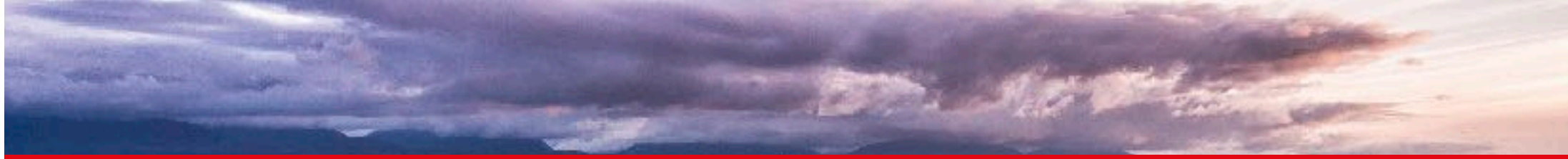
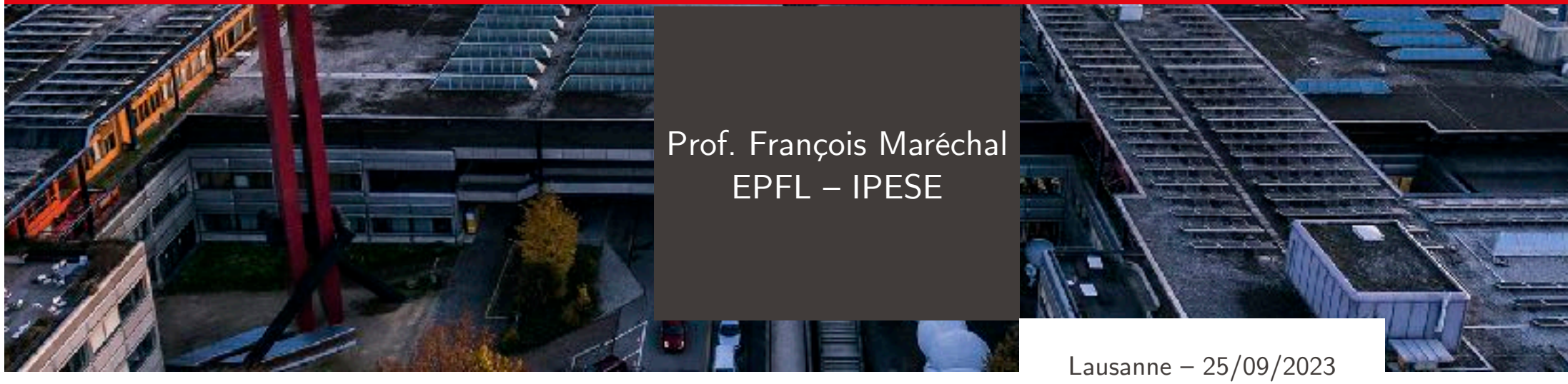


Energy conversion and Renewables An Introduction



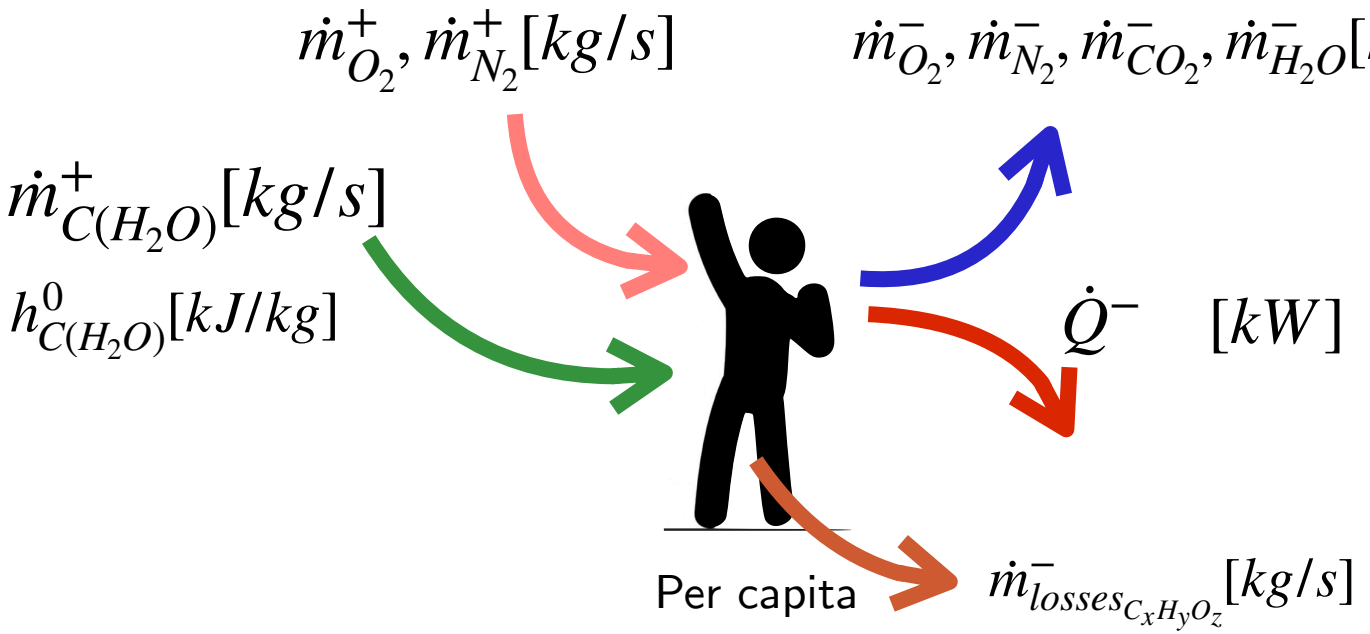
Prof. François Maréchal
EPFL – IPESE

Lausanne – 25/09/2023

École polytechnique fédérale de Lausanne

Human needs energy to live

$$C(H_2O) + O_2 \rightarrow CO_2 + H_2O + \Delta E \qquad \Delta E \approx 20[MJ/kg_{C(H_2O)}]$$



Energy Balance at every time of life t

- 20% muscles : work ($\dot{m}_{e^-}\Delta v$ [kW])
- 20% brain : control (($\dot{m}_{e^-}\Delta v$ [kW])
- 10% heart : distribution ($\dot{m} \cdot \delta \cdot \Delta P$ [kW])
- 30% leaver : conversion ($\dot{m} \cdot \Delta h^r \quad [kW]$)
- 20% other : including storage ($\dot{m}_{fat} \cdot h^0_{fat}$ [kW])
- temperature control : 37°C
  by cogeneration ($M \cdot c_p \cdot \Delta T$ [kW])

$$\dot{Q}^-[kW] = \dot{m}^+_{C(H_2O)} \cdot h^0_{C(H_2O)} - \Delta M_{fat} \cdot h^0_{fat} - \dot{m}^-_{losses_{C_xH_yO_z}} \cdot h^0_{C_xH_yO_z}$$

$$\dot{Q}^- = 70 - 100 \quad [kW]$$

François Maréchal – francois.marechal@epfl.ch

Physical units of energy : Joule

- International system (MKSA): Metre, Kilogramme, Second, Ampère
- Energy forms
  - Kinetic energy E_c = ½mass x speed^2 $\quad Energy \quad [E_c] = kg \cdot (m \cdot s^{-1})^2 = Joule[J]$
  - Work = force x displacement; [T] = N x m $\quad Force \quad [N] = kg \cdot m \cdot s^{-2}$
  - Potential Energy E = stored to produce work $\quad Energy \quad [J] = [N]x[m] = kg \cdot m \cdot s^{-2} \cdot m$
    - [E] = J : Ex. weight energy : mass x g x altitude = mgh

$$J = \frac{kg \cdot m^2}{s^2} = N \cdot m = Pa \cdot m^3 = W \cdot s$$

James Prescott Joule
(1818–1889)

François Maréchal – francois.marechal@epfl.ch

Different forms of energy

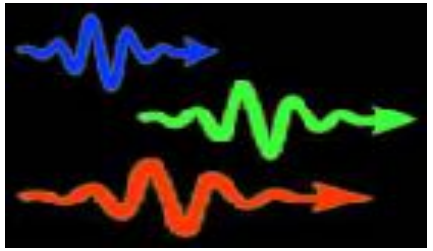
- Work due to the pressure = pressure x volume;
- [E] = kg/(ms^2) x m^3 = N x m
- Heat = disordered energy of the movements due to temperature

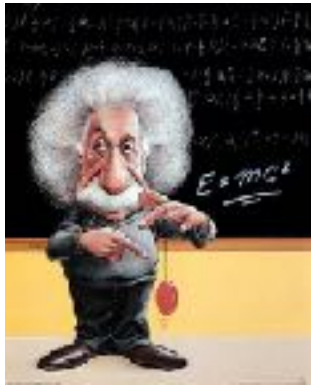
$$E_c = N \times \frac{1}{2} m \langle v^2 \rangle = \frac{3}{2} N k_B T \qquad k_B = 1{,}380\,648\,8 \times 10^{-23} \mathrm{J \cdot K^{-1}}$$

Où k_B est la constante de Boltzmann, N le nombre de particules et T la température (en kelvins).

- Electrical energy = charge x electrical potential
- Chemical energy = Molecule formation x chemical reaction progress
- Nuclear energy = Atome formation x nuclear reaction progress
- Quantic energy E = hν; h Planck constant, ν light frequency

$$h \approx 6{,}62606957 \times 10^{-34}\ \mathrm{J \cdot s},$$





c = 299 792 458 m·s-1

- Relative energy of a resting mass E = mc^2

François Maréchal – francois.marechal@epfl.ch

Energy units

James Prescott Joule (1818–1889)

Facteur	Préfixe	Symbole	Facteur	Préfixe	Symbole
10^{1}	deca	da	10^{12}	tera	T
10^{2}	hecto	h	10^{15}	peta	P
10^{3}	kilo	k	10^{18}	exa	E
10^{6}	mega	M	10^{21}	zetta	Z
10^{9}	giga	G	10^{24}	yotta	Y

General Conversion Factors for Energy

To: / From:	TJ	Gcal	Mtoe	MBtu	GWh
	multiply by:				
TJ	1	238.8	2.388×10^{-5}	947.8	0.2778
Gcal	4.1868×10^{-3}	1	10^{-7}	3.968	1.163×10^{-3}
Mtoe	4.1868×10^{4}	10^{7}	1	3.968×10^{7}	11630
MBtu	1.0551×10^{-3}	0.252	2.52×10^{-8}	1	2.931×10^{-4}
GWh	3.6	860	8.6×10^{-5}	3412	1

Joule

calorie

ton of oil equivalent

British thermal unit

Watt hour

Energy scales

- Energy system scale
  - Exajoule EJ = 10^{18}J; TeraWatt-years TWyr = 31.5EJ; Tonnes of oil equivalent toe = 42 GJ
    - Energy consumption of the world ~500EJ (~15TWyr ~12×10^9 toe) of energy per year
- Industrial scales
  - kiloWatt-hour 1kWh = 3.6×10^6J
    - A household ~200kWh/m^2 per year
  - Oil barrel (~energy of 160l of oil) ~6×10^9J
    - world consumption ~4×10^{10} barrels of oil per year (~200EJ)
- Human scale
  - calorie = energy needed to increase by 1°C the temperature of 1g of water ; 1cal=4.19J
    - Un plat de pâtes = 500'000 cal = 2100 kJ
- Microscopic scale
  - Electron-Volt = energy of one electron under a potential of 1 Volt; 1eV = 1.6×10^{-19}J
    - Energy of 1 red photon = 1.5eV

François Maréchal – francois.marechal@epfl.ch

Physical units of Power

Power is the rate (flow) of the energy

- [P]= [E]/s = J/s = Watt (W)

!!!! Power : 1 J/s = 1 W (Watt) !!!!
!!!! Energy : 1 Wh = 3600 J !!!!

Scottish engineer James Watt
(1736–1819)

François Maréchal – francois.marechal@epfl.ch

Examples of energy and power content

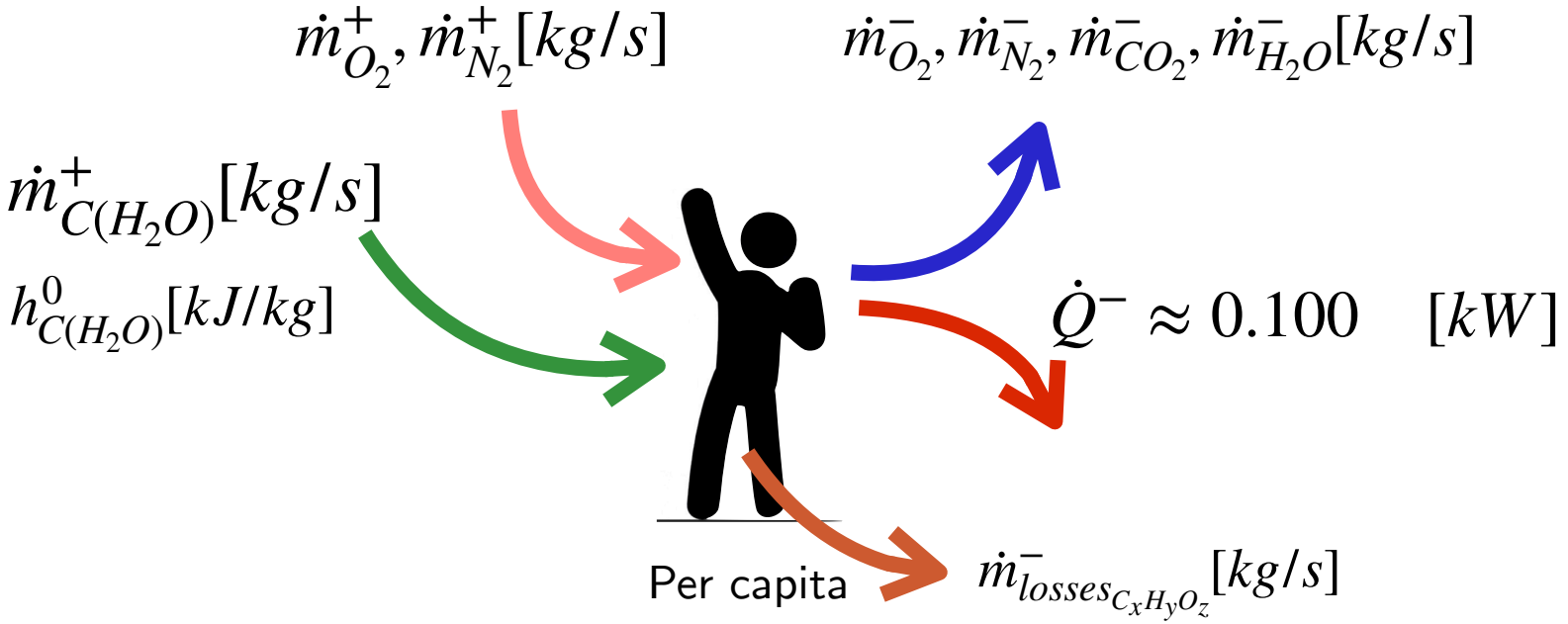
- **Energy**
  - Daily need of an adult : 6-8 [MJ]
  - 1 Liter of Oil : 36 [MJ]
  - 100 km in a VWGolf : 230 [MJ] (6.4l)

- **Power**
  - Computer : 100 -200 [W] (J/s)
  - Professional cyclist : 450 [W]
  - Adult : 100 [W]
  - 100 students : 15 [kW]
  - Car engine : 75 [kW]
  - Filling your tank at the filling station : $\frac{50[l/min] \cdot 36[MJ/l]}{60[sec/min]} = 30[MJ/s] = 30[MW]$

François Maréchal – francois.marechal@epfl.ch

Human body needs energy to live

$$C(H_2O) + O_2 \rightarrow CO_2 + H_2O + \Delta E$$



$$\dot{Q}^{-}[kW] = \dot{m}^{+}_{C(H_2O)} \cdot h^{0}_{C(H_2O)} - \Delta M_{fat} \cdot h^{0}_{fat} - \dot{m}^{-}_{losses_{C_xH_yO_z}} \cdot h^{0}_{C_xH_yO_z}$$

$$\dot{Q}^{-} = 70 - 100 \quad [kW]$$

0.25
l*/day

100
l*/year

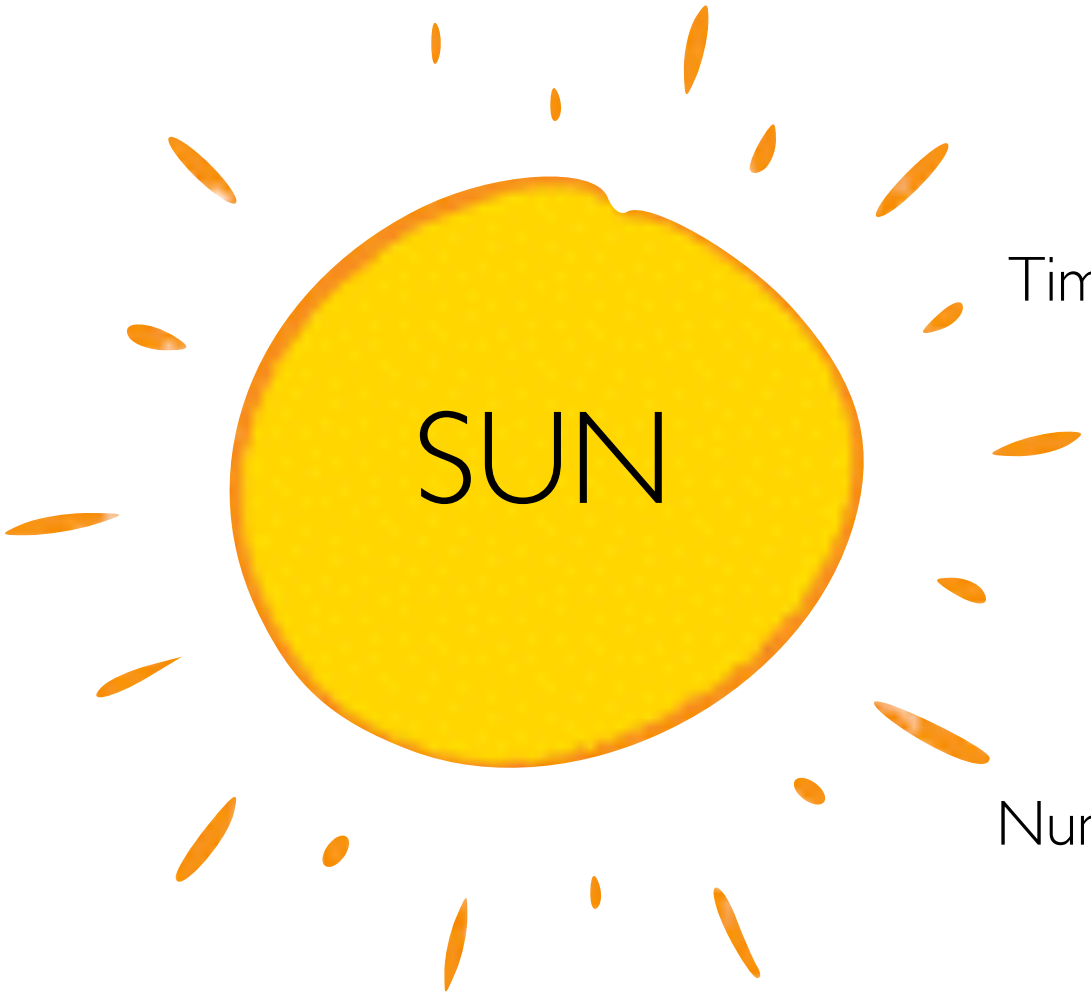
9
CHF/day (1)

* l = 1 l of oil equivalent = 10 kWh = 36000 MJ

(1) https://www.bfs.admin.ch/bfs/fr/home/statistiques/situation-economique-sociale-population/revenus-consommation-et-fortune/budget-des-menages.assetdetail.3882095.html

François Maréchal – francois.marechal@epfl.ch

Do we have a problem of energy ?



1.5 hours

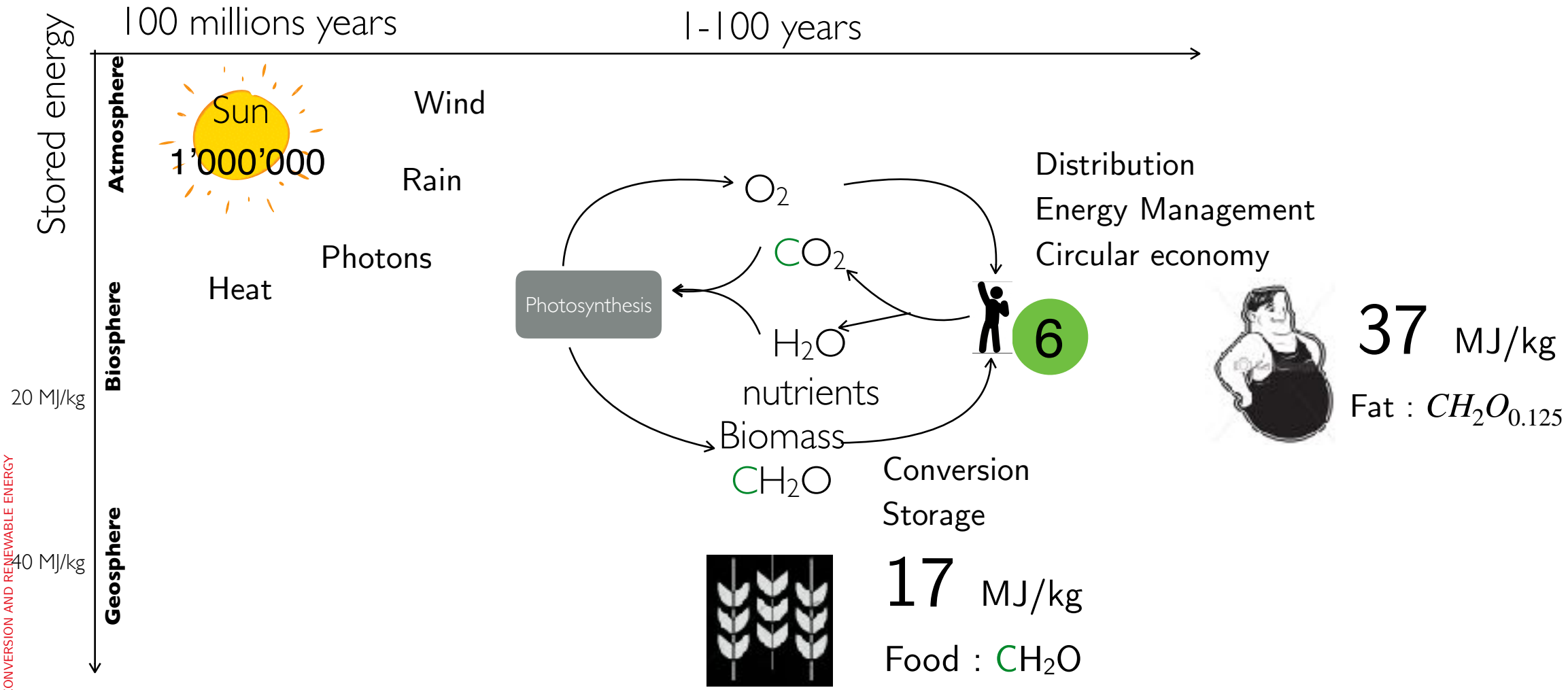
Time needed for the irradiation of the sun to cover all our annual needs

6500 years

Number of years we can survive with one year of solar irradiation energy.

François Maréchal – francois.marechal@epfl.ch

The gift of Mother Nature : Energy conversion and storage



100 = 390 EJ

François Maréchal – francois.marechal@epfl.ch

Mother nature Learning outcomes

Energy is not the problem, the problem is energy management

- Demand is intermittent and stochastic
- Resources are intermittent, stochastic and diverse
- High storage density at different scales is needed
- Co-production of chemical products : trees (structures) - leaves (fibers/polymers)
- Integrated supply chain
- Circular economy

" Nothing is lost, every atom and the energy is conserved "

" Energy can be converted from one form to another but can not be produced "

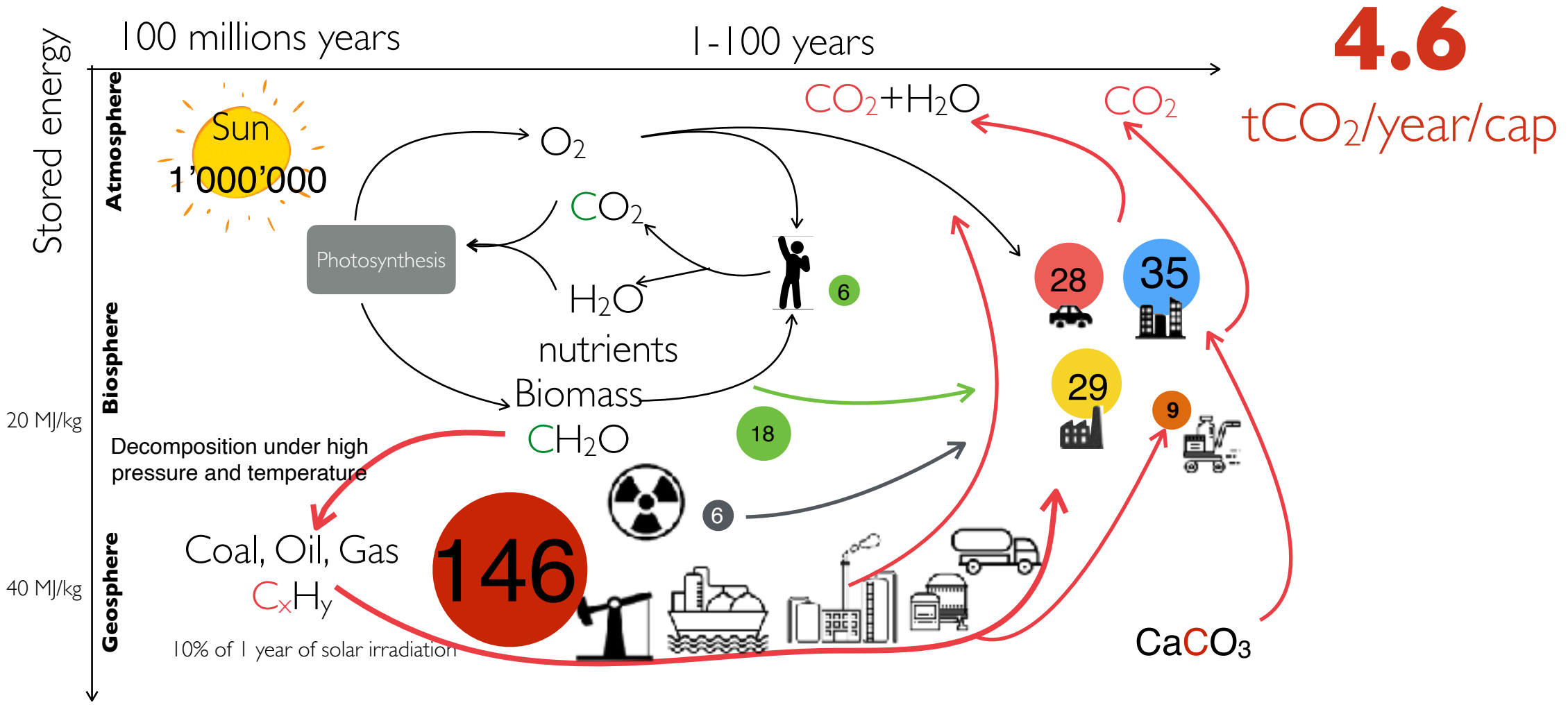
François Maréchal – francois.marechal@epfl.ch

Energy is the driving force of our society

- Provides the living comfort
  - Lightning
  - Heating/cooling
  - Food
  - Health
- Allows the fabrication of goods and products
  - Heavy industries
  - Manufacturing
- Provides mobility
  - Bikes
  - Cars
  - Trains
  - Airplanes
  - Ships
- Provides communication
  - Internet
  - Banks
  - Markets

François Maréchal – francois.marechal@epfl.ch

The earth/human energy



4.6

tCO_2/year/cap

World balance 2013 100 = 390 EJ = final energy consumption (source : iea.org)

François Maréchal – francois.marechal@epfl.ch

Humans need energy …

Food

0.25 l*/day

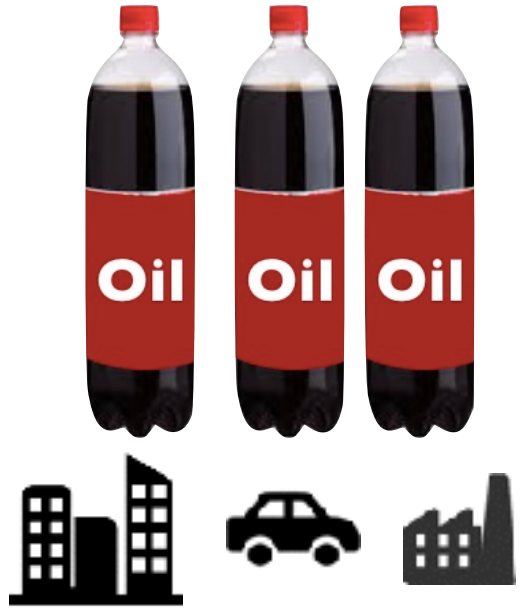
100 l*/year

Per capita

9 CHF/day

Oil

5.5 l/day



Per Swiss capita

8.5 - 12 CHF/day

Gas : **9 - 13** cts/kWh
Electricity : **17 - 31** cts/kWh
Gasoline : **16 - 21** cts/kWh

in which 3 - 7 CHF/day for import

Poutine effect

* l = 1 l of oil equivalent = 10 kWh = 36000 MJ

http://www.bfe.admin.ch/themen/00526/00541/00542/00631/index.html?lang=fr&dossier_id=00763

(1) https://www.bfs.admin.ch/bfs/fr/home/statistiques/situation-economique-sociale-population/revenus-consommation-et-fortune/budget-des-menages.assetdetail.3882095.html

François Maréchal – francois.marechal@epfl.ch

The conversion chain

$$[kJ_p/hab/an] = \eta_e[kJ_p/kJ_e] \cdot \eta_s[kJ_e/kJ_s] \cdot e_d[kJ_s/an/m^2] \cdot d_{hab}[m^2/hab] \cdot hab[hab]$$

Primary energy
Extraction->resource

Conditioning
resource->distributed

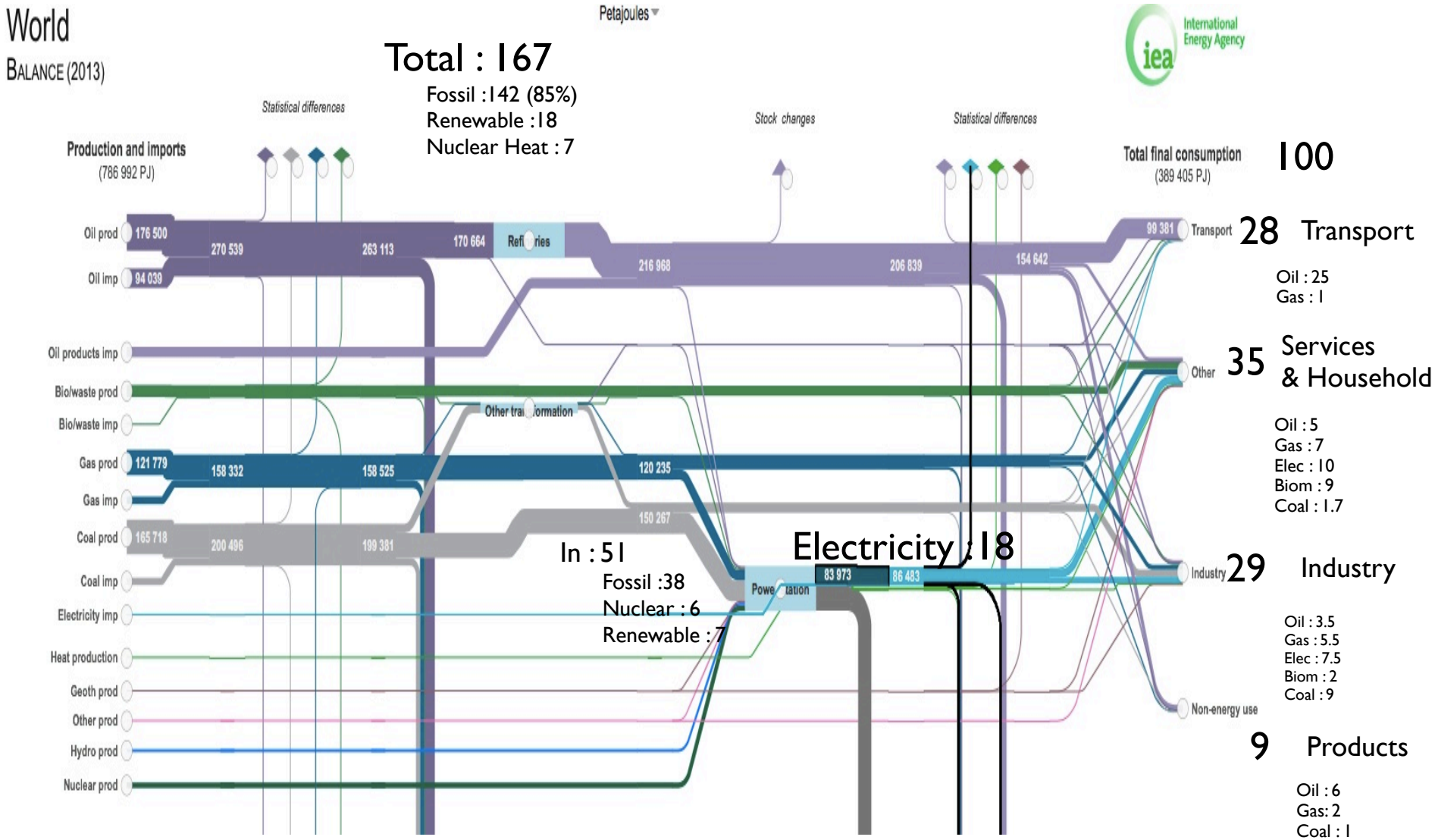
Conversion
distributed->energy

Services
Energy->services

Needs
services->cap

Population
cap

The World Energy Balance



75 % of electricity is fossil based

http://www.iea.org/Sankey/

François Maréchal – francois.marechal@epfl.ch

Energy density = energy storage

	MJ/l	MJ/kg	l (equiv essence)
Diesel	37.7	44.0	0.87
Jet fuel	34.8	41.4	0.94
Chocolate	33.1	25.0	0.99
Gasoline	32.8	44.9	1.00
High grade coal	23.3	29.2	1.41
Ethanol	23.3	29.2	1.41
Methanol	17.7	21.6	1.85
Low grade coal	12.0	16.0	2.72
CNG	10.3	7.2	3.17
Compressed H2	5.6	5.9	5.83
Lithium ion battery	1.8	0.6	18.70
Ni-MH battery	0.8	0.3	41.42
Lead acid battery	0.3	0.2	95.52
Hydrodam	0.00098	0.00098	33385.12
Fission (U-235)		85'000'000	
Fusion (D-T)		**3'500'000'000**	
$E = mc^2$		**90'000'000'000**	

C. F. Shih, T. Zhang, J. Li and C. Bai, Powering the Future with Liquid Sunshine, Joule 2(1), pp. 1925-1949, 2018.

Dams = 100 m height

François Maréchal – francois.marechal@epfl.ch

Fossil based Energy system : Learning outcomes

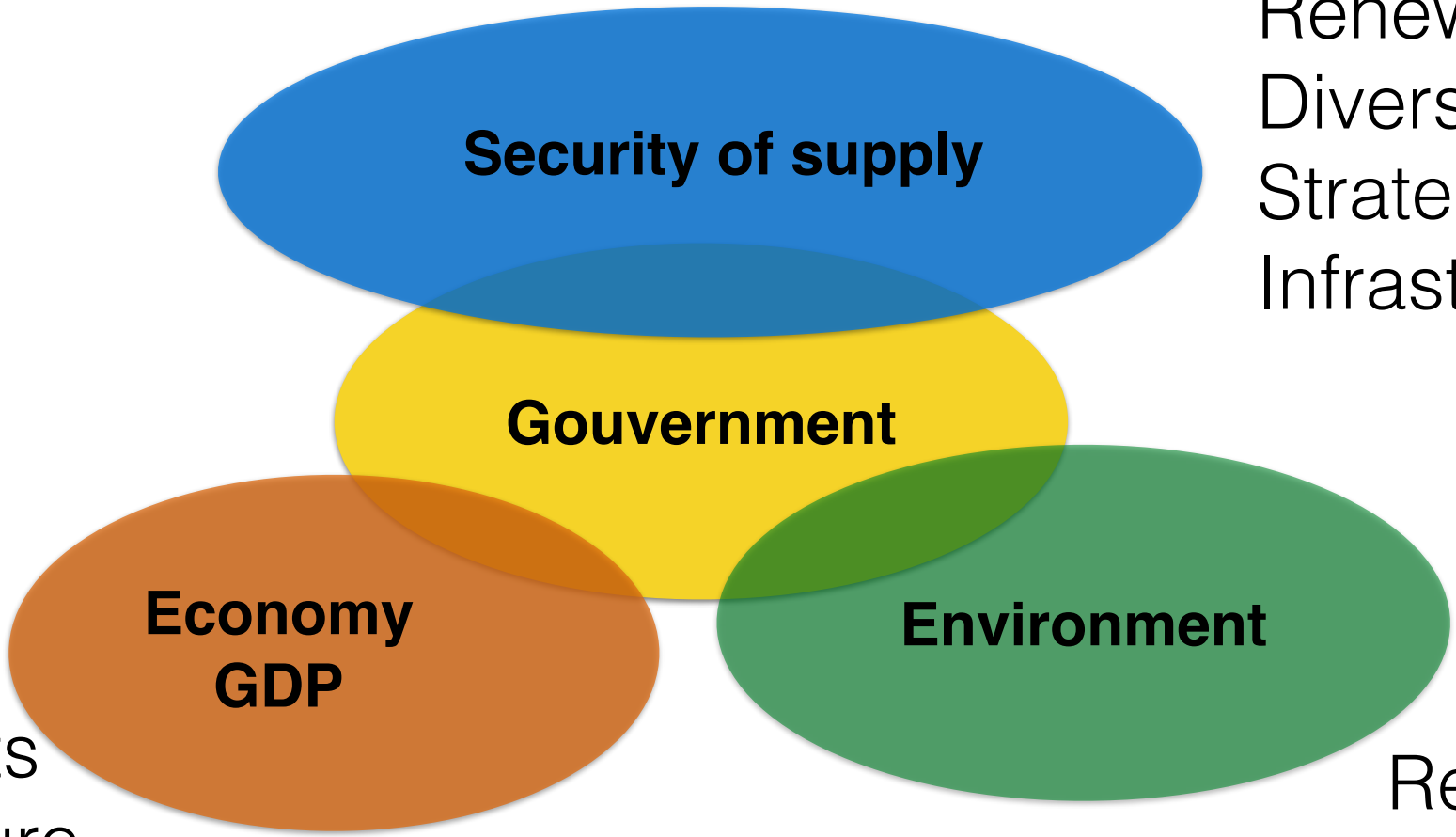
Energy is not the problem, the problem is energy management

- Demand is intermittent and stochastic
- Resources are intermittent and stochastic and diverse
- High storage density at different scales is needed
  - 2 months of oil supply
- Integrated supply chains
- but fossil **CO2** is an insulation layer and is a thread to humanity

François Maréchal – francois.marechal@epfl.ch

François Maréchal – francois.marechal@epfl.ch

The energy trilemma



Local ressources
Renewables
Diversification
Strategic Stocks
Infrastructure

Subsidies
Investments
Infrastructure
Taxes
Cost of impact

Regulation
Taxes
Deals

François Maréchal – francois.marechal@epfl.ch

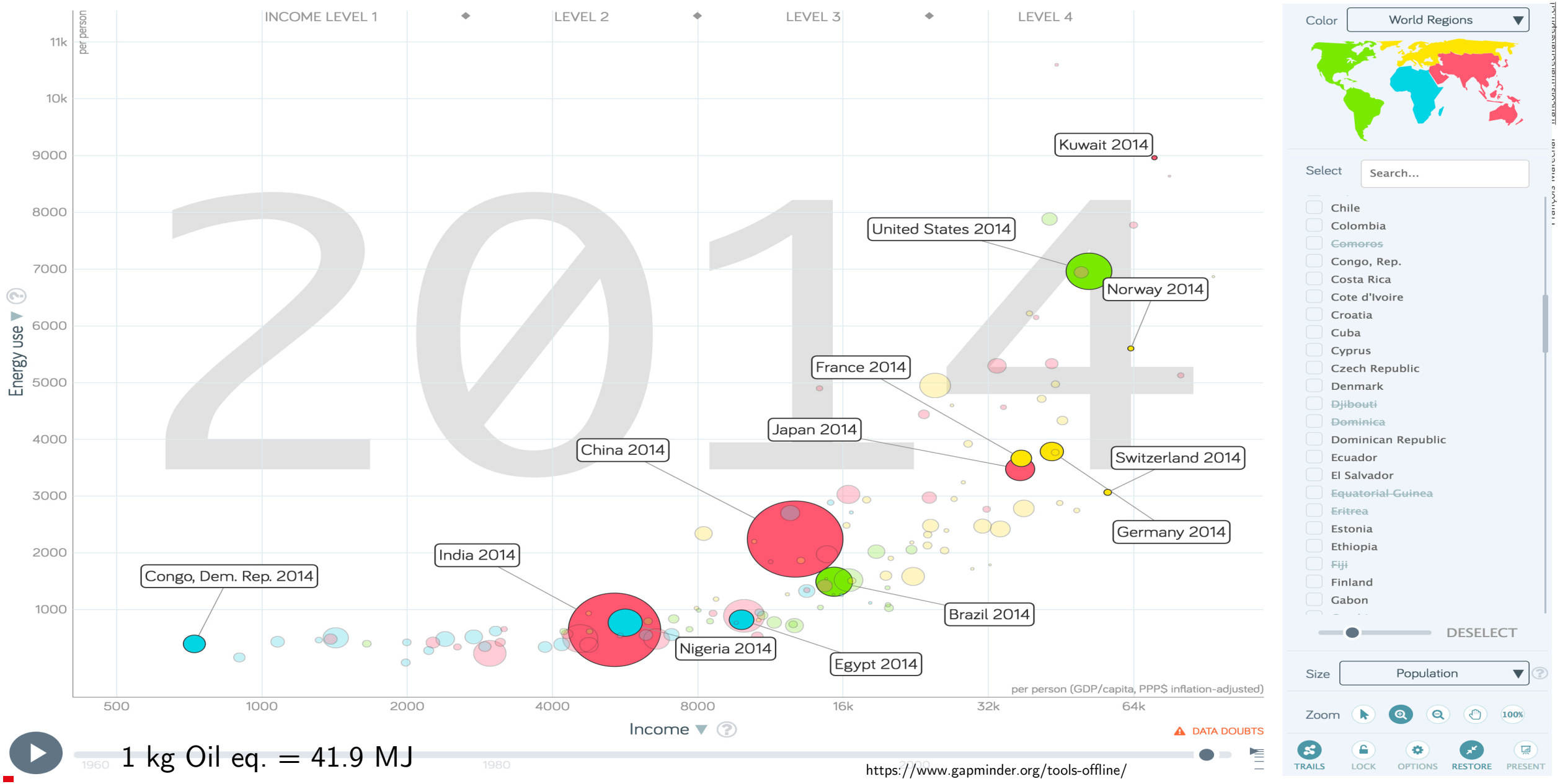
Energy and the global economy

- Global markets: World GDP ~72'000 milliards $
  - Agriculture ~2'300 billions $ /year (~3%)
  - R&D ~1'500 billions $ /year (~2%)
  - Military ~1'750 billions $ /year (~2.5%)
  - Education ~3'500 billions $ /year (~5%)
  - Health ~7'200 billions $ /year (~10.%)
  - Drugs (crime) ~1'000 billions $ /year (~1.5%)
  - Energy ~15'-20'000 billions $ /year (~ 20-27%)
  - Resources
    - Oil ~3'600 billions $ /year
    - Gas ~1'300 billions $ /year
    - Coal ~1'200 billions $ /year

Source *The World Bank*
IAEA

François Maréchal – francois.marechal@epfl.ch

Energy use (kg Oil eq./capita) vs income



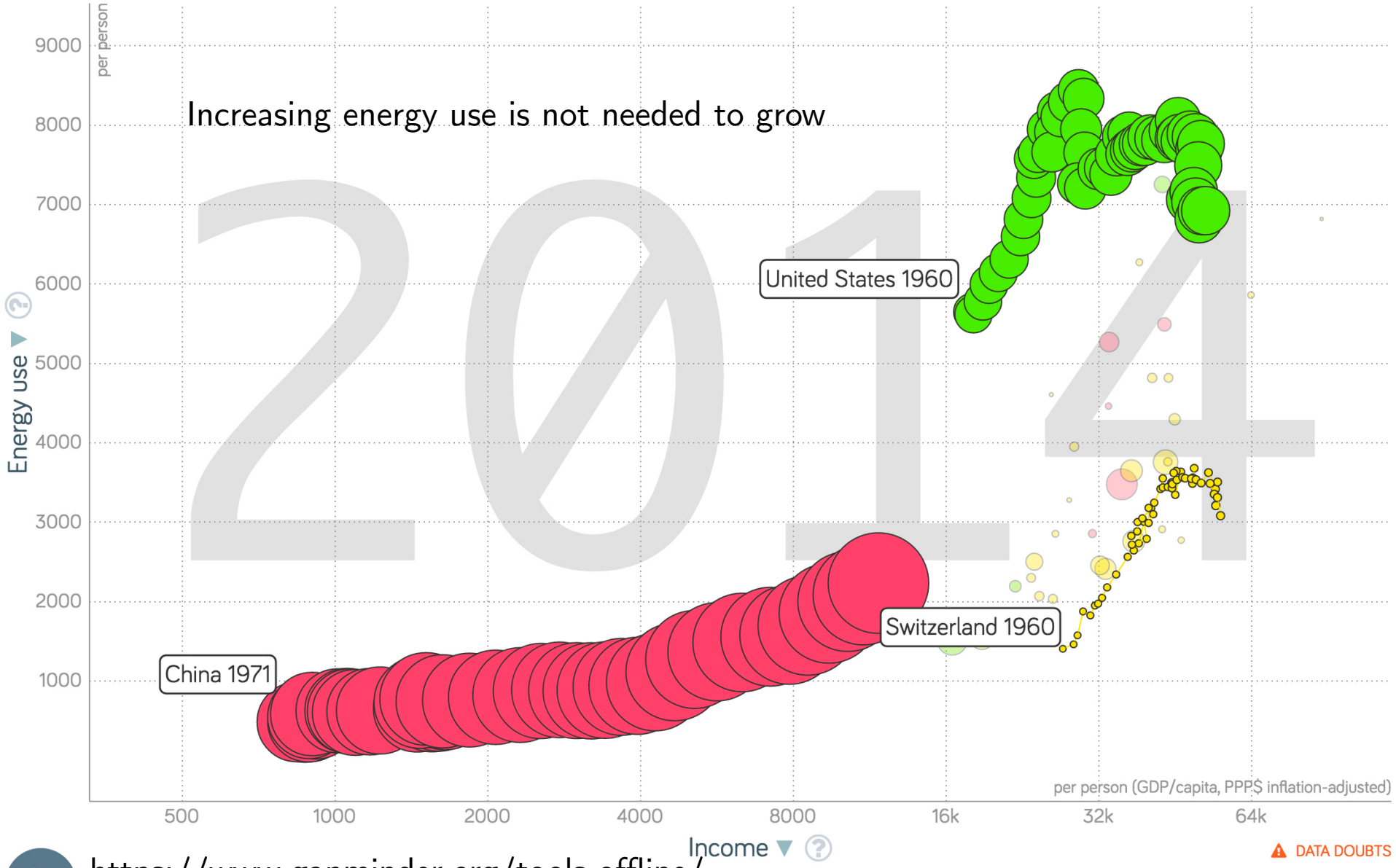
1 kg Oil eq. = 41.9 MJ

https://www.gapminder.org/tools-offline/

https://www.gapminder.org/tools-offline/

François Maréchal – francois.marechal@epfl.ch

Energy and development : decorelation



https://www.gapminder.org/tools-offline/

www.gapminder.org

François Maréchal – francois.marechal@epfl.ch

Geopolitical impact

- Energy is the engine of the society
  - Comfort,Health, Mobility, Education, Safety
- Political goals
  - Electrification, security of supply
  - Economies
- Geopolitical impacts
  - Irak, Syria (ressources, EI ?)
  - Ukraine (EU supply from Russia)
  - North Corea, Iran (nuclear)
  - Venezuela, Russia (revenue)
  - USA (security of supply)
  - Yemen/South Arabia
  - Greece vs Turkey (gas resources)

Greece slams Turkish move on gas exploration in eastern Med

Greece has slammed Turkey's move to conduct energy exploration in the eastern Mediterranean in an area Athens says overlaps its own continental shelf

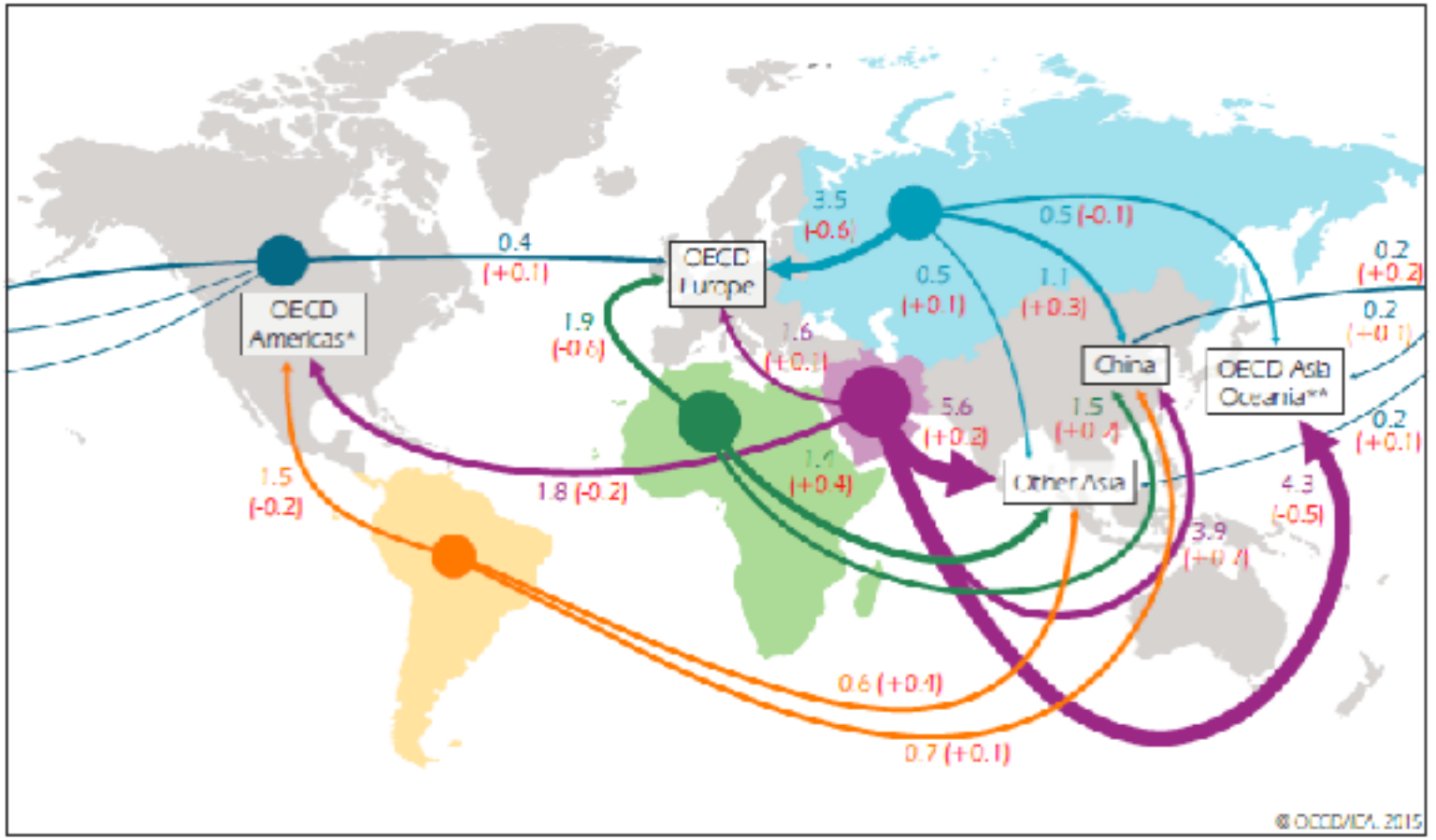
By **ELENA BECATOROS Associated Press**
10 August 2020, 21:54 • 6 min read

The Associated Press

François Maréchal – francois.marechal@epfl.ch

Geopolitical impacts (supply)

Map 3.1 Crude exports in 2020 and growth in 2014-20 for key trade routes



This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries and to the name of any territory, city or area.

Note: Excludes intra regional trade.

* Includes Chile.

** Includes Israel. The statistical data for Israel are supplied by and under the responsibility of the relevant Israeli authorities. The use of such data by the OECD and/or the IEA is without prejudice to the status of the Golan Heights, East Jerusalem and Israeli settlements in the West Bank under the terms of international law.

https://www.iea.org/publications/freepublications/publication/MTOMR_2015_Final.pdf

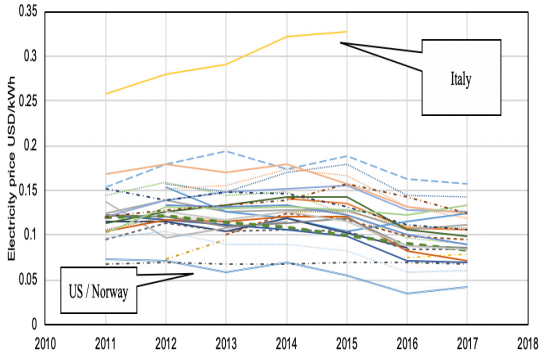
François Maréchal – francois.marechal@epfl.ch

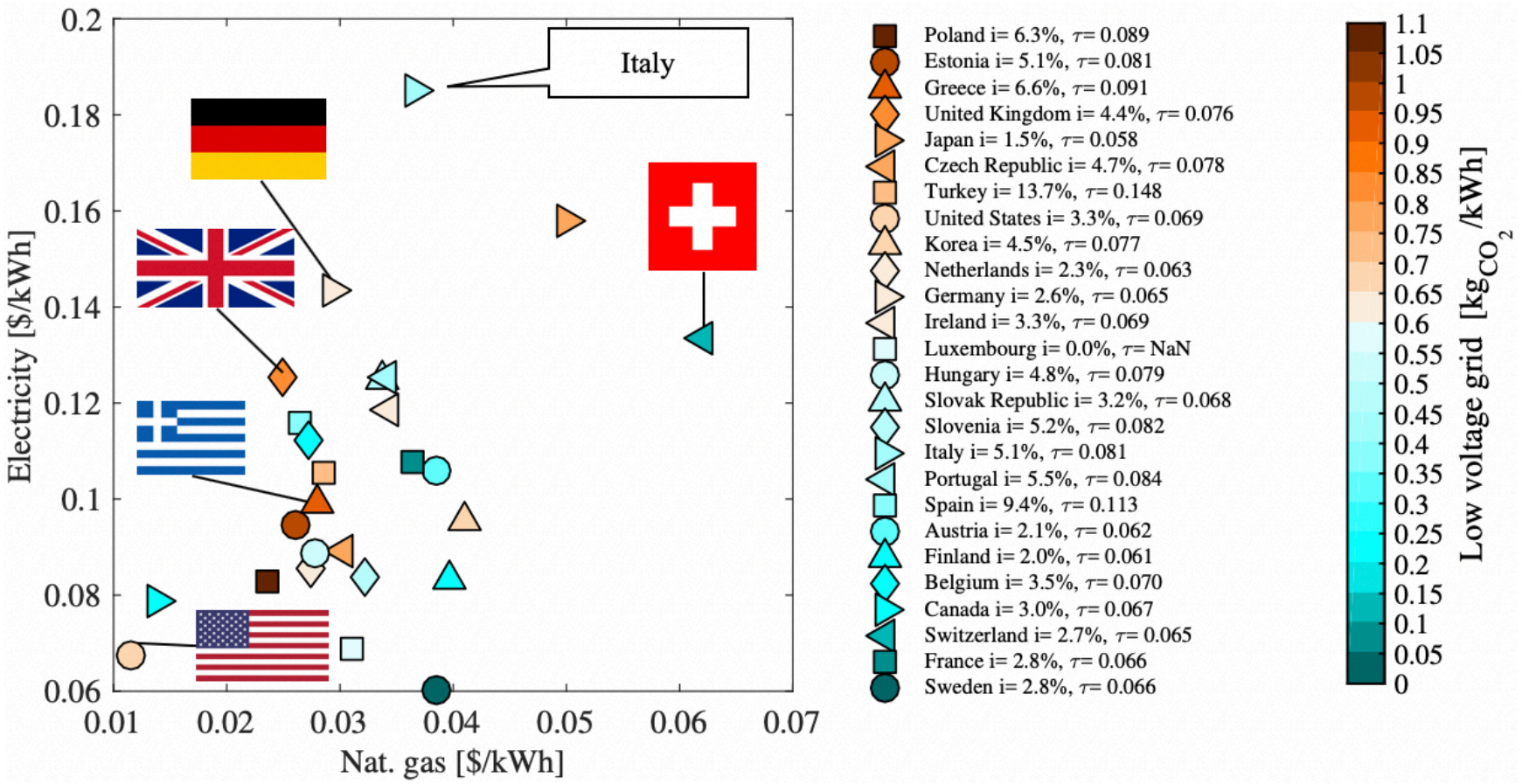
Each element of the supply chain is critical

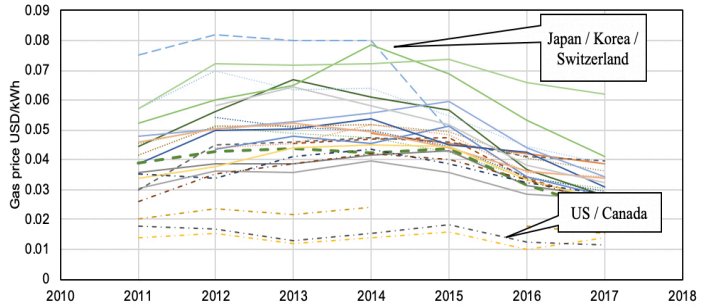
https://www.trtworld.com/magazine/uk-s-driver-shortage-caused-shutdowns-of-oil-stations-50218
26.09.2021

François Maréchal – francois.marechal@epfl.ch

The energy market price







Source: *A.S. Wallerand, Thesis EPFL 2018*

François Maréchal – francois.marechal@epfl.ch

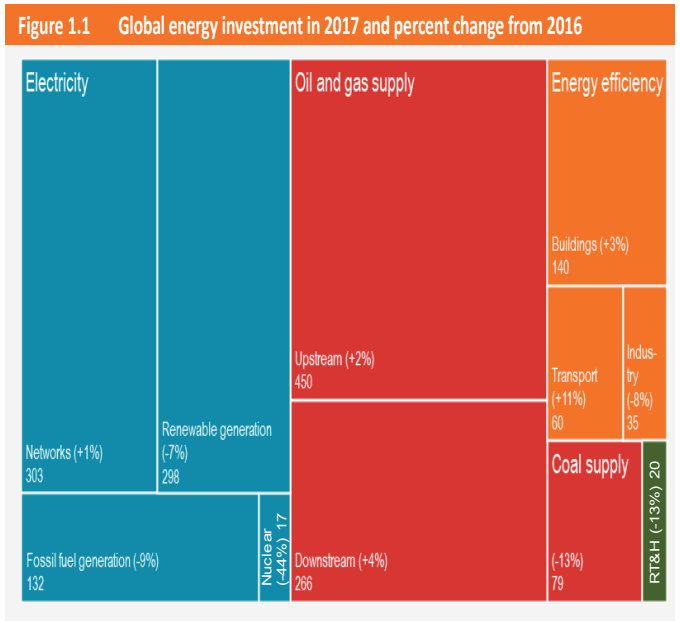
Do we have the money ?
2015 fossil spendings world wide

1.0 US$

Investment by industry

1'800

bUS$/year (2017)



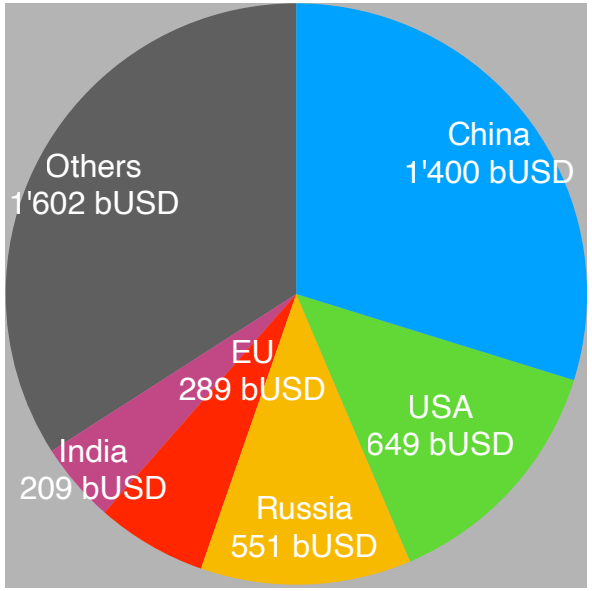
World energy investment 2018 IEA.org

2.5 US$

Subsidies by countries

4'700

bUS$/year (2015)



World energy subsidies 2015 imf.org

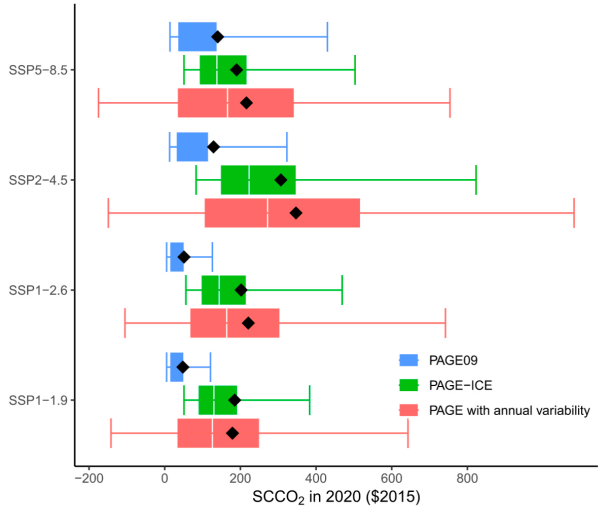
4.0 US$

Social/Repair

7'200

bUS$/year (2015)

repairing the damages



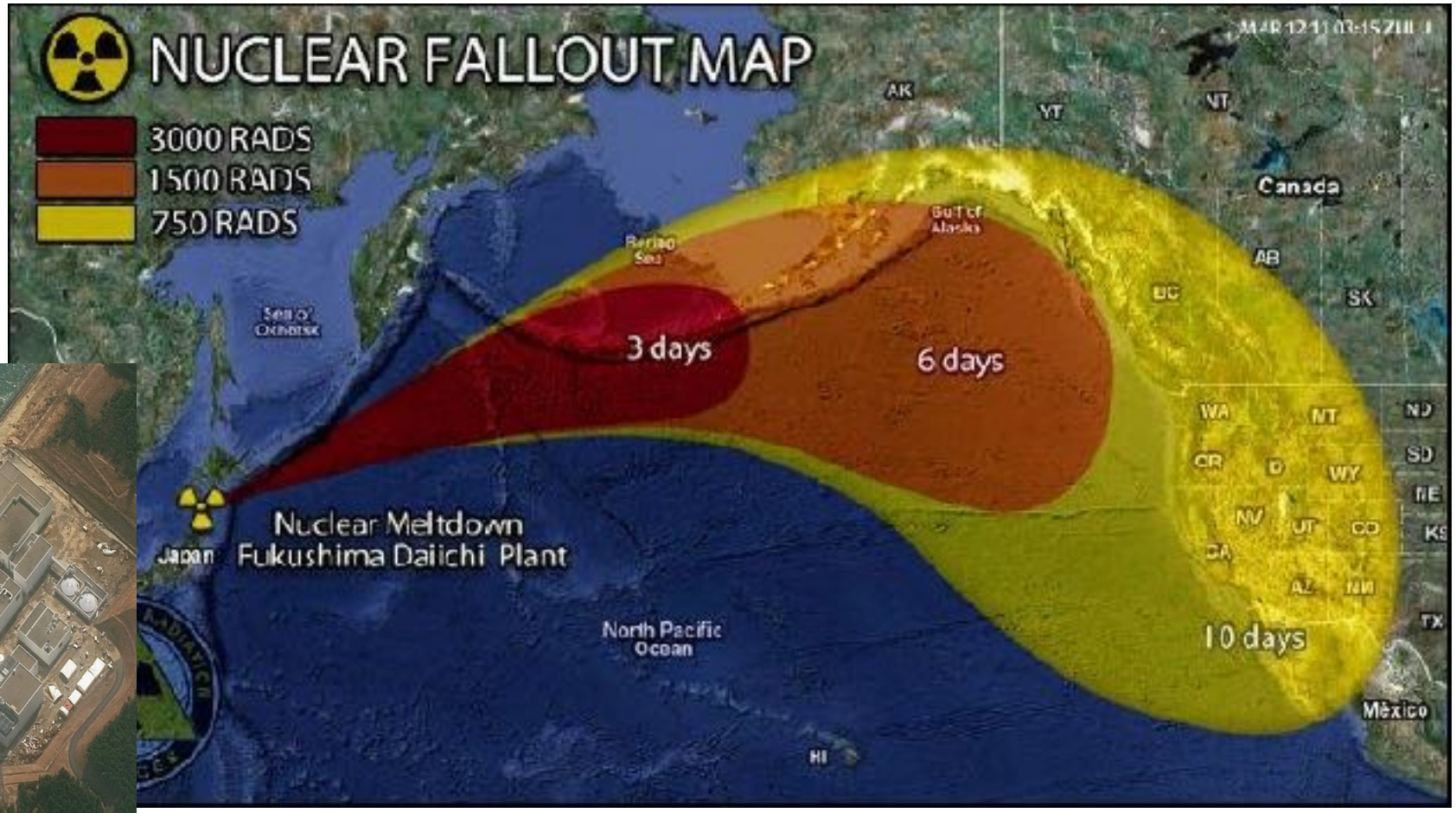
200 USD/t CO2

Jarmo S Kikstra et al 2021 Environ. Res. Lett. 16

François Maréchal – francois.marechal@epfl.ch

Energy has a global impact

- World wide impact



François Maréchal – francois.marechal@epfl.ch

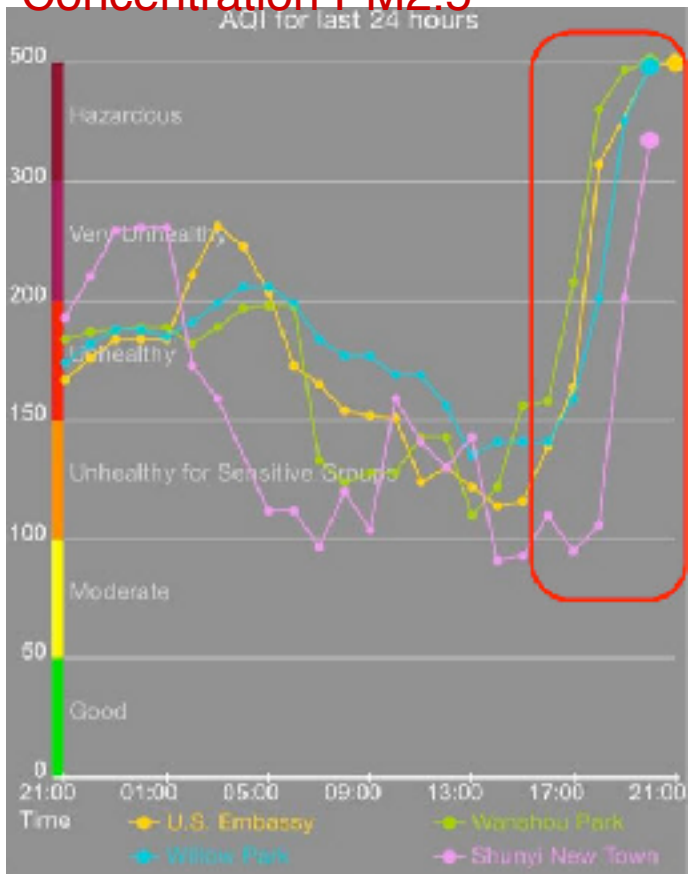
Energy and policy

- 2011 : Fukushima accident
  - Switzerland, Germany defining new policy :
    *The energy transitio*n (Energiewende)
- 2015 - Climate change
  - 195/196 countries signed the Paris agreement (COP 21) to limit earth temperature increase to 1.5°C

François Maréchal – francois.marechal@epfl.ch

Coal combustion and its impact (Pekin, winter, 2014)

Concentration PM2.5



theguardian.com, Tuesday 25 February 2014 - *Chinese scientists have warned that the country's toxic air pollution is now so bad that it resembles a nuclear winter, slowing photosynthesis in plants – and potentially wreaking havoc on the country's food supply.*

François Maréchal – francois.marechal@epfl.ch

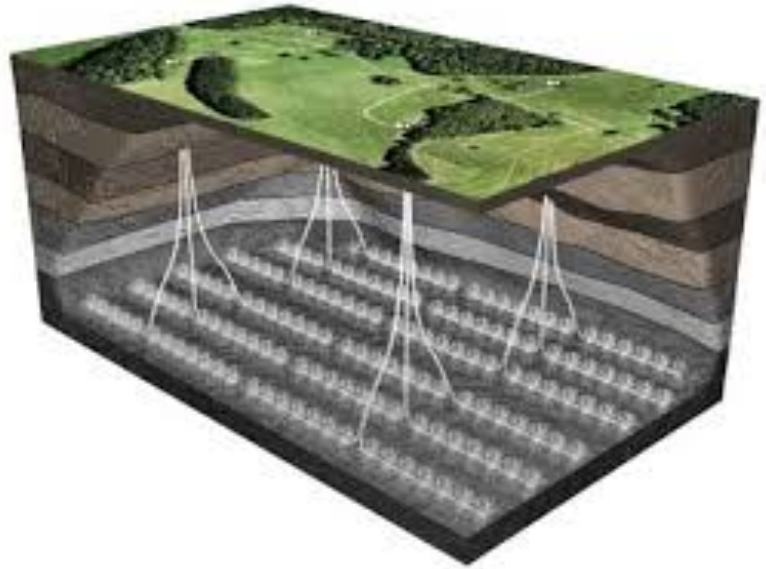
Environmental impact

Land occupation
7-10 years of exploitation

Marcellus field (US)

Eau de Fracking

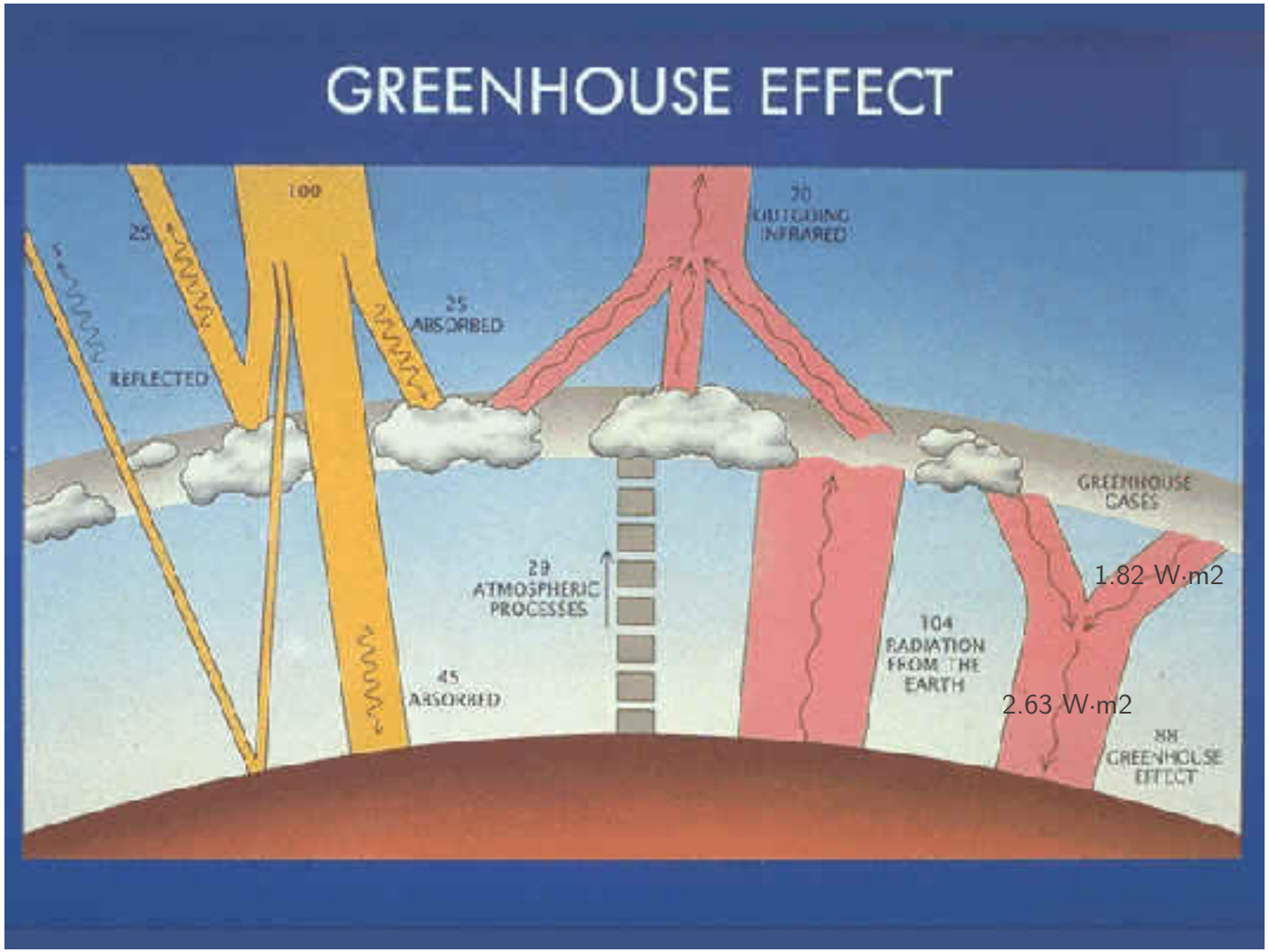
Leakage in the aquifer



Under ground ? -> Earthquake

François Maréchal – francois.marechal@epfl.ch

Greenhouse gases and climate change



- Greenhouse gases = insulation
- CO_2 by human activities
  - 1850 : 290 ppm
  - 1960 : 316 ppm
  - 2000 : 369 ppm
  - 2020 : 414 ppm
  - 2023 : 420 ppm
  - 2024 : 424 ppm

Without the greenhouse effect we would not have liquid water on our planet.

ftp://aftp.cmdl.noaa.gov/products/trends/co2/co2_mm_mlo.txt

François Maréchal – francois.marechal@epfl.ch

SCIENTIFIC EXPLANATION : CO2 AND GREENHOUSE EFFECT

1896

Svante Arrhenius' 1896 Paper

Prof. S. Arrhenius *on the Influence of Carbonic Acid in the Air upon the Temperature of the Ground.*

Philosophical Magazine and Journal of Science
Series 5, Volume 41, April 1896, pages 237-276.

THE
LONDON, EDINBURGH, AND DUBLIN
PHILOSOPHICAL MAGAZINE
AND
JOURNAL OF SCIENCE.

[FIFTH SERIES.]

APRIL 1896.

XXXI. *On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground.* By Prof. SVANTE ARRHENIUS *.

1. *Introduction : Observations of* Langley *on Atmospherical Absorption.*

A GREAT deal has been written on the influence of the absorption of the atmosphere upon the climate. Tyndall † in particular has pointed out the enormous importance of this question. To him it was chiefly the diurnal and annual variations of the temperature that were lessened by this circumstance. Another side of the question, that has long attracted the attention of physicists, is this: Is the mean temperature of the ground in any way influenced by the presence of heat-absorbing gases in the atmosphere? Fourier‡ maintained that the atmosphere acts like the glass of a hot-house, because it lets through the light rays of the sun but retains the dark rays from the ground. This idea was elaborated by Pouillet§; and Langley was by some of his researches led to the view, that "the temperature of the earth under direct sunshine, even though our atmosphere were present as now, would probably fall to −200° C., if that atmosphere did not possess the quality of selective

* Extract from a paper presented to the Royal Swedish Academy of Sciences, 11th December, 1895. Communicated by the Author.
† 'Heat a Mode of Motion,' 2nd ed. p. 435 (Lond., 1865).
‡ *Mém. de l'Ac. R. d. Sci. de l'Inst. de France*, t. vii. 1827.
§ *Comptes rendus*, t. vii. p. 41 (1838).

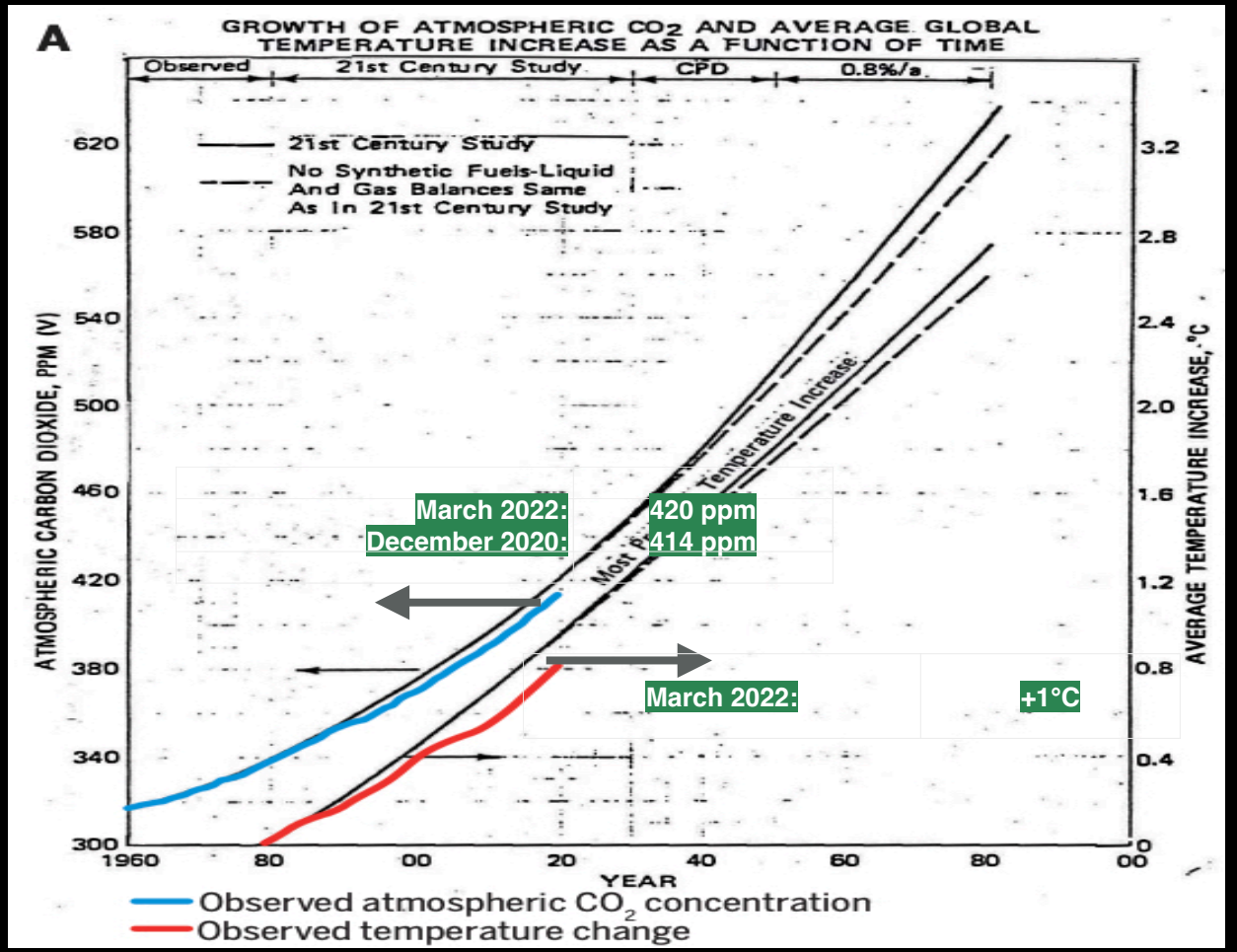
Phil. Mag. S. 5. Vol. 41. No. 251. *April* 1896. S

2x CO_2 in the atmosphere,
T goes up by 5^0 C
Later refined his calculation
to include *feedbacks* to get 2.1^0 C

1982 : INDUSTRY ESTIMATES ITS IMPACT

- Exxon study (1982)

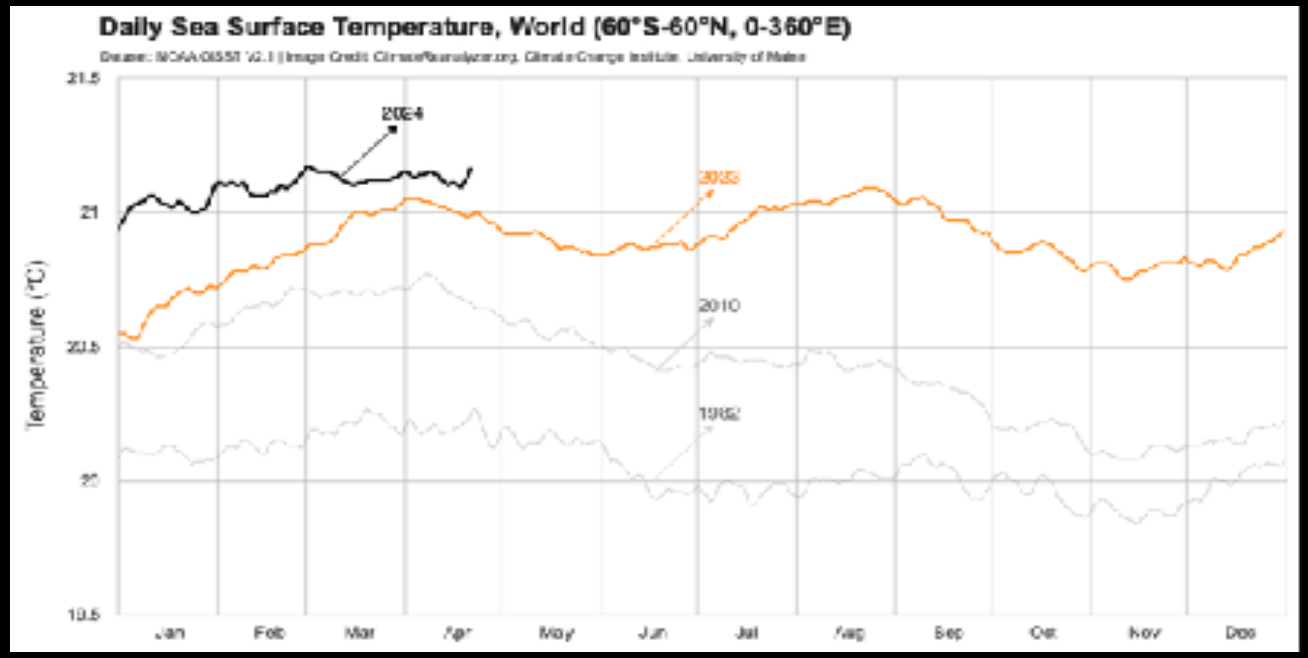
Exxon's private prediction of the future growth of carbon dioxide levels (left axis) and global temperature relative to 1982 (right axis). Elsewhere in its report, Exxon noted that the most widely accepted science at the time indicated that doubling carbon dioxide levels would cause a global warming of 3°C. Illustration: 1982 Exxon internal briefing document



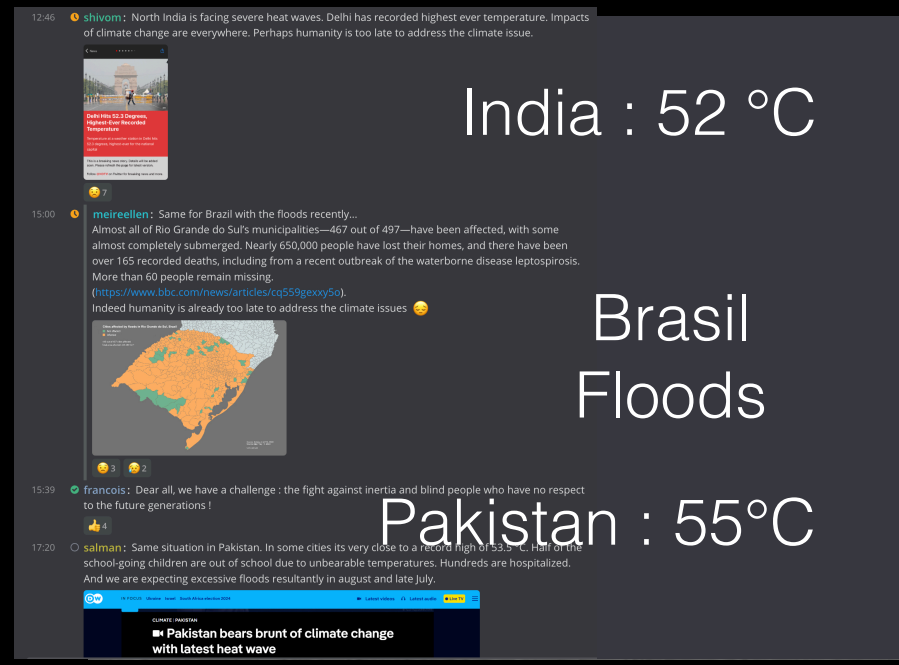
Supran et al., Science 379, 153 (2023) 13 January 2023

Greenhouse gas effect : climate change

Ocean's temperature
90% of the imbalance



Consequences
Mai 2024



India : 52 °C

Brasil
Floods

Pakistan : 55°C

CO2 IS A REAL THREAD !

+ 2°C

In Switzerland

+200 $/t CO2

Costs to you

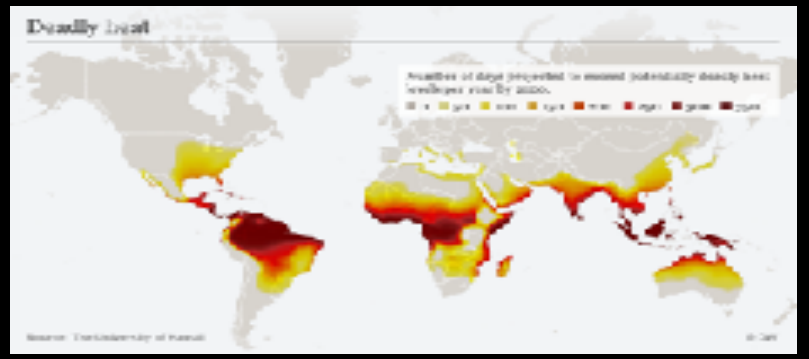
Floodings

Fires and Droughts

Youth Revolution

and scientists…

Heat waves

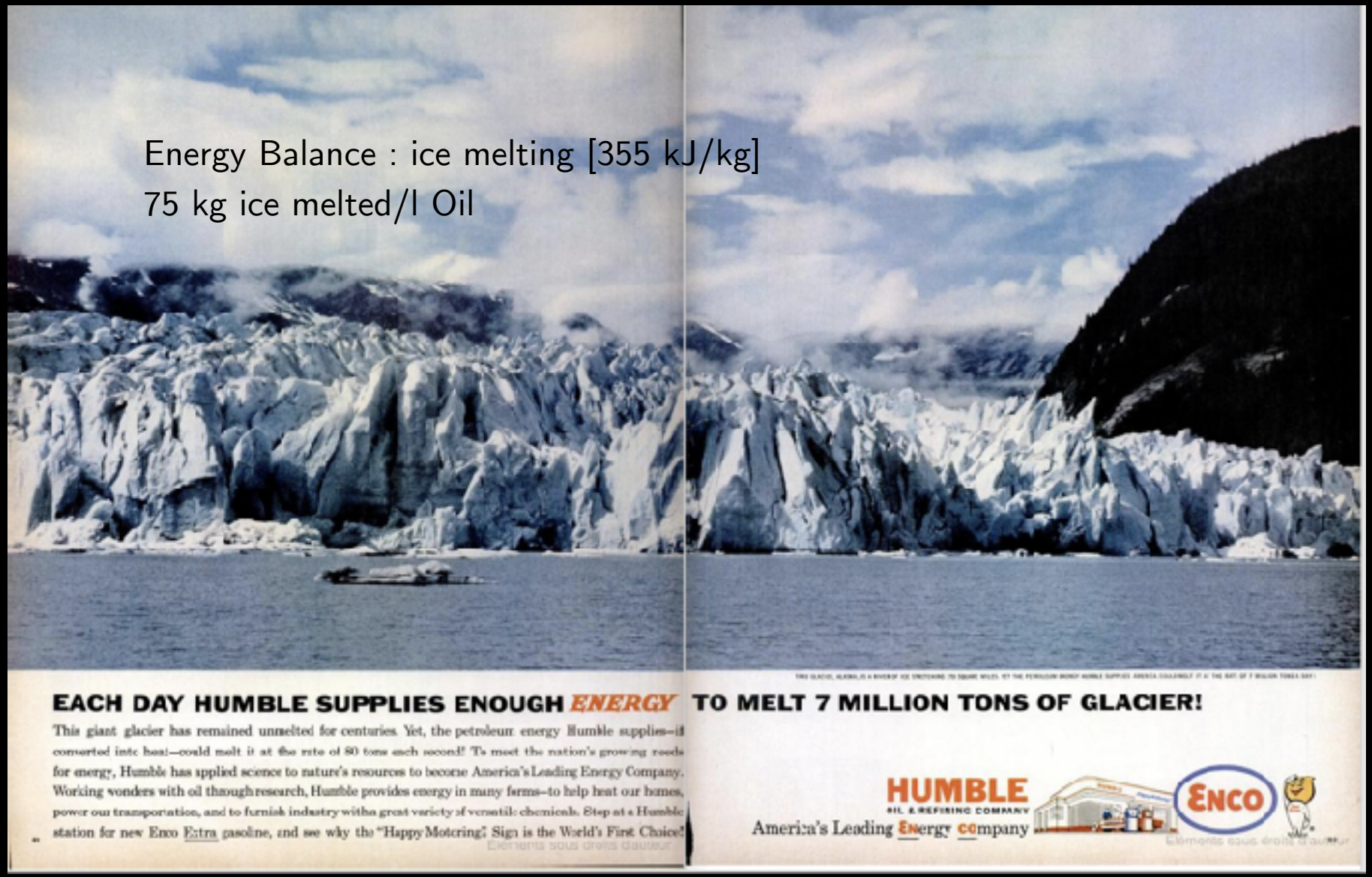


Migration

Zones in the world where the temperature is higher than the cooling temperature of the body

EPFL

IN BEGINNING (1960) THE MAN WAS PROUD OF HIS DISCOVERY



IN REALITY

- From 1970-2021 : climate change
  - 7 kg glacier melted / kg CO2
  - 18.8 kg / litre d'essence
  - 1 kg / km (6l/100 km car)

La grotte de glace s'est probablement effondrée dans la nuit de lundi à mardi.
Arollablabla

Global warming gases emissions

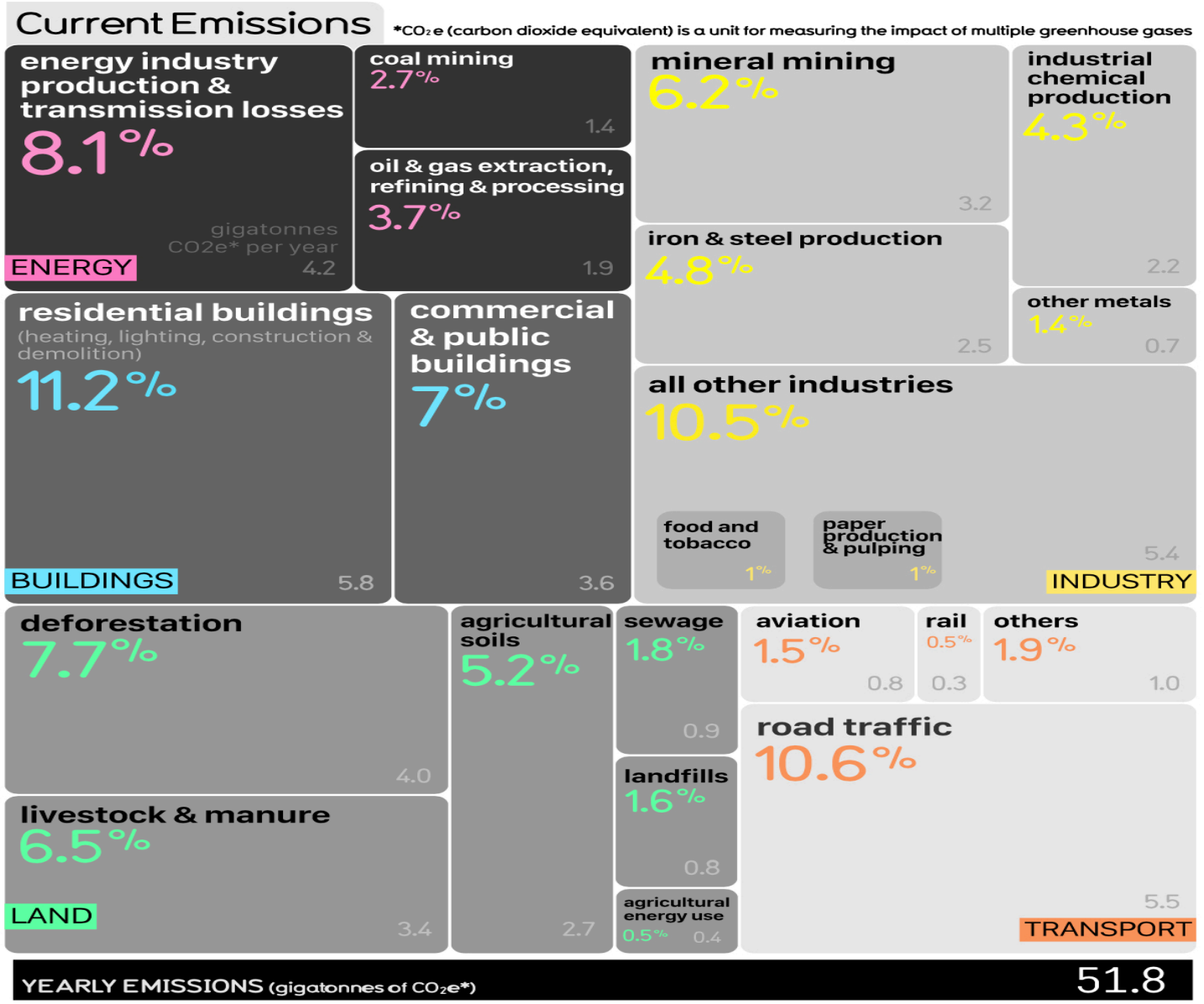
Human activities related

36.5

GT CO2/y

48%

remains in the atmosphere



https://informationisbeautiful.net/visualizations/how-to-reduce-the-worlds-carbon-footprint-by-2050/

François Maréchal – francois.marechal@epfl.ch

CO2 emissions of one Swiss citizen

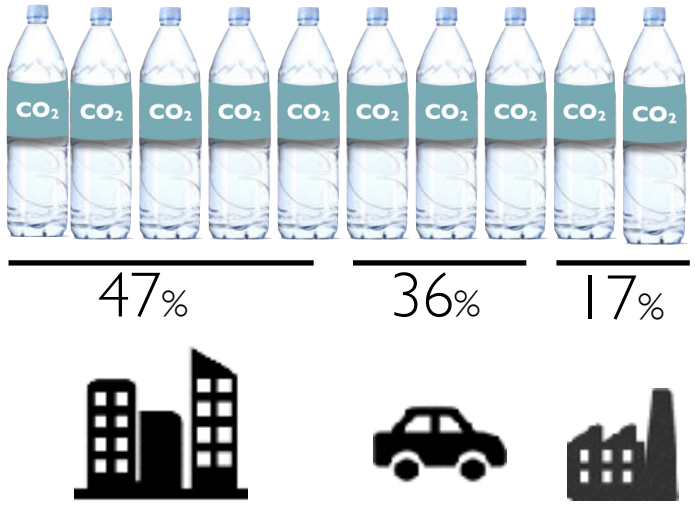
41

kg/day/cap

In Switzerland

15

kg/day/cap



Outside Switzerland

24

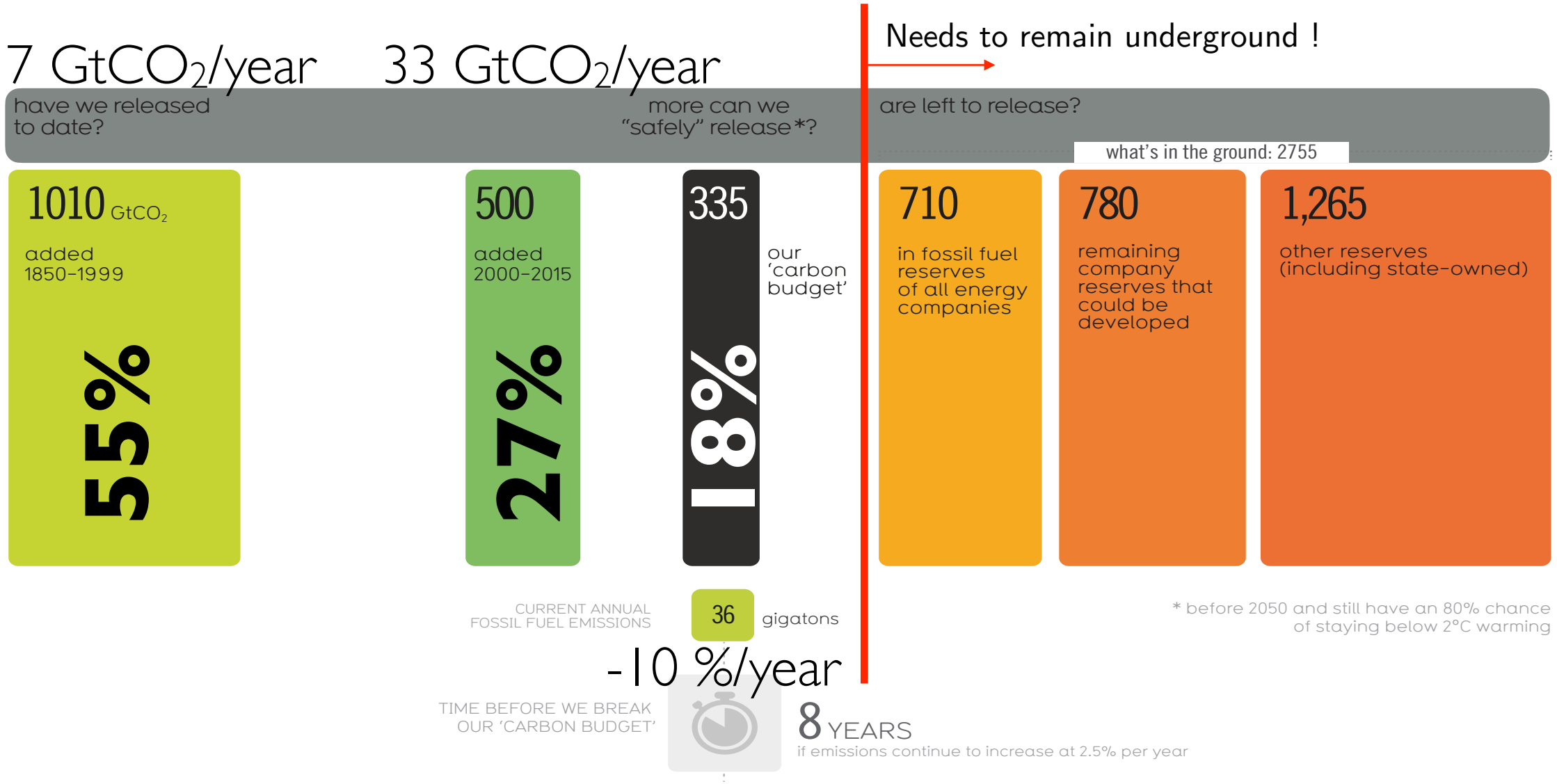
kg/day/cap

2

kg/day/cap

François Maréchal – francois.marechal@epfl.ch

The world carbon emissions and its budget



informationisbeautiful.org All data & workings: http://bit.ly/CO2Gigatons2016

François Maréchal – francois.marechal@epfl.ch

Our chalenge : Engineering the Efficiency for a Net-Zero future

Fossil resources

From where-When-How much - At which cost ?

Renewable resources

Where-When-How much ?

Circularity

Waste to products
CO2 to products
Waste to energy

Waste-Water-Energy

Investments

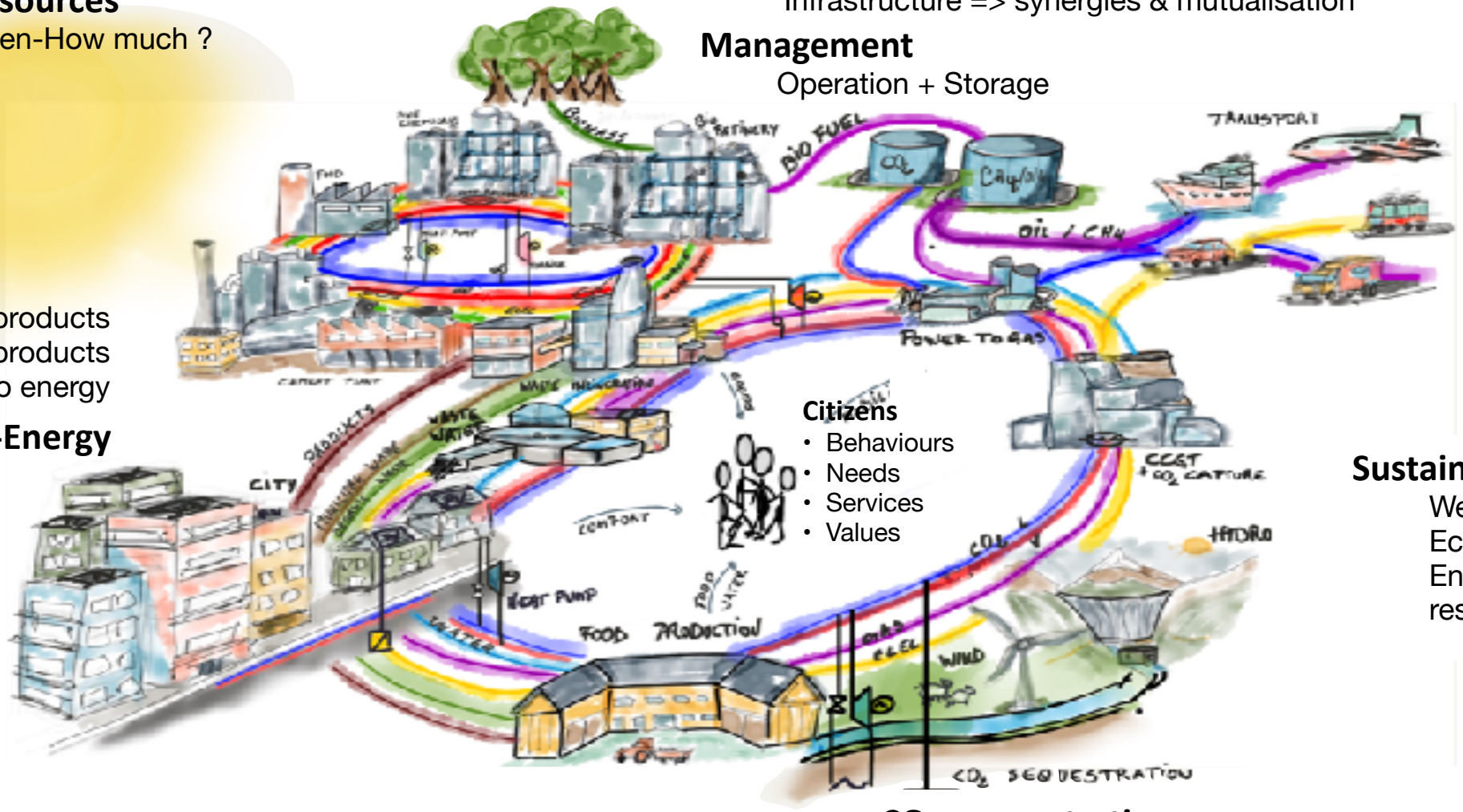
(**New**) Technologies
sizes : conversion and storage
Infrastructure => synergies & mutualisation

Management

Operation + Storage

Demand

Products
Services
Security of supply



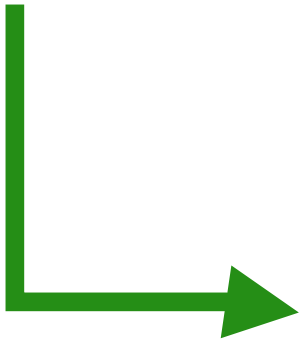
Sustainability metrics

Wealth
Economy
Environment
resiliency

CO2 sequestration

This course : Energy conversion and renewable energy

From Fossil resources
to Renewable resources



Conversion

(**New**) Technologies

Management

Storage

CO2 capture and sequestration

Sustainability metrics

Economy
Environmental
Social

Demand

Products
Services
Security of supply