Substitution of Fossil Fuels with Renewable Energy

Andreas Züttel, Shin-Ichi Orimo, Heena Yang

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

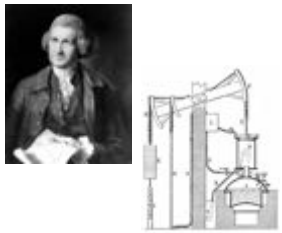
2nd International Symposium Hydrogenomics
16. - 19. May 2022, Web

History of Energy

Steam turbine

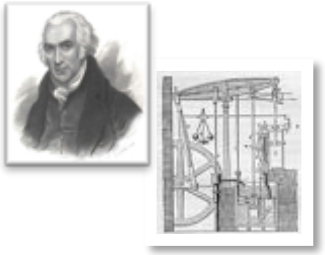
Hero of ALEXANDRIA
10 - 70

1st Steam engine



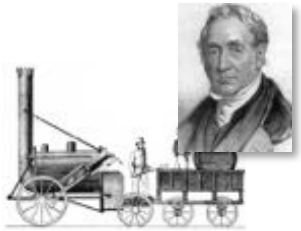
Thomas NEWCOMEN
1712

Steam engine opt.



James WATT
1783

1st Steam locomotive



George STEPHENSON
1828

Standard Oil Company

John D. ROCKEFELLER
1865

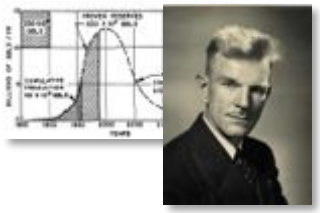
Patent Motorwagen

Carl BENZ
1886

1st motorized flight

Wilbur & Orville WRIGHT
1903

Model for oil mining



M. King HUBBERT
1957

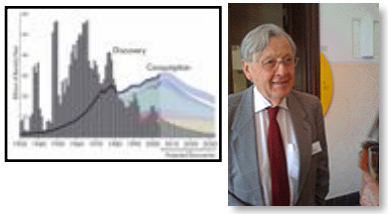
Club of Rome

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

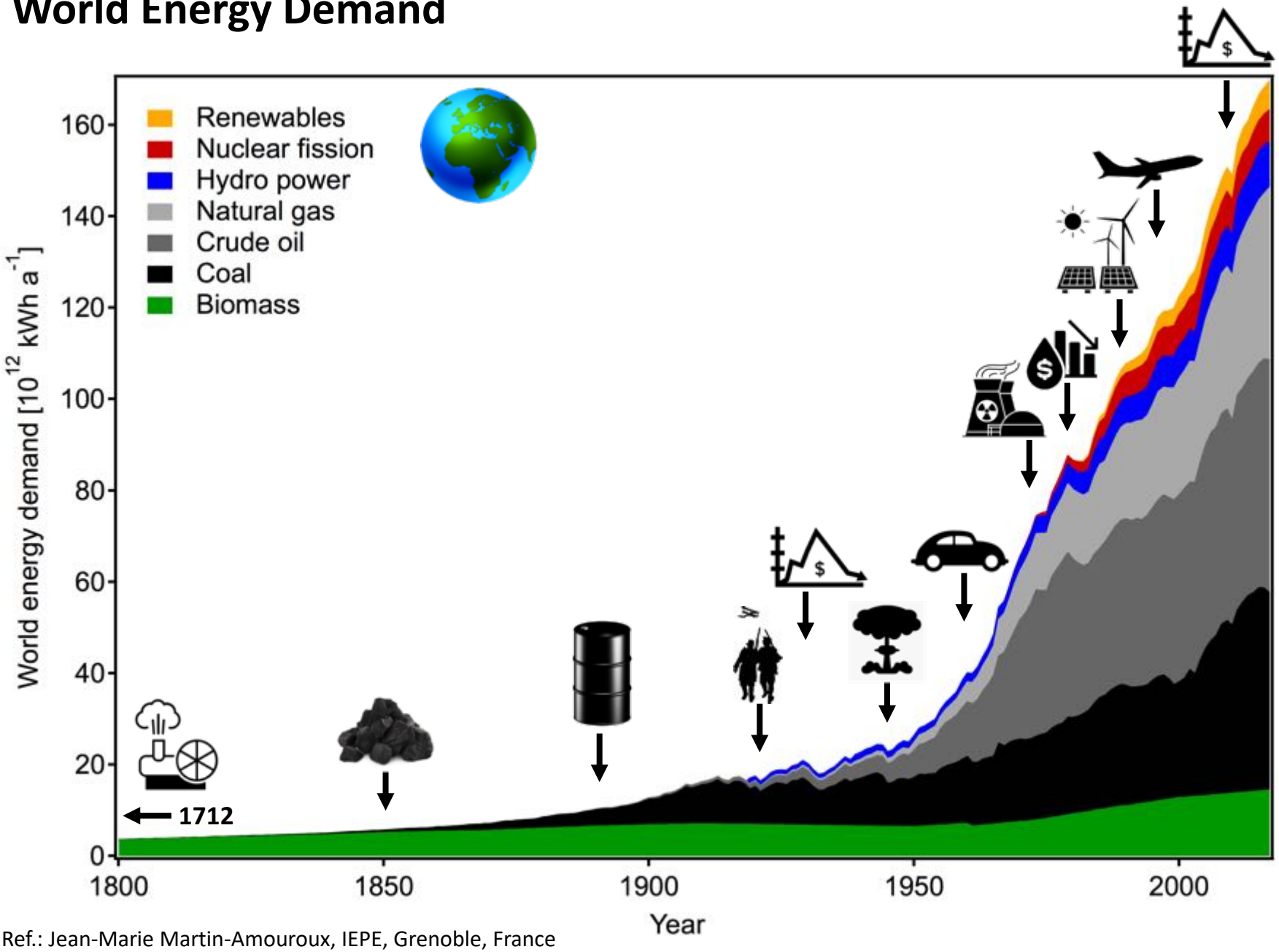
CO_2 Air Capture

Klaus S. LACKNER
2009

Gapminder

Hans ROSLING
2009

World Energy Demand

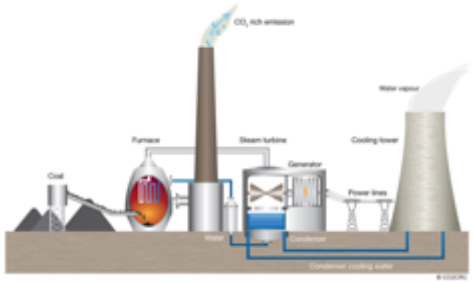


Ref.: Jean-Marie Martin-Amouroux, IEPE, Grenoble, France

World Energy Demand 19 TW

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

2000 GW



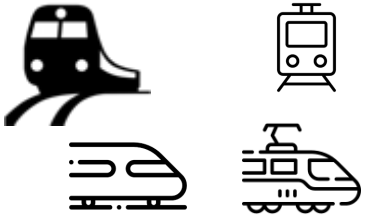
380 GW

500 GW + 300 GW

Mobility 4.2 TW

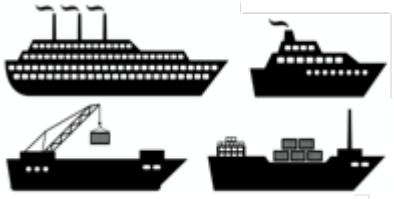
3230 GW

24 GW



380 GW

570 GW



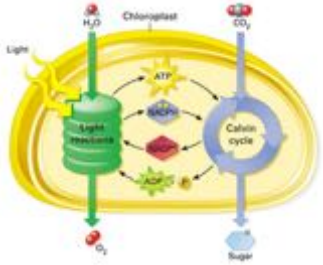
Residential & Industry 7.5 TW

1200 GW

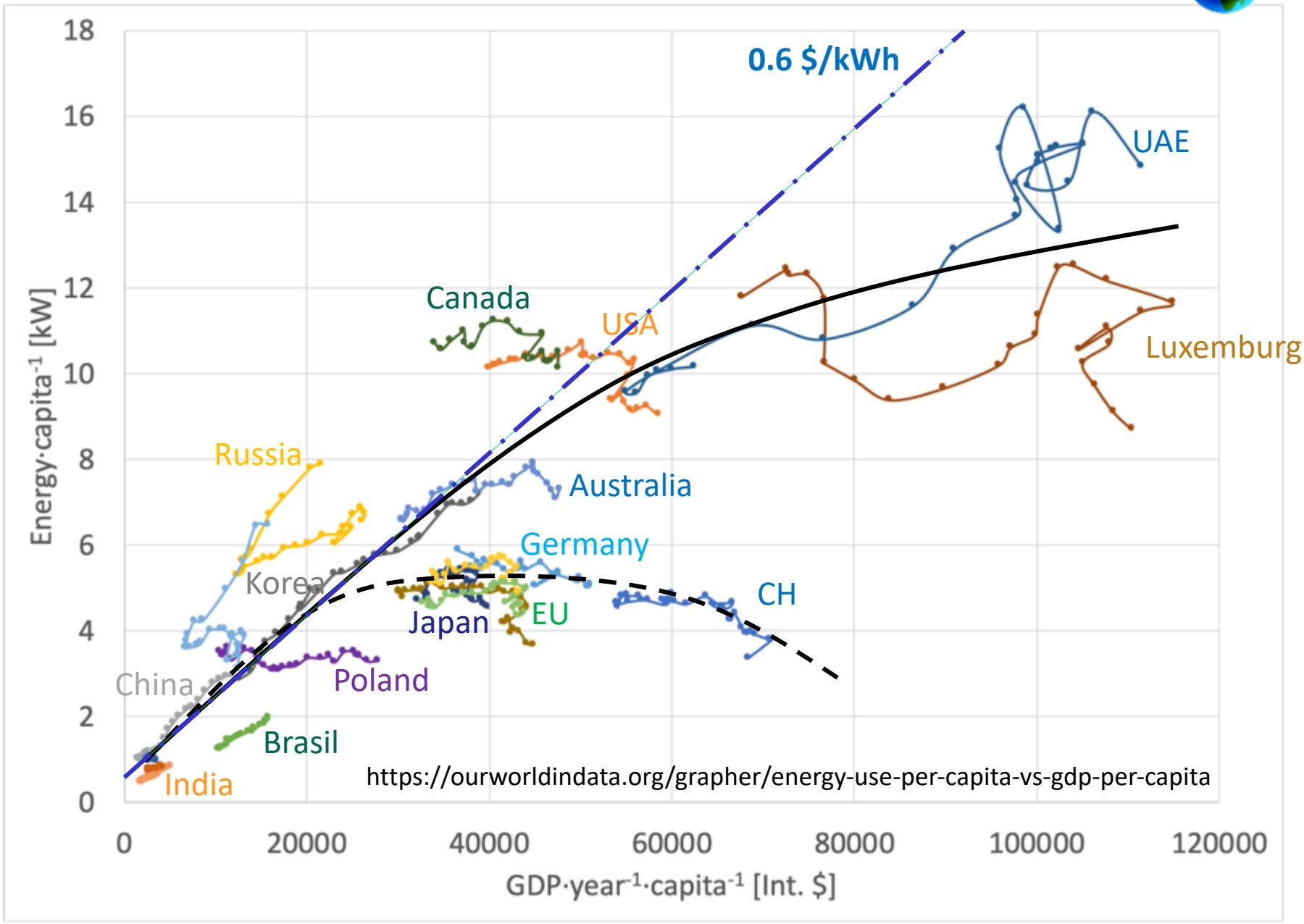
1900 GW

4370 GW

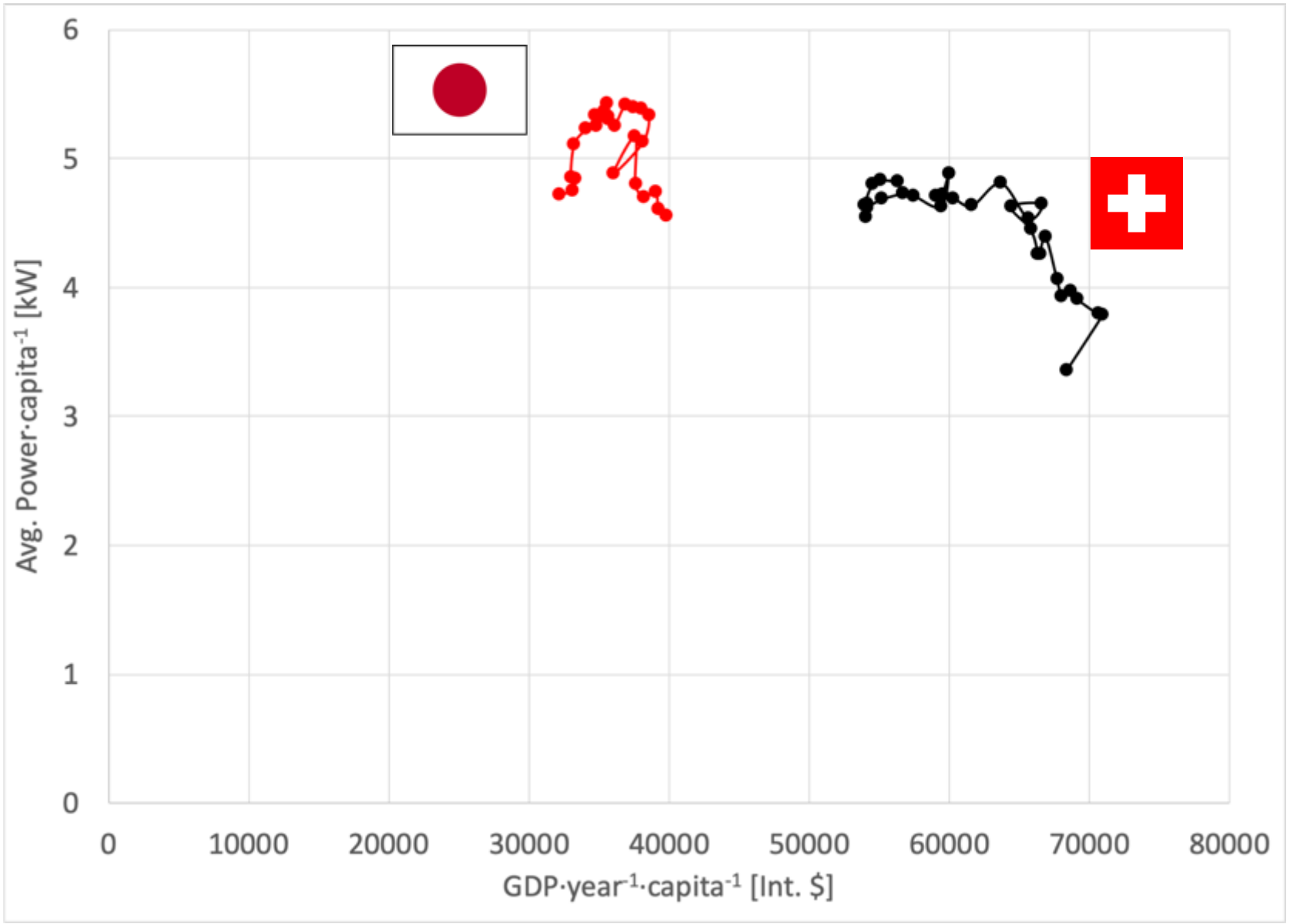
1200 GW



Global Energy and Economy

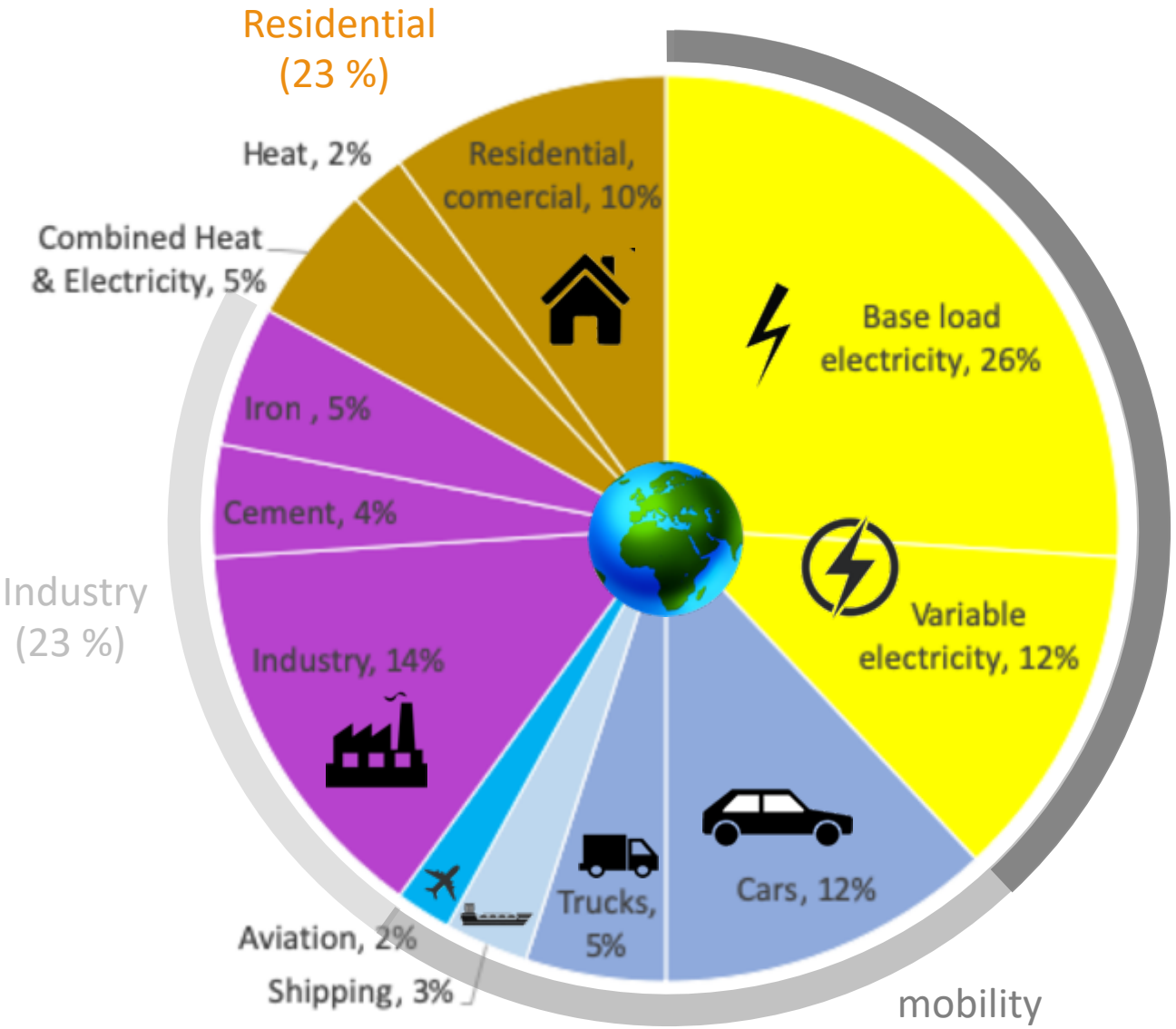


Energy and Economy in Japan



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

CO_2 Emitters by Sectors

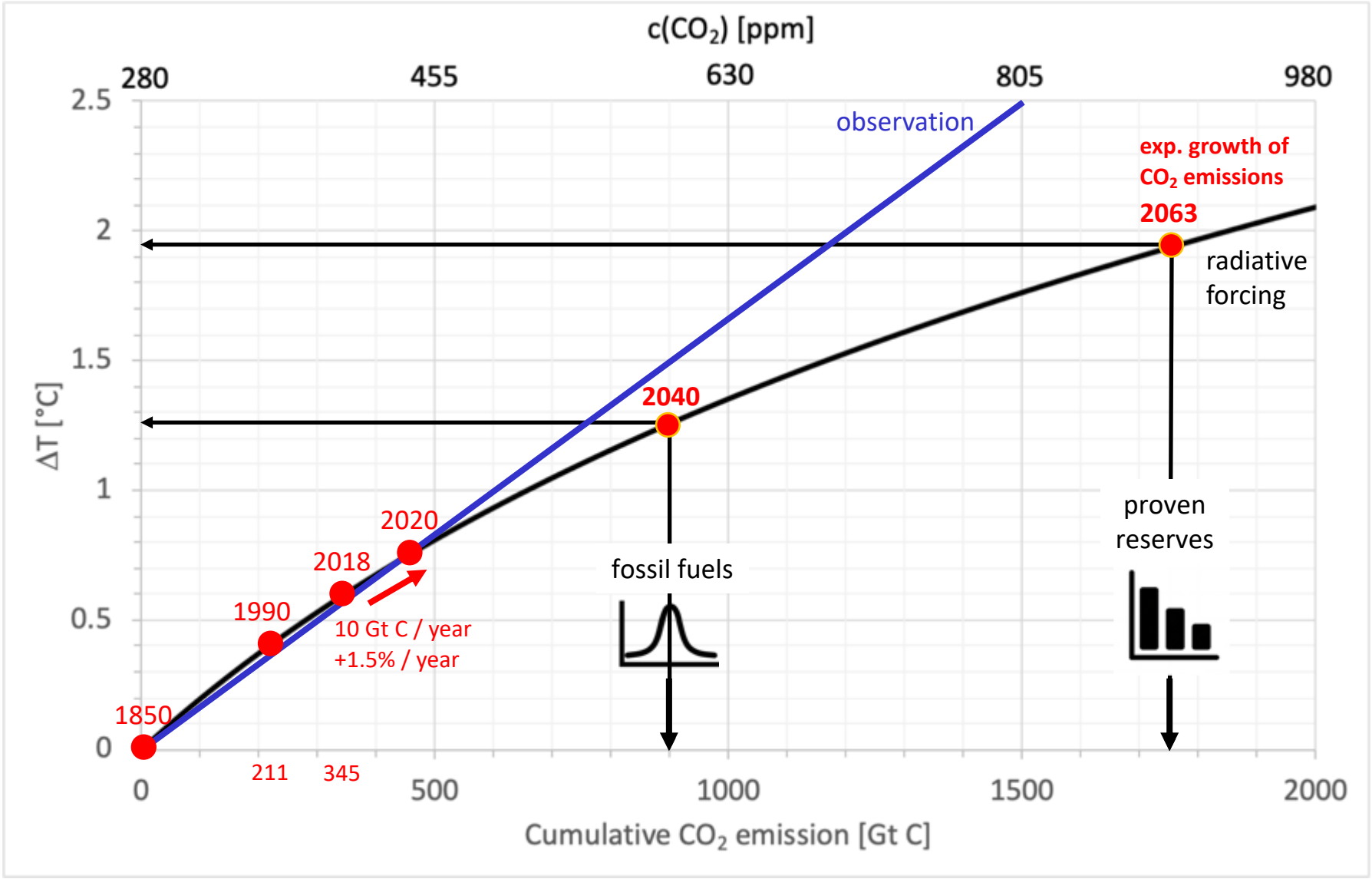


100% = 33.9Gt
(2014)

electricity production
(38 %)

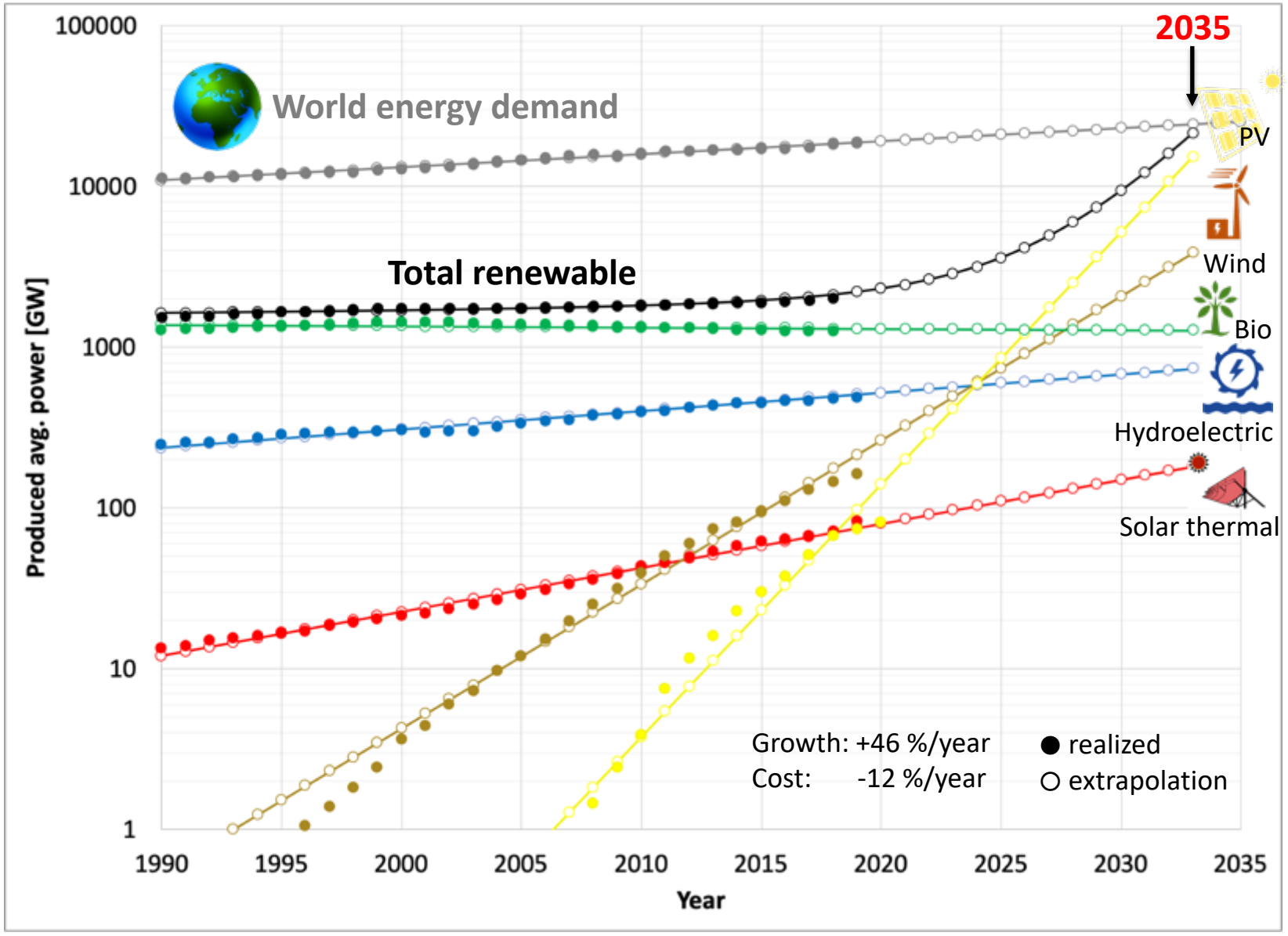
Ref.: Davis, S. J. et al. « Net-zero emissions energy systems », *Science* 360 (2018), pp. 1–9.

Global 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

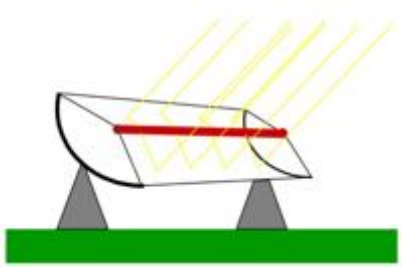
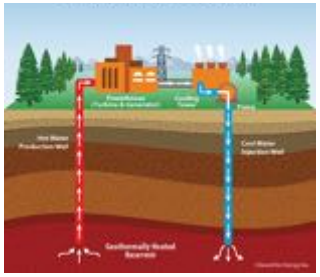
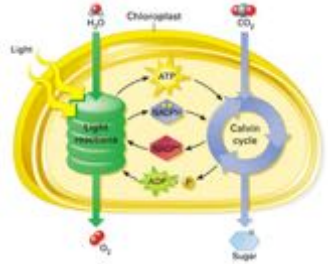
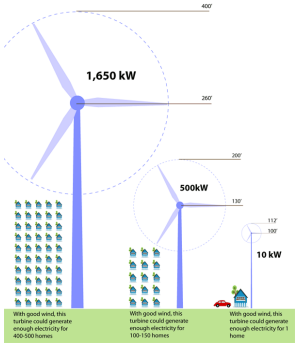
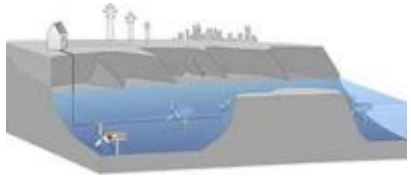
Renewable Energy Production



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

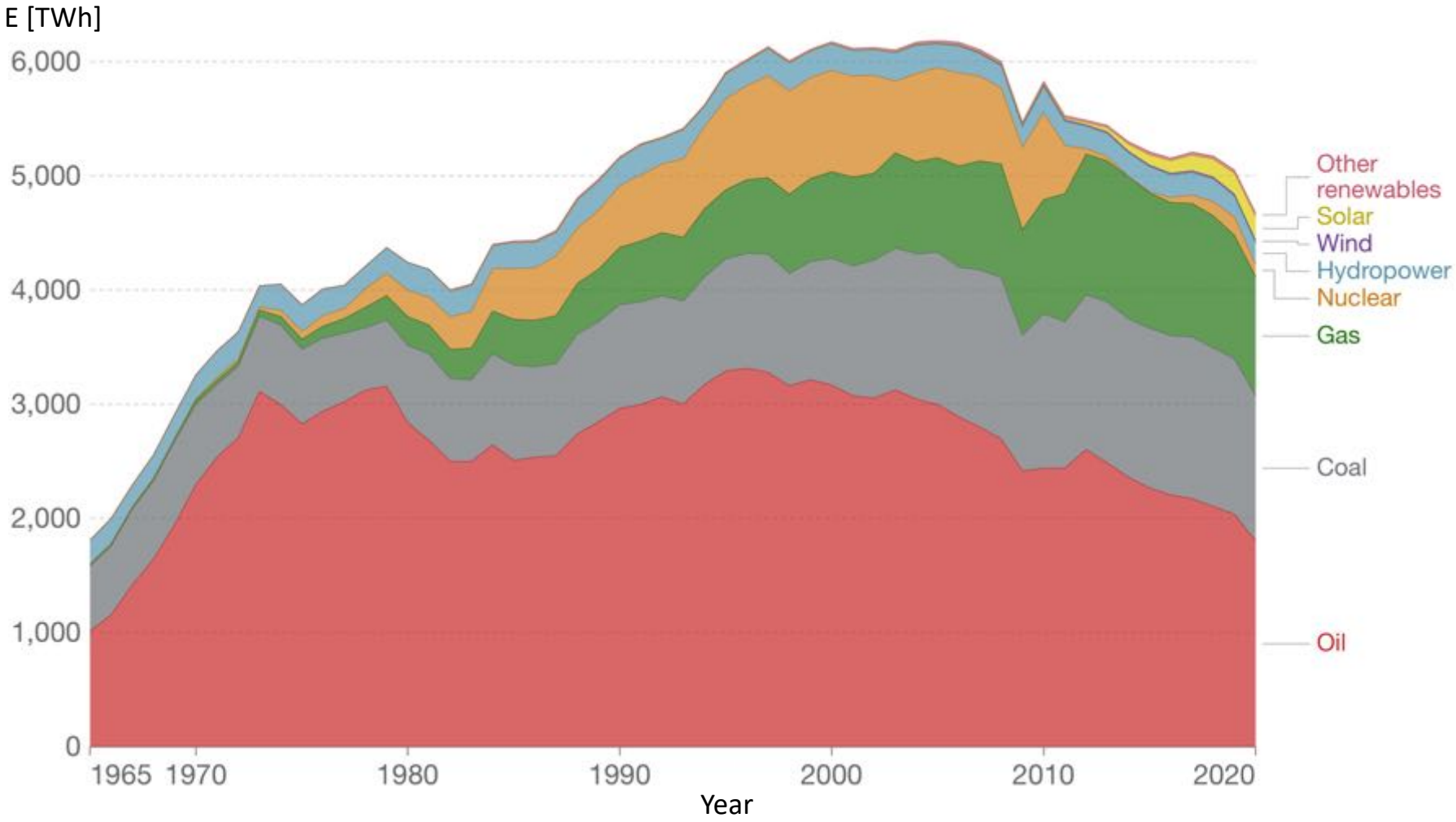
Electricity and Renewable Energy

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	

Final Energy Consumption by Source in Japan

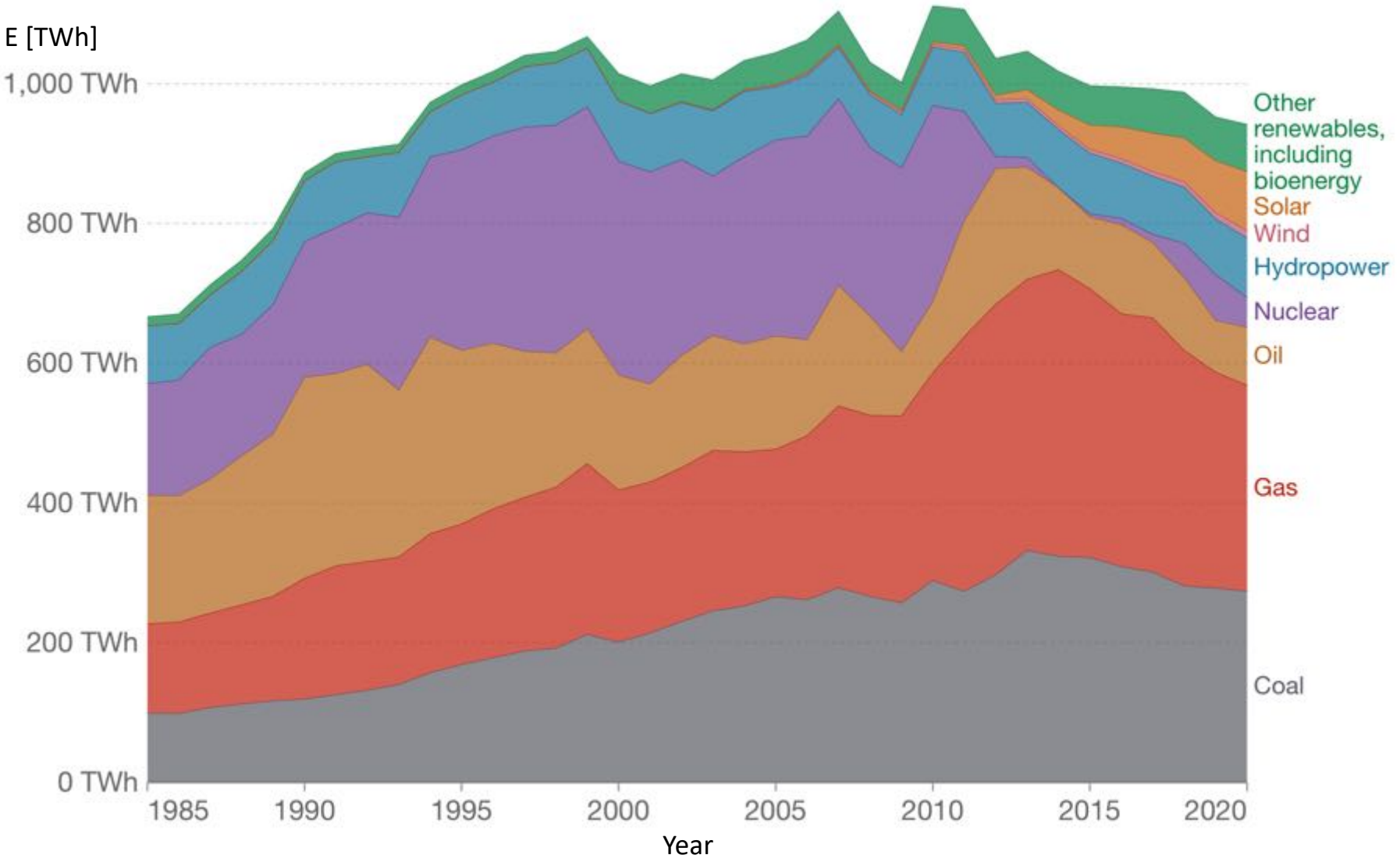
Here an inefficiency factor (the 'substitution' method) has been applied for fossil fuels, meaning the shares by each energy source give a better approximation of final energy consumption.



Ref.: Source: BP Statistical Review of World Energy, OurWorldInData.org/energy • CC BY

Note: 'Other renewables' includes geothermal, biomass and waste energy

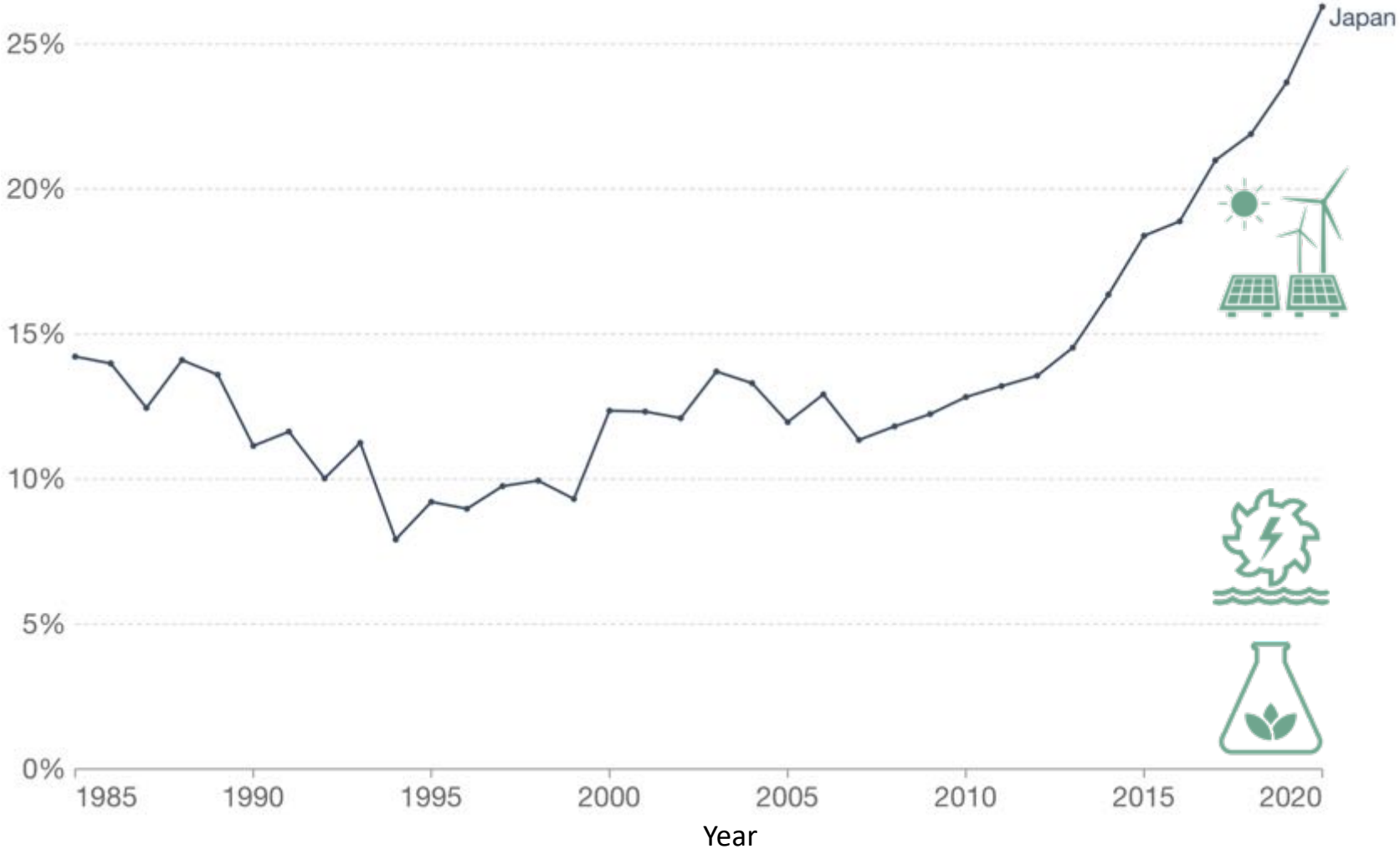
Electricity Production by Source in Japan



Ref.: Our World in Data based on BP Statistical Review of World Energy & Ember (2022), OurWorldInData.org/energy
Note: 'Other renewables' includes geothermal, biomass and waste energy

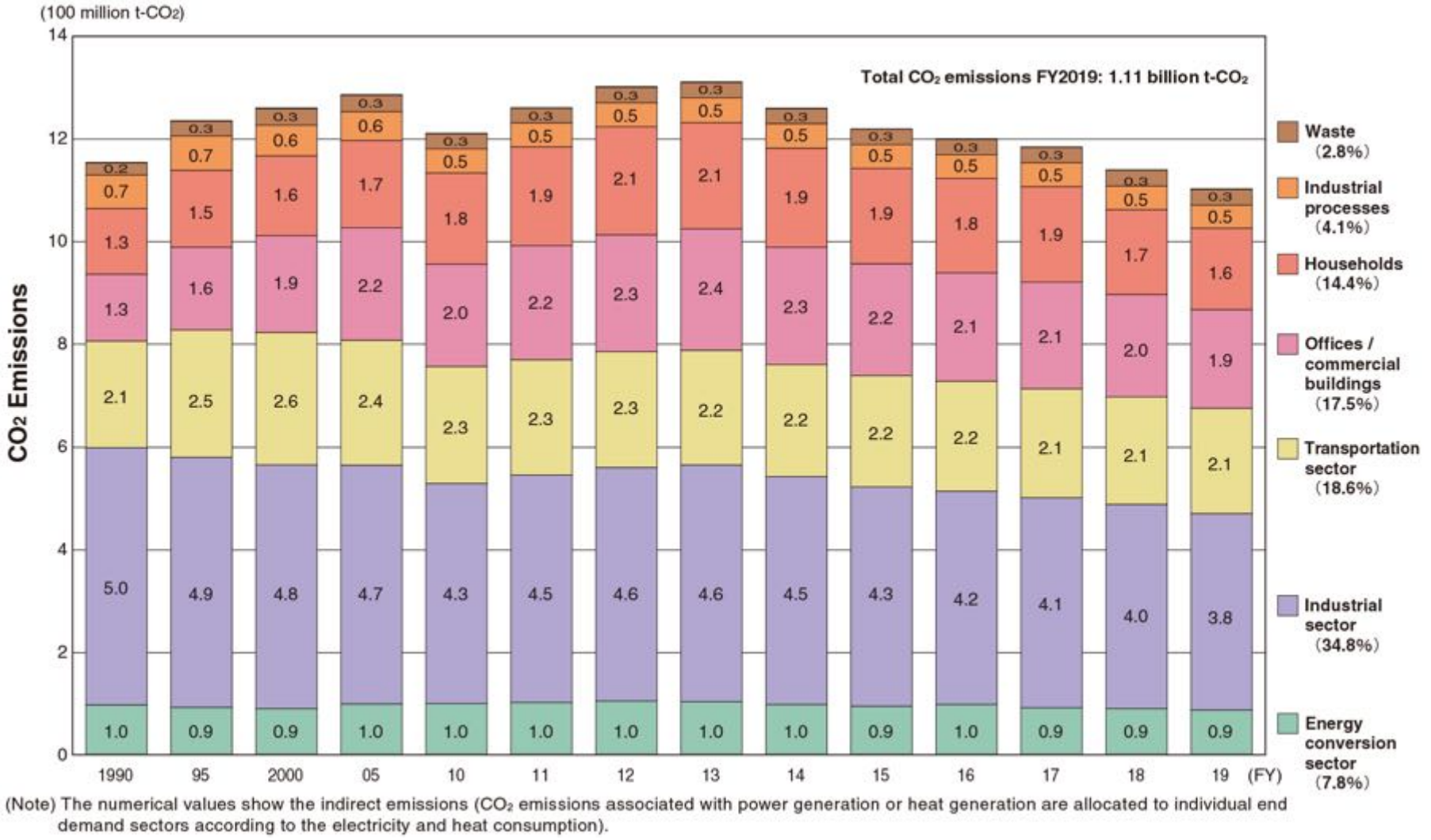
Share of Electricity Produced by Renewables in Japan

Renewables includes electricity production from hydropower, solar, wind, biomass and waste, geothermal, wave and tidal sources.



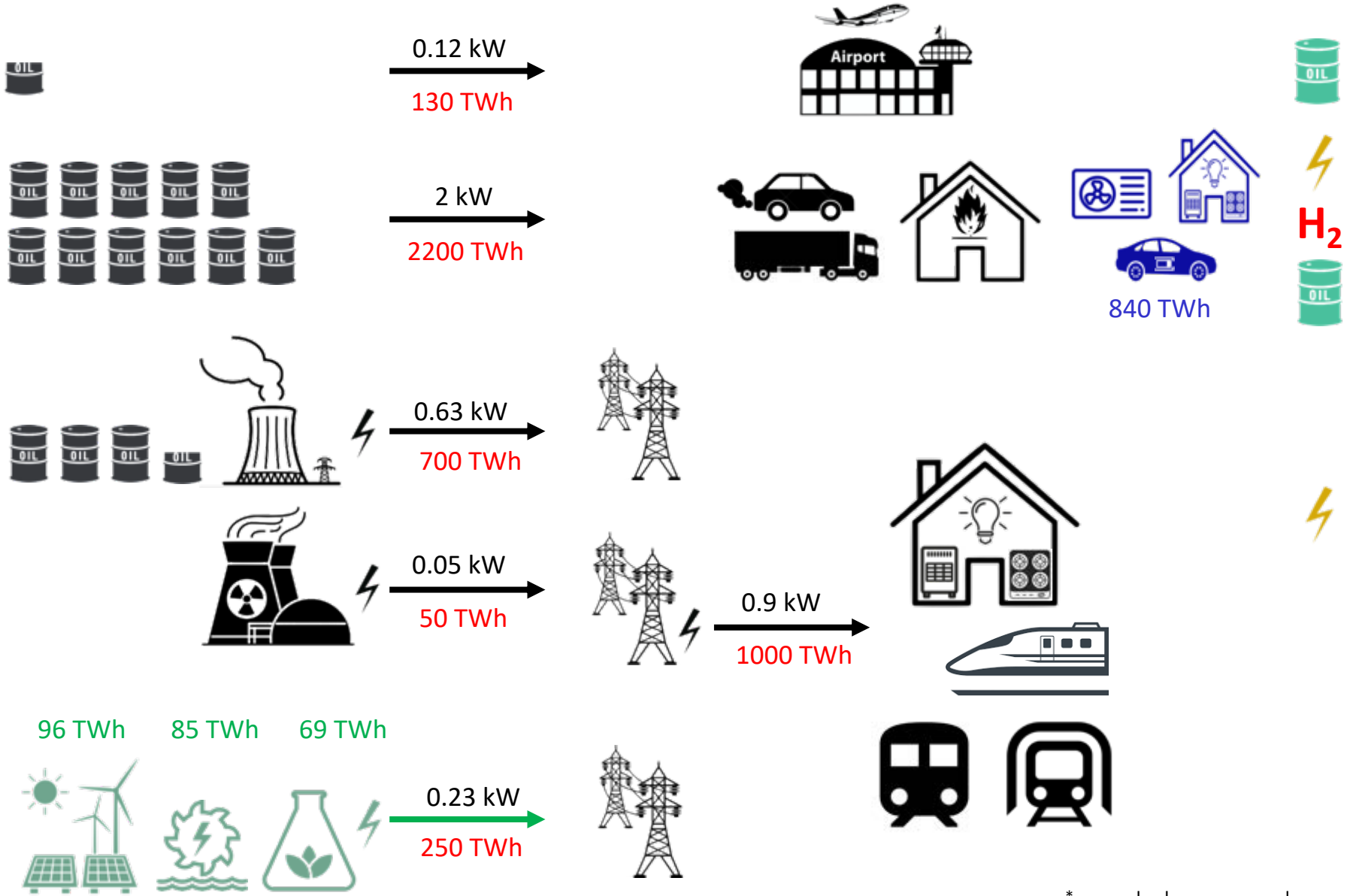
Ref.: Source: BP Statistical Review of World Energy, OurWorldInData.org/energy • CC BY

CO_2 Emissions by Sector in Japan



Ref.: https://www.ene100.jp/map_2_en

Current Energy Supply in Japan (2021)

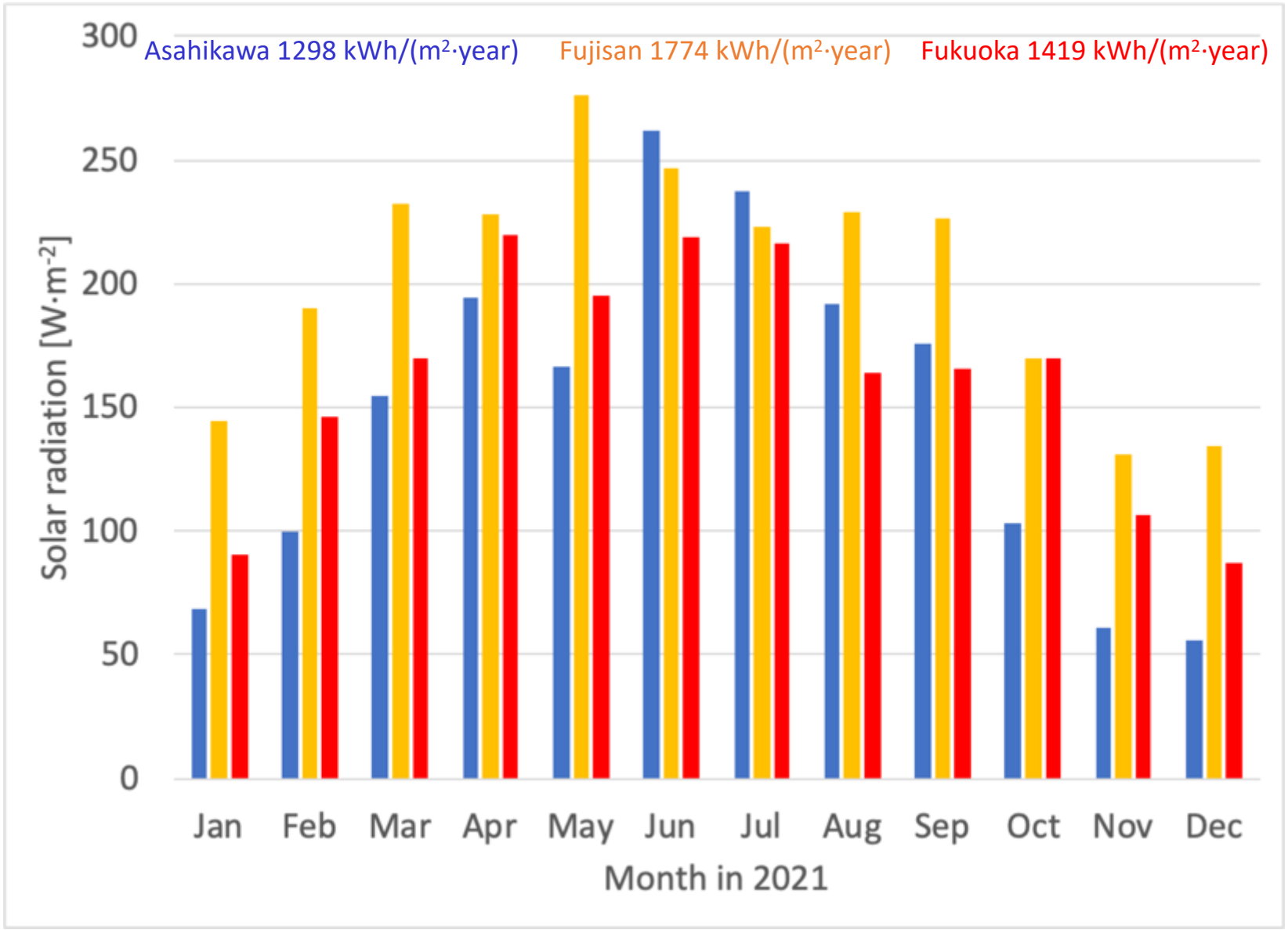


*rounded energy values

Solar Radiation in Japan

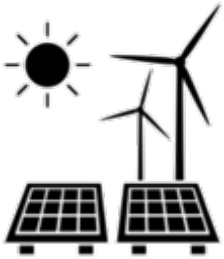
Ref.: https://solargis.com/maps-and-gis-data/download/japan

3.4. Monthly Solar Irradiation



Ref.: https://www.data.jma.go.jp/obd/stats/etrn/view/monthly_s3_en.php?block_no=47401&view=11

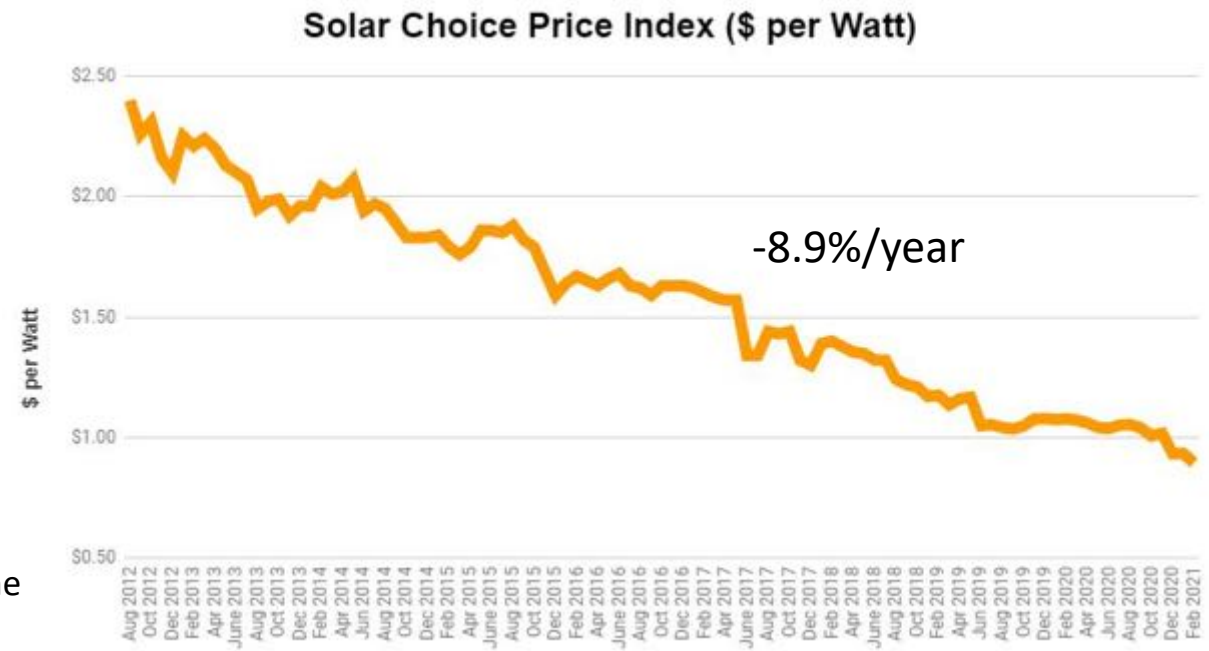
Photovoltaic Development



Cost: 750 \$/kW$_P$
(offers <400 \$/kW$_p$)

PV still working after 30 years.

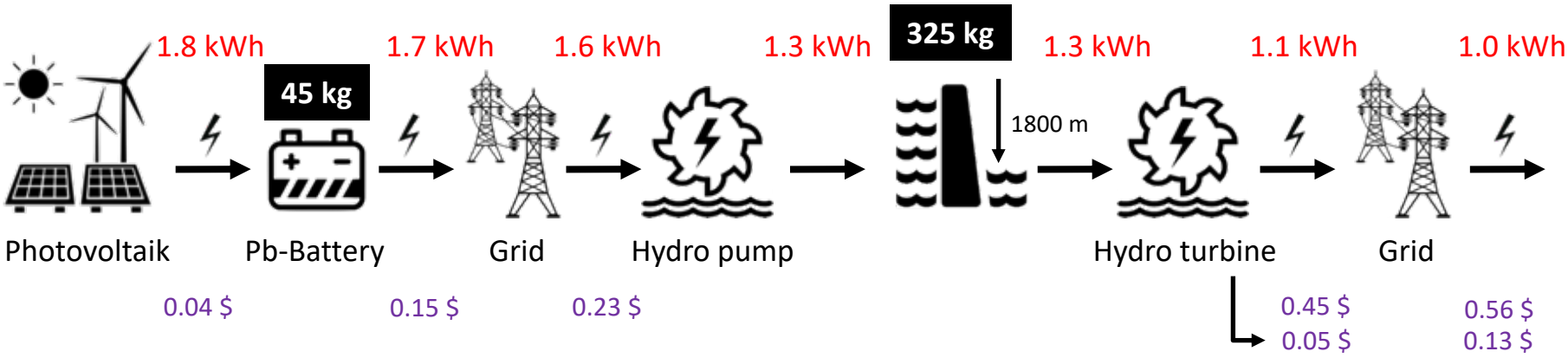
The cost of installation increases the cost of photovoltaics to ≈1200 \$/kW$_p$

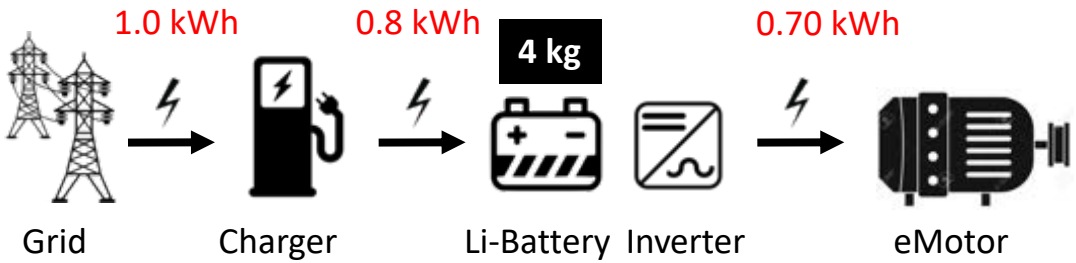


Ref.: https://www.solarchoice.net.au/blog/solar-power-system-prices

Parameter	Relationship	Value
Average power	$\langle P \rangle$	$\langle P \rangle$ = 1 kW
Annual energy per year	$W = \langle P \rangle \cdot 8760h/y$	W = 8.76 MWh/y
Annual solar irradiation	$1050 \leq I \leq 1550$ kWh·m^{-2}·y^{-1}	$\langle I \rangle$ = 1100 kWh·m^{-2}·y^{-1}
Efficiency	η	η = 20%
PV surface area	$A = W \cdot I^{-1} \cdot \eta^{-1}$	A = 40 m^2
PV peak power	$P_P = 1$ kW·m^{-2}·A·η = 1 kW·m^{-2}·I^{-1}·$\langle P \rangle$·8760h/y	P_P = 8 kW
Power Factor	$\langle P \rangle / P_p = I \cdot (1 \text{ kW} \cdot \text{m}^{-2} \cdot 8760h/y)^{-1}$	$\langle P \rangle / P_p$ = 0.125

Electricity based Energy Systems





Cost of 1 kWh
from PV
from Hydro

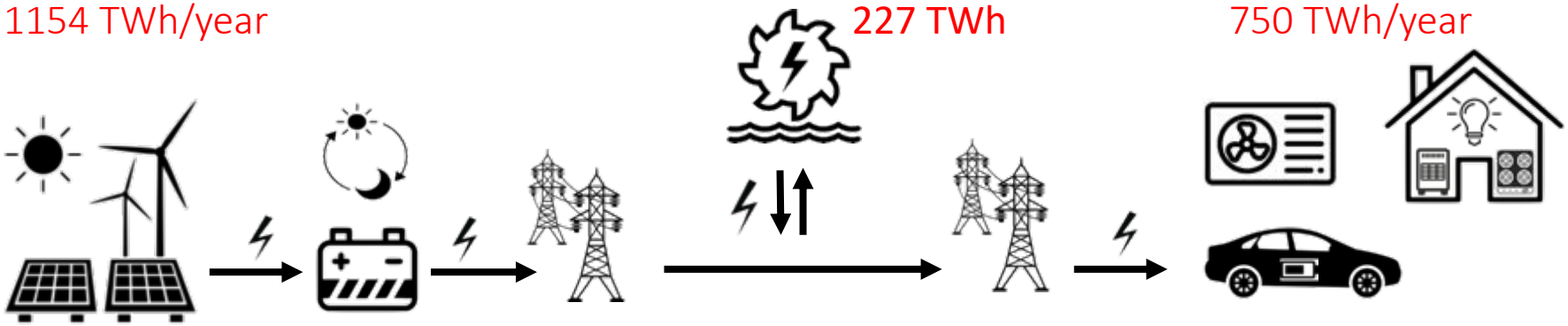
Electricity direct PV Day	0.04 $/kWh
Electricity Hydro Grid	0.13 $/kWh
Electricity direct PV Night	0.15 $/kWh
Electricity from PV Grid	0.23 $/kWh
Electricity seasonal storage	0.56 $/kWh

Replace fossil produced electricity with PV electricity

1154 TWh/year

227 TWh

750 TWh/year



4273 km²

2884 GWh

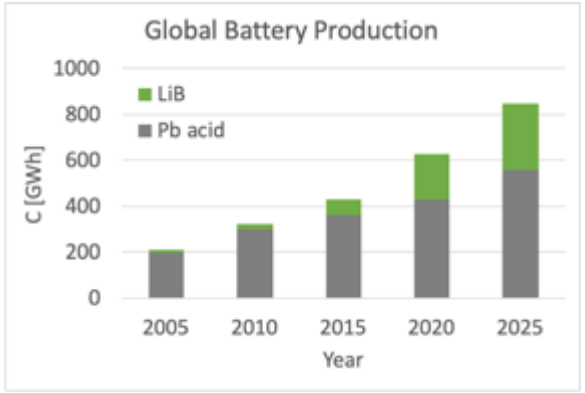
86 GW

0.34 $/kWh

PV 1.1% of Japan

P_P = 855 GW

4 year global battery prod.



C = 2884 GWh

+23 x Okawachi

W_{el} = 10 GWh

P = 1280 MW, t = 8 h

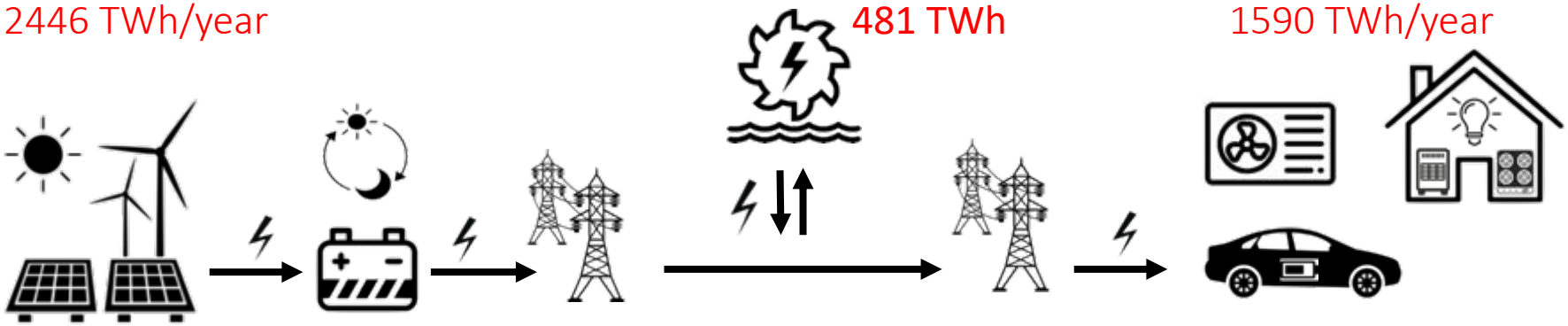
Ref.: Andreas ZÜTTEL, Noris GALLANDAT, Paul J. DYSON, Louis SCHLAPBACH, Paul W. GILGEN, Shin-Ichi ORIMO, "Future Swiss Energy Economy: the challenge of storing renewable energy", Frontiers in Energy Research: Process and Energy Systems Engineering, 9 (2022), https://doi.org/10.3389/fenrg.2021.785908

Replace fossil energy with PV electricity

2446 TWh/year

481 TWh

1590 TWh/year



9059 km²

6115 GWh

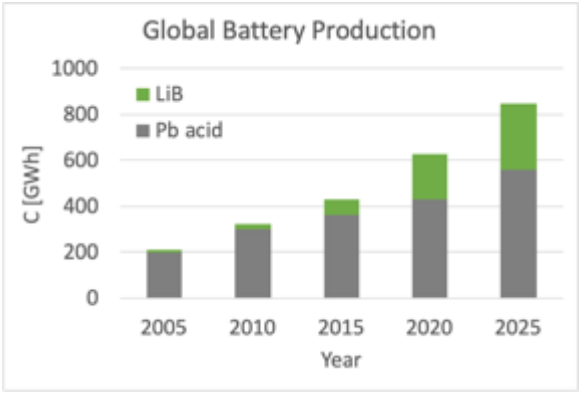
182 GW

0.34 $/kWh

PV 2.4% of Japan

P_P = 1800 GW

>7 year global battery prod.



C = 6115 GWh

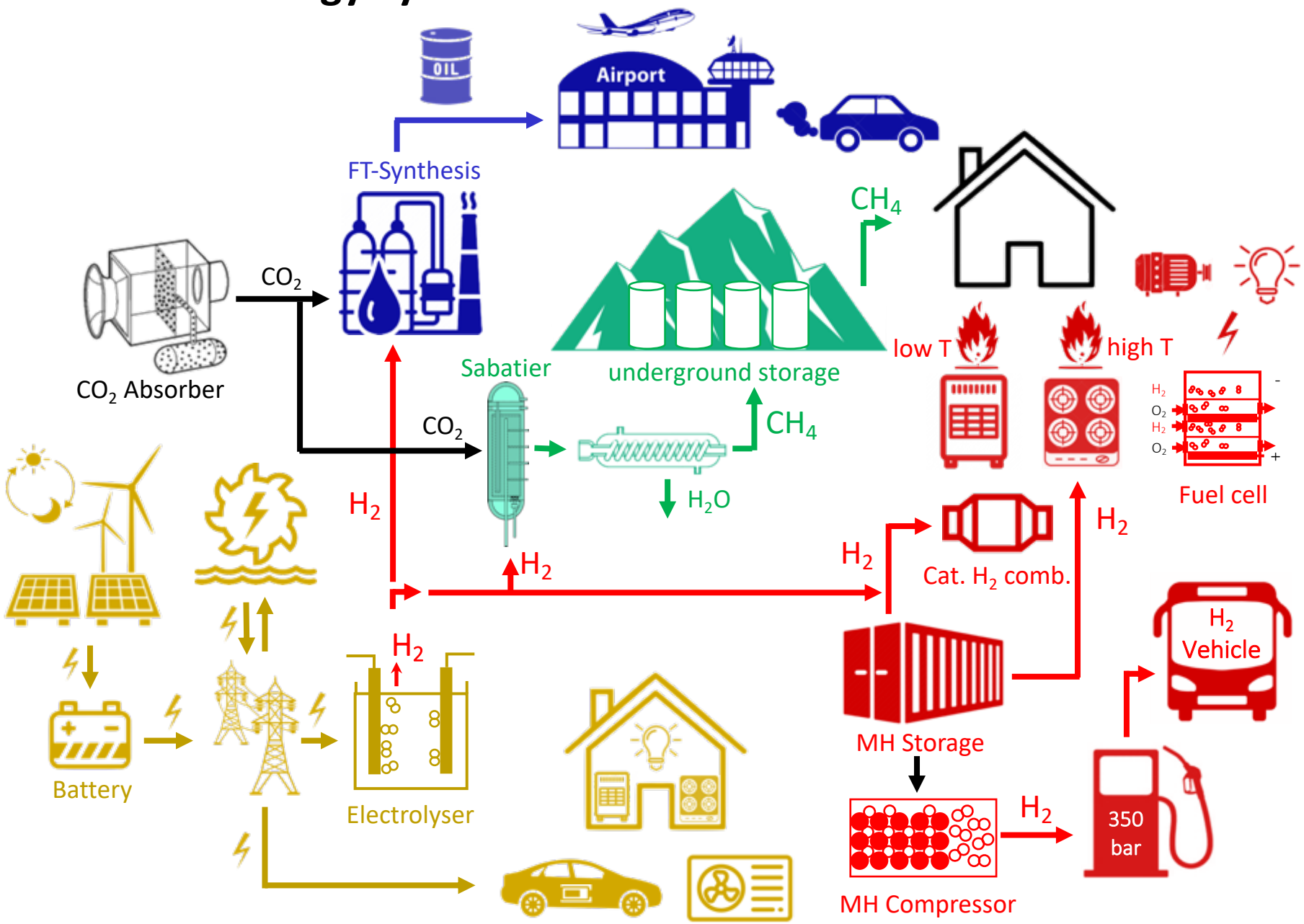
+48 x Okawachi

W_{el} = 10 GWh

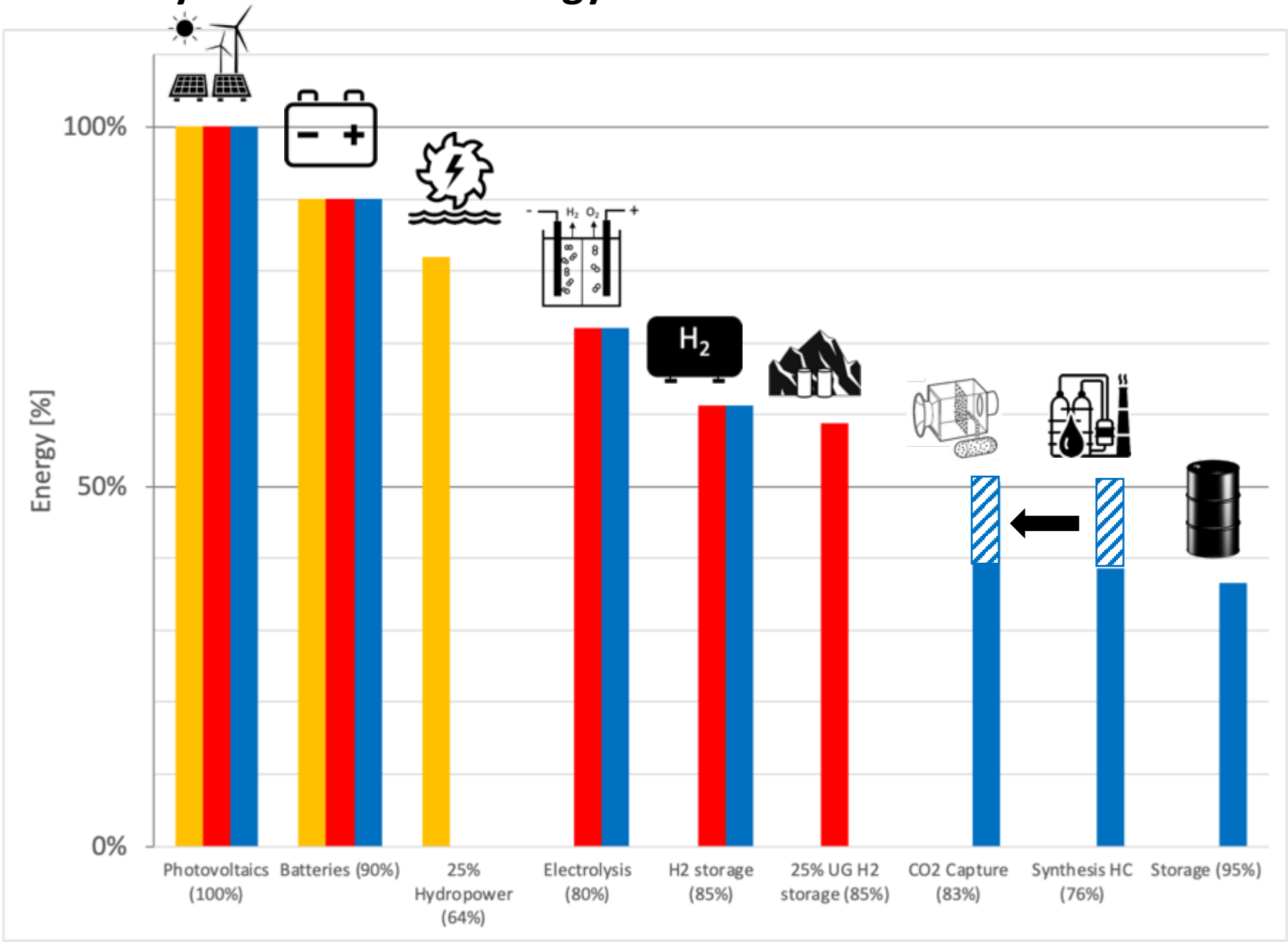
P = 1280 MW, t = 8 h

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 Systems



Efficiency of Renewable Energy Conversion

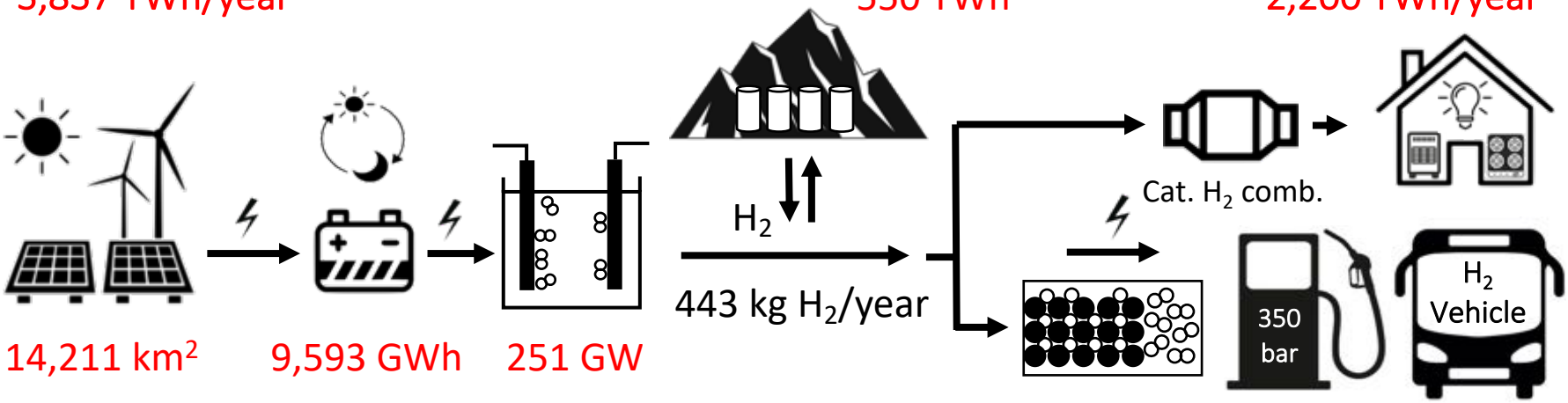


Replace fossil energy with PV electricity and H_2

3,837 TWh/year

550 TWh

2,200 TWh/year



14,211 km² 9,593 GWh 251 GW

443 kg H_2/year

18 $/kg H_2

0.46 $/kWh

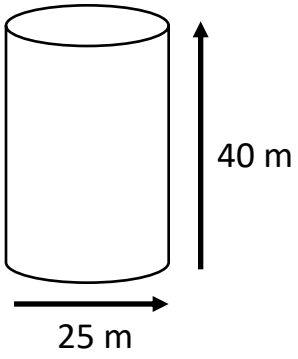
PV 3.8 % of Japan

P_P = 2842 GW

underground hydrogen storage

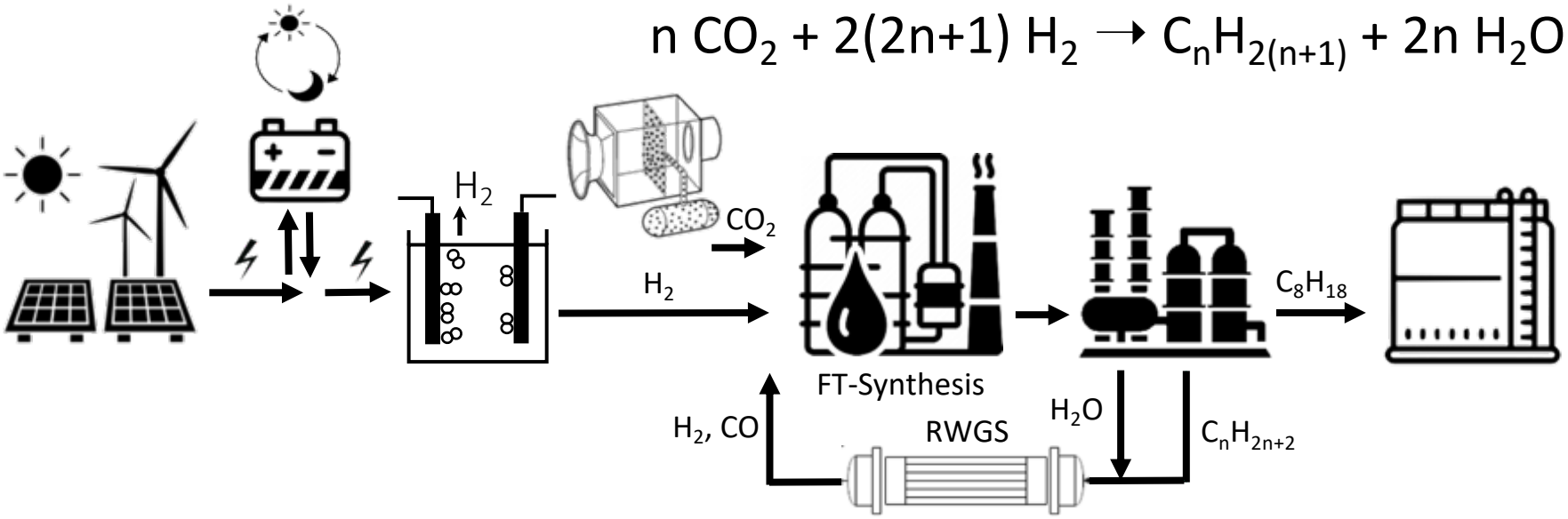
V = 979 Mm³

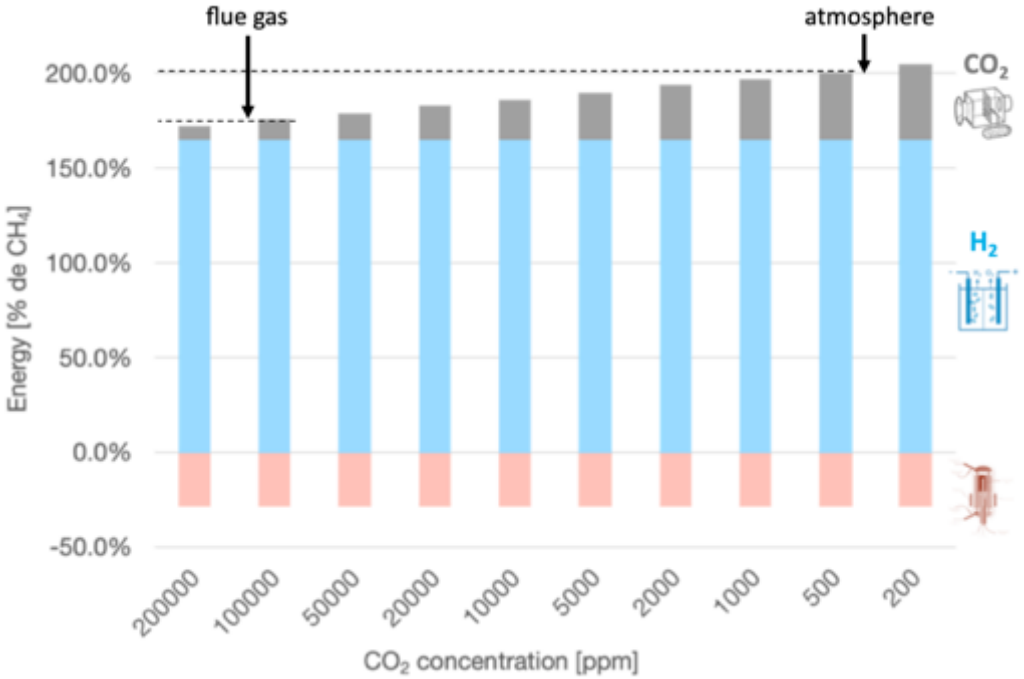
50,000 Zylinder



Synthetic Hydrocarbons

$$n\,CO_2 + 2(2n+1)\,H_2 \rightarrow C_nH_{2(n+1)} + 2n\,H_2O$$





Cost

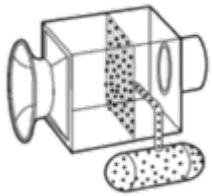
CO_2 air capture: 0.5 - 3 $/kg CO_2

FT Synthesis: 0.2 - 0.5 $/kWh

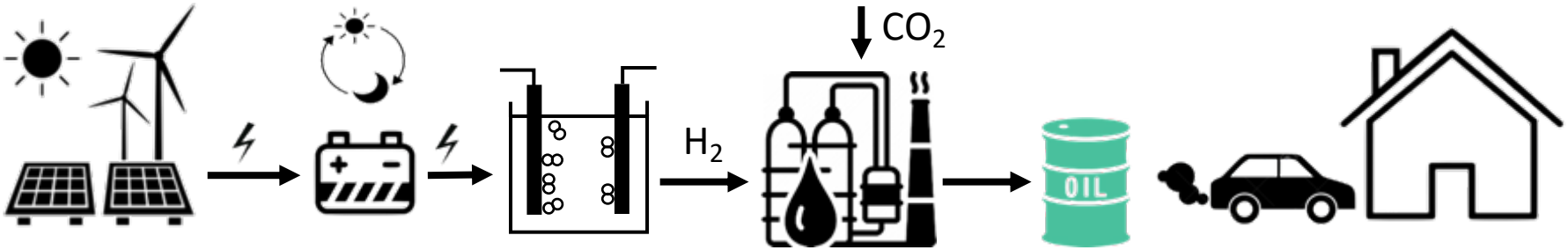
Storage: 0.01 $/kg HC

Replace fossil energy with PV and synthetic hydrocarbons

572 Mt CO_2/year



5,996 TWh/year



2,200 TWh/year

22,210 km² 14,242 GWh 366 GW 1628 M barrel/year

PV 4.5 % of Japan

P_P = 4442 GW

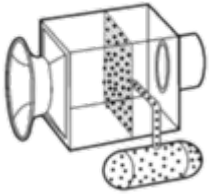
7.4 $/L HC
0.75 $/kWh

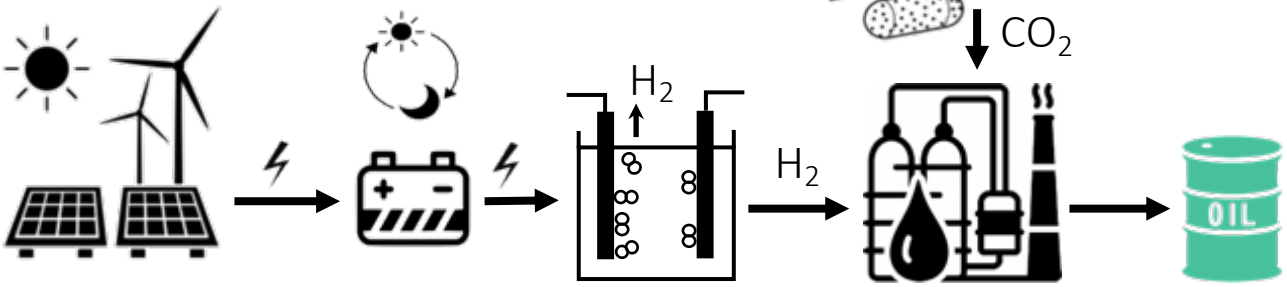
2053 L HC/year

Production of Aviation fuel

34 Mt CO_2/year

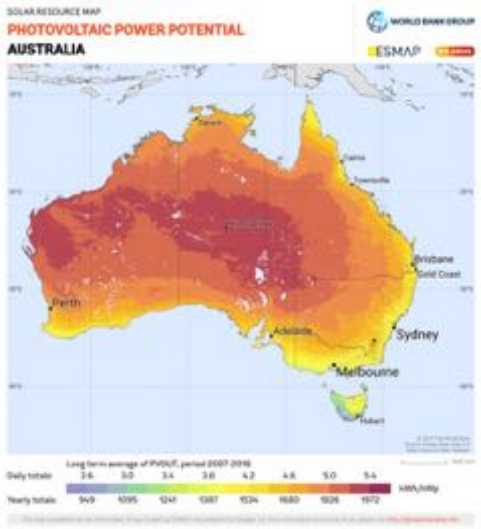
354 TWh/year





130 TWh/year

1312 km^2 | 842 GWh | 21 GW | FT-Synthesis | 96 M barrel/year



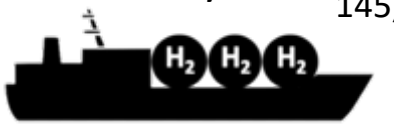
7.4 $/L HC
0.75 $/kWh

Synthesis of hydrocarbons

2 x GTL Qatar
140'000 barrel/day

263,000 barrel/day

Electrification and Hydrogen Power Plant during Winter



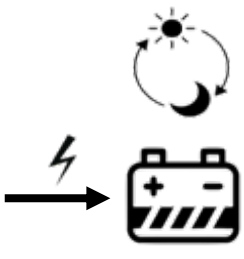
H_2 Shiph
(LH_2 Ship 250'000 m^3)

5 month
145,000 t/day
H_2

H_2 gas fired power plant

481 TWh/5 months

2446 TWh/year



1590 TWh/year

9059 km^2

6115 GWh

182 GW

0.34 - 0.98 $/kWh

PV 2.4% of Japan

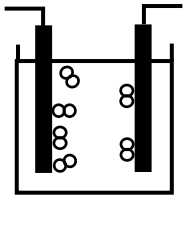
P_P = 1800 GW

Hydrogen Production in Australia

1307 TWh/5 months

Photovoltaics
11,518 km²
(107 km)²

Pb-Battery
7842 GWh



Electrolyser
234 GW

H_2 0.05 kWh

Compressor

Pipeline

H_2

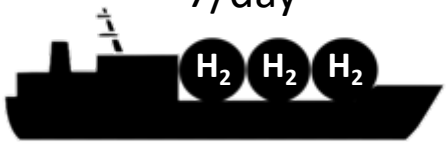
854 TWh/5 months

H_2

H_2 Liquifaction

H_2

7/day



H_2 Shiph
(LH_2 Ship 250'000 m³)

H_2

Compressor

H_2

Pipeline

H_2

5 months
145,000 t/d

20.23 $/kg H_2

H_2

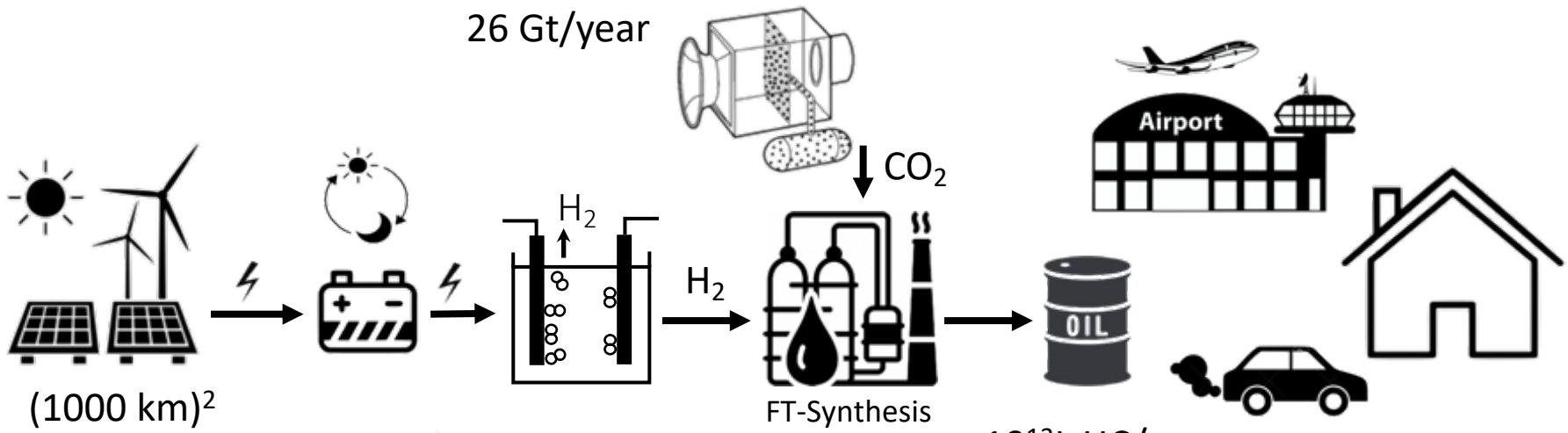
H_2 gas fired power plant

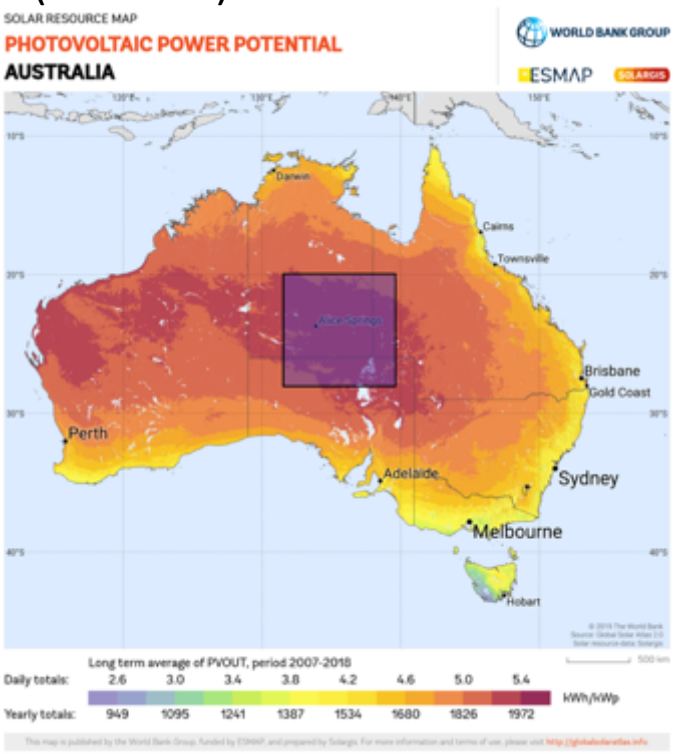
Grid

481 TWh/5 months

0.98 $/kWh

Hydrocarbon Production for the World (12TW)





Synthesis of hydrocarbons

1300 x GTL Qatar
140'000 barrel/day

175 Mio. barrel/day

7.4 $/L HC
0.75 $/kWh

Market volume: 7400 B$/year
Benefit: 740 B$/year
GDP(Australia): 1300 B$/year (2019)
Coal Export: 0.3 Gt/year (30 B$/year)

9.1. Renewable Energy


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

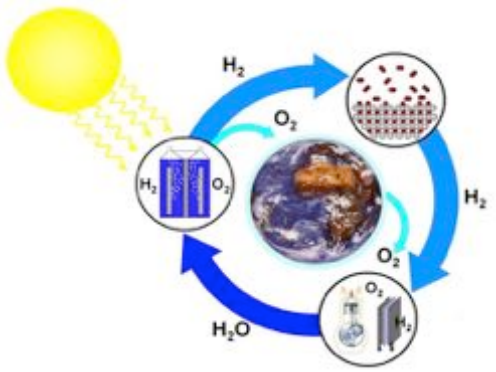

Used biomass


Existing hydropower plants

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

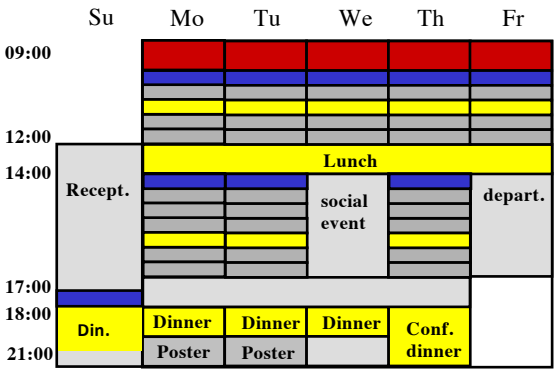
STEERING COMMITEE

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 Hjörvarsson, Sweden
Sabrina Sartori, Norway
Peter Wasserscheid, Germany

PROGRAM



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

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