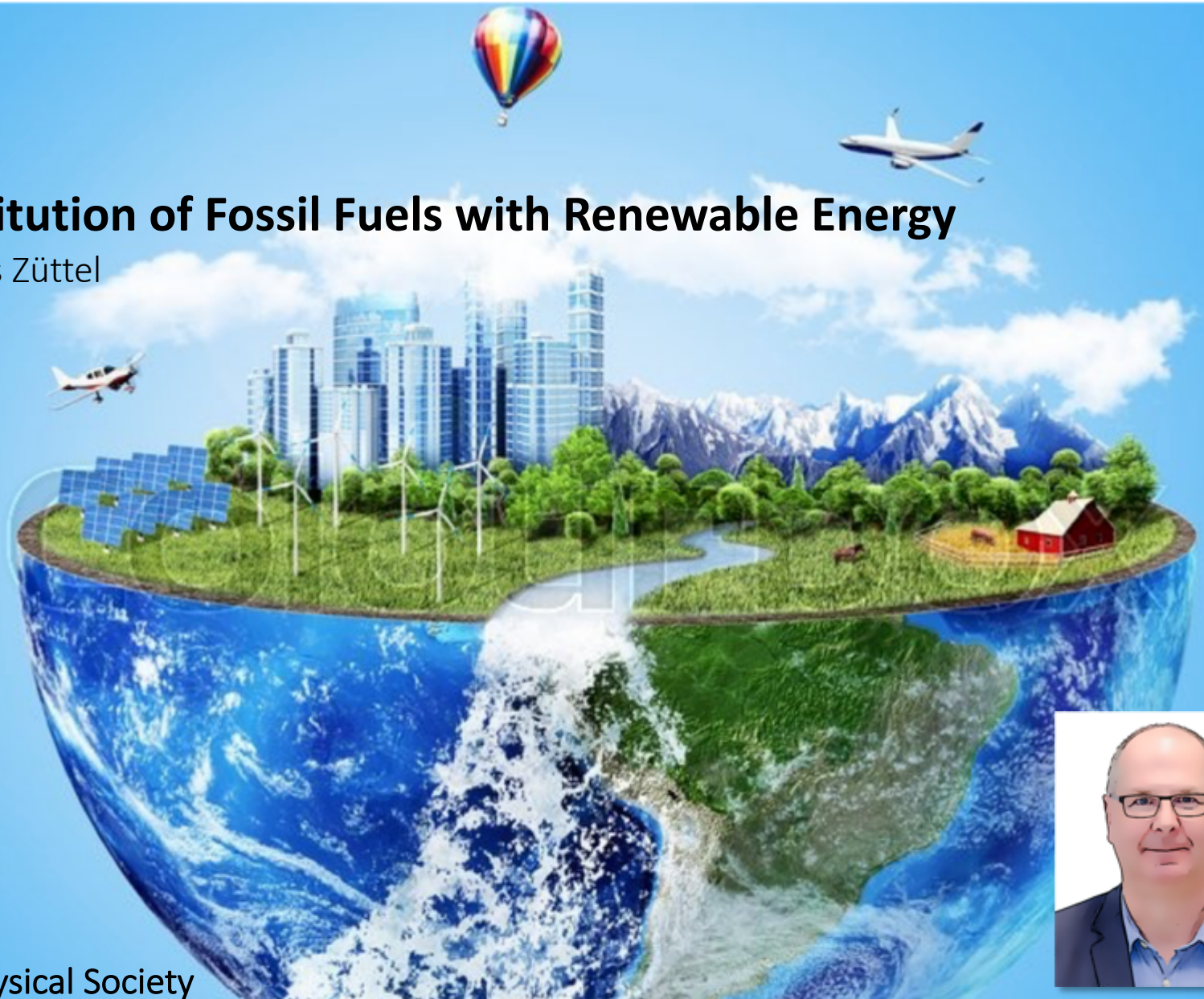
Substitution of Fossil Fuels with Renewable Energy

Andreas Züttel



Swiss Physical Society

Special: 100th Anniversary of the International Union of Pure and Applied Physics (IUPAP)

Thursday, 30.06.2022, Room JD 002

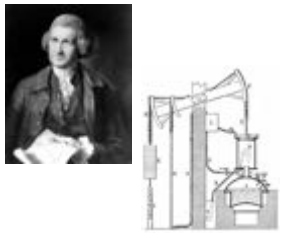
Andreas ZÜTTEL, Prof. Dr.
e: andreas.zuettel@epfl.ch
m: +41 79 484 2553
U: http://lmer.epfl.ch

History of Energy

Steam turbine

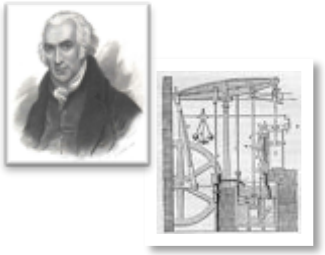
Hero of ALEXANDRIA
10 - 70

1st Steam engine



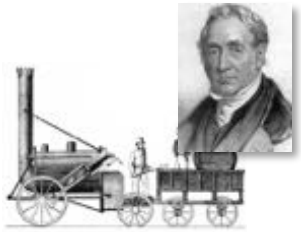
Thomas NEWCOMEN
1712

Steam engine opt.



James WATT
1783

1st Steam locomotive



George STEPHENSON
1828

Standard Oil Company

John D. ROCKEFELLER
1865

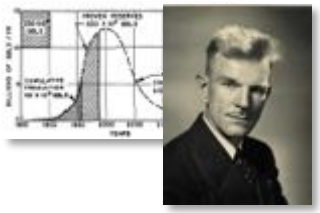
Patent Motorwagen

Carl BENZ
1886

1st motorized flight

Wilbur & Orville WRIGHT
1903

Model for oil mining



M. King HUBBERT
1957

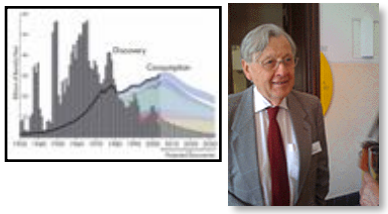
Club of Rome

Jimmy“ CARTER
1978

Solar energy & H_2

Carl-J. WINTER
1989

Fossil resource model



Colin J. CAMPBELL
1998

SEWTHA

Sir David J. C. MACKAY
2008

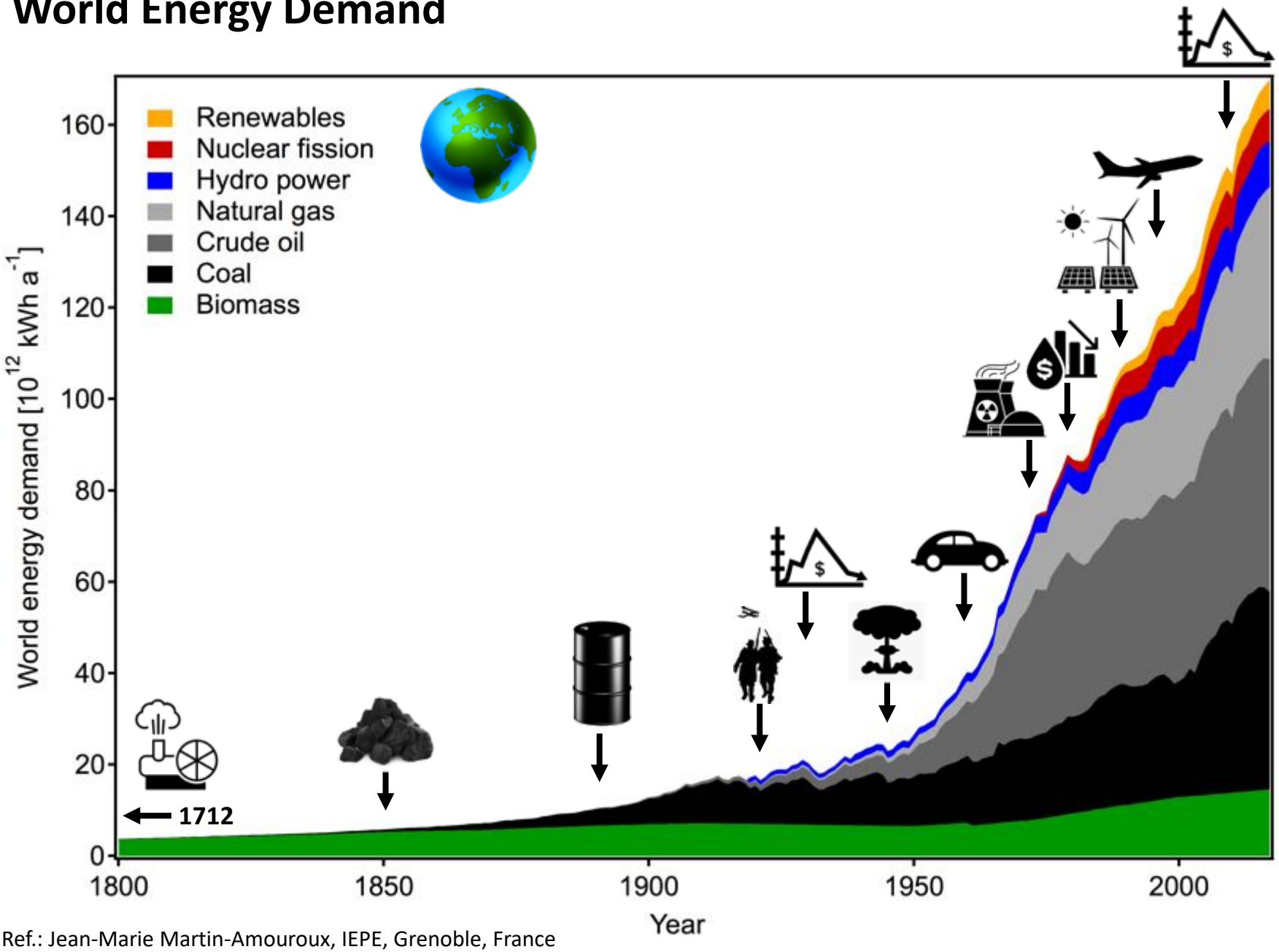
CO_2 Air Capture

Klaus S. LACKNER
2009

Gapminder

Hans ROSLING
2009

World Energy Demand

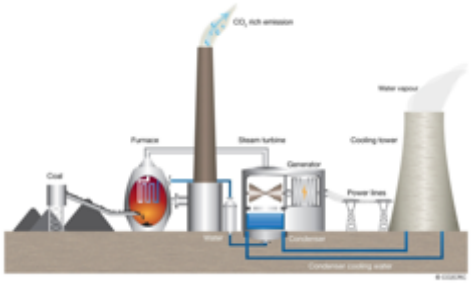


Ref.: Jean-Marie Martin-Amouroux, IEPE, Grenoble, France

World Energy Demand 19 TW

Electricity 7.3 TW = 3.2 $TW_{el.}$

2000 GW **40% → 15%**



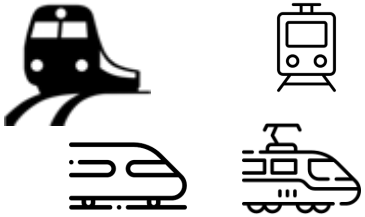
380 GW

500 GW + 300 GW

Mobility 4.2 TW

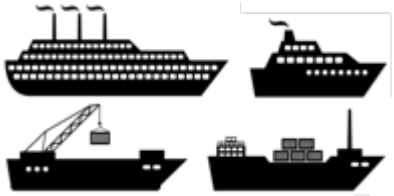
3230 GW **20%**

24 GW



380 GW

570 GW

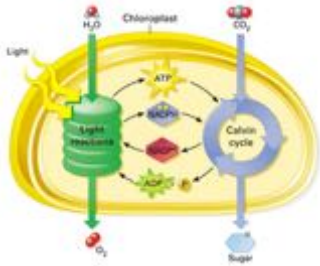


Residential & Industry 7.5 TW

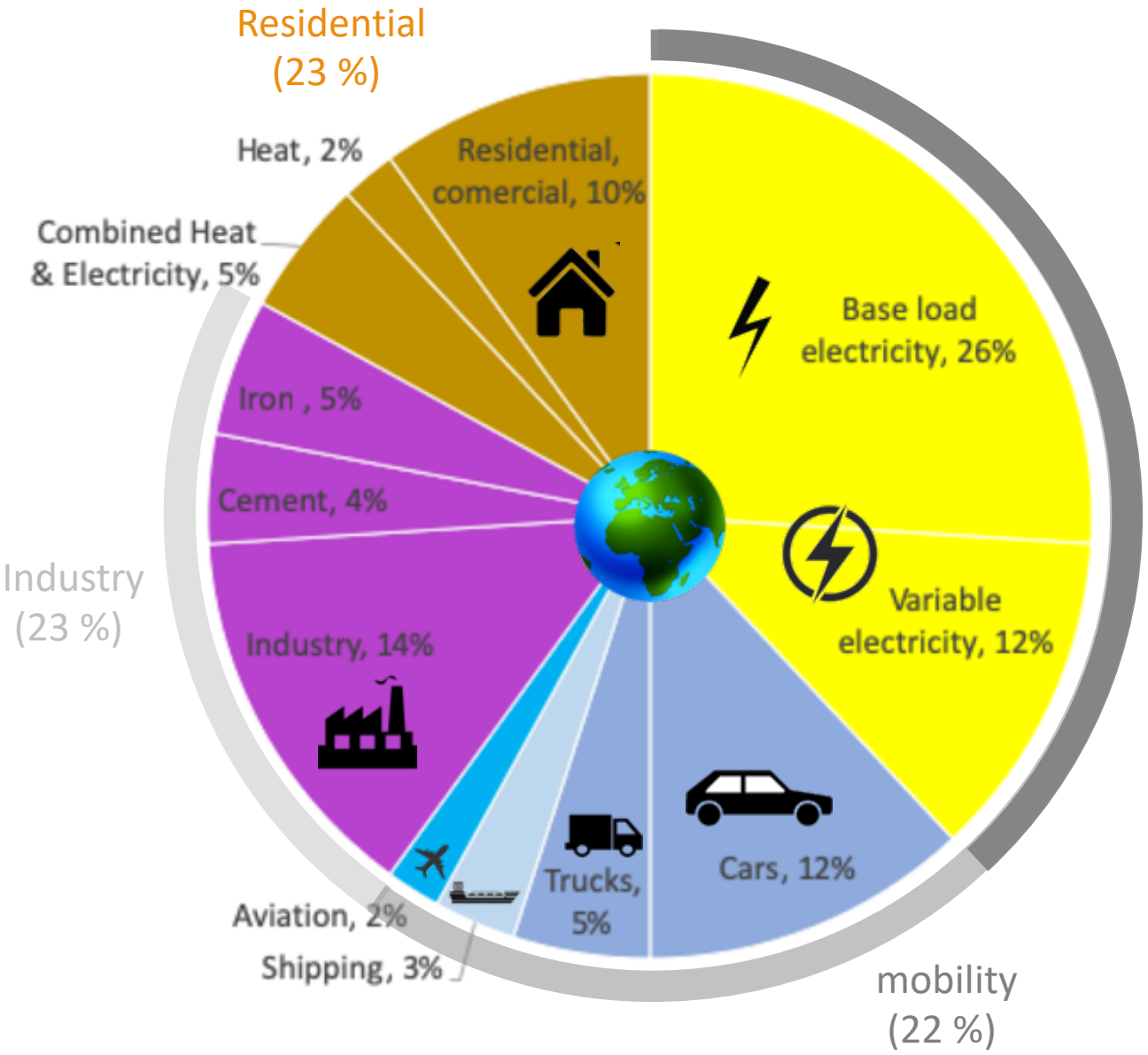
1200 GW **40%** 1900 GW

4370 GW

1200 GW



CO_2 Emitters by Sectors

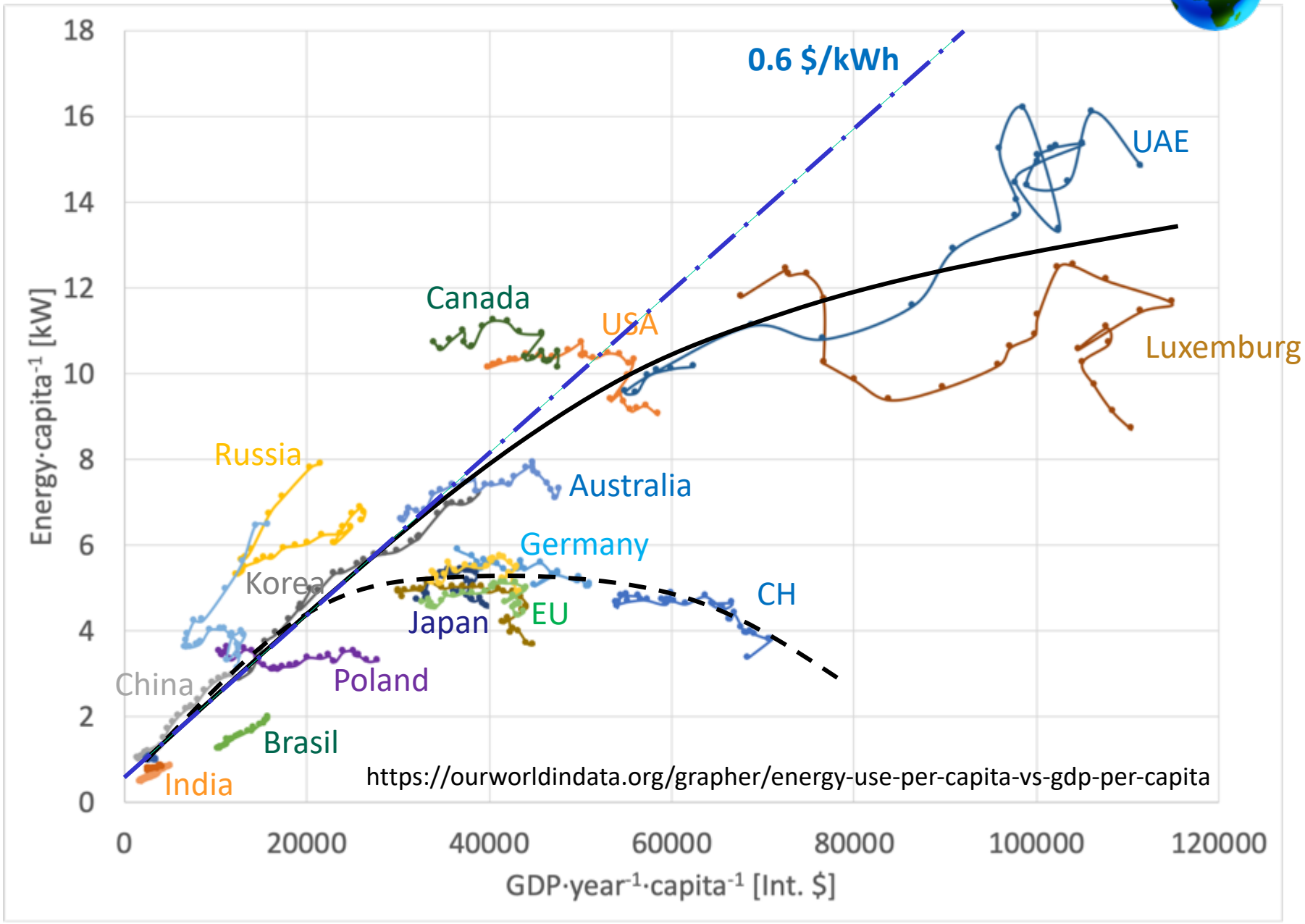


100% = 33.9Gt (2014)

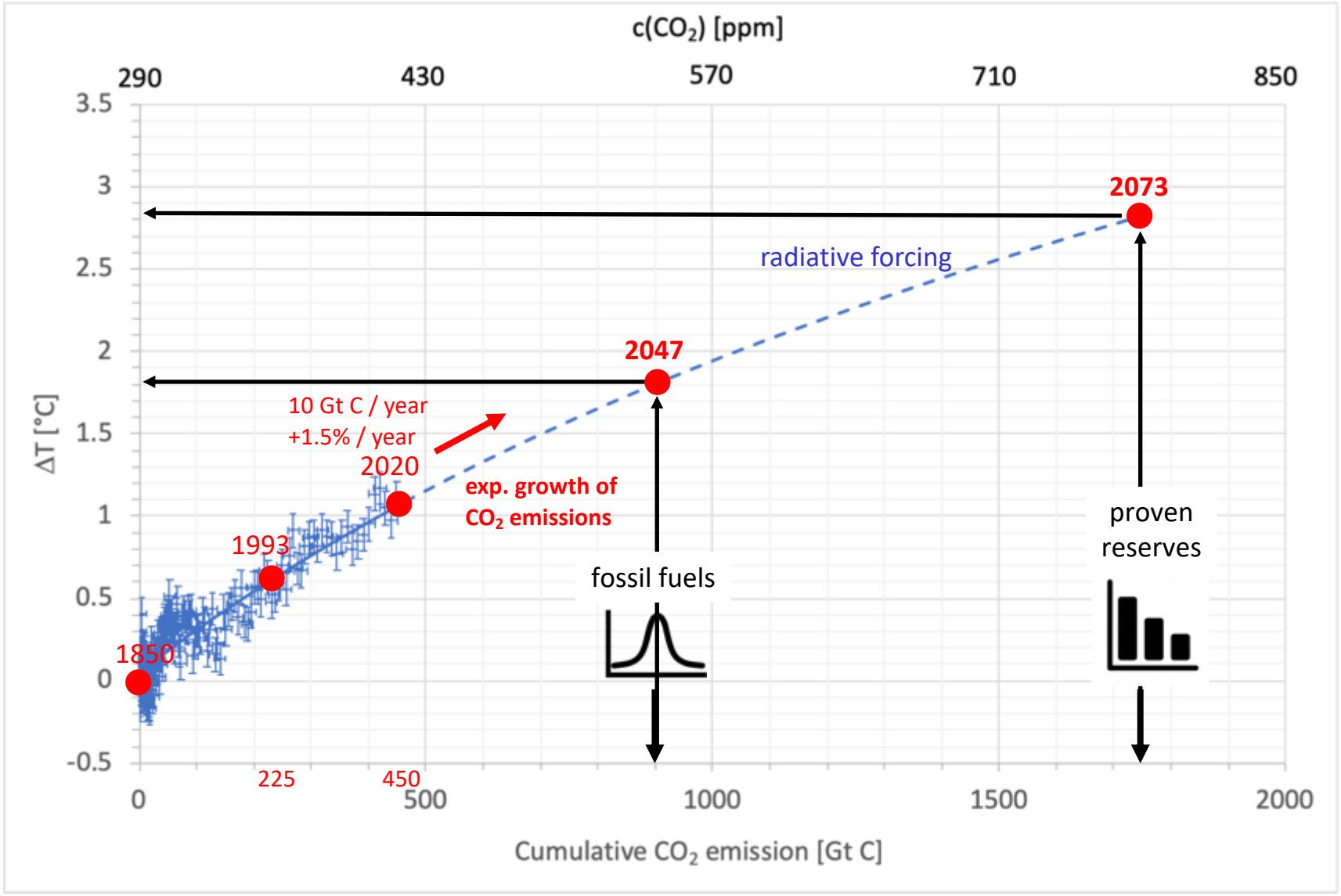
electricity production (38 %)

Ref.: Davis, S. J. et al. « Net-zero emissions energy systems », *Science* 360 (2018), pp. 1–9.

Global Energy and Economy

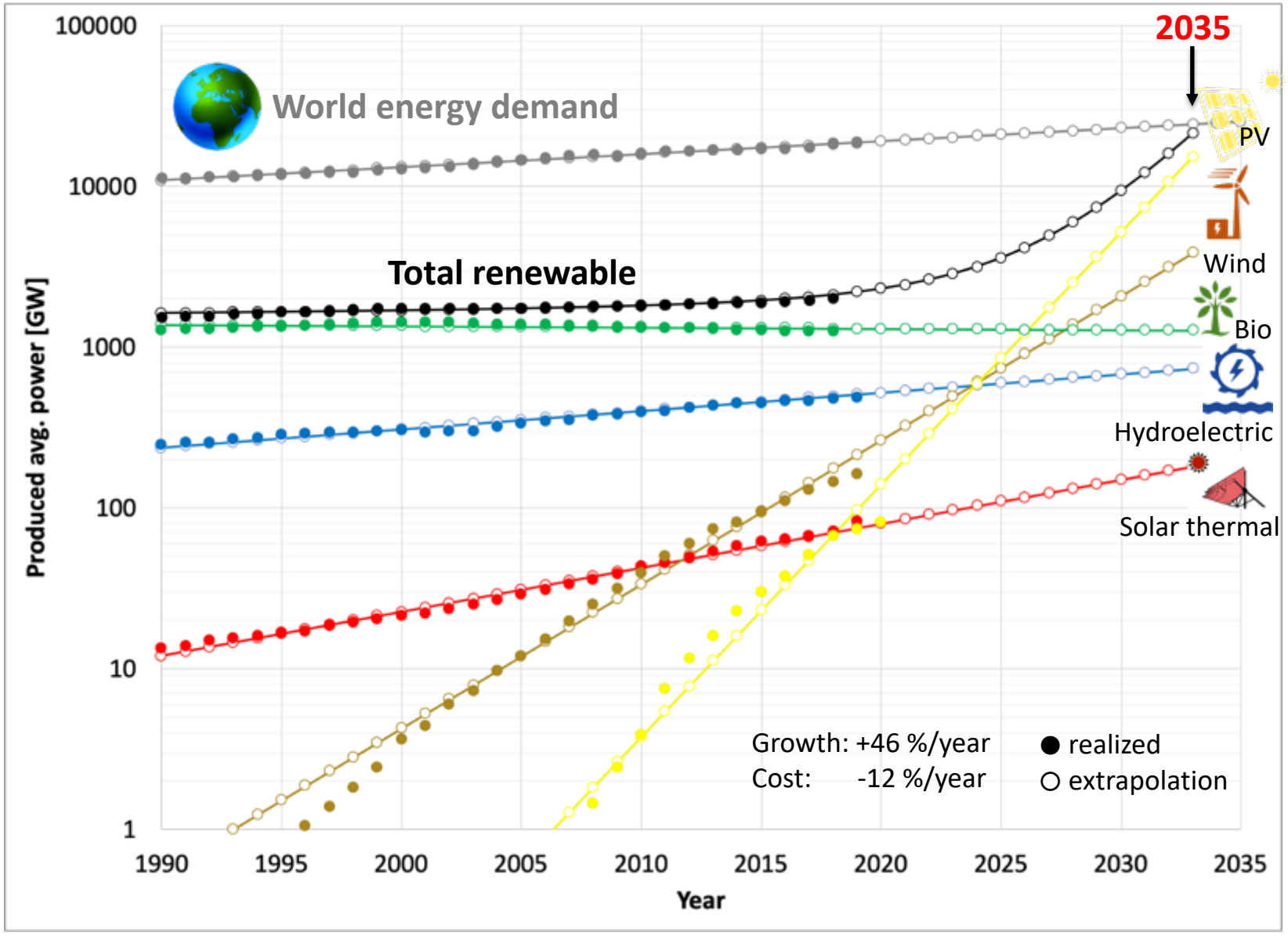


Global Warming vs. Cumulative CO_2 Emissions



Ref.: http://www.globalwarmingequation.info/global%20warming%20eqn.pdf and
Ollila, A. (2014), "The potency of carbon dioxide (CO_2) as a greenhouse gas", Development in Earth Science, Vol. 2, pp. 20-30, available at: www.seipub.org/des/paperInfo.aspx?ID=17162

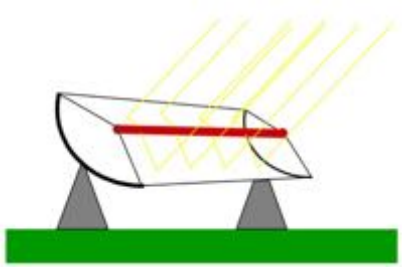
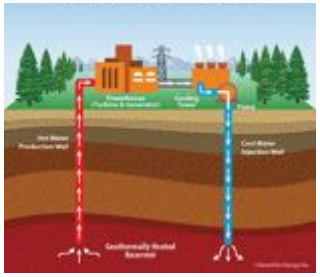
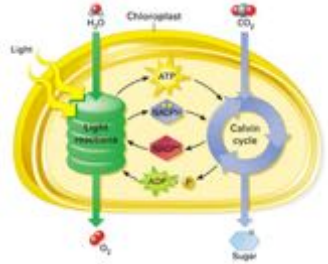
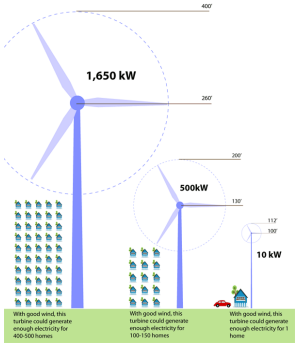
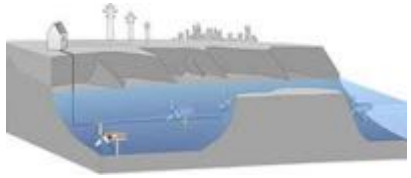
Renewable Energy Production



Ref.: https://ourworldindata.org/energy

Electricity and Renewable Energy

Global Electricity demand 3.2 TW
Renewable energy: 0.87 TW

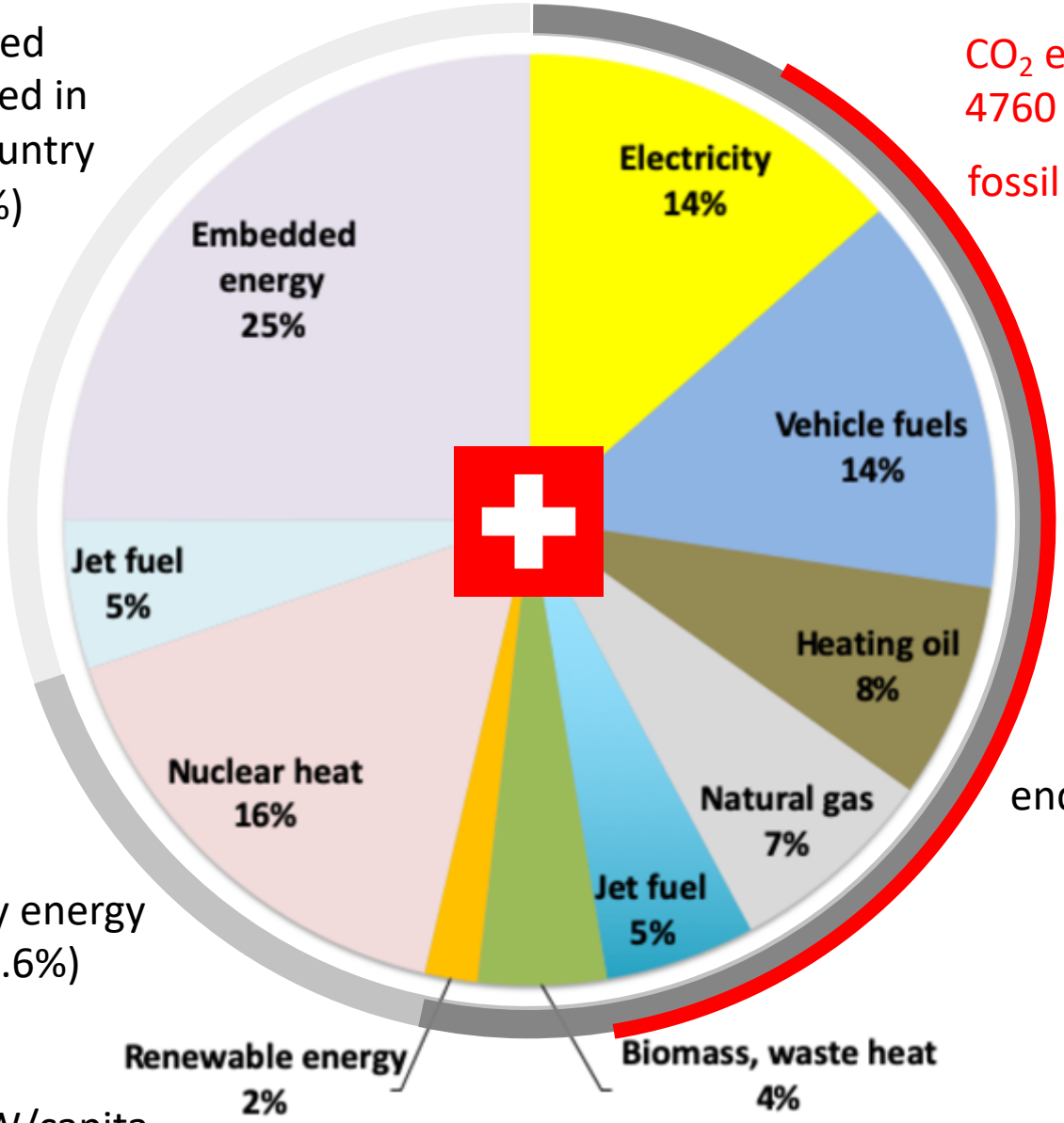
0.67 TW_{el} **0.8 TW_p**	**0.16 TW** **1.2 TW_P**	**0.04 TW**	**1.2 TW**
500 GW (*3000 GW*)	80 GW (*23000 GW*)	21 GW (*2000 GW*)	1200 GW (*2400 GW*)
			
Hydropower	Solar thermal	Geothermal	Biomass
170 GW (*70000 GW*)	80 GW (*3000 GW*)	19 GW (*300 GW*)	
			
Wind power	Photovoltaic	Tidal power	

Energy Demand in Switzerland 2019

estimated energy used in foreign country (30.1%)

CO_2 emission: 4760 kg CO_2/year

fossil energy

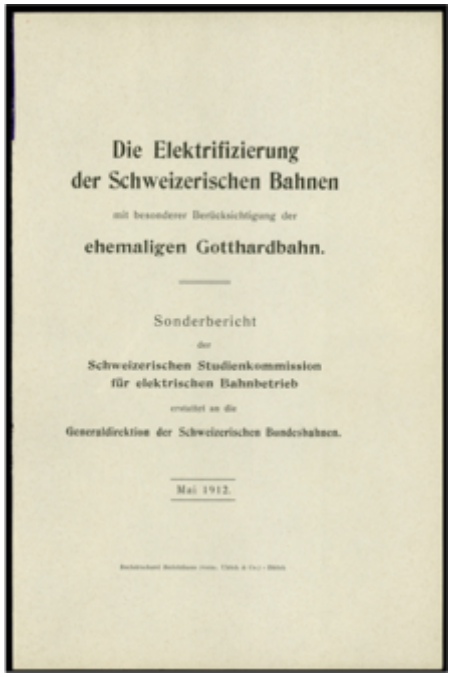


end energy use (53.6%)

primary energy (69.6%)

100% energy = 6 kW/capita

Swiss Decision for Electricity

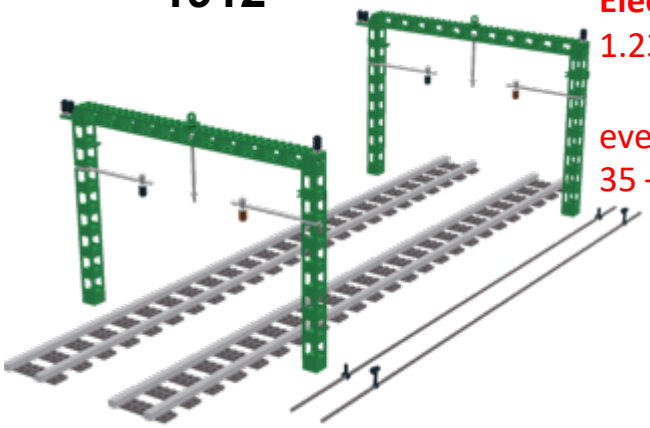

Die Elektrifizierung
der Schweizerischen Bahnen
mit besonderer Berücksichtigung der
ehemaligen Gotthardbahn.
Sonderbericht
der
Schweizerischen Studienkommission
für elektrischen Bahnbetrieb
erstattet an die
Generaldirektion der Schweizerischen Bundesbahnen.
Mai 1912.

1912

1898 Hydroelectric plant Gampel

1920 Mühleberg

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.



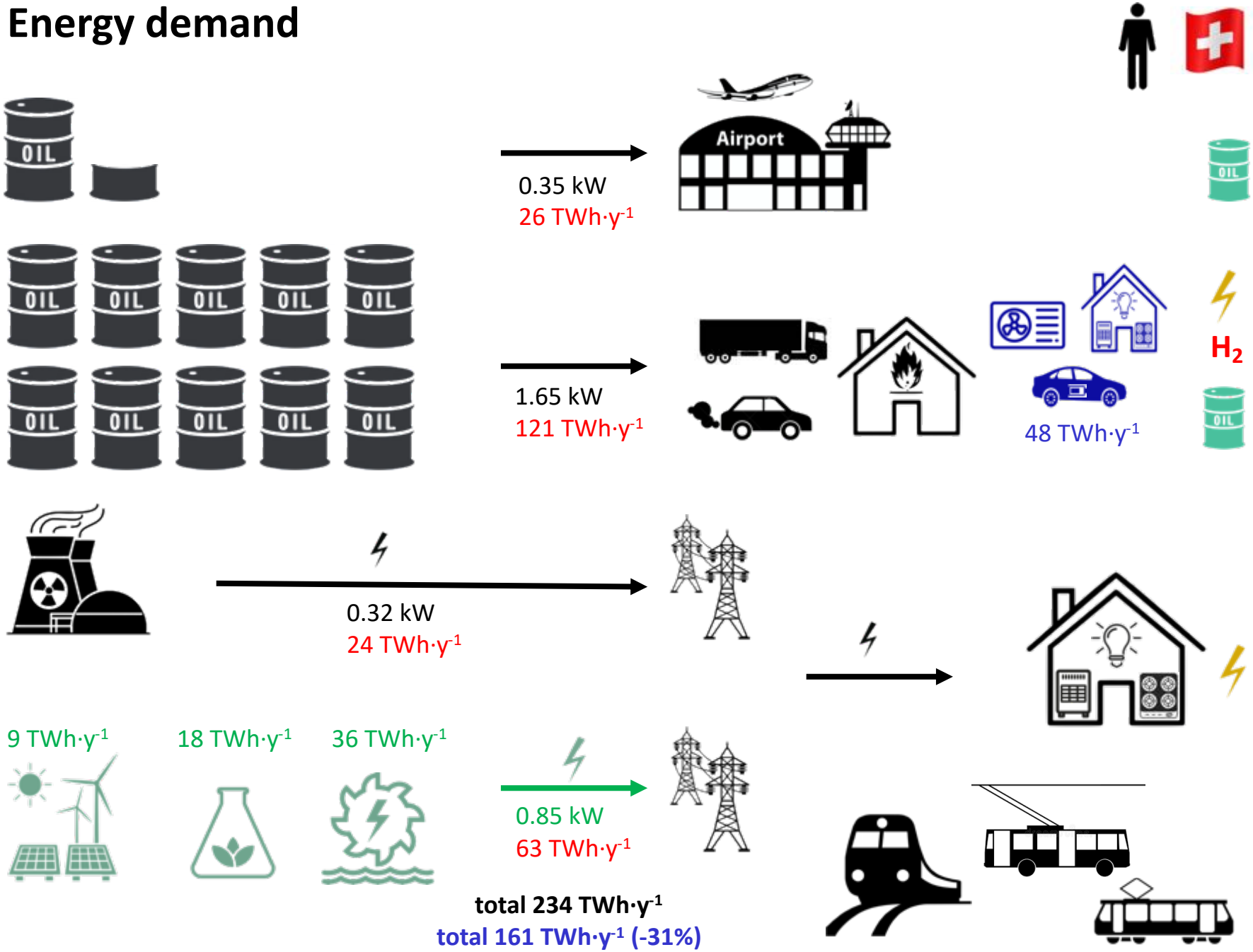
Electrifying
1.23 – 2.6 Mio.€/km

every 27m is a pole,
35 – 70 k€ per pole

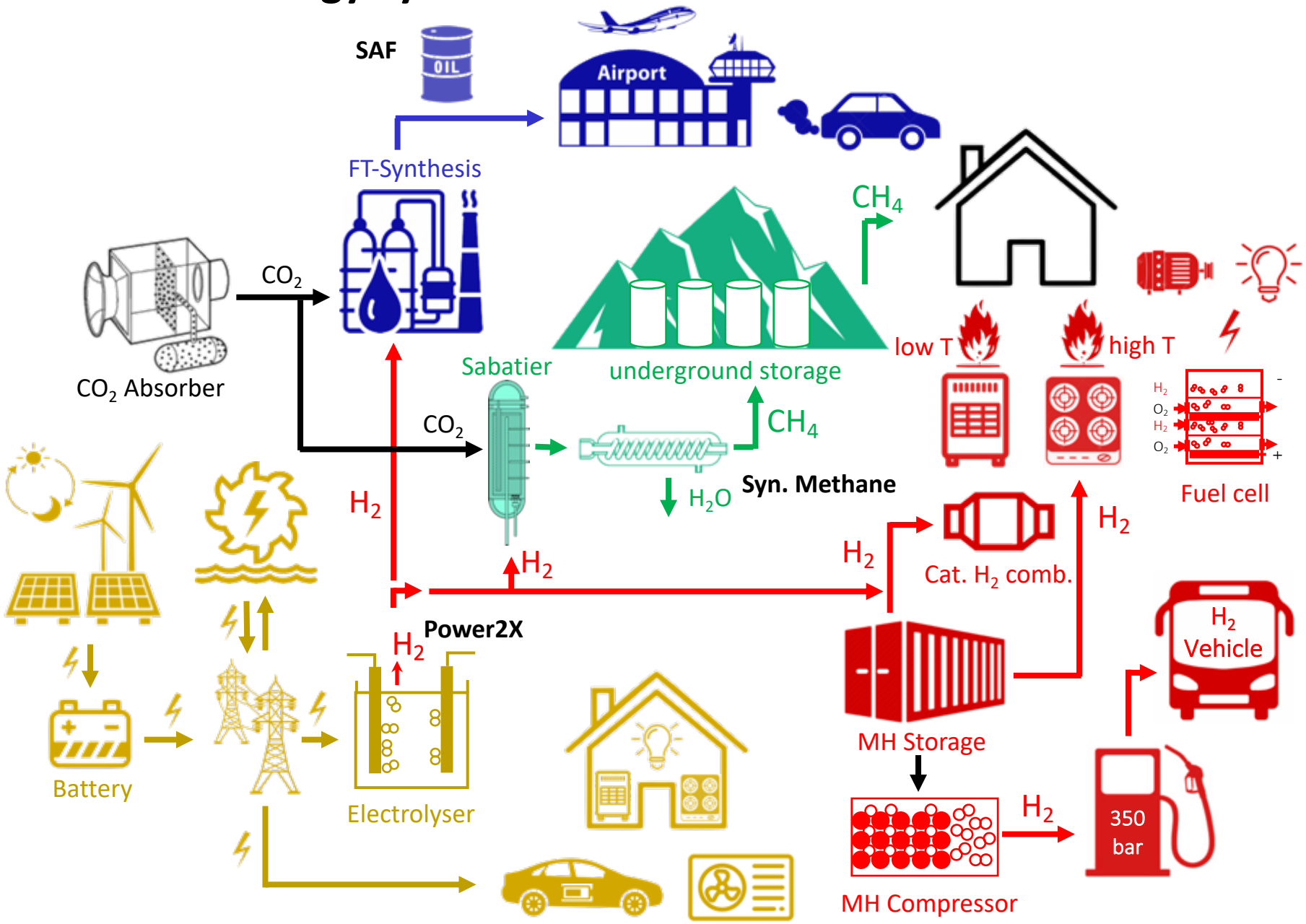
Railway track costs 62 Mio. CHF/km
(Highway costs 150 - 330 Mio.CHF/km)

Ref.: Germany: Lindau -München 500 Mio.€ for 189km incl. noise protection, new train station...
Denmark: whole railway 1'600 Mio.€ for 1300 km

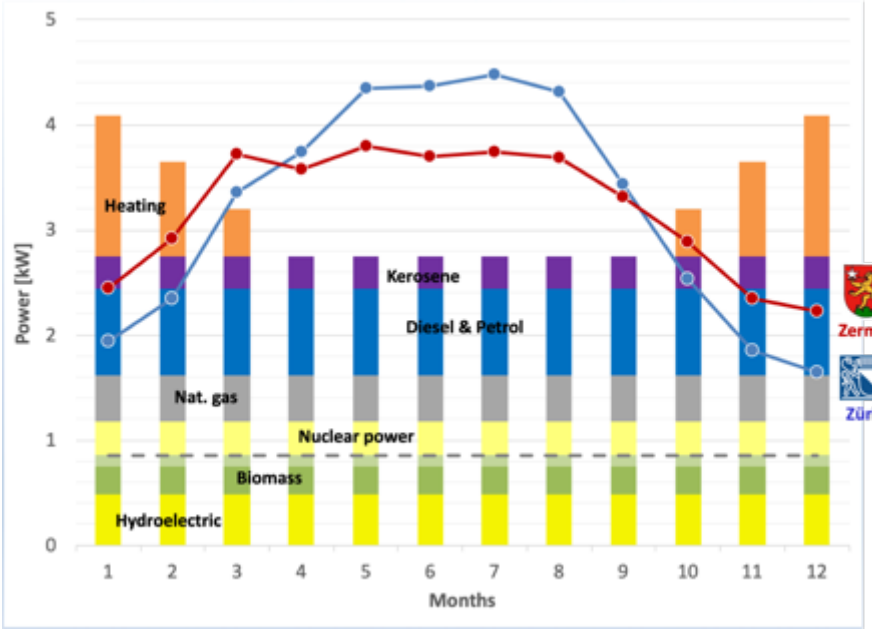
Energy demand

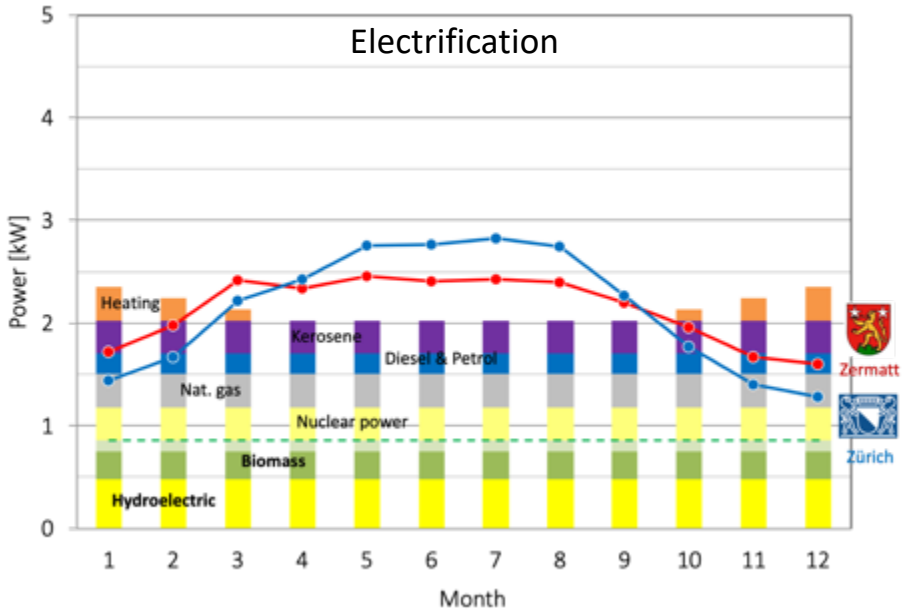


Renewable Energy Systems



Electricity demand and PV production

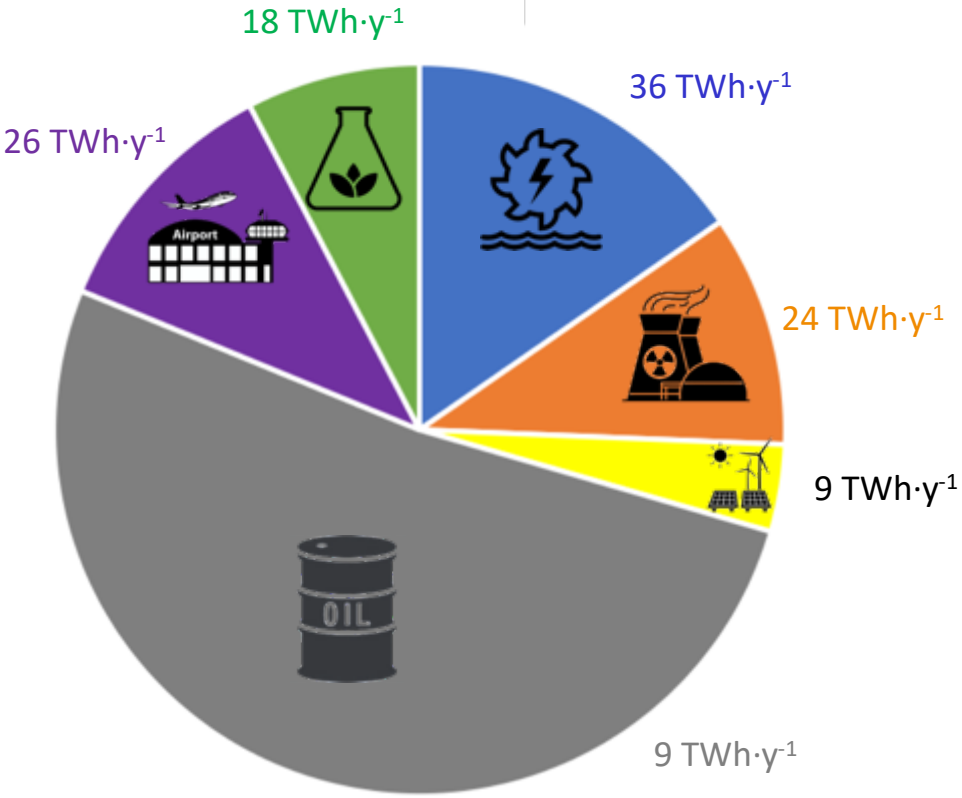




Energy [kW·capita^{-1}]	Currently	Form of energy	Renewable	
Hydroelectricity	0.48		0.48	
other renewables	0.11		0.11	
Biomass	0.27		0.27	
Nuclear	0.32	PV Electricity	0.32	
Vehicle fuel	0.83	PV Electricity	0.65	
Heating oil	0.45	H_2 or syn. HC		1.71
Natural gas	0.43			
Jet fuel	0.31	Synthetic HC	0.31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

End Energy demand

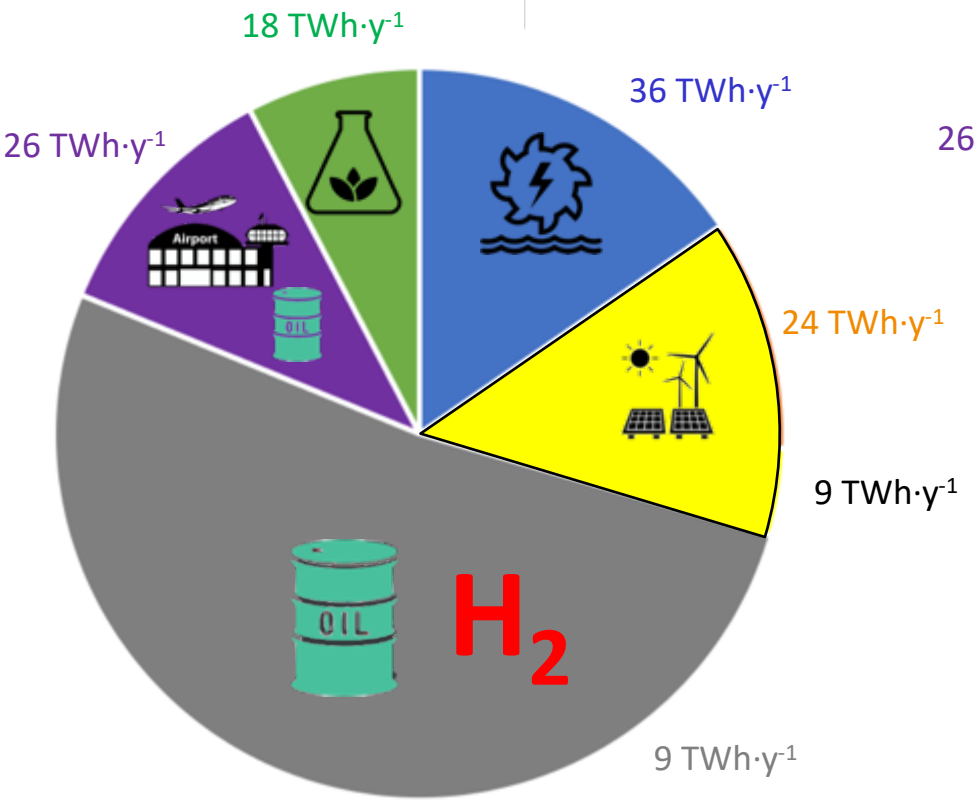
End energy 2019



234 TWh·y^{-1}

End Energy demand

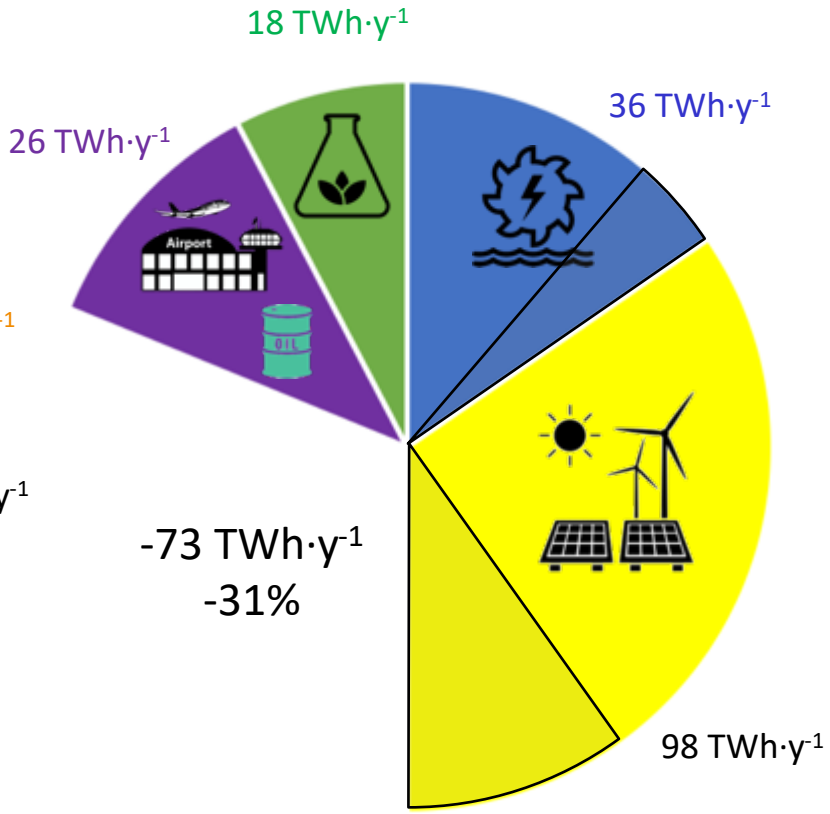
End energy 2050



234 TWh·y^{-1}

OIL H_2

End energy 2050

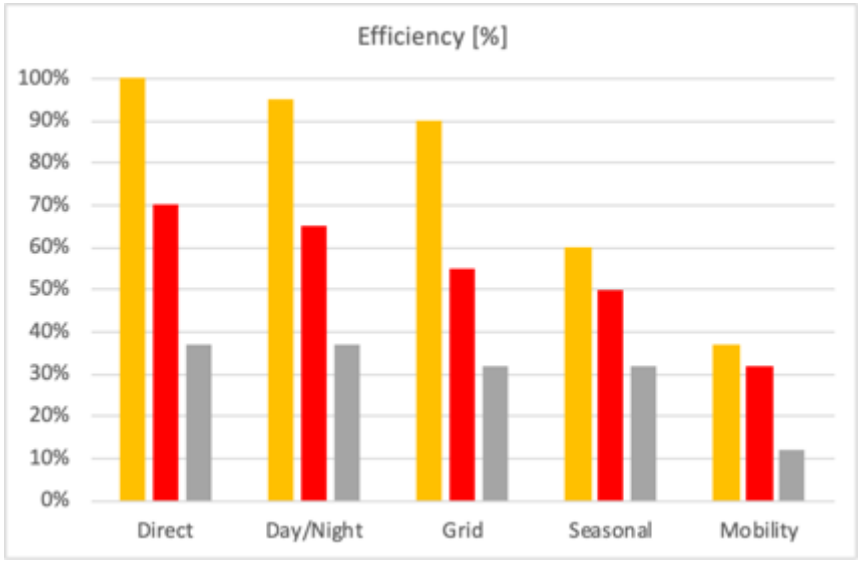


161 TWh·y^{-1}

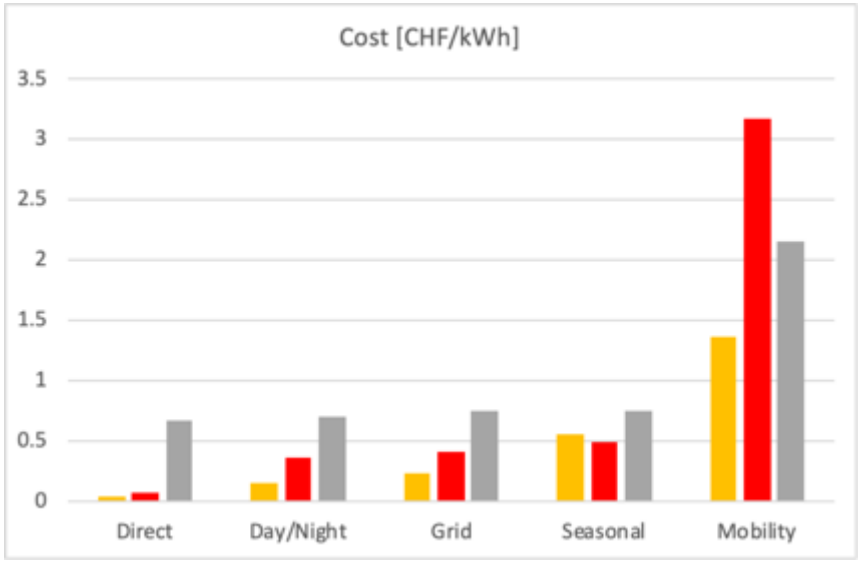
Efficiency and Cost

H_2

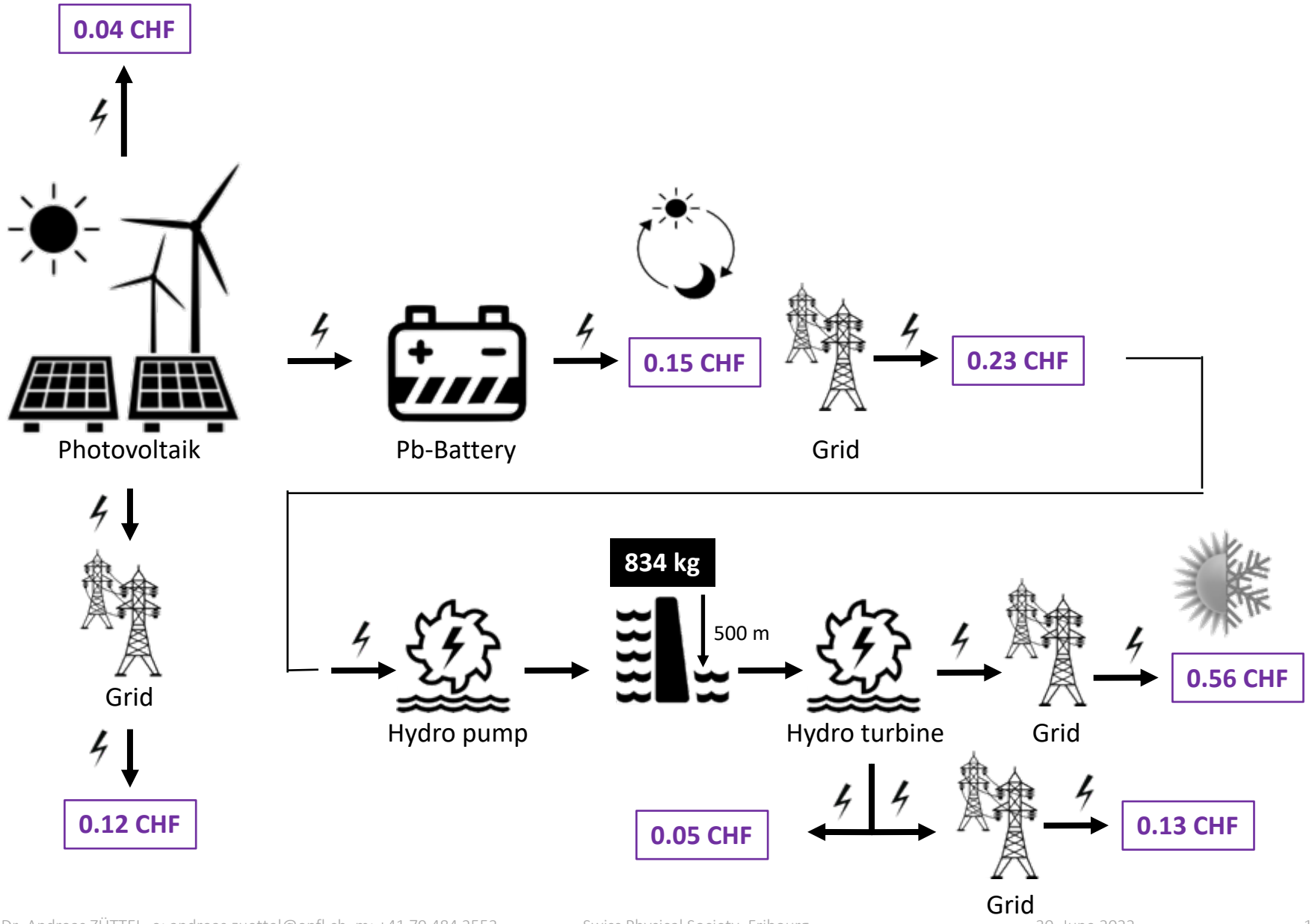
Efficiency [%]



Cost [CHF/kWh]



Cost of 1 kWh Electricity



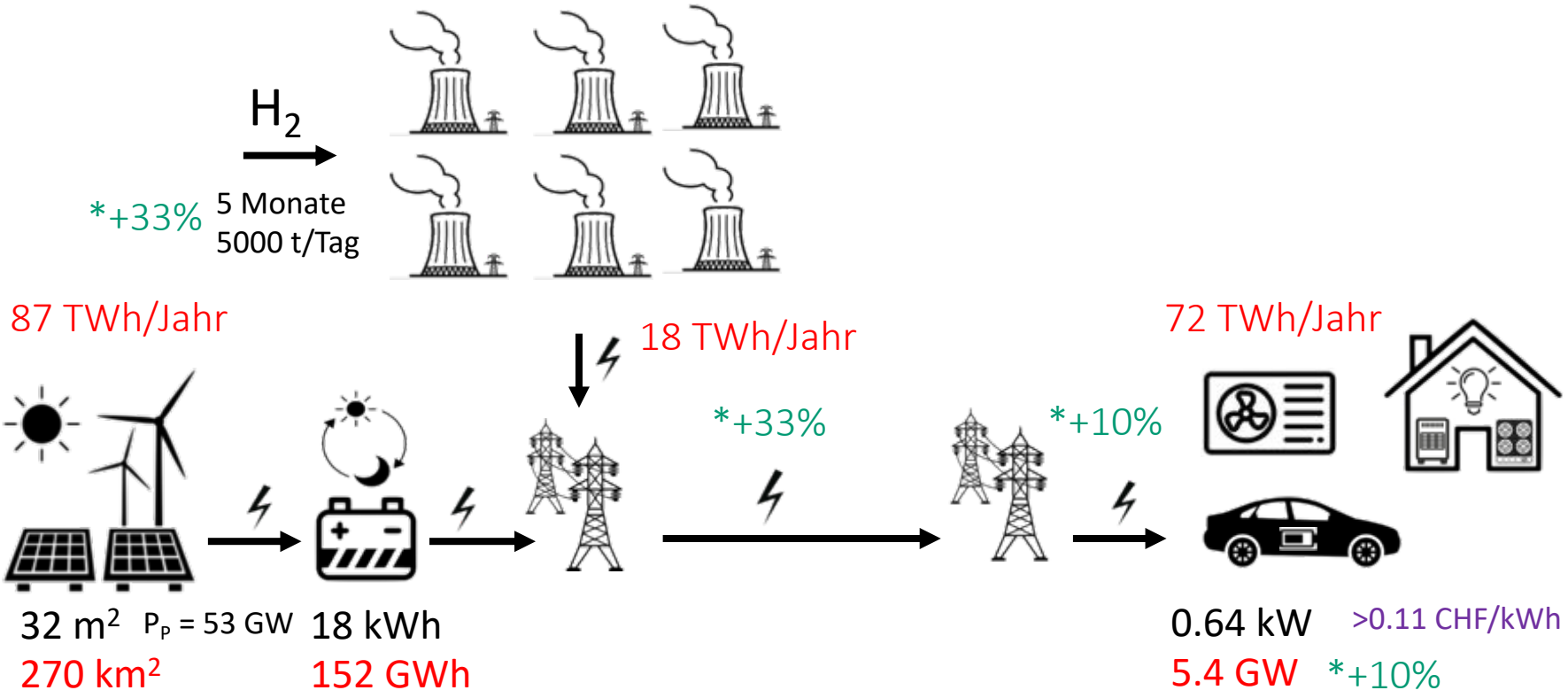
Renewable Energy Systems: Technology

	Electricity	Hydrogen	Syn. Fuel
 24 TWh·y^{-1}	1 x 75 GWh 4 x		
 121 TWh·y^{-1}, 48 TWh·y^{-1}	2 x 134 km^2 150 GWh 9 x 1.5 TWh	6 x 480 GWh 25 x 2 Mm^3 200 bar	12 x 920 GWh 94 Mio. 159 L
 26 TWh·y^{-1}			2 x 140 GWh 14 Mio.
existing PV, Biomass, Hydropower 63 TWh·y^{-1}	 9 TWh·y^{-1} 18 TWh·y^{-1} 36 TWh·y^{-1}		

Renewable Energy Systems: Annual Cost/capita

	Electricity 3669.-	Hydrogen 5683.-	Syn. Fuel 9712.-
24 TWh·y^{-1}	1 x 75 GWh 316.- 4 x		
121 TWh·y^{-1}, 48 TWh·y^{-1}	2 x 134 km^2 150 GWh 642.- 9 x 1.5 TWh	6 x 480 GWh 2656.- 25 x 2 Mm^3 200 bar	12 x 920 GWh 6684.- 94 Mio. 159 L
26 TWh·y^{-1}			2 x 140 GWh 1212.- 14 Mio.
existing PV, Biomass, Hydropower 63 TWh·y^{-1}	1500.- 9 TWh·y^{-1} 18 TWh·y^{-1} 36 TWh·y^{-1}		

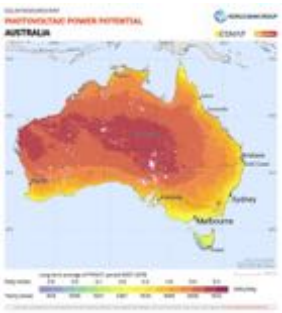
Renewable Energy without Seasonal Storage

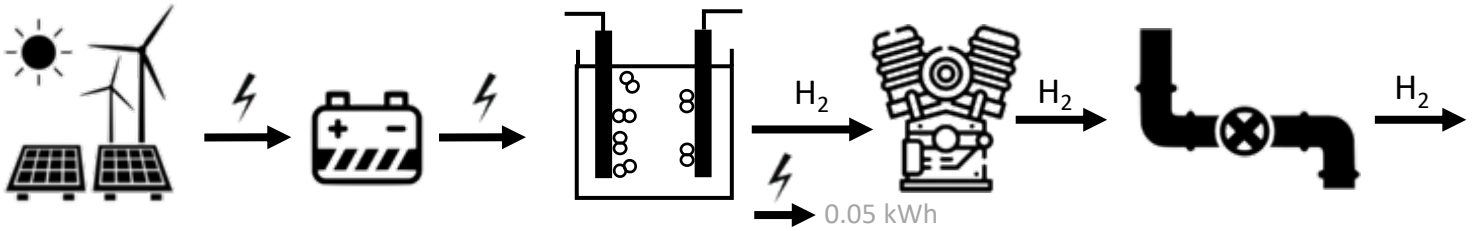


*green numbers represent additional energy if biomass is used for synthetic air fuel

Production of Hydrogen in Australia

57 TWh/5 Monate *+33%





Photovoltaik 48 km²

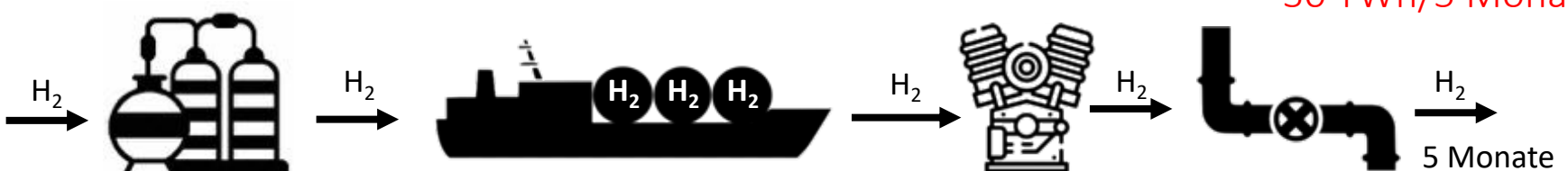
Pb-Battery 180 GWh

Electrolyseur 15 GW

Kompressor

Pipeline

30 TWh/5 Monate



H_2 Verflüssiger

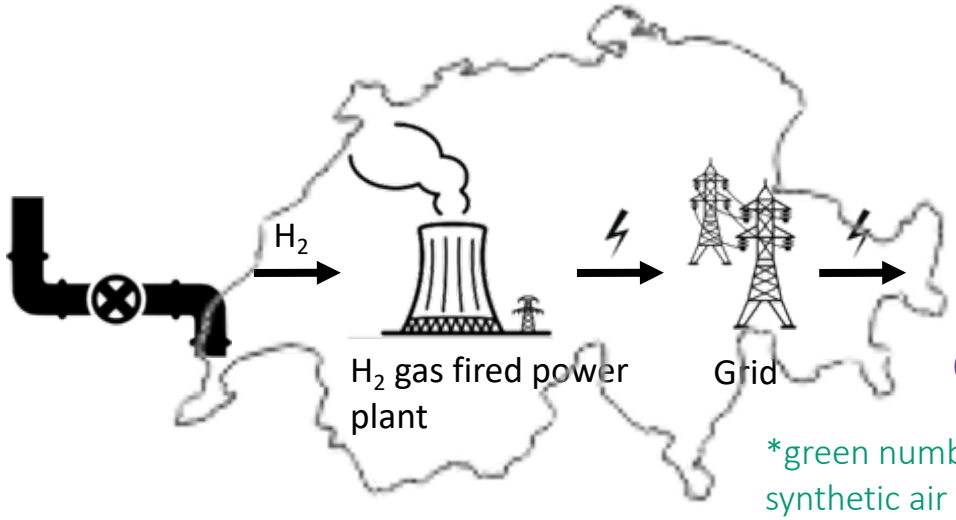
H_2 Schiff (LNG Schiff 250'000 m³)

Kompressor

Pipeline

5 Monate 5000 t/d

16.5 CHF/kg H_2



H_2 gas fired power plant

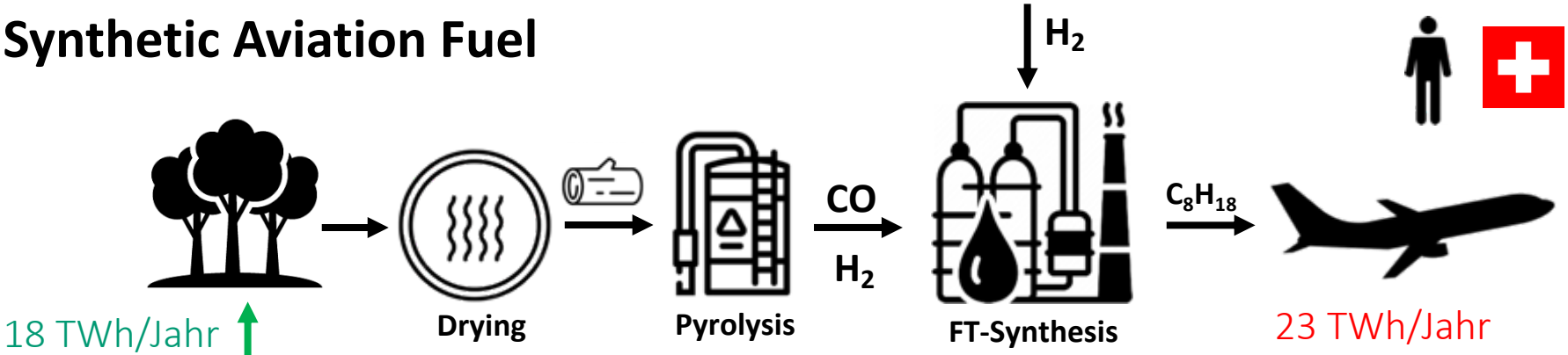
Grid

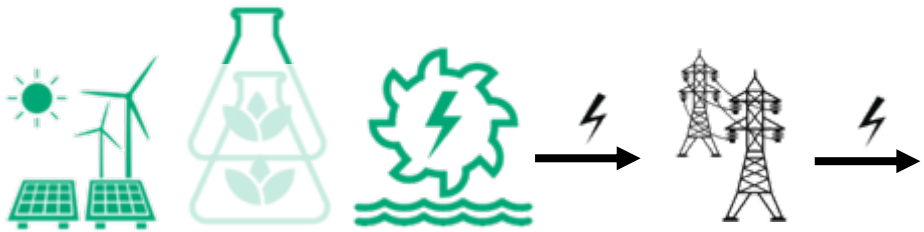
18 TWh/5 Monate

0.89 CHF/kWh

*green number represent additional energy if biomass is used for synthetic air fuel

Synthetic Aviation Fuel



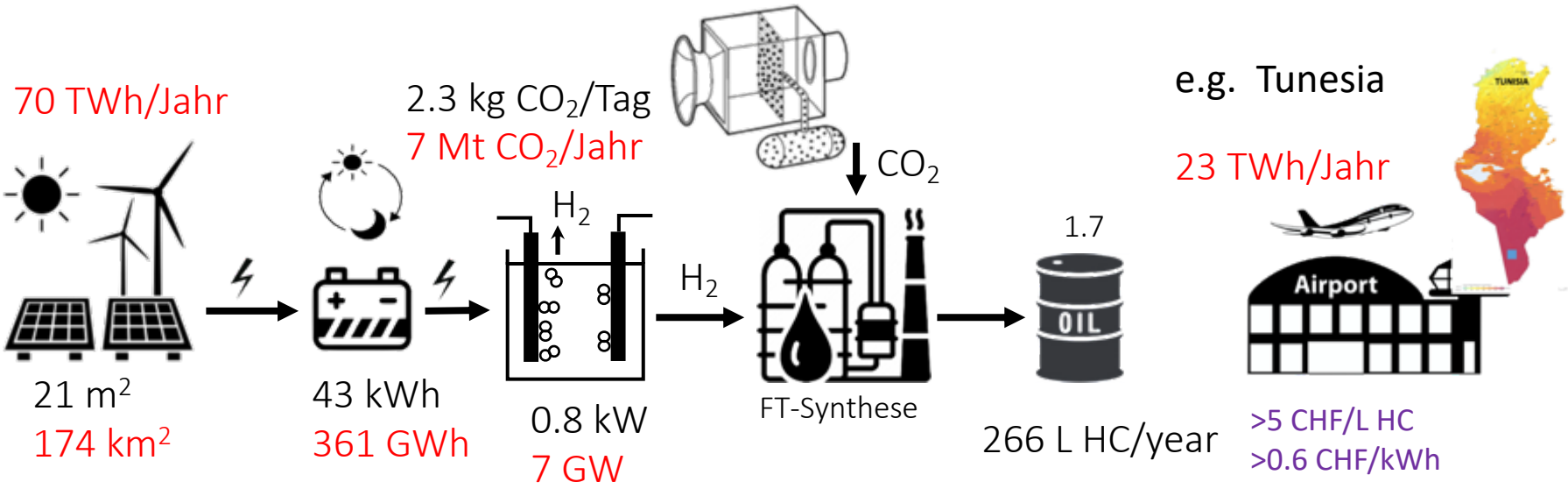


63 TWh/Jahr

*45 TWh/Jahr

*green number represent additional energy if biomass is used for synthetic air fuel

or produktion close to equator



Swiss Energy Strategy 2050+

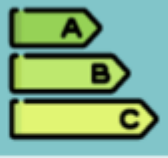
Ausstieg aus der Kernenergie

- Keine neuen Kernkraftwerke (KKW)
- Bestehende KKW werden betrieben, solange sie sicher sind (Entscheid ENSI)
- Bereits stillgelegt:
  - Mühleberg (2019)
- Noch in Betrieb:
  - Beznau I (seit 1969)
  - Beznau II (seit 1971)
  - Gösgen (seit 1979)
  - Leibstadt (seit 1984)

Ausbau erneuerbarer Energien

- Ziel: Produktion erneuerbare Energien 2035 ohne Wasserkraft: 11400 GWh (2020: 4700 GWh)
- Ziel: Produktion Wasserkraft 2035: 37 400 GWh (2020: 36 740 GWh)
- Erhöhung des Netzzuschlags von 1,3 auf 2,5 Rp. pro kWh
- Neues Fördermodell Photovoltaik: Einmalvergütung statt KEV
- Gleichstellung mit Landschaftsschutz (Güterabwägung)

Steigerung der Energieeffizienz



- Ziel: Gesamtenergieverbrauch pro Kopf bis 2035 um 43 % senken
- Ziel: Stromverbrauch pro Kopf bis 2035 um 13 % senken
- Mobilität: verschärfte Emissionsvorschriften seit 2021
- Gebäudeprogramm: CO_2-Abgabe und steuerliche Anreize für Sanierung
- Intelligente Stromzähler (Smart Meter)

+24 TWh·y^{-1}

Speicher oder +7 TWh

2 x 1GW H_2 Kraftwerke 151 Tage/Jahr

9 TWh·y^{-1}

+48 TWh·y^{-1}

18 TWh·y^{-1}

Speicher +14 TWh

36 TWh·y^{-1}

oder

Elektrifizierung -31%
zusätzlich -13%

4 x 1GW H_2 Kraftwerke 151 Tage/Jahr

+26 TWh·y^{-1}

Ref.: Andreas ZÜTTEL, Noris GALLANDAT, Paul J. DYSON, Louis SCHLAPBACH, Paul W. GILGEN, Shin-Ichi ORIMO, "Future Swiss Energy Economy: the challenge of storing renewable energy", Frontiers in Energy Research: Process and Energy Systems Engineering, 9 (2022), https://doi.org/10.3389/fenrg.2021.785908

Renewable Energy for the World

space, solar intensity, shifted season

Albanese vows to transform Australia into clean energy 'superpower'

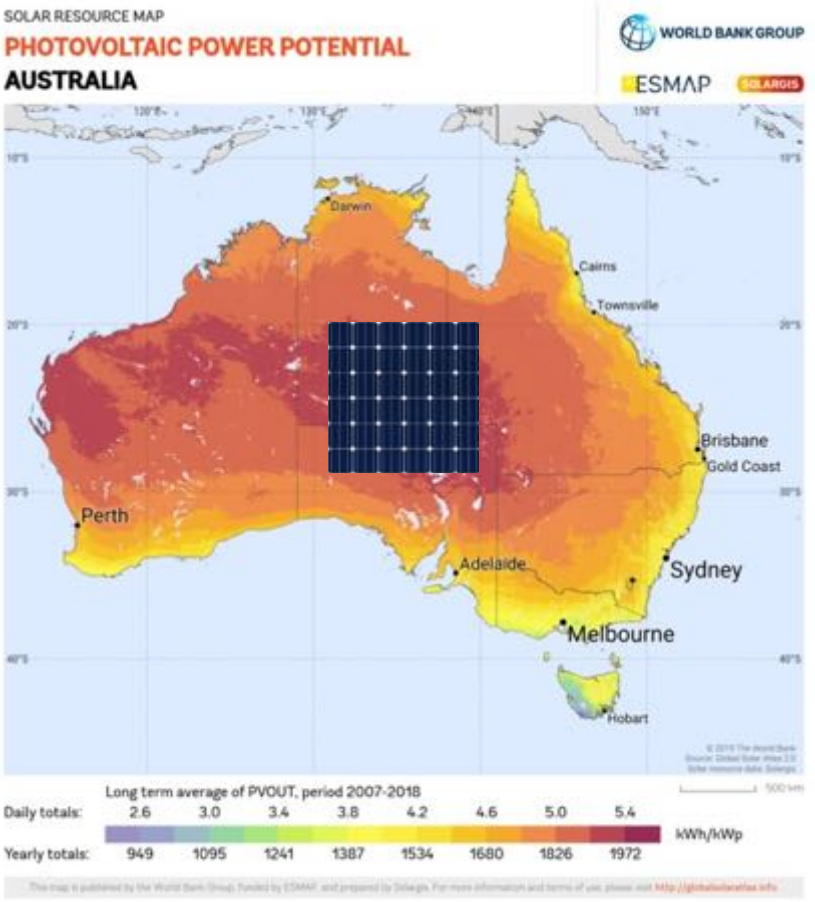
Incoming Australian prime minister Anthony Albanese has promised to make the nation a "renewable energy superpower" in the wake of Labor's federal election victory at the weekend.

MAY 23, 2022 DAVID CARROLL

MARKETS & POLICY | POLICY | SUSTAINABILITY | AUSTRALIA

Anthony Albanese is promising an end to the "climate wars".

Image: Facebook



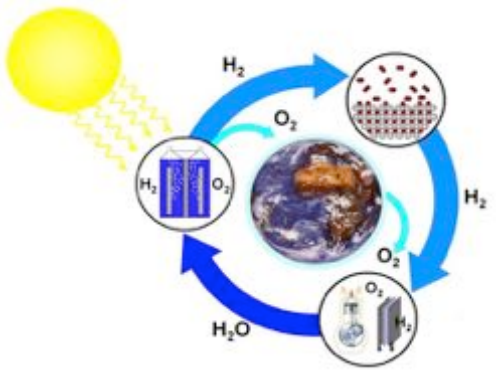
20 TW as H_2 $(1000\ km)^2$

18 GW as H_2 $(30\ km)^2$

Substitution of Fossil Fuels with Renewable Energy

15th INT. SYMPOSIUM HYDROGEN & ENERGY

22. - 27. January 2023
Seeblick Höhenhotel, Emmetten, Switzerland



http://hesymposium.ch/

SUBJECTS

- Hydrogen production
- Hydrogen storage
- Fuel Cells
- Batteries
- Synthetic fuels
- Theory & modelling
- Applications

ORGANIZER

Prof. Dr. Andreas ZÜTTEL, Mrs. Ivana SUTER
Ecole Polytechnique Fédérale de Lausanne (EPFL)
Institut des sciences et ingénierie chimiques (ISIC),
CH-1015 Lausanne, Switzerland

STEERING COMMITEE

Craig JENSEN, Hawaii, USA
Shin-Ichi ORIMO, Japan
Min ZHU, China
Jinqiu ZHANG, China
Andreas ZÜTTEL, Switzerland

INVITED SPEAKERS

Henning ZOZ, Germany
Noris GALLANDAT, Switzerland
Berend SMIT, Switzerland
Shin-Ichi ORIMO, Japan
Klaus LACKNER, USA
Allan WALTON, England
Heena YANG, Korea
Björgvin HJÖVARSON, Sweden
Sabrina SARTORI, Norway
Robert SCHLÖGEL, Germany

PROGRAM

	Su	Mo	Tu	We	Th	Fr
09:00						
12:00		Lunch				
14:00	Recept.			social event		depart.
17:00						
18:00	Din.	Dinner	Dinner	Dinner	Conf. dinner	
21:00		Poster	Poster			

inv. lec. inv. talk, talk

LOCATION

SEEBLICK HÖHENHOTEL
Hugenstrasse 24, CH-6376 Emmetten, Switzerland
T: +41 41 624 41 41, e: info@hotelseeblick.ch
U: http://www.hotelseeblick.ch

REGISTRATION

Conference fee CHF 1400
incl. conference facilities, internet, proceedings and social event, excursion, coffee breaks, lunch, dinner, conference dinner, beverages at poster sessions.

Registration online:
http://hesymposium.ch/
Registration and abstract submission:
before 1st October 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]*

[1]Laboratory of Materials for Renewable Energy (LMER), Institute of Chemical Sciences and Engineering (ISIC), École Polytechnique Fédérale de Lausanne, EPFL, Lausanne, Switzerland, [2]Empa Materials Science and Technology, Dübendorf, Switzerland, [3]Laboratory of Organometallic and Medicinal Chemistry (LCOM), Institute of Chemical Sciences and Engineering (ISIC), École Polytechnique Fédérale de Lausanne, EPFL, Lausanne, Switzerland, [4]Emeritus Empa and ETH Zürich and Université de Fribourg, Fribourg, Switzerland, [5]Formerly Empa Materials Science and Technology, Dübendorf, Switzerland, [6]WPI-Advanced Institute for Materials Research (WPI-AIMR), Tohoku University, Aoba-ku, Sendai, Japan

OPEN ACCESS

Edited by:
Carlo Roselli,
University of Sannio, Italy

Reviewed by:
Francesco Liberato Cappiello,
Second University of Naples, Italy
Giovanni Ciampi,
Università degli Studi della Campania Luigi Vanvitelli, Italy

***Correspondence:**
Andreas Züttel
andreas.zuettel@epfl.ch

Specialty section:
This article was submitted to Process and Energy Systems Engineering, a section of the journal Frontiers in Energy Research

Received: 29 September 2021
Accepted: 17 November 2021
Published: 25 January 2022

Citation:
Züttel A, Gallandat N, Dyson PJ, Schlapbach L, Gilgen PW and Orimo S-I (2022) Future Swiss Energy Economy: The Challenge of Storing Renewable Energy. Front. Energy Res. 9:785908. doi: 10.3389/fenrg.2021.785908

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_p, annual energy received from the energy system; OPEX, operational cost; C_e, cost of the energy.

Prof. Dr. Andreas ZÜTTEL

Dr. Noris GALLANDAT

Prof. Dr. Paul DYSON

Prof. Dr. Louis SCHLAPBACH

Mr. Paul W. GILGEN

Prof. Dr. Shin-Ichi ORIMO

Andreas ZÜTTEL, Noris GALLANDAT, Paul J. DYSON, Louis SCHLAPBACH, Paul W. GILGEN, Shin-Ichi ORIMO, "Future Swiss Energy Economy: the challenge of storing renewable energy", Frontiers in Energy Research: Process and Energy Systems Engineering, 9 (2022), https://doi.org/10.3389/fenrg.2021.785908

LMER

EPFL Valais Wallis Empa

Andreas ZÜTTEL, Prof. Dr.

Laboratory of Materials for Renewable Energy (LMER)
Institute of Chemical Sciences and Engineering (ISIC)
Basic Science Faculty (SB)
École polytechnique fédérale de Lausanne (EPFL) Valais/Wallis
Rue de l'Industrie 17, CP 440
CH-1951 Sion, Switzerland

e: andreas.zuettel@epfl.ch
m: +41 79 484 2553
T: +41 21 695 8304 (Secretary)
U: http://lmer.epfl.ch

Icons


Nuclear energy


Mobility & heat

Aviation


PV feasible roof area in Switzerland


Batteries for day & night storage


Hydropower plant of the size of Grand Dixence

Barrel (159 L)


Cavity of the size of the Gotthard base tunnel


Existing PV und wind power plants


Used biomass


Existing hydropower plants