Renewable Energy

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MER Jan van Herle

Laboratory of Renewable Energy Sciences and Engineering

Administration

- Course:
  - Tuesday: 2h lecture (10:15-12:00), CM15
  - Responsible: Prof. Haussener, ME D0 2926,
    MER van Herle, ME A2 392

- Exercise:
  - Tuesday, 1h exercises (12:15-13:00), CM 1105
  - Responsible part Haussener: Natalie Frassl and Guilherme Armas
- Remarks:
  - Expected contributions from your side:
    4 credits ≈ 4x30 hours = 120 hours
    14x3 hours lecture/exercise → 120-42 = 78 hours at home/library
    = 5.5 hours/week at home/library

Administration

- Exam: written at the end of the semester

  closed books, only calculator and 10 A4 pages (single sided, or 5 pages double sided) personal summary can be used

- Course notes and exercises are online before the lecture (moodle.epfl.ch)

  Please print them individually if you need a printout

- References (complementary):
  - David McKay, Sustainable Energy – without the hot air, UIT Cambridge (available on web)
  - Kreith and Goswami, editors, Handbook of energy efficiency and renewable energy, Taylor and Francis Group, 2007.

Course structure

<u>Outline</u>

1. Introduction to energy economy
2. Revisiting power cycles
3. Electrochemistry and batteries
4. Storage
5. Hydrogen
6. Solar:
    - Solar thermal
    - Solar electricity
    - Solar fuels
7. Biomass:
    - Biofuels
    - Biomass to electricity
8. Wind
9. Geothermal
10. Hydro, ocean, tidal, wave

Course structure

	Lecture Tuesday (10:15-12:00)	Lecturer	Exercise Tuesday (12:15-13:00)
Week 1 (17.2)	Introduction	SH	Exercise 1
Week 2 (24.2)	Power cycles, ORC, co-generation	SH	Exercise 2
Week 3 (3.3)	Electrochemistry, batteries	SP	Exercise 3
Week 4 (10.3)	Storage	SP/SH	Exercise 4
Week 5 (17.3)	Hydrogen	SH	Exercise 5
Week 6 (24.3)	Solar thermal	SH	Exercise 6
Week 7 (31.3)	Solar electricity	SH	Exercise 7
Week 8 (14.4)	Solar fuels	SH	Exercise 8
Week 9 (21.4)	Biomass	JVh	Exercise 9
Week 10 (28.4)	Biomass	JVh	Exercise 10
Week 11 (5.5)	Wind	JVh	Exercise 11
Week 12 (12.5)	Wind	JVh	Exercise 12
Week 13 (19.5)	Geothermal	JVh	Exercise 13
Week 14 (26.5)	Ocean, tidal and wave	JVh	Exercise 14

What you will learn in this course:

- What is renewable energy?

- What are it's current/future contribution to energy supply?

- For the different renewable energy sources:
  - the potential: theoretical vs. realistic
  - the essential physics and chemistry for conversion and storage
  - approaches to «harness» them
  - status of the technologies
  - the most useful applications and complementarities

- Renewable power plants you will know:
  B-IGCC, PV, CSP, PEC, EGS, (μ)CHP, ...

Order of magnitude understanding

How much solar energy falls on 1 m^2 in 1 s on a nice sunny day at noon ?

- ○ 1 J
- ○ 10 J
- ○ 100 J
- ✗ 1000 J

… and in winter, during any day, at any latitude?

Order of magnitude understanding

How much power can a water turbine develop from water flowing at 1 m^3/s and falling from 100 m high ?

- ○ 10 kW
- ○ 100 kW
- ✗ 1 MW
- ○ 10 MW

… and how big a wind turbine must be to develop the same power from a typical wind speed?

… (and what wind speed is 'typical'?)

Order of magnitude understanding

How much power is contained in an ocean wave (per m width), 1 m high, and of wavelength 100 m ?

- ○ 1 kW / m
- ○ 3 kW / m
- ○ 10 kW / m
- ✗ 30 kW / m

… and its difference to tidal power?

Order of magnitude understanding

How deep do we have to drill the earth soil to find it hot at 300°C ?

- ○ 300 m
- ○ 1 km
- ○ 3 km
- ✗ 10 km

... and then how can we convert this to electrical power ?

… and furthermore:

- is heat pumping from the soil renewable?
- are bioethanol and biodiesel going to replace petrol?
- what about the biomass-energy competition with food ?
- can we go 100% renewable?
- ‘there is 10’000 times more solar energy around than what all humans consume around the planet, no worries!’
- it’s just of matter of cost?
- But renewable energy is free fuel, isn’t it?
- … or a matter of time, for fossil fuels to run out?
- … or of progress in new technologies?
- … or of political incentive and subsidies?

What you are expected to know at the end

- the real potential of the different renewable sources
- use mass, momentum, and energy balance to estimate orders of magnitude
- be able to easily grasp and switch between kWh, MJ, GW, Mtoe, TWh, …
- the right orders of magnitude (energy and power)
- the technologies to harvest fossil and renewable energies
- explain and calculate the main emission sources of energy conversion processes
- their best service in the energy supply spectrum
- be able to solve the exercises

Common energy units

• 10^6	mega	M	MJ	MW	MWh
• 10^9	giga	G	GJ	GW	GWh
• 10^{12}	tera	T	TJ	TW	TWh
• 10^{15}	peta	P	PJ		
• 10^{18}	exa	E	EJ		

TWh terawatthour = 10^{12} Wh = 1000 GWh = 3.6 PJ (electricity)

GWh gigawatthour = 10^9 Wh = 3600 GJ (electricity)

Mtoe megatonne-oil-equivalent = 10^9 (kg) x 41.9 (MJ/kg) = 41.9 PJ

EPFL

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 (~100 hp)

From resources to products

- **The energy used is not the energy that is harvested**

- **Energy resources (primary energy)**
  - Non renewable (from a reservoir)
  - Renewable (capturing the sun energy and incorporating into a system)

- **Energy services (final Energy)**
  - Temperature in a room
  - Data from internet
  - Mobility

Definitions

- **Primary energy consumption**
  - Energy contained in raw fuels before the start of the conversion chain.

- **Final (distributed) energy consumption**
  - Energy received by consumers and businesses, not including the energy losses in the conversion sector, and from distribution. This indicator evaluates the participation of each type of fuel (solid fuels, oil, gas, renewables)

Let's enumerate all energy sources we know…

BIOMASS

WIND

WASTES

COAL

GAS

SOLAR – DIRECT

HYDRO

TIDES

NUCLEAR

GEOTHERMAL

OIL

SOLAR – P.V.

WAVES

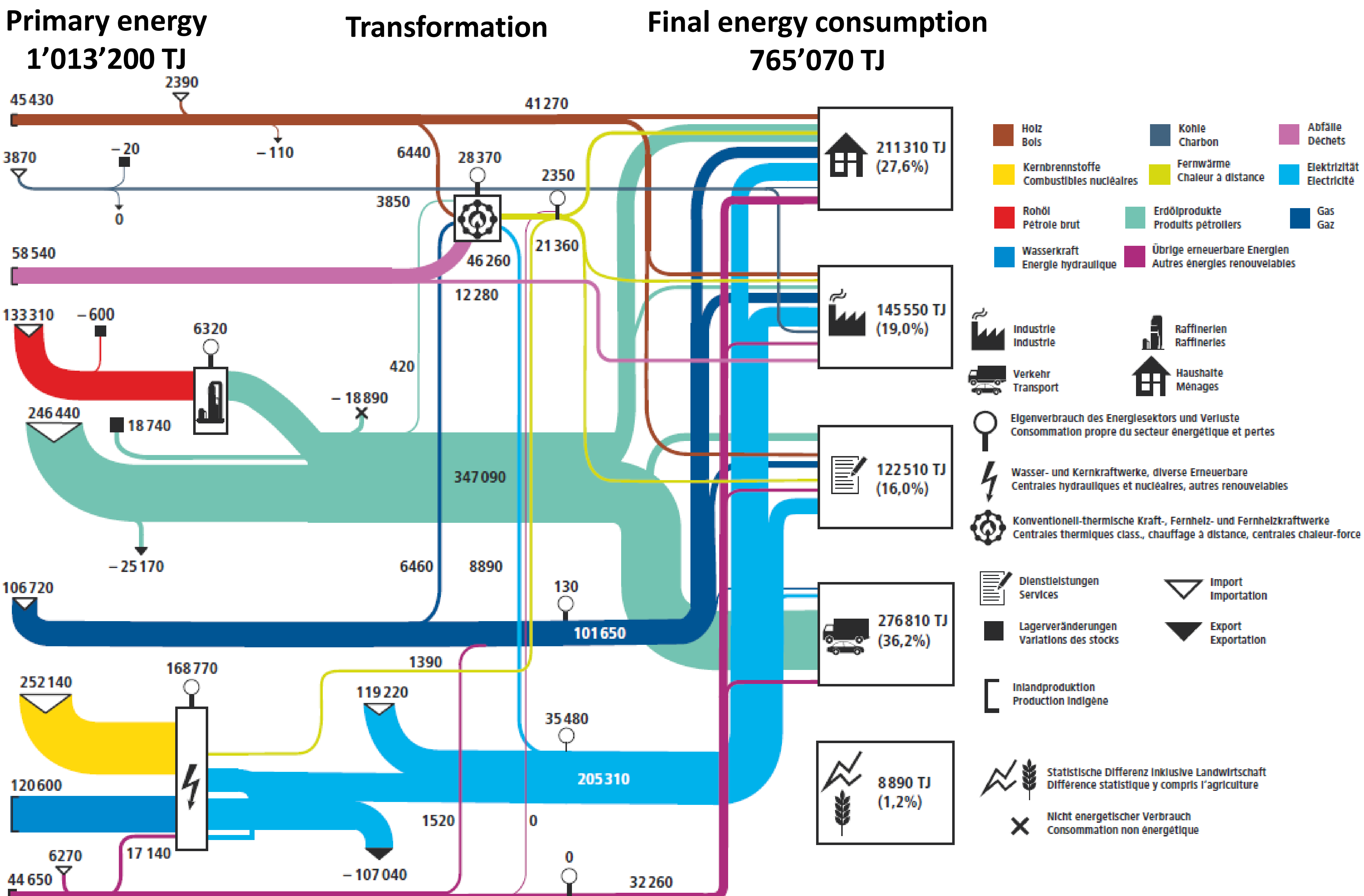
SOLAR – THERMAL

…and see how we have been using these

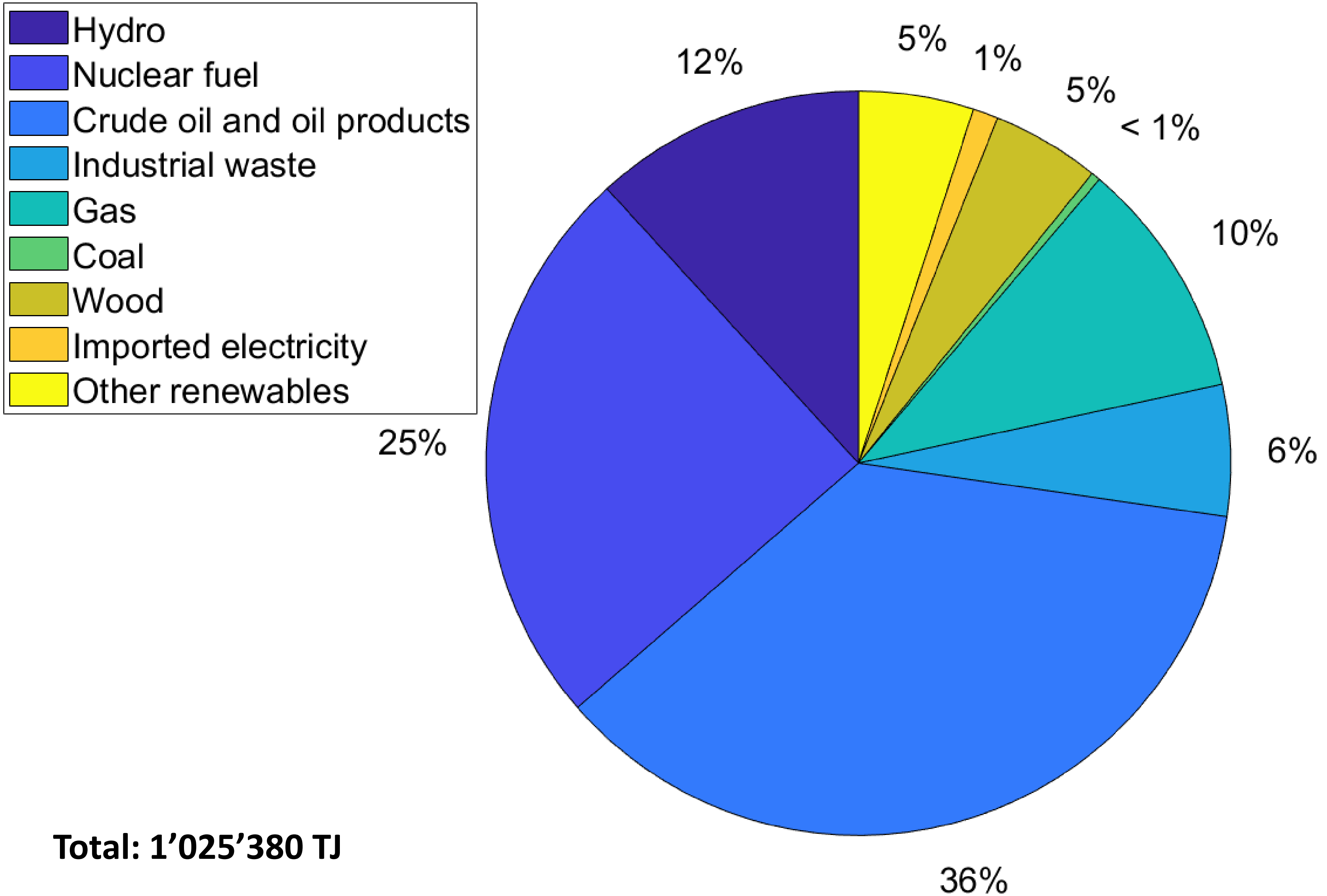
Switzerland - Energy

Where do we stand today? Switzerland

Schweizerische Gesamtenergiestatistik 2022
Bundesamt für Energie



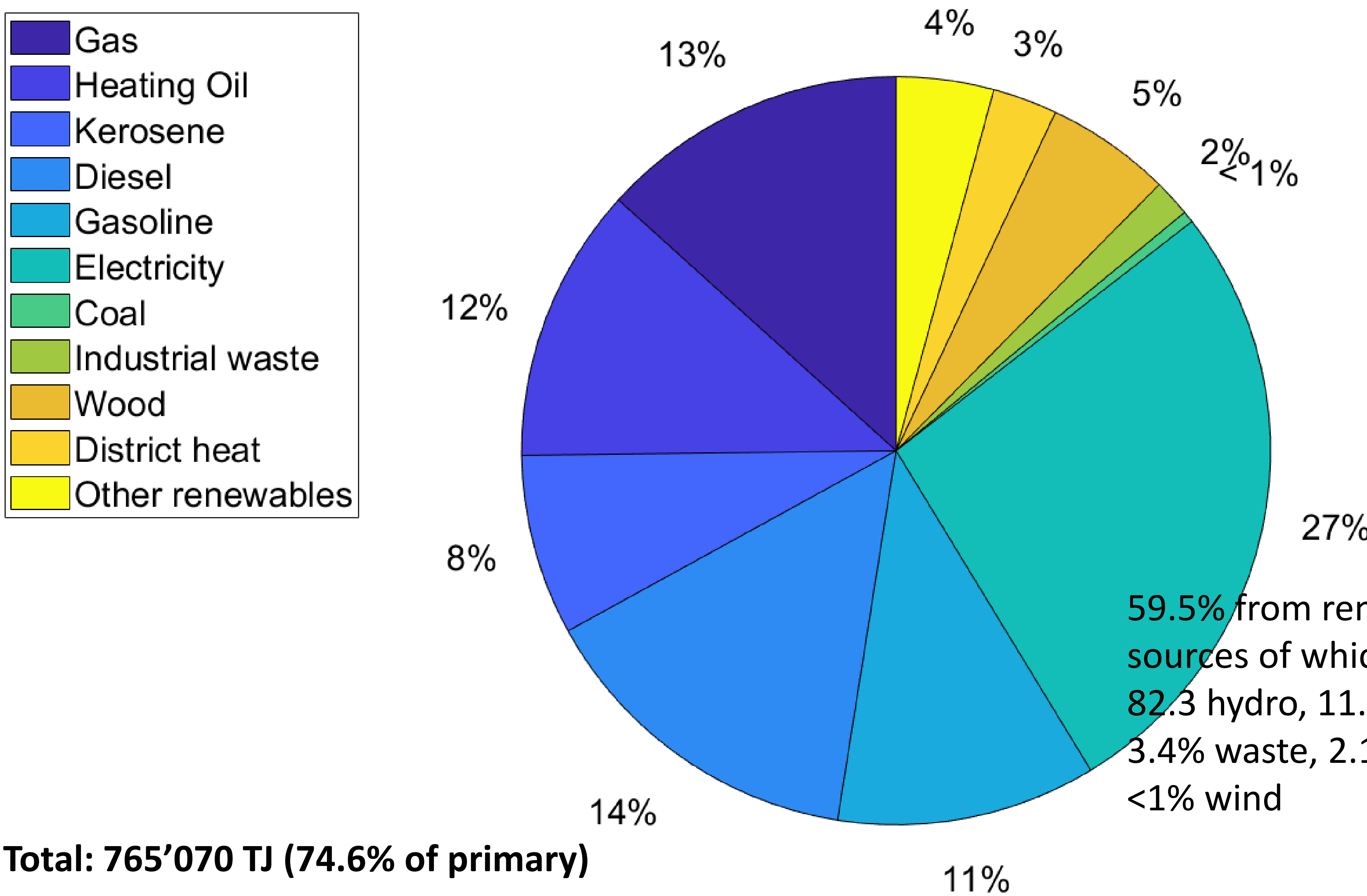
Primar Energy - CH 2022



Total: 1’025’380 TJ

Other renewables: Solar, wind, biogas, biofules, environmental heat

Final Energy - CH 2022



59.5% from renewable sources of which: 82.3 hydro, 11.4% solar, 3.4% waste, 2.1% biomass, <1% wind

Total: 765'070 TJ (74.6% of primary)

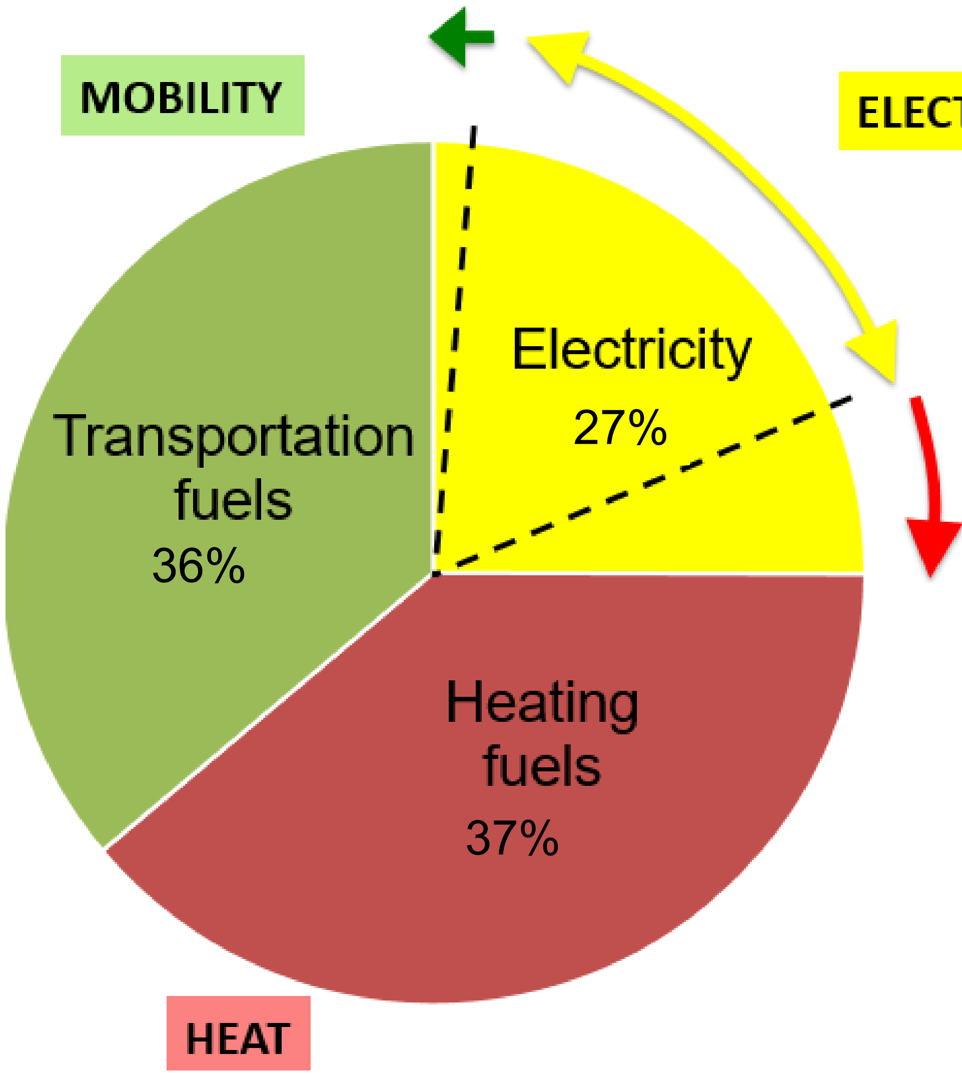
Other renewables (4.2%): Solar (0.3%), environmental heat (2.7%), biofules (0.9%), biogas (0.2%)

EPFL

Energy per capita and year: 2.775 kW/cap

End-use shares by application

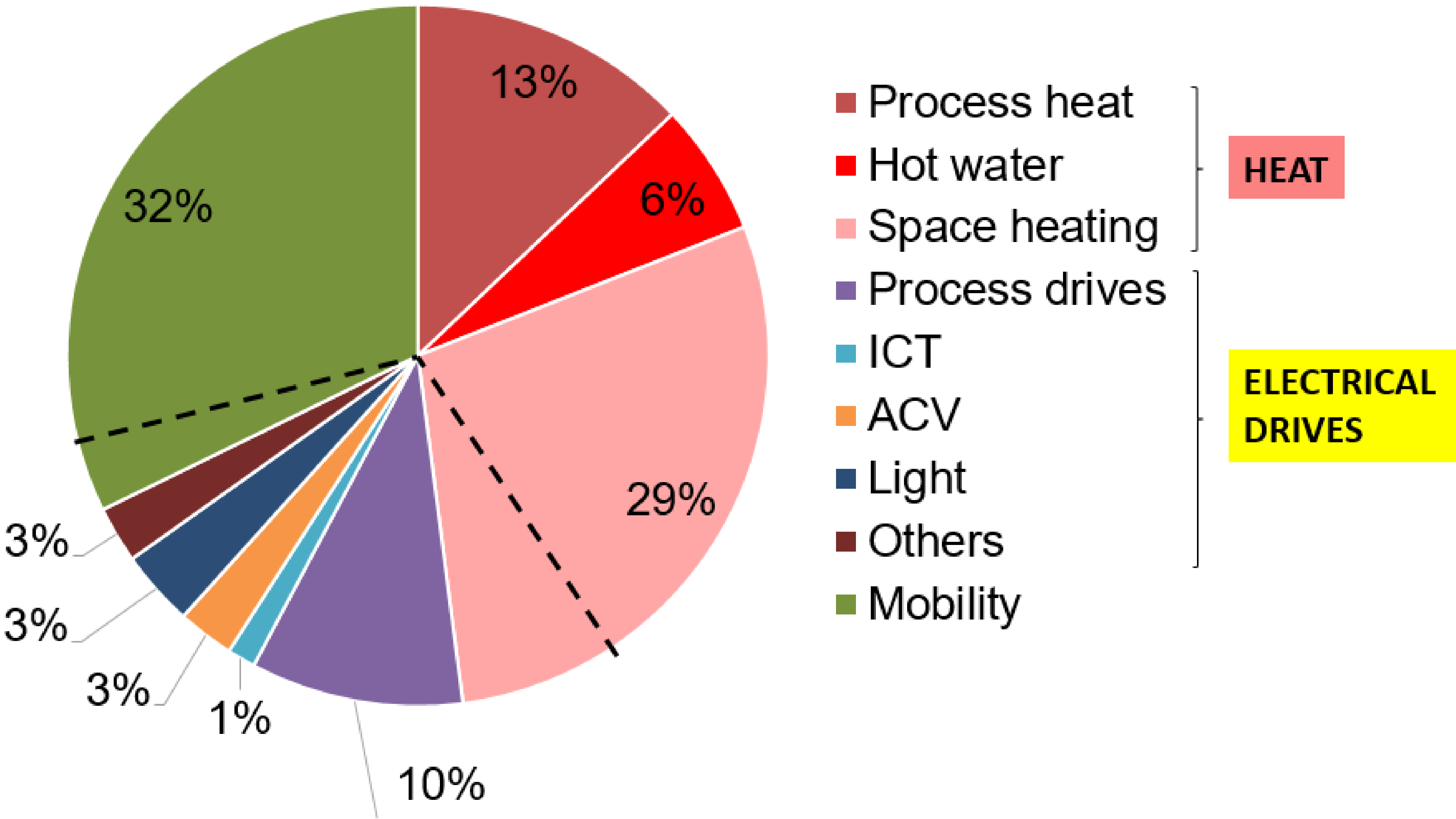
6.3% of electricity used in transport
(mostly railway: 89%)



ELECTRICAL DRIVES

Part of electricity (ca. 30%) used in heating:
9 PJ for heat pumps
and ~ 53 PJ for direct electric heating
(2/3 process heat and 1/3 space heat)

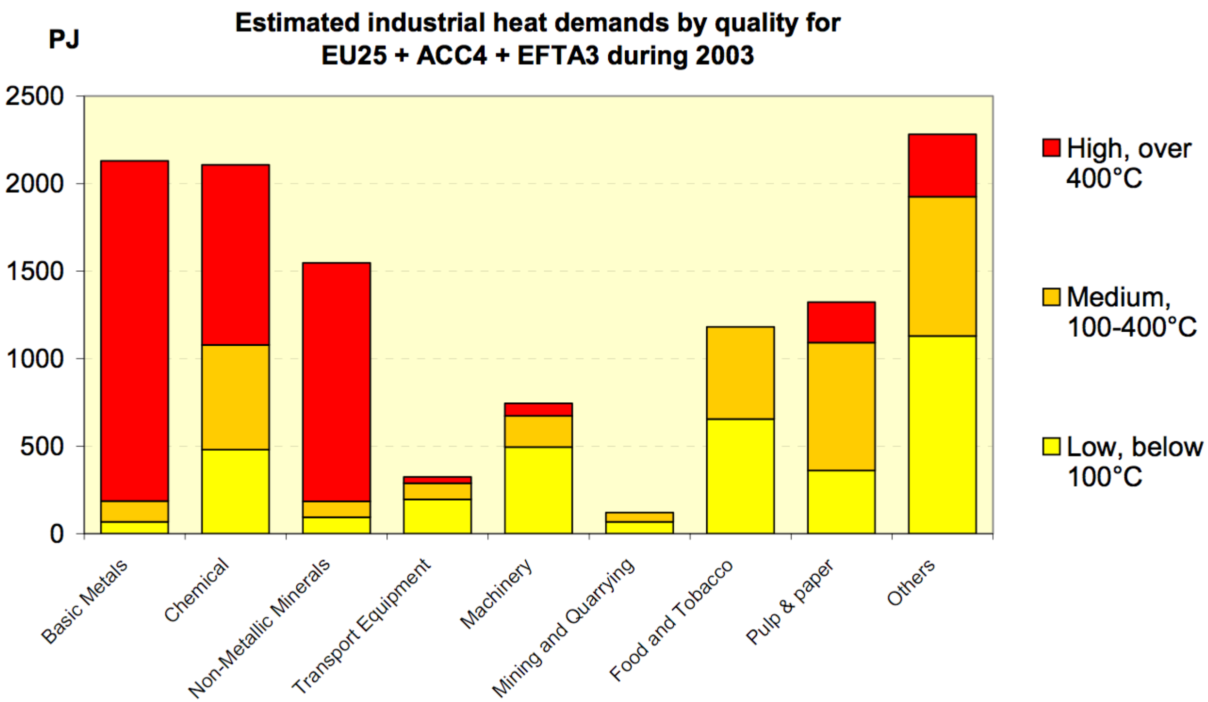
End-use by application: detail



Final energy use …

- There are 5 energy end services:

  - Space heat 20°C
  - Sanitary hot water 40°C
  - Process heat >40°C
  - Electricity
  - Mobility

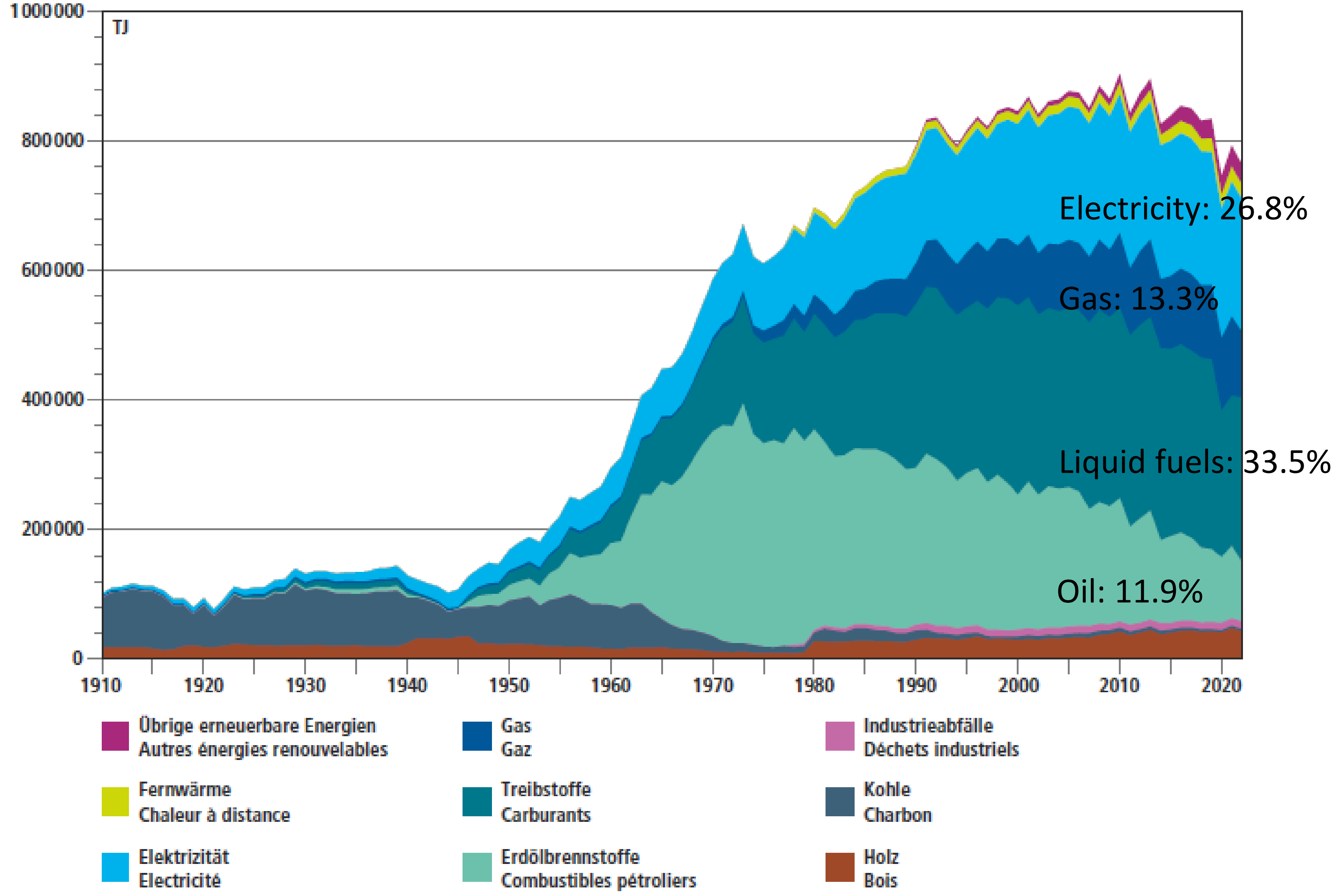


[2]ECOHEATCOOL, *The European Heat Market*, 2006

… and primary energy supply

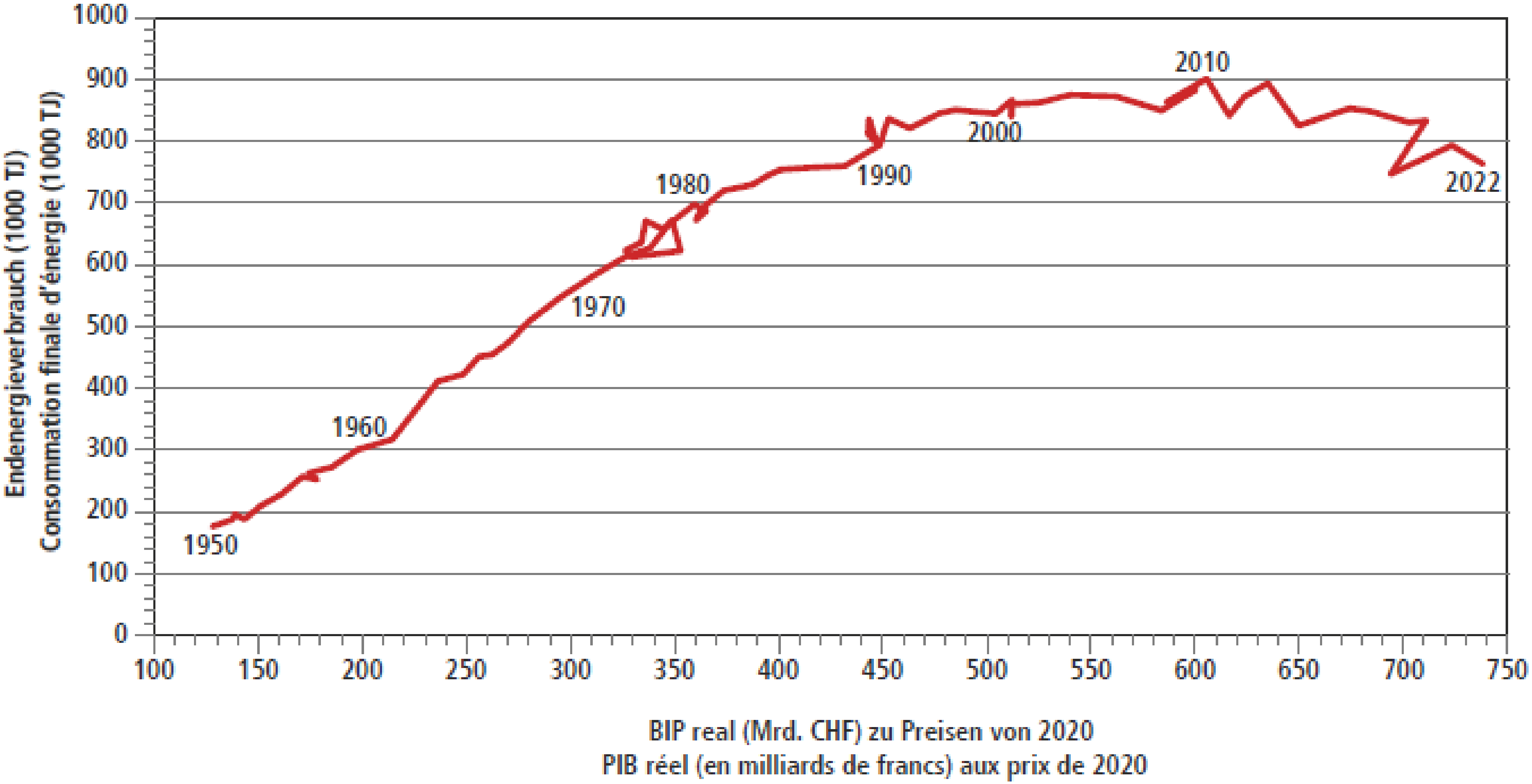
- Key is to supply these end services in the most meaningful ways, considering:
  - Temperature level
  - Thermodynamics
  - Conversion technology
  - Scale of service / technology
  - **Efficiency**
  - **Savings**
  - Emissions, pollution, impact,…

Temporal evolution of final energy use



The link with the PIB

Fig. 15 Zusammenhang zwischen Energieverbrauch und wirtschaftlicher Entwicklung (1950–2022)
Relation entre la consommation finale et l'évolution économique (1950–2022)

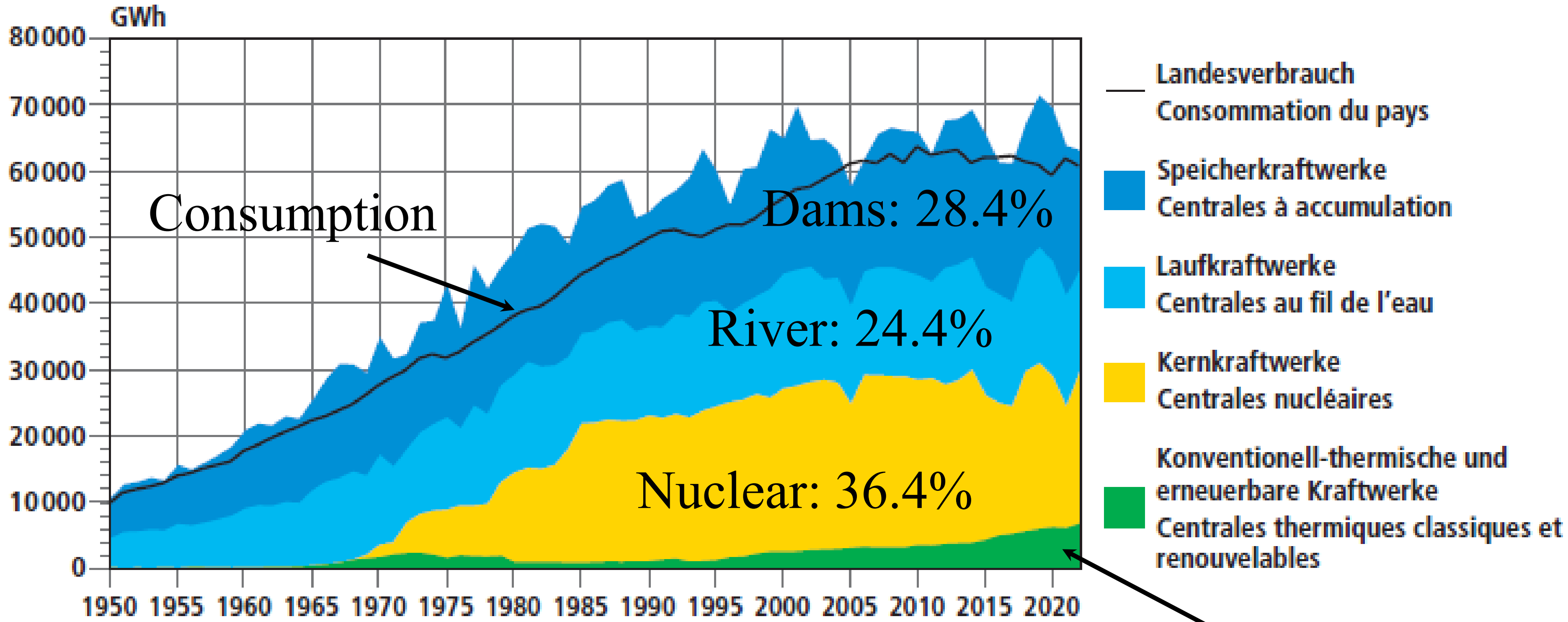


BFE, Schweizerische Gesamtenergiestatistik 2022 (Fig. 15)
OFEN, Statistique globale suisse de l'énergie 2022 (fig. 15)

Switzerland - Electricity

Temporal evolution of electricity production

Fig. 9 Entwicklung der einzelnen Erzeugerkategorien seit 1950
Evolution des différentes catégories de production depuis 1950

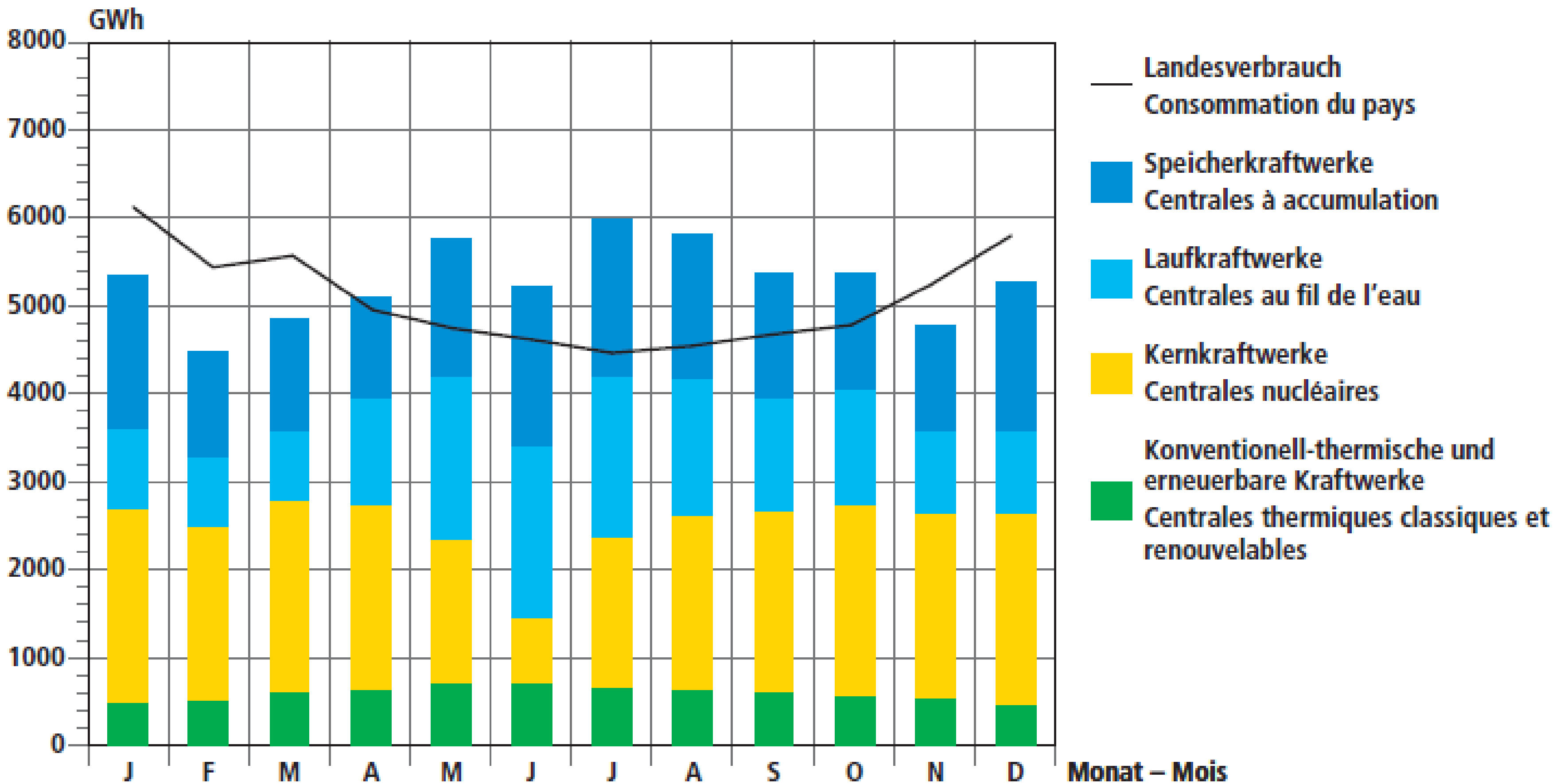


BFE, Schweizerische Elektrizitätsstatistik 2022 (Fig. 9)
OFEN, Statistique suisse de l'électricité 2022 (fig. 9)

Conventional thermal and new renewables: 10.8%

Electricity balance: Production vs Consumption

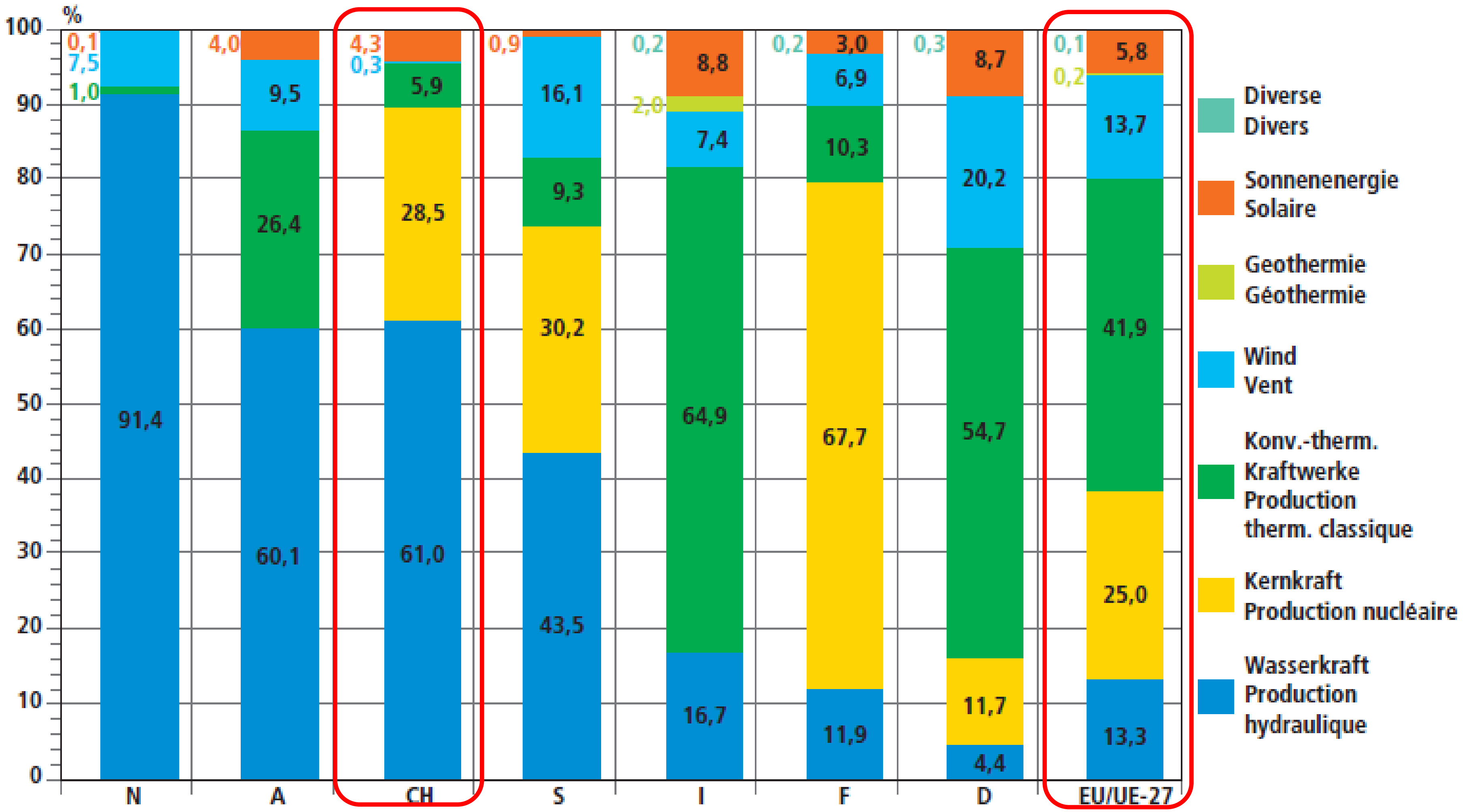
Fig. 10 Monatliche Erzeugungsanteile und Landesverbrauch im Kalenderjahr 2022
Quotes-parts mensuelles et consommation du pays durant l'année civile 2022



BFE, Schweizerische Elektrizitätsstatistik 2022 (Fig. 10)
OFEN, Statistique suisse de l'électricité 2022 (fig. 10)

Electricity production in Europe

Fig. 5 Produktionsstruktur einiger Länder 2021
Structure de production de divers pays 2021

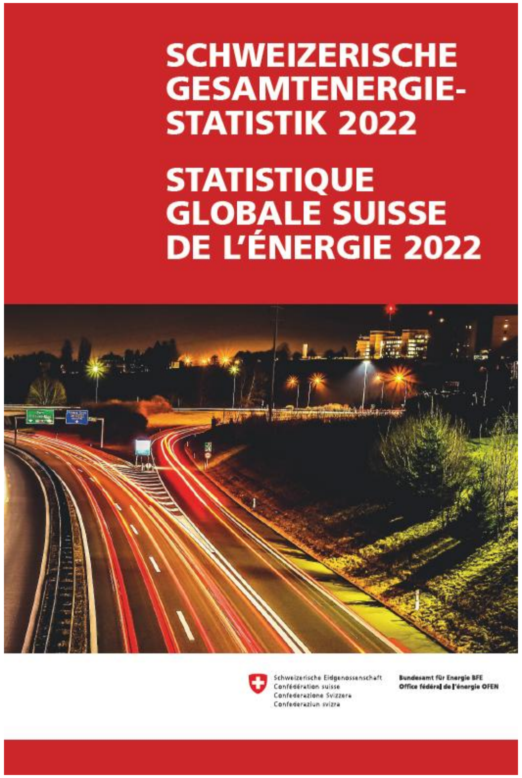


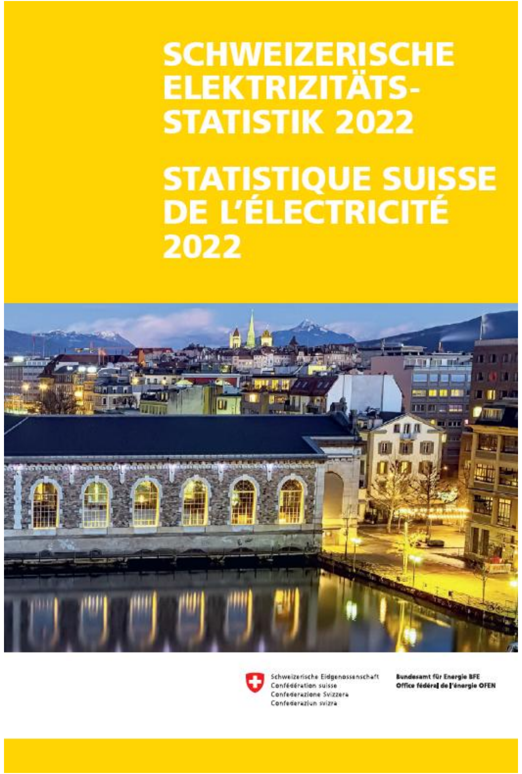
BFE, Schweizerische Elektrizitätsstatistik 2022 (Fig. 5)
OFEN, Statistique suisse de l'électricité 2022 (fig. 5)

Energy in Switzerland

The Swiss Energy …

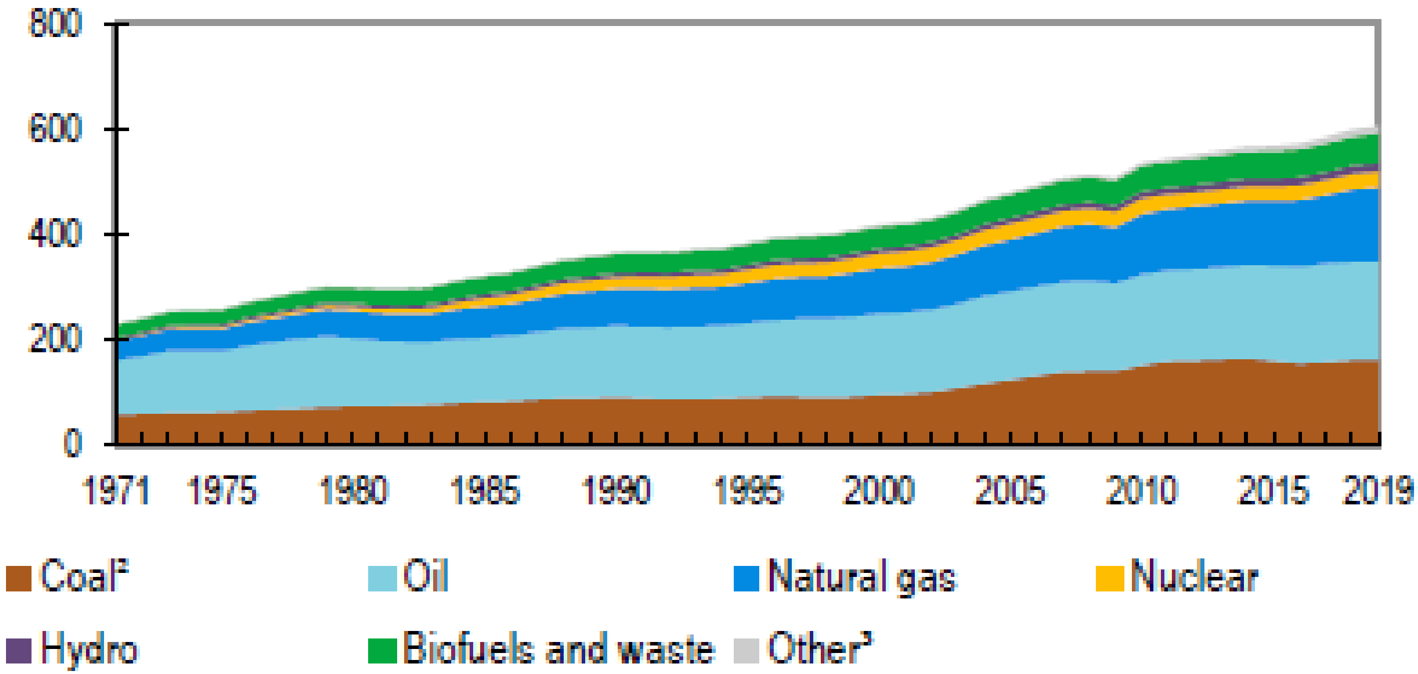
www.bfe.admin.ch





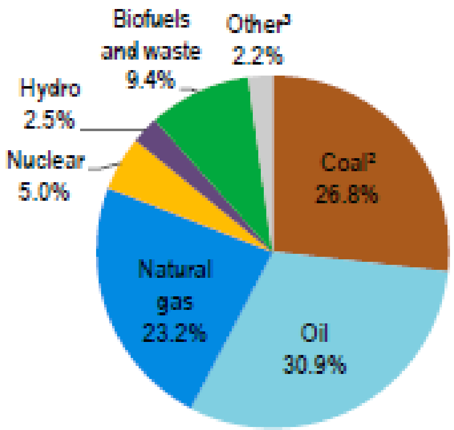
Global - Energy

Where do we stand today? Global

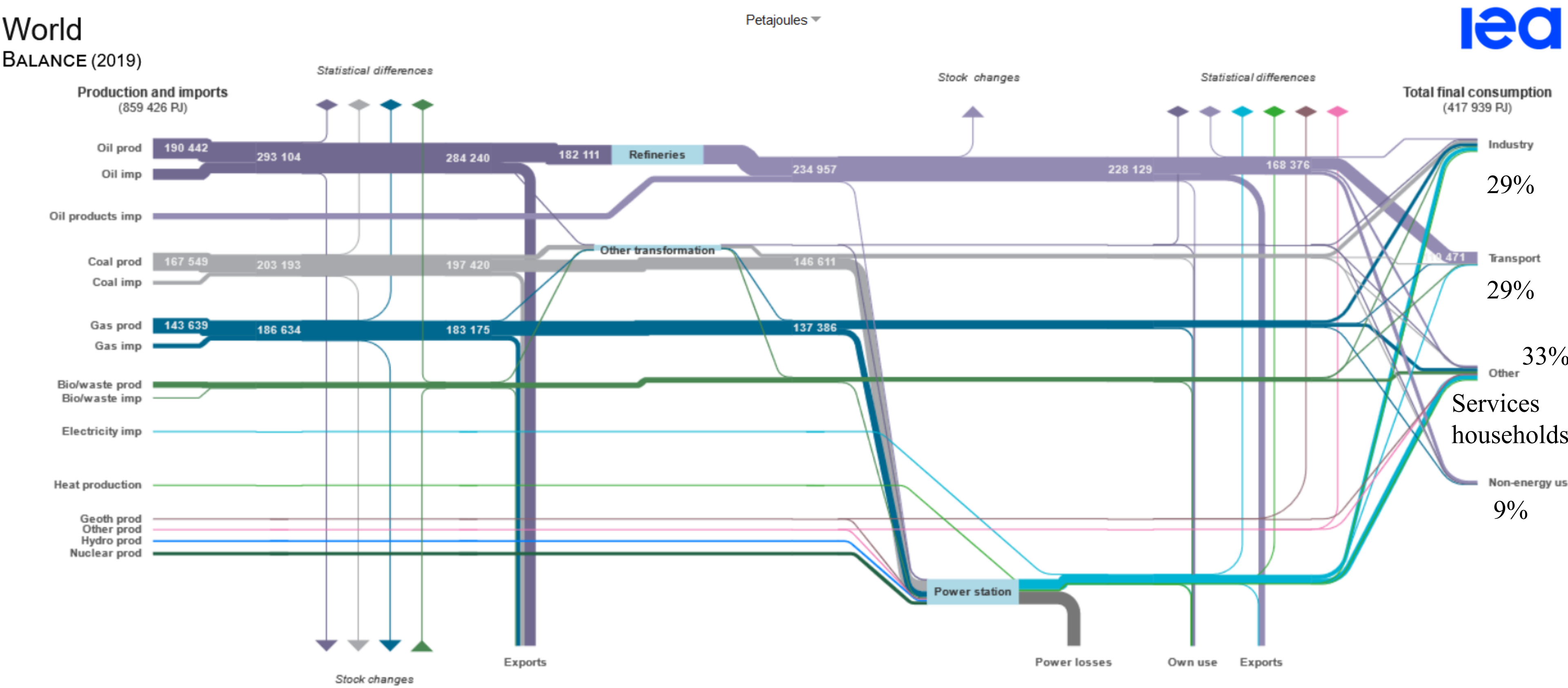


2019: 606 EJ

86% Non-renewable



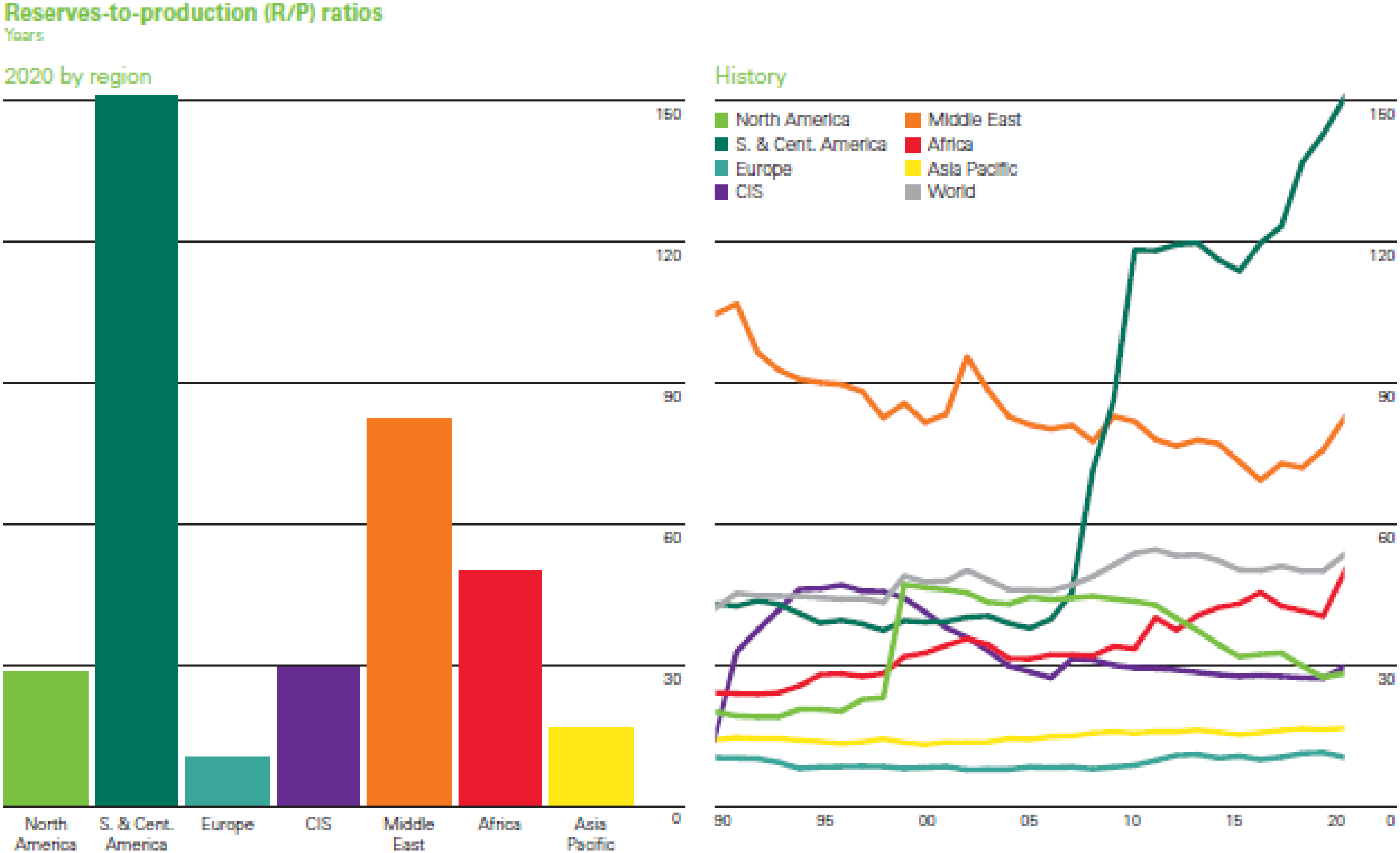
The World Energy Balance



72% of electricity is fossil based
52% losses in electricity generation

Oil reserves

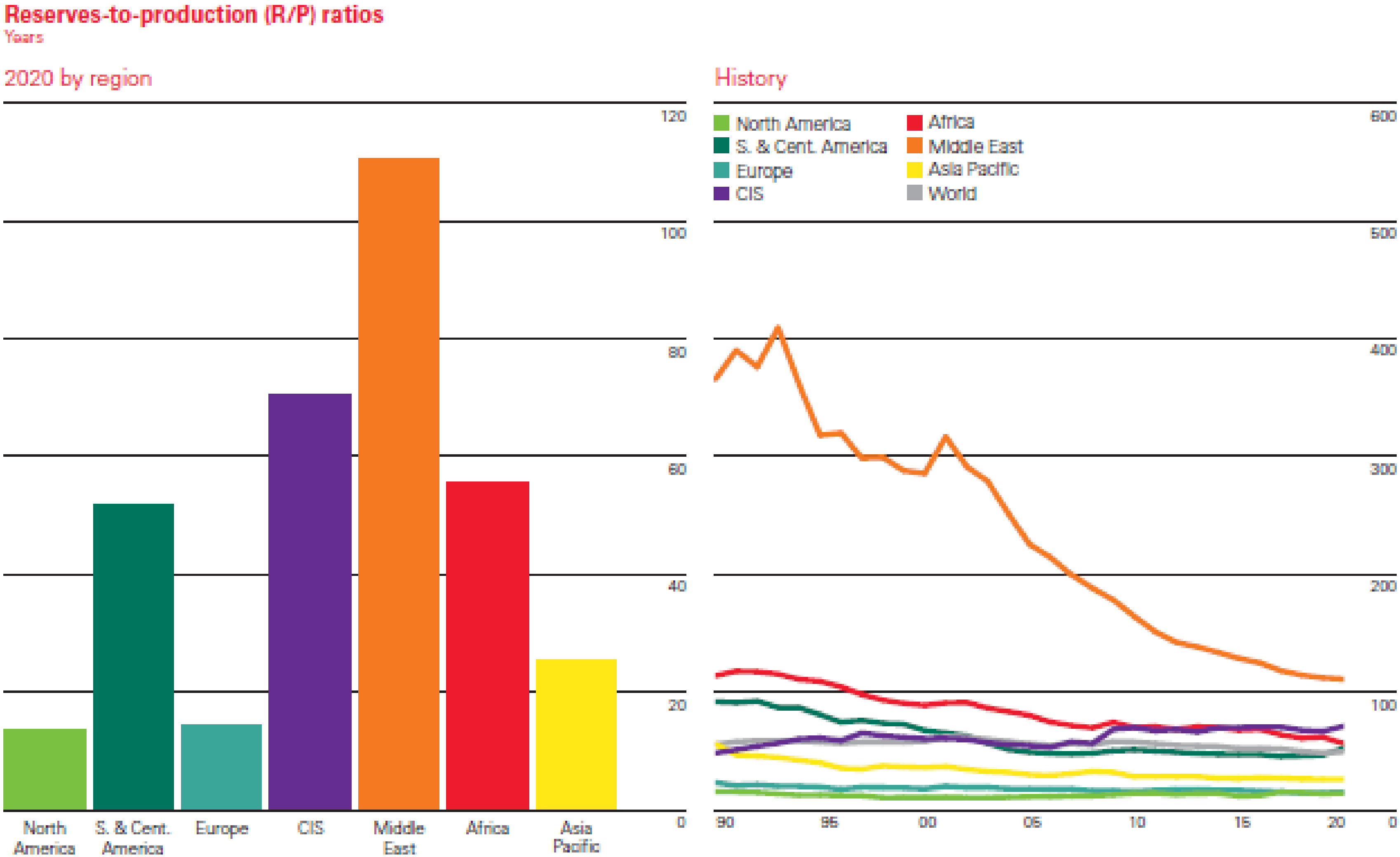
BP World energy statistics review 2021



Global proved oil reserves were 1732 billion barrels at the end of 2020, down 2 billion barrels versus 2019. The global R/P ratio shows that oil reserves in 2020 accounted for over 50 years of current production. OPEC holds 70.2% of global reserves. The top countries in terms of reserves are Venezuela (17.5% of global reserves), closely followed by Saudi Arabia (17.2%) and Canada (9.7%).

Gas reserves

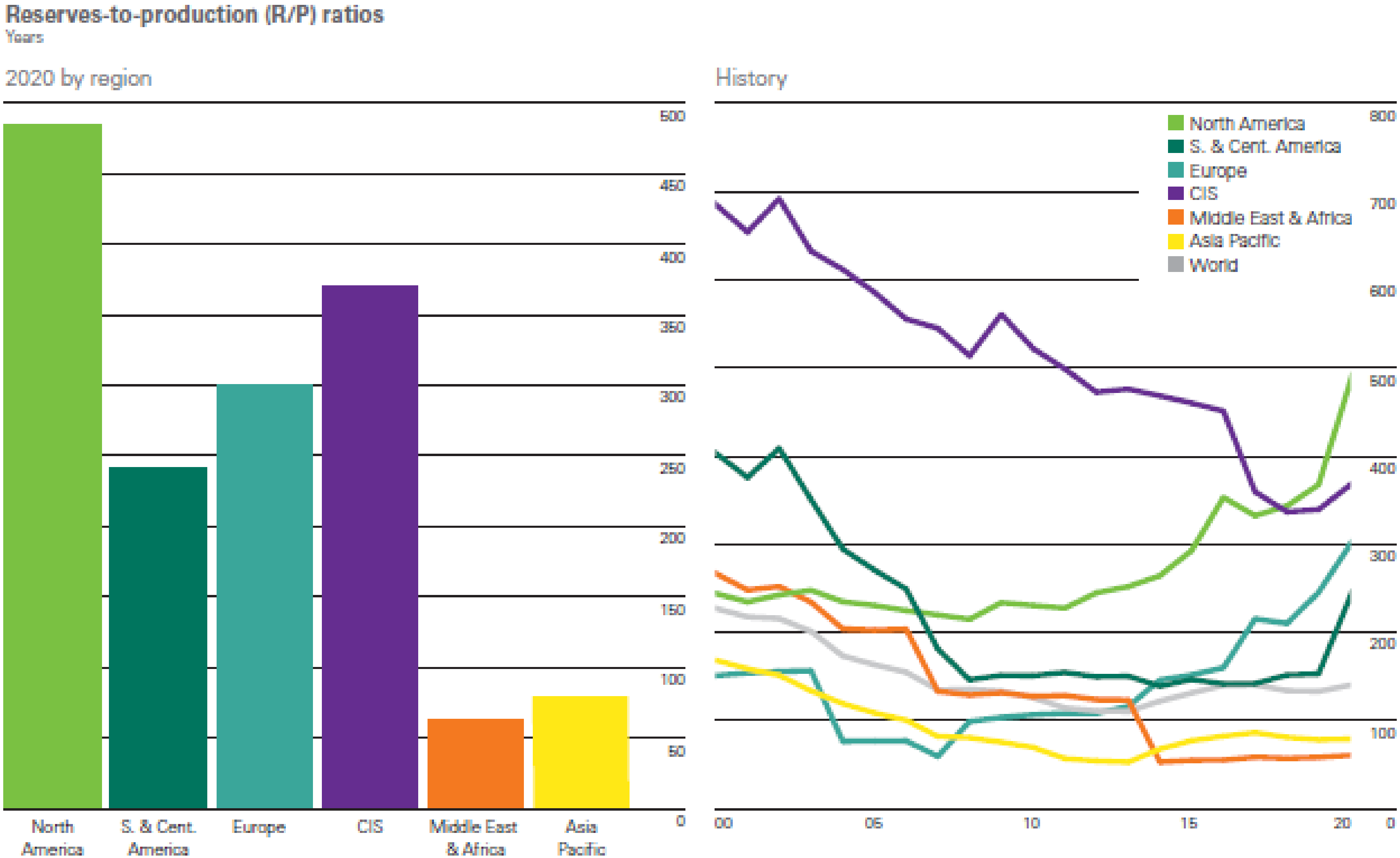
BP World energy statistics review 2021



World proved gas reserves decreased by 2.2 Tcm to 188.1 Tcm in 2020. A revision to Algeria (-2.1 Tcm) provided the largest decrease, partially offset by a 0.4 Tcm increase in Canadian reserves. Russia (37 Tcm), Iran (32 Tcm) and Qatar (25 Tcm) are the countries with the largest reserves. The current global R/P ratio shows that gas reserves in 2020 accounted for 48.8 years of current production. The Middle East (110.4 years) and CIS (70.5 years) are the regions with the highest R/P ratio.

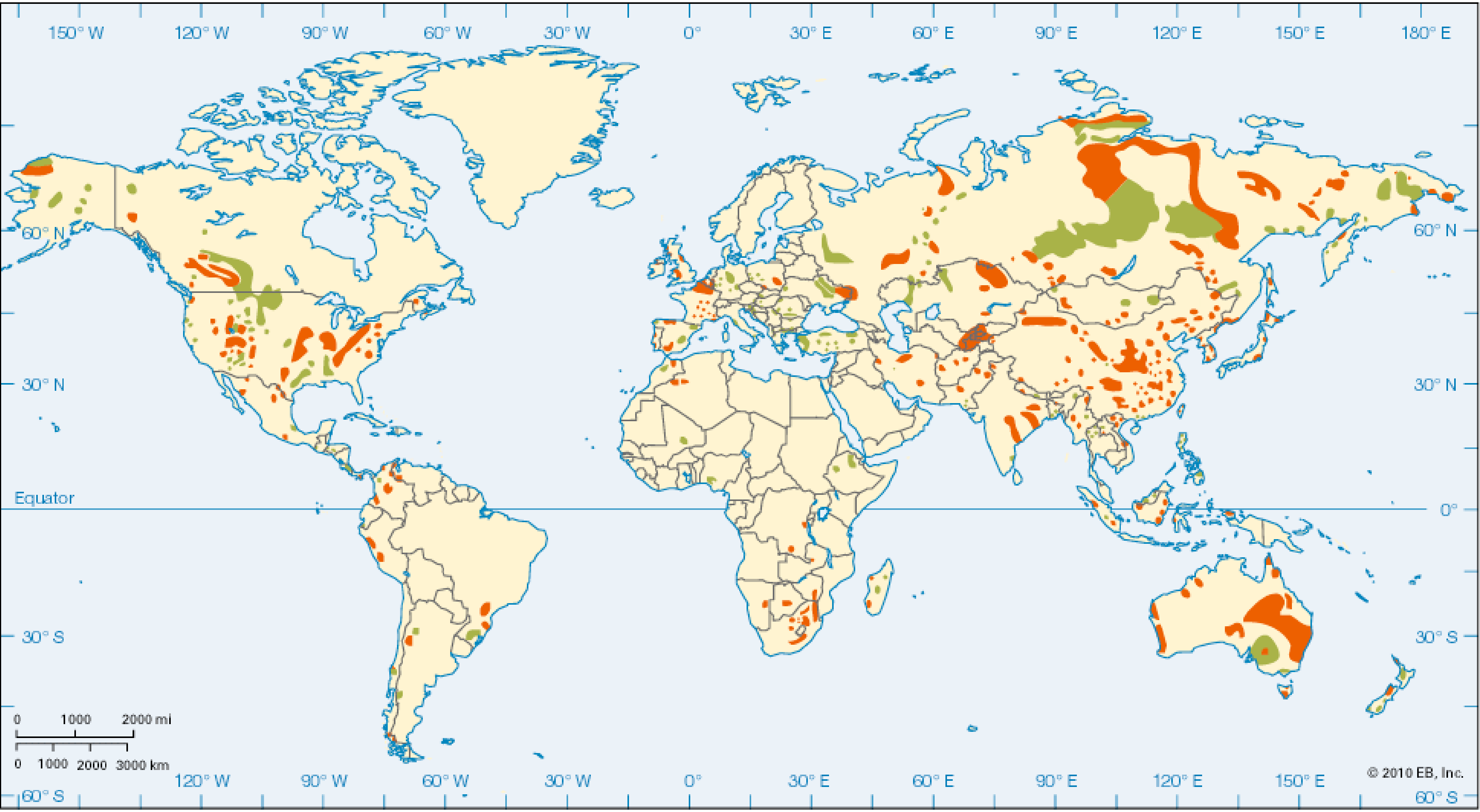
Coal reserves

BP World energy statistics review 2021



World coal reserves in 2020 stood at 1074 billion tonnes and are heavily concentrated in just a few countries: US (23%), Russia (15%), Australia (14%) and China (13%). Most of the reserves are anthracite and bituminous (70%). The current global R/P ratio shows that coal reserves in 2020 accounted for 139 years of current production with North America (484 years) and CIS (367 years) the regions with the highest ratios.

Coal mines in the world

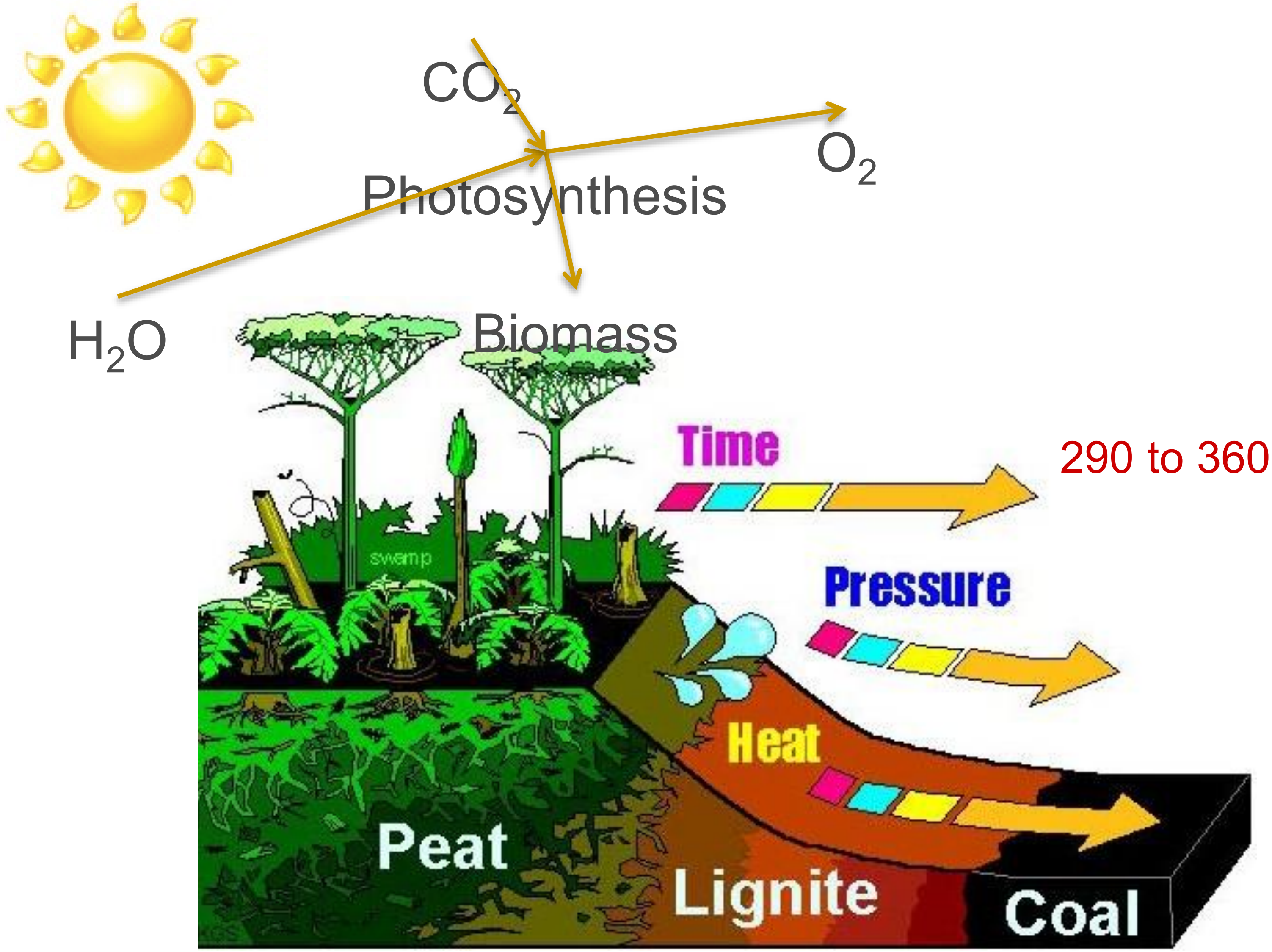


Anthracite and Bituminous Coal

Lignite

EPFL

Coal



290 to 360 mio. years

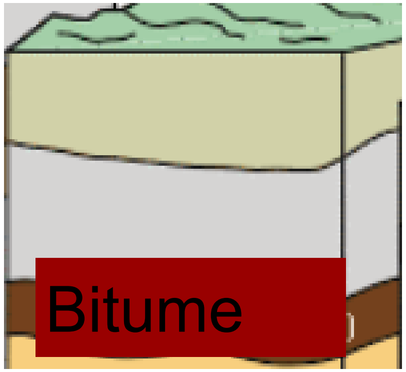
Coal

water	25%
volatiles	50%
C	20%
ash	5%

200-400m

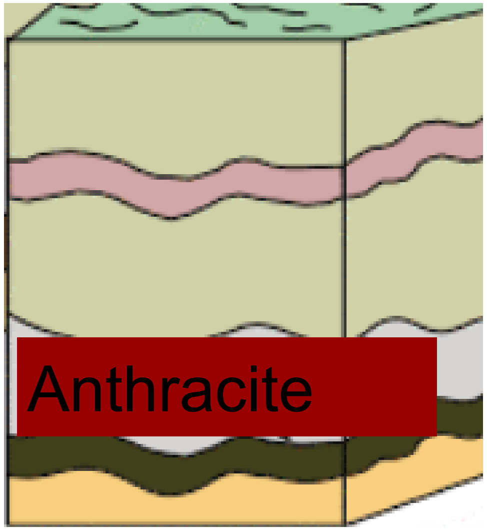
water	35%
volatiles	30%
C	25%
ash	10%

1-2 km



water	5%
volatiles	20%
C	70%
ash	5%

3-4 km

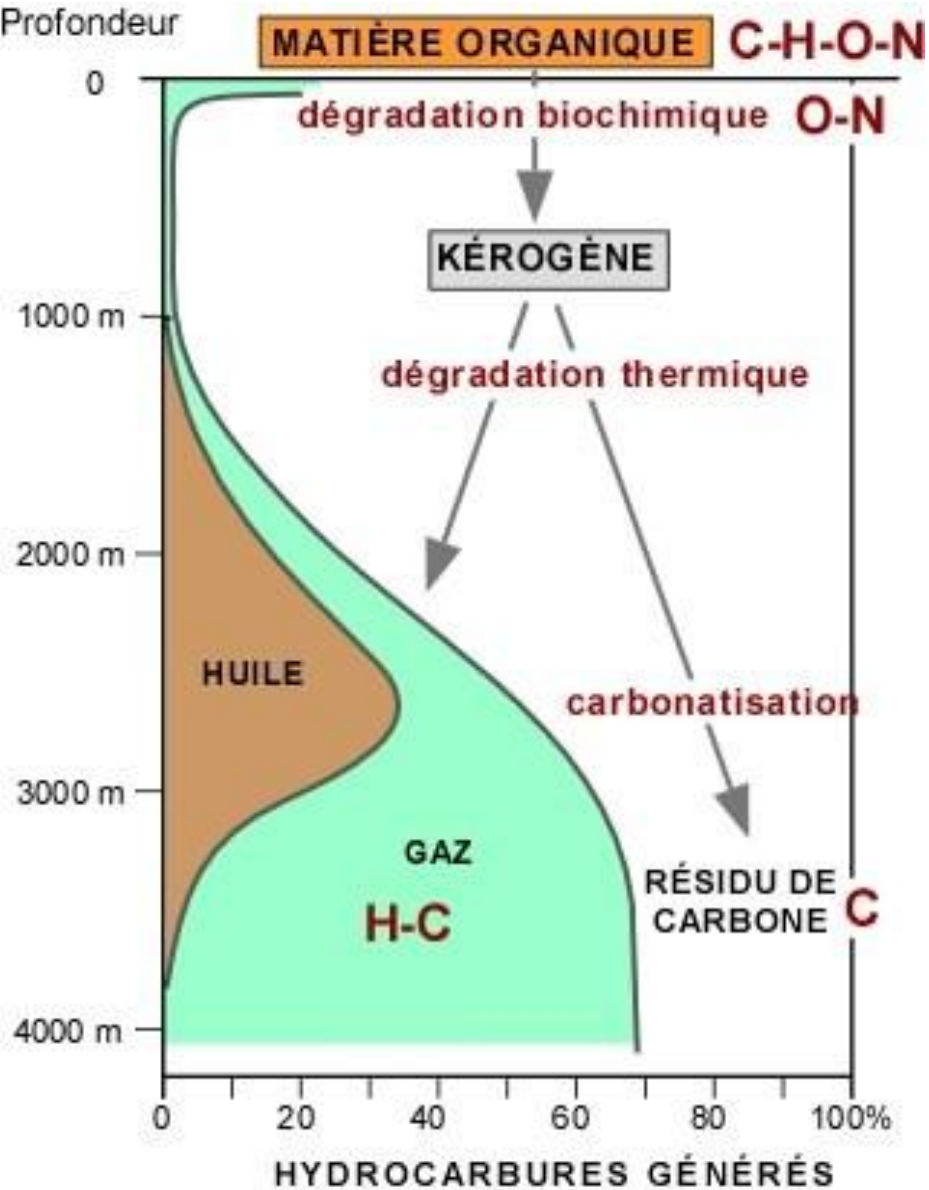


water	2%
volatiles	3%
C	90%
ash	5%

Energy →

14GJ/tonne 19GJ/tonne 24-30GJ/tonne 30-32GJ/tonne

Liquid and gas fuels



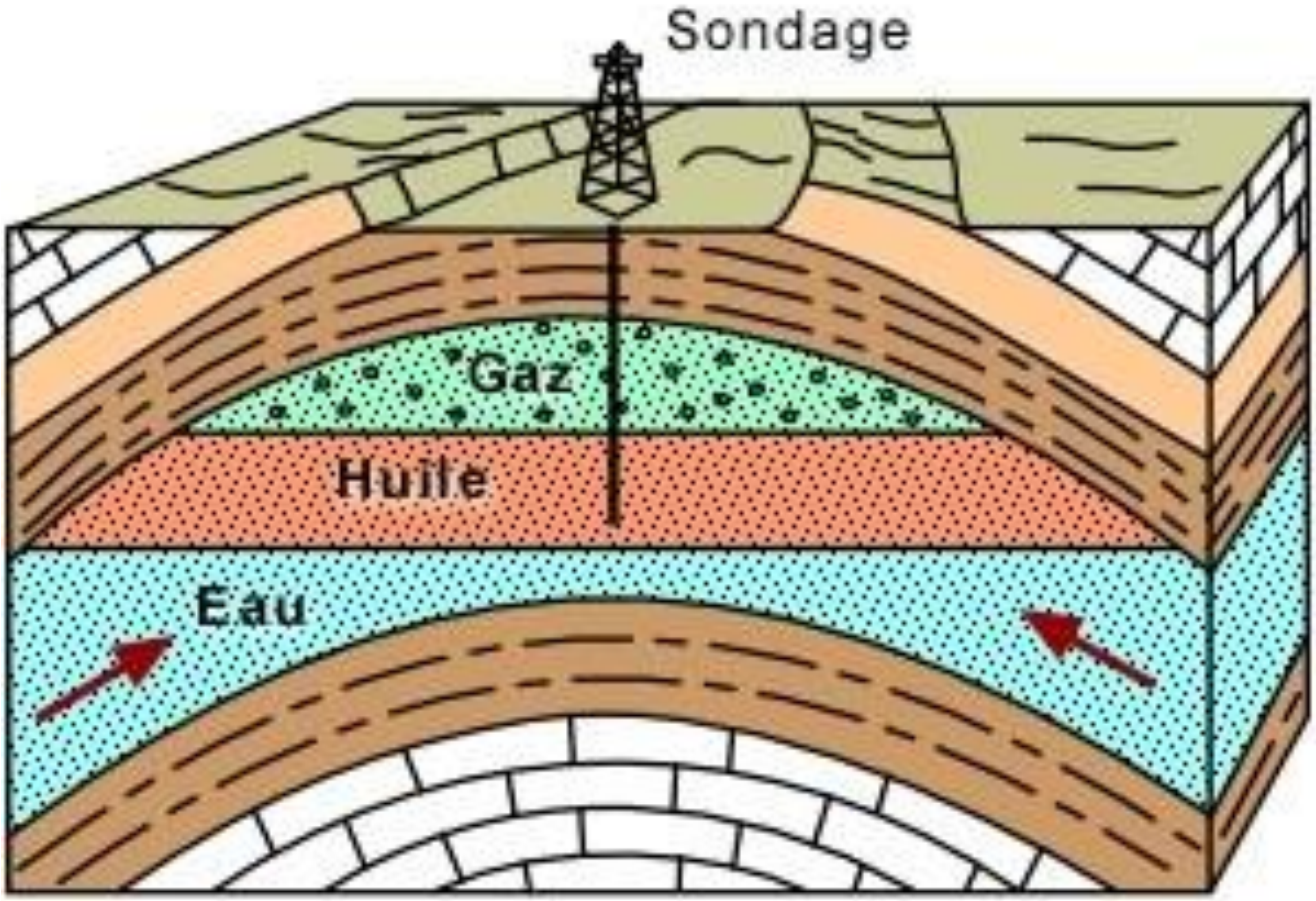
In the first 1 km, bacteria convert organic matter into kerogen (embryonic oil).

> 1 km, burying leads to a gradual transformation of the sediment rock and thermal degradation (~100°C) of kerogen.

Between 2 and 3 km, this is where the kerogen produces a lot of oil.

At 3.5 km, less to none oil is produced but lots of gas.

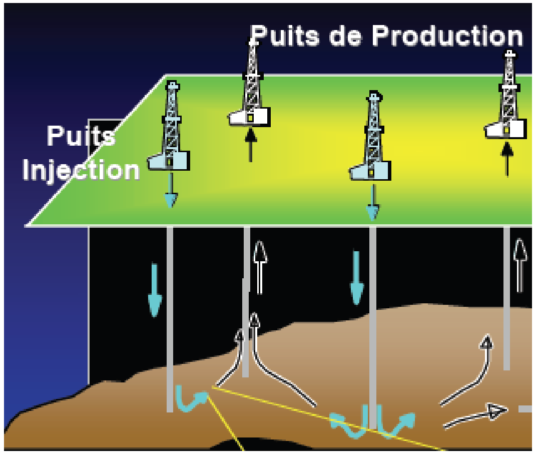
A geological cap captures the oil/gas



Drilling and extraction

Spontaneous extraction from the pressure of the well

Mechanical extraction

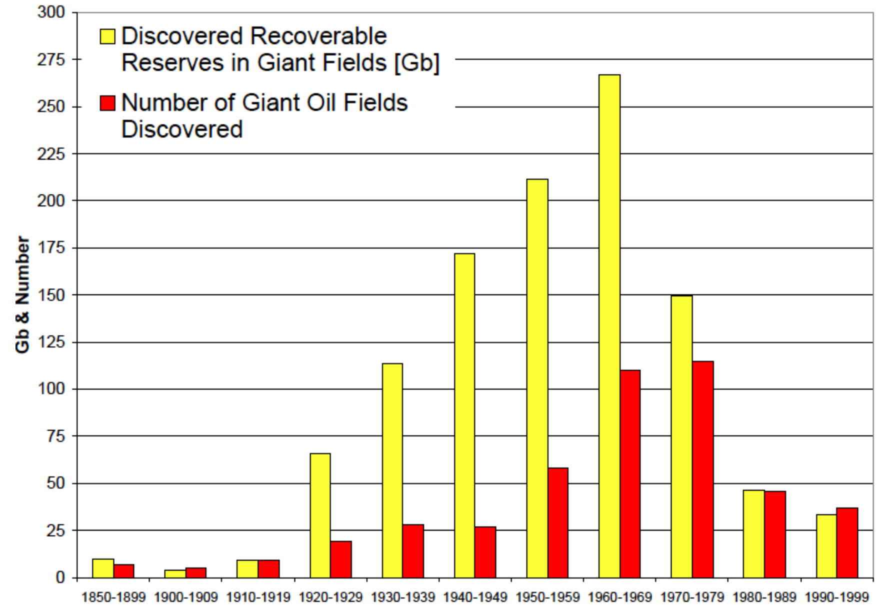


Enhanced oil and gas recovery by water/CO_2 injection
→ CO_2 sequestration

The biggest fields

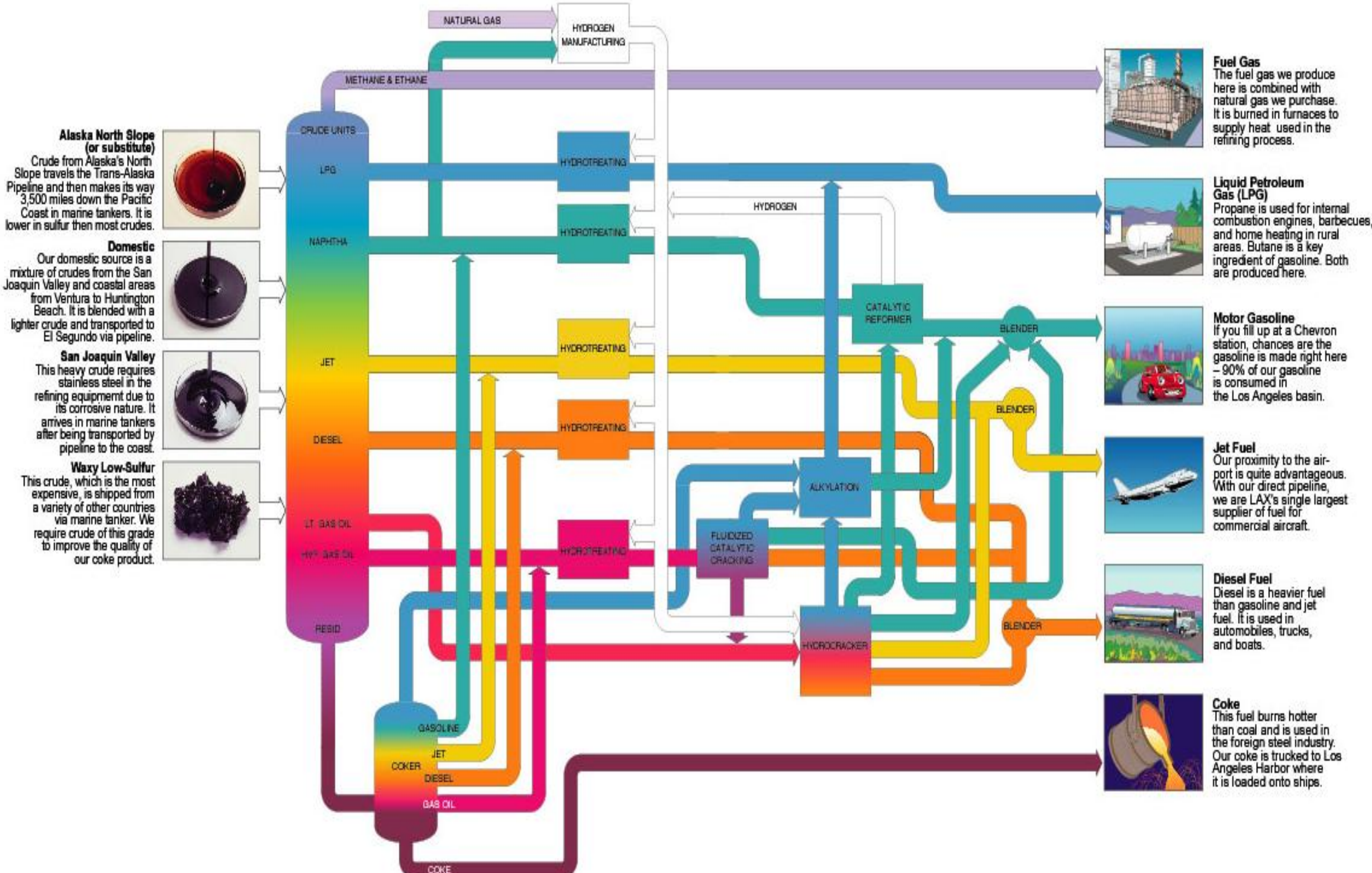
Field Name	Country	Discovery year	Range of URR [GB]
Ghawar	Saudi Arabia	1948	66-100
Burgan Greater	Kuwait	1938	32-60
Safaniya	Saudi Arabia	1951	21-36
Bolivar Coastal	Venezuela	1917	14-36
Berri	Saudi Arabia	1964	10-25
Rumalia N&S	Iraq	1953	22
Zakum	Abu Dhabi	1964	17-21
Cantarell Complex	Mexico	1976	11-20
Manifa	Saudi Arabia	1957	17
Kirkuk	Iraq	1927	16
Gashsaran	Iran	1928	12-15
Abqaiq	Saudi Arabia	1941	10-15
Ahwaz	Iran	1958	13-15
Marun	Iran	1963	12-14
Samotlor	Russia	1961	6-14
Agha Jari	Iran	1937	6-14
Zuluf	Saudi Arabia	1965	12-14
Prudhoe Bay	Alaska	1969	13

Field	Country	Discovery Year	Ultimate Recoverable Reserves [Gb]
Kashagan	Kazakhstan	2000	7-9
Azadegan	Iran	1999	6-9
Roncador	Brazil	1996	2.9
Cusiana/Cupiagua	Colombia	1991	1.6
Sihil	Mexico	1999	1.4
Ourhoud	Algeria	1994	1.2
Thunder Horse	US GoM	1999	1-1.5



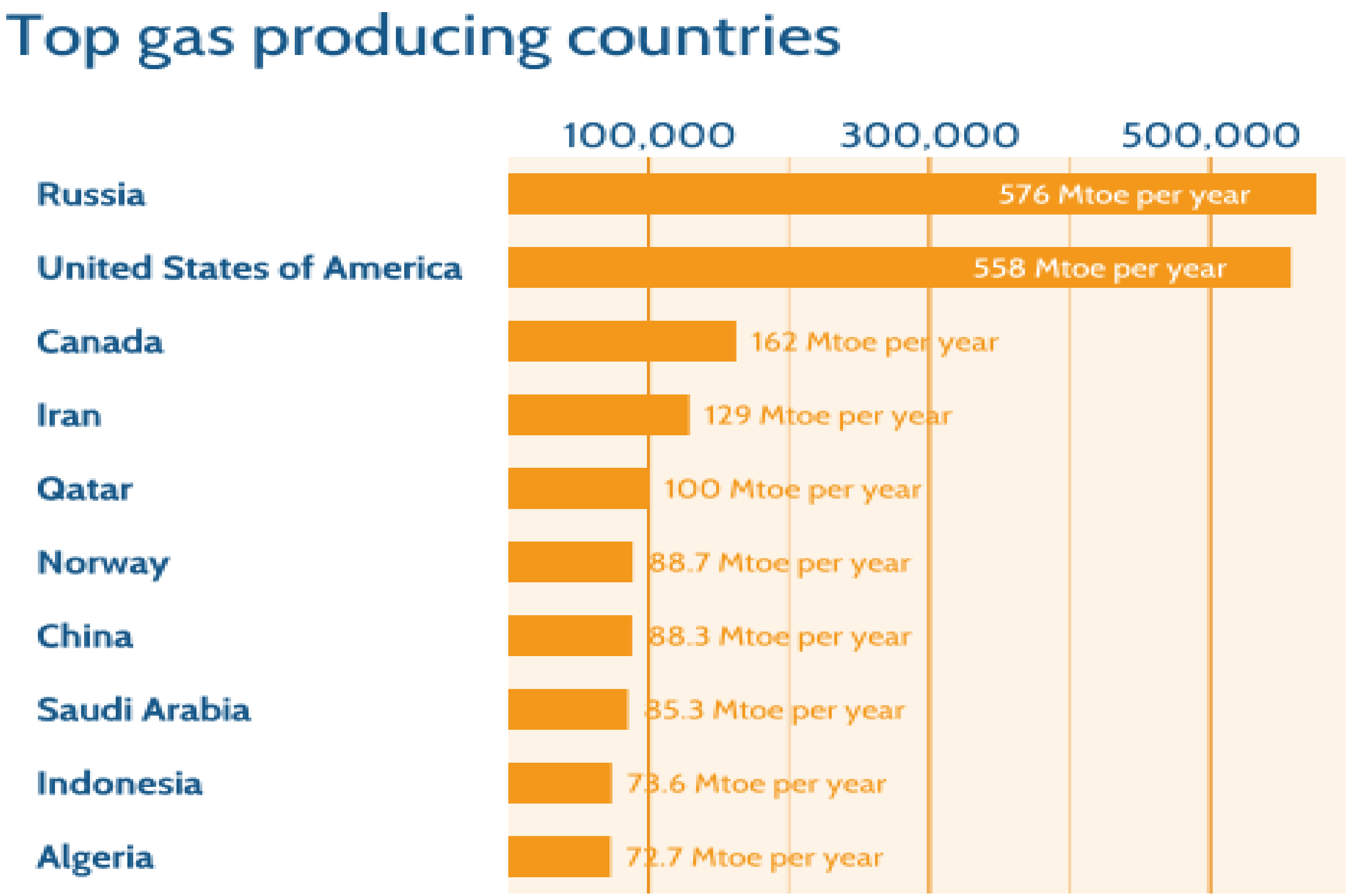
Source: AAPG, UHDSG

Oil refinery



http://independentrefining.com

Natural gas


Top gas producing countries
100,000
300,000
500,000
Russia
576 Mtoe per year
United States of America
558 Mtoe per year
Canada
162 Mtoe per year
Iran
129 Mtoe per year
Qatar
100 Mtoe per year
Norway
88.7 Mtoe per year
China
88.3 Mtoe per year
Saudi Arabia
85.3 Mtoe per year
Indonesia
73.6 Mtoe per year
Algeria
72.7 Mtoe per year

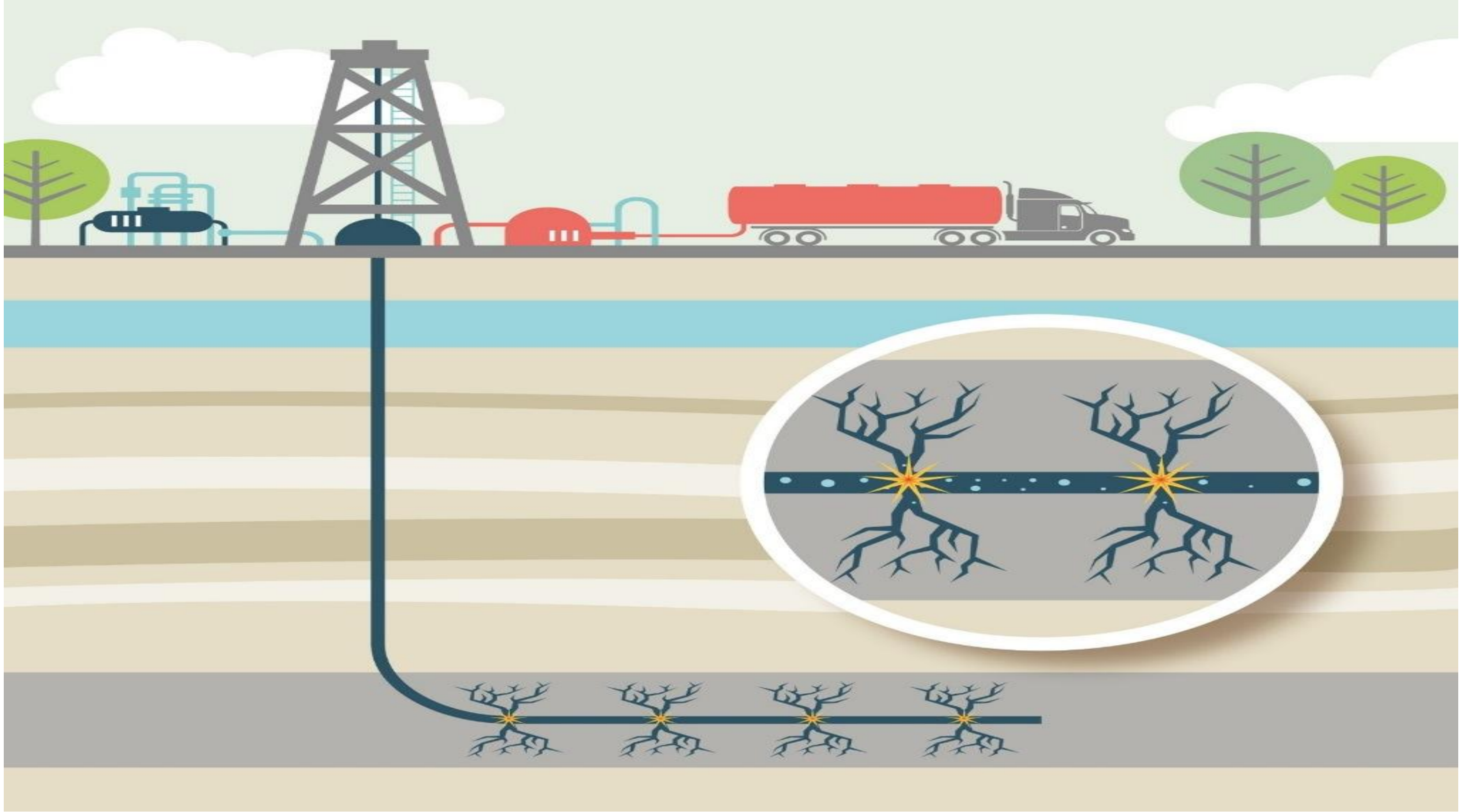
Non convention gas and oil

Hydraulic fracking: Oil and Gas

High pressure (500 bar) water

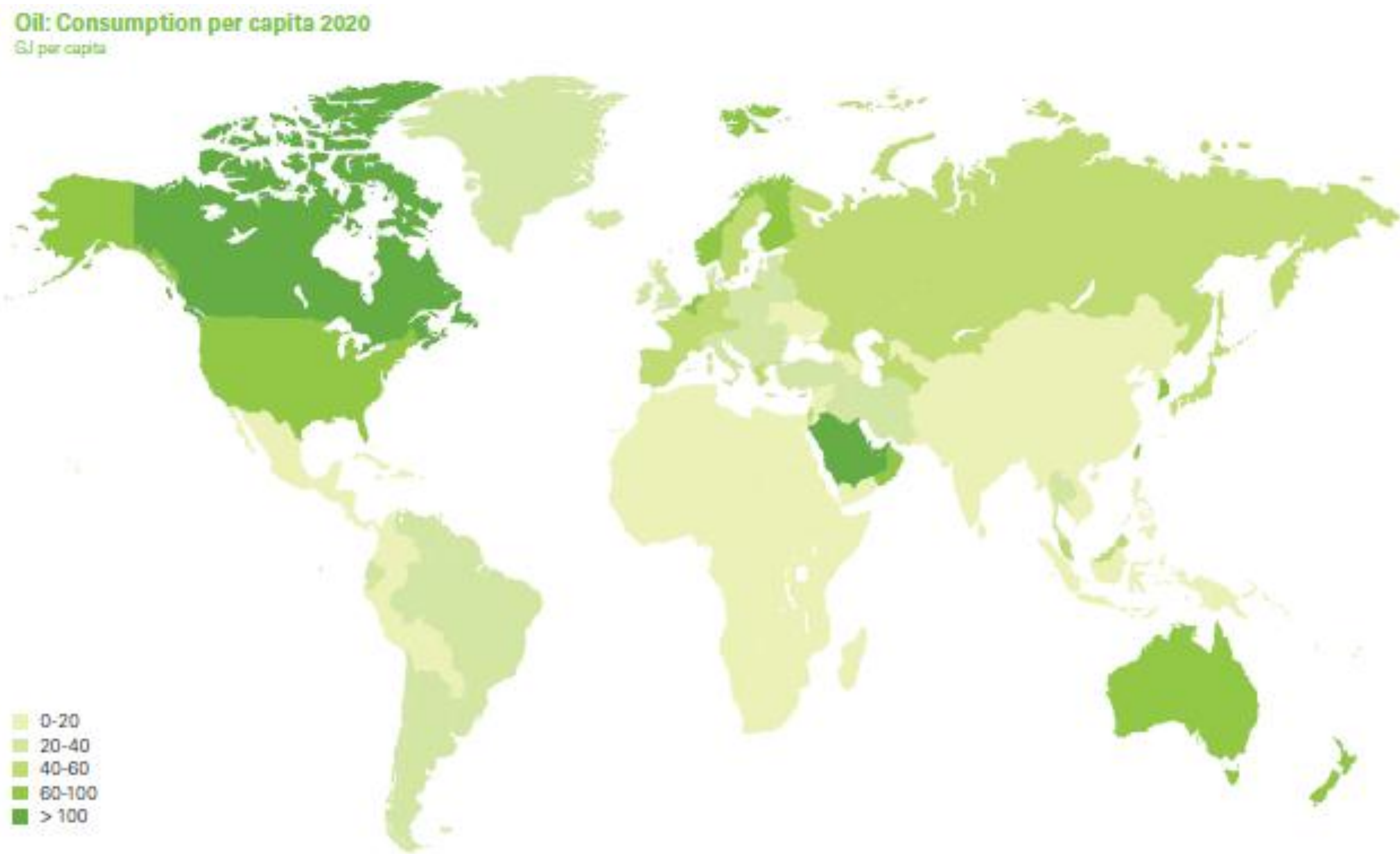
Tensio-active and biocide compounds to ease the extraction

Water is extracted and has to be treated



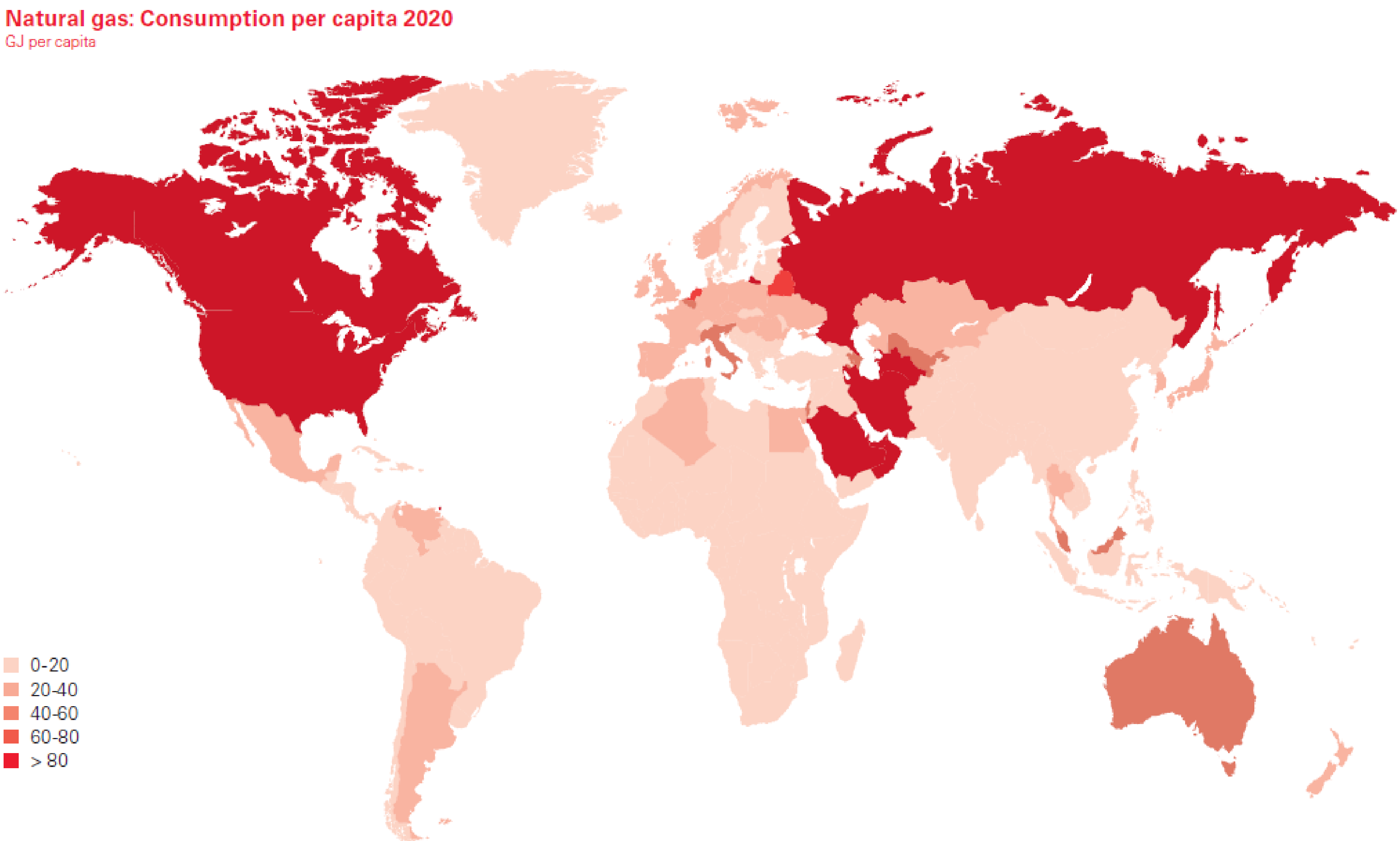
Who consumes the oil?

BP World energy statistics review 2021



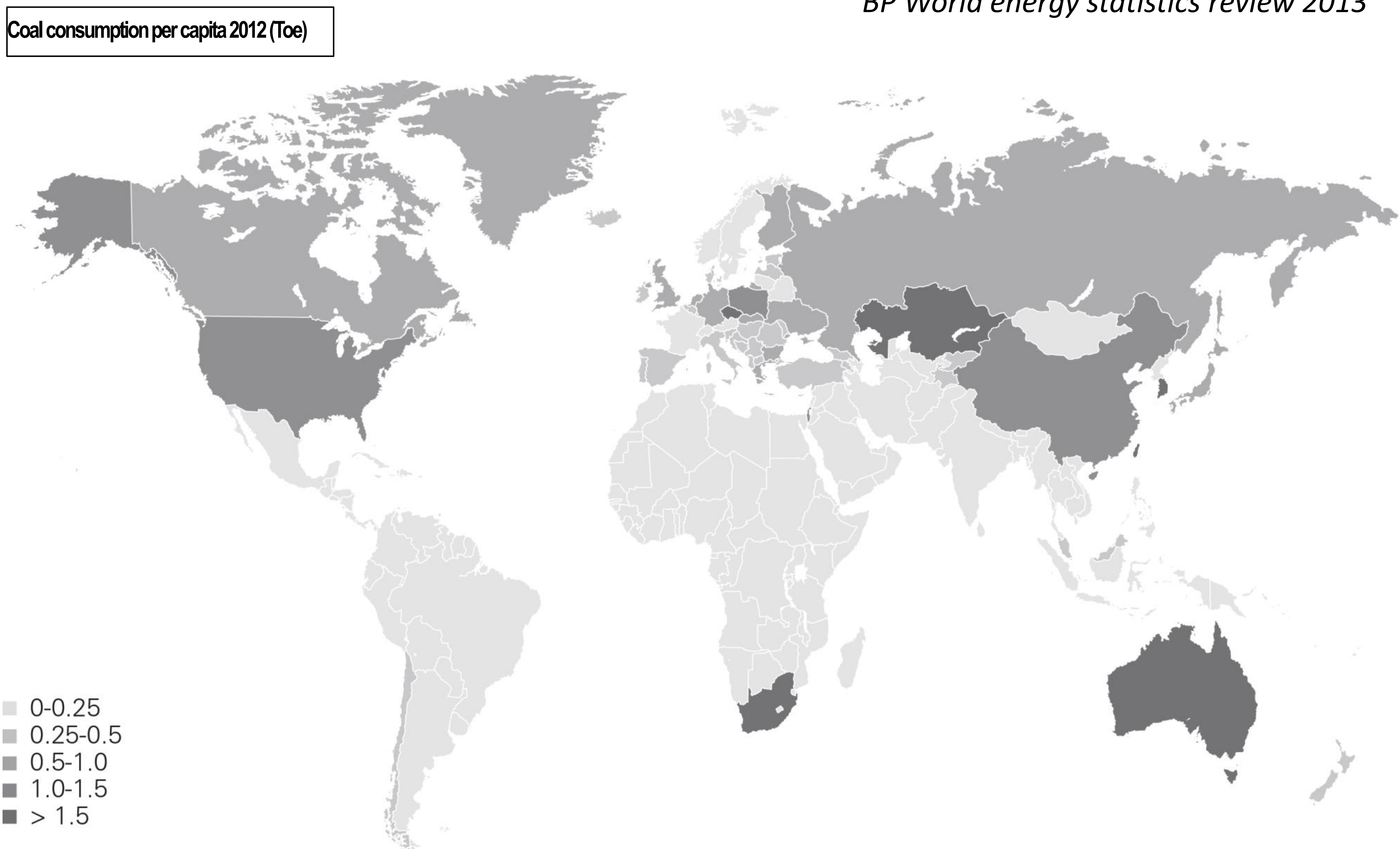
Who consumes the gas?

BP World energy statistics review 2021



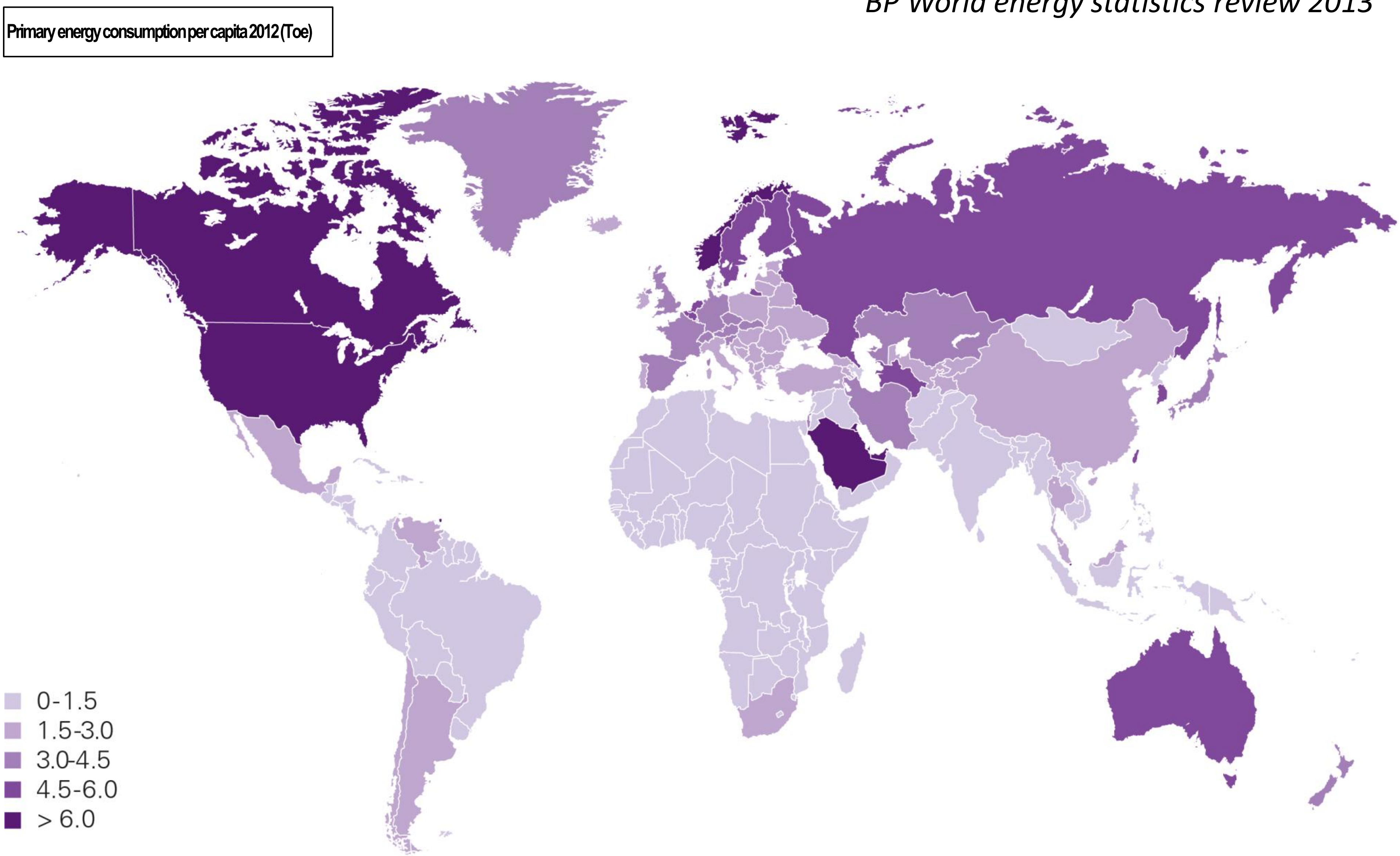
Who consumes the coal?

BP World energy statistics review 2013



Where is the overall primary energy consumption?

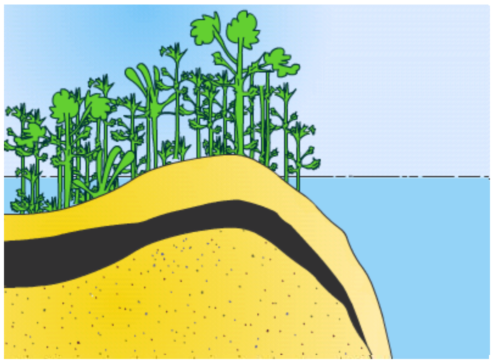
BP World energy statistics review 2013



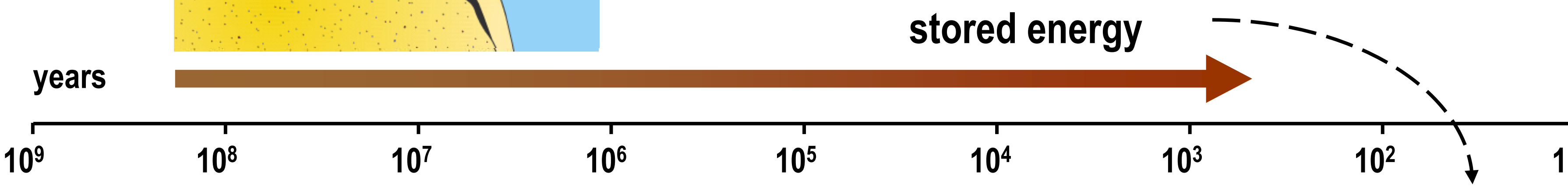
‘Reserves’ and ‘fuel cost’

- The given reserves are proven and valid for current production rates, at present economics
- Ultimate reserves (physical) could be 10x larger for coal and 4-5x larger for oil and gas, recoverable at higher cost, and extending the use to several centuries
- Isn’t renewable energy, by contrast, ‘free’ fuel?
- No! What matters is the cost of harnessing any fuel, anywhere (localization, extraction, storage, transport, conversion,…)
- In this way, only direct solar energy that warms your body could be considered free; else, when not considering the cost of harnessing, also gas, oil and coal are free fuels, made by nature!

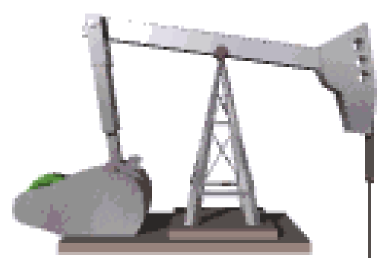
Time scale for fuel generation and consumption

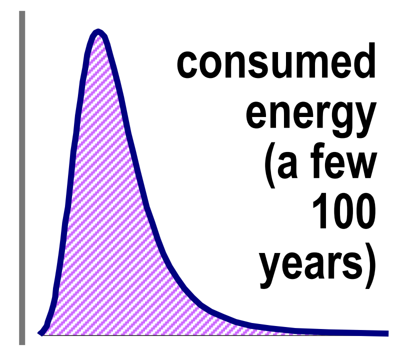


Generation time : 100 - 400 10^6 years



consumption time
<< generation time



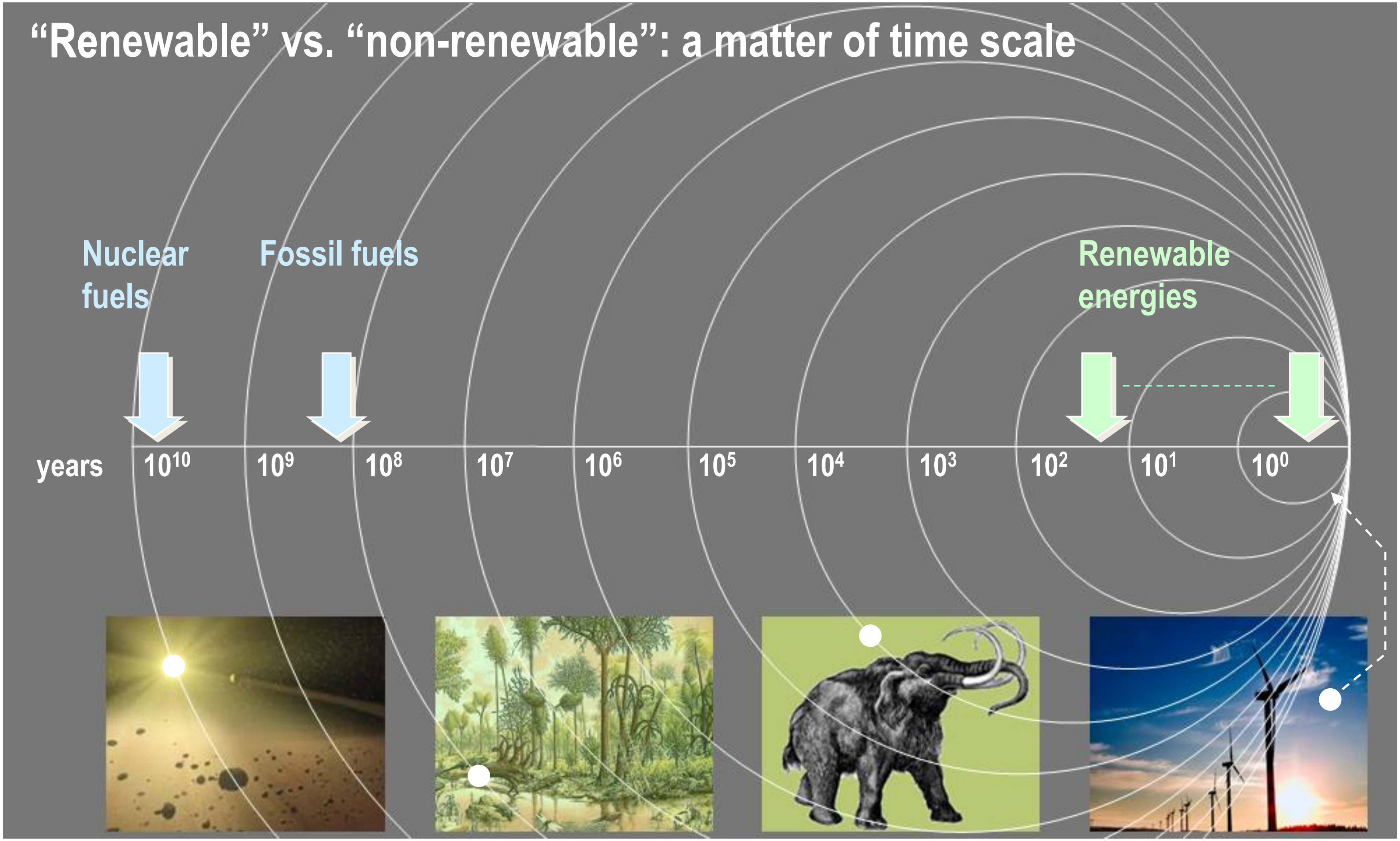


$\Rightarrow$ non-renewable

EPFL

Renewable = sustainable

Fuel generation time ≤ fuel consumption time

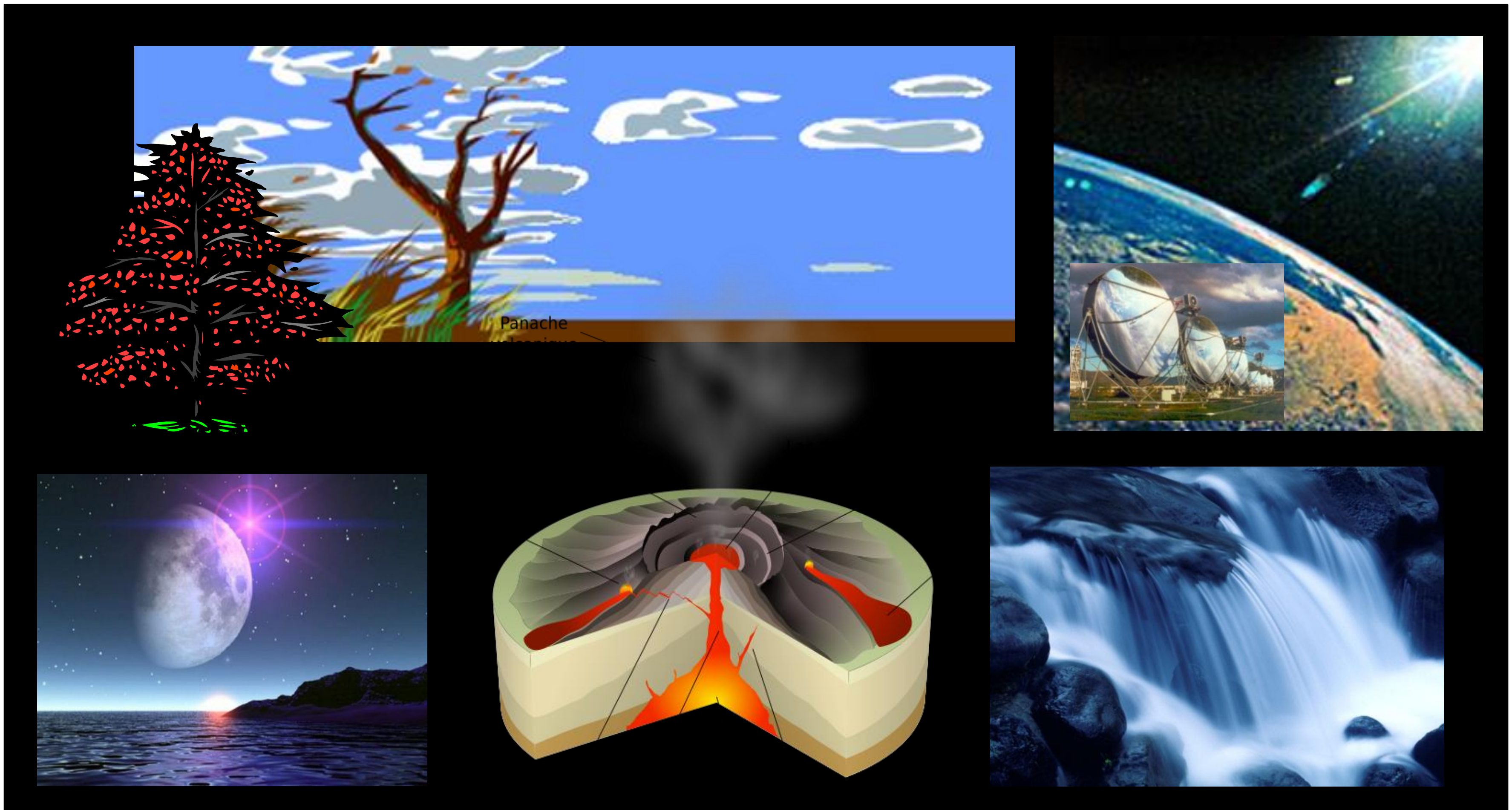


Non renewable = stored energy

Fossil (and nuclear) fuels are like energy **capital**, in the 'bank' for present use. Once used, it's no longer replenished on the life scale of mankind.

Renewable ≈ energy fluxes (mostly unstored)

Unlike ‘burning energy capital’, we have to harvest these fluxes on a ‘daily’ basis for our energy ‘income’.



Classification w.r.t. timescale

Instantaneous use (seconds, minutes)	Short term storage (days, weeks)	Medium term storage (months, years)	V. long term storage (millions of years)
SOLAR – DIRECT	WIND	BIOMASS	OIL
SOLAR – THERMAL	HYDRO	WASTES	GAS
SOLAR – P.V.	WAVES	GEOTHERMAL	COAL
WIND	TIDES		NUCLEAR
HYDRO			GEOTHERMAL

Classification w.r.t. origin

$E = mc^2$

MATTER

FUSION

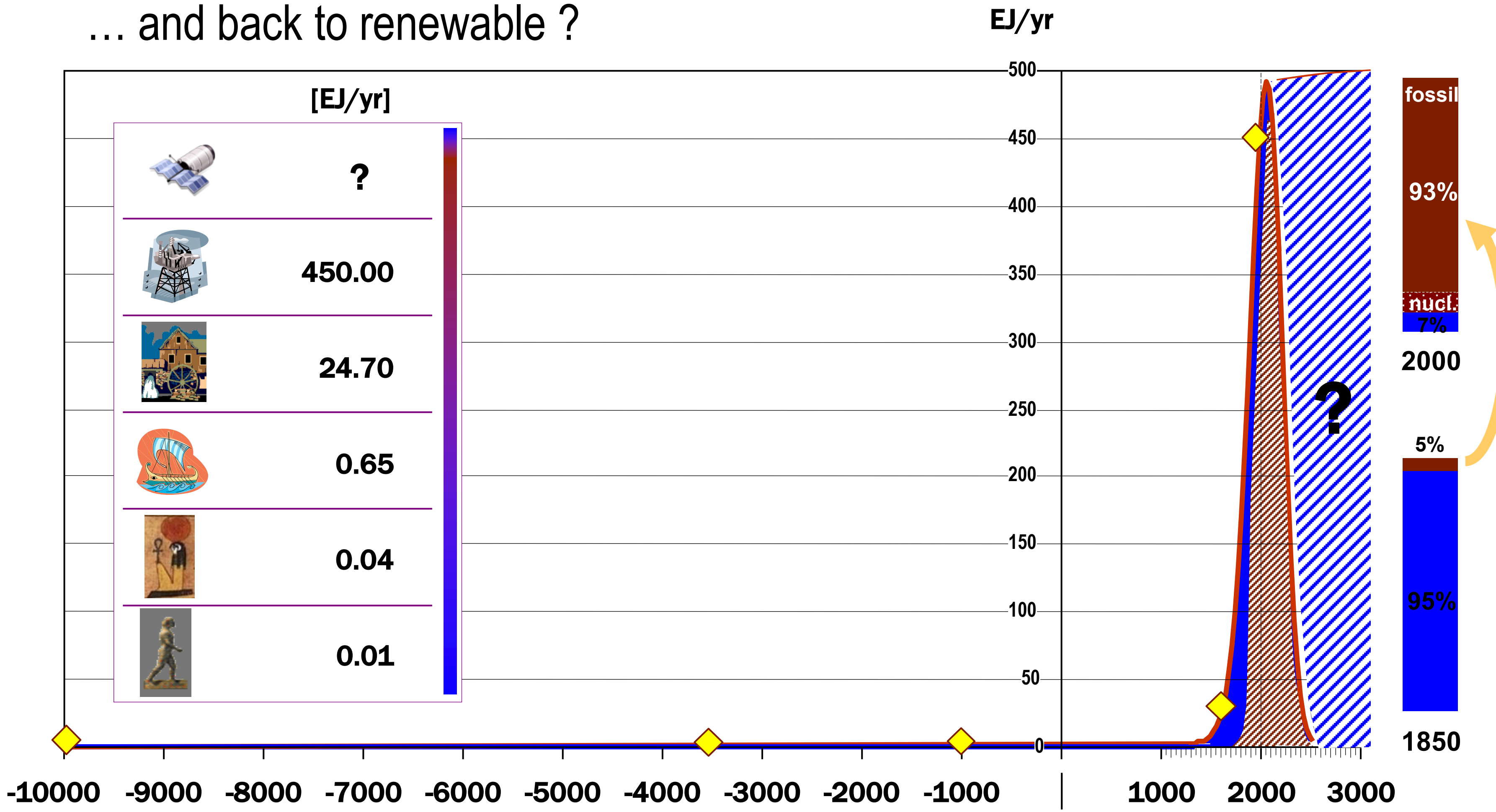
STARS

(dead) stars	the sun		other
			
	Immediate use or short-term storage	Long-term geological storage	
• uranium • thorium • hydrogen (deuterium, tritium)	• solar • hydro • wind • biomass • ocean heat • ocean waves	• coal • oil • natural gas	• tidal • geothermal

EPFL

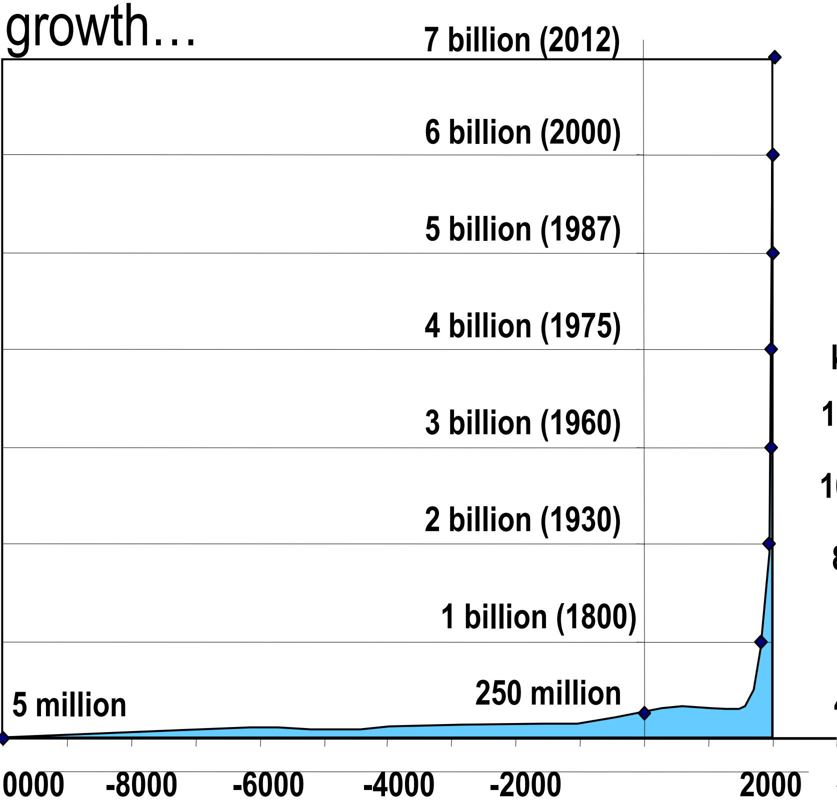
Humankind and energy: ever on the rise

From renewable to fossil energies
… and back to renewable ?



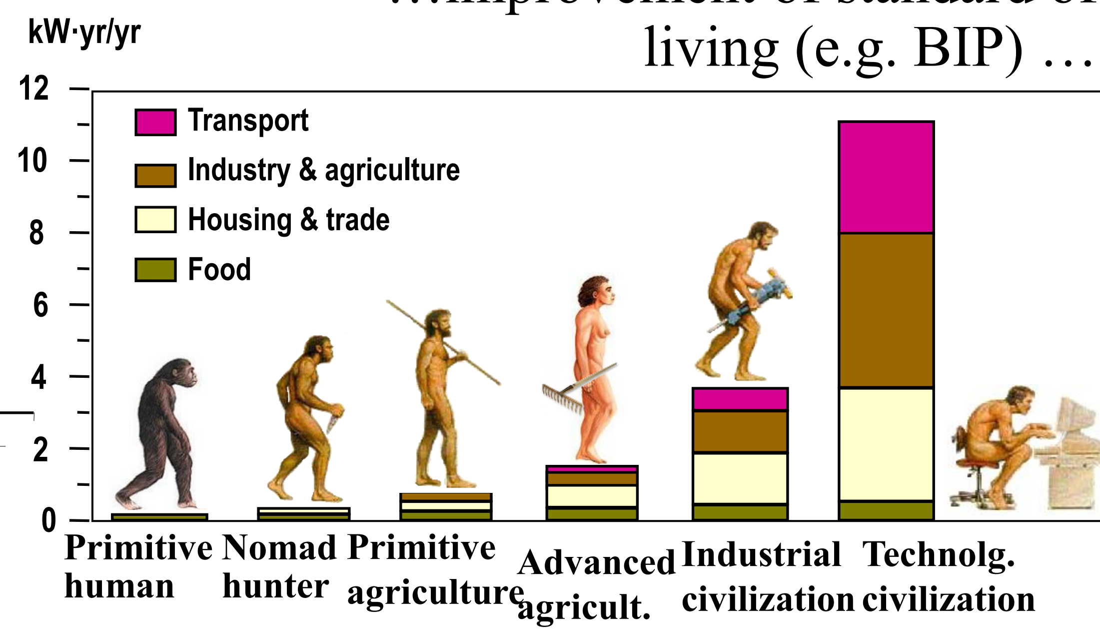
Main drivers for rise in energy demand

Demographic growth…

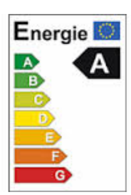


..X..

…improvement of standard of living (e.g. BIP) …



..X..



.. Energy intensity of energy service

Sustainability

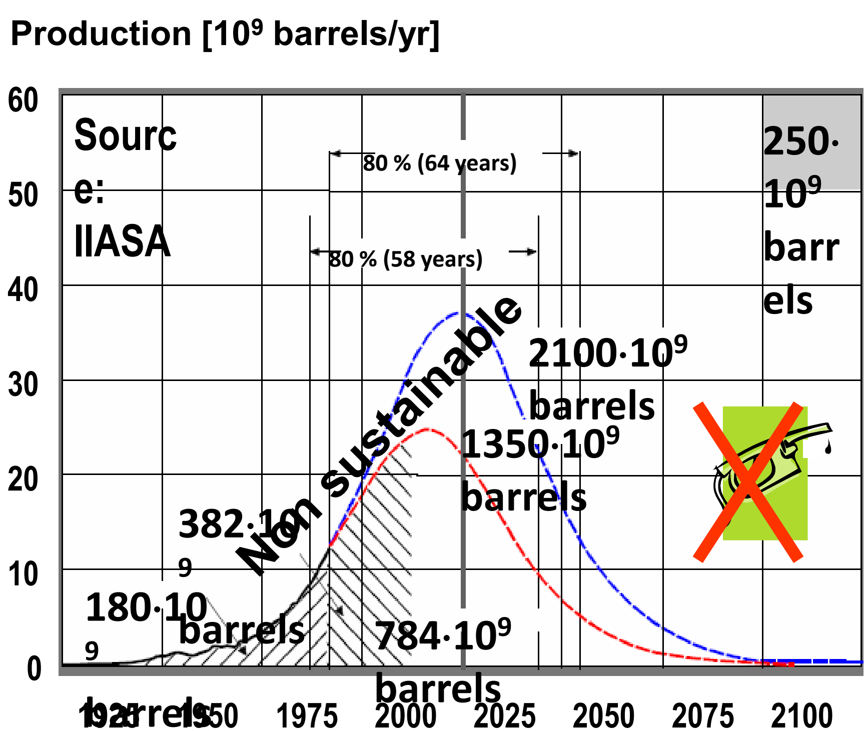
Not only a ‘source’ issue, but now even more a ‘sink’ issue !

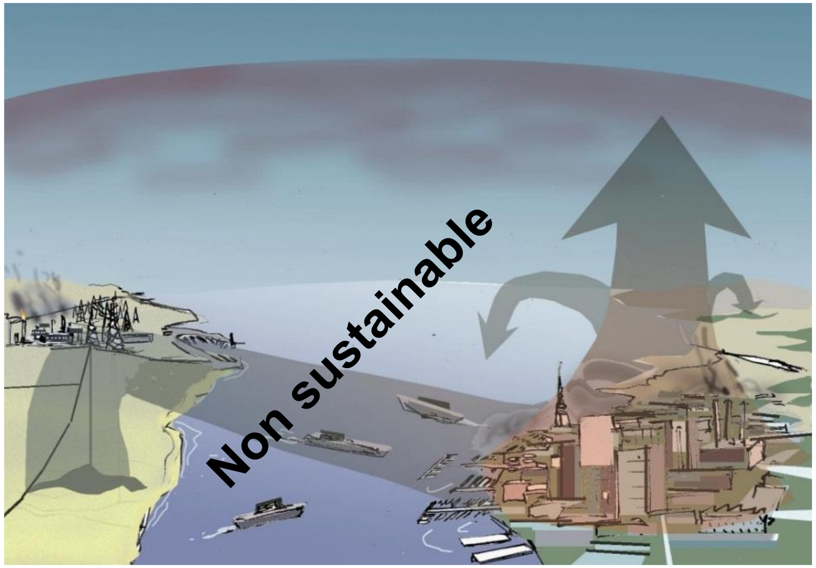
consumption rate >>> generation rate

emissions rate > ‘recovery’ rate

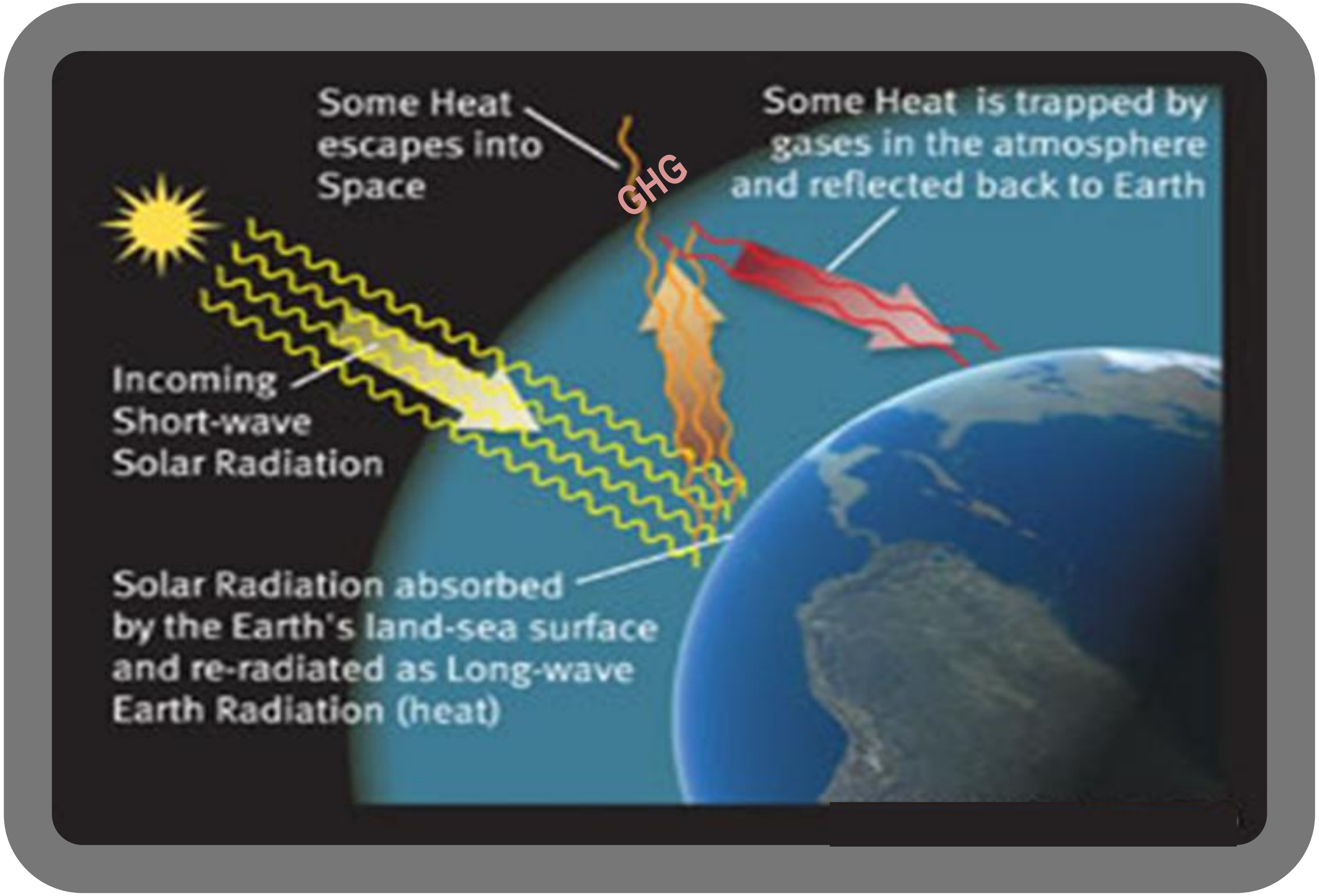
Burning of energy capital

Irreversible damageable impacts on the environment

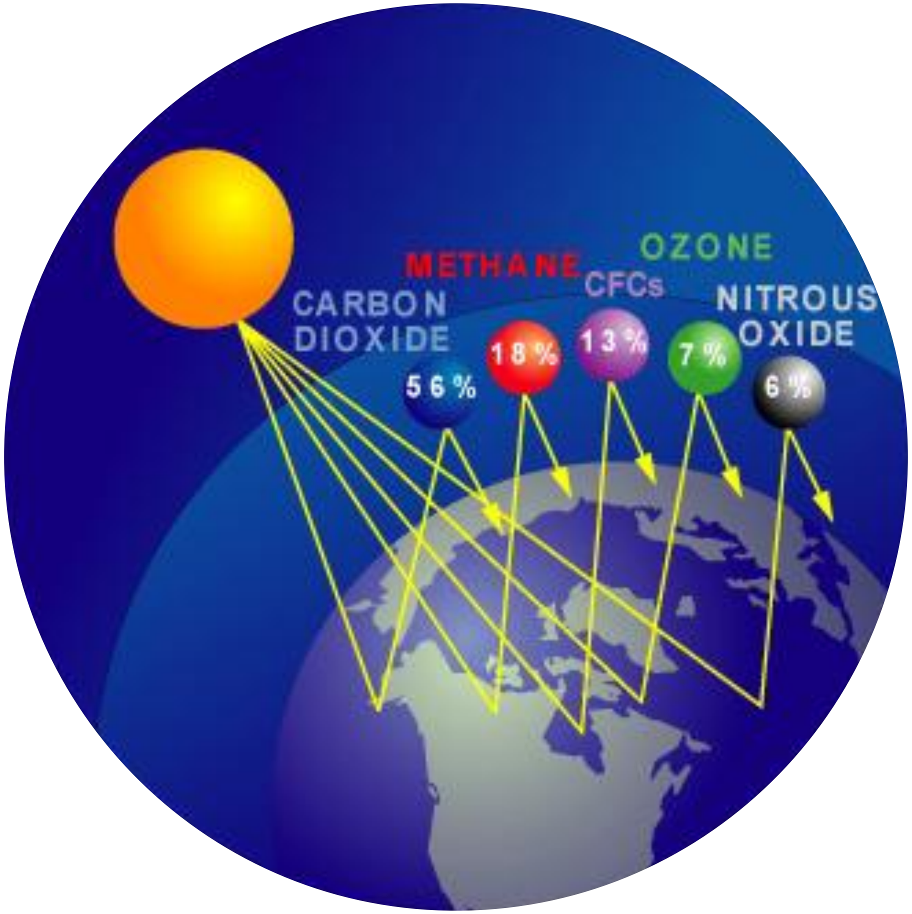


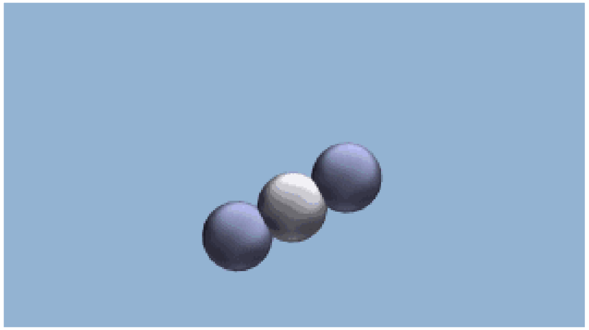


The sink: anthropogenic climate change



The green house effect

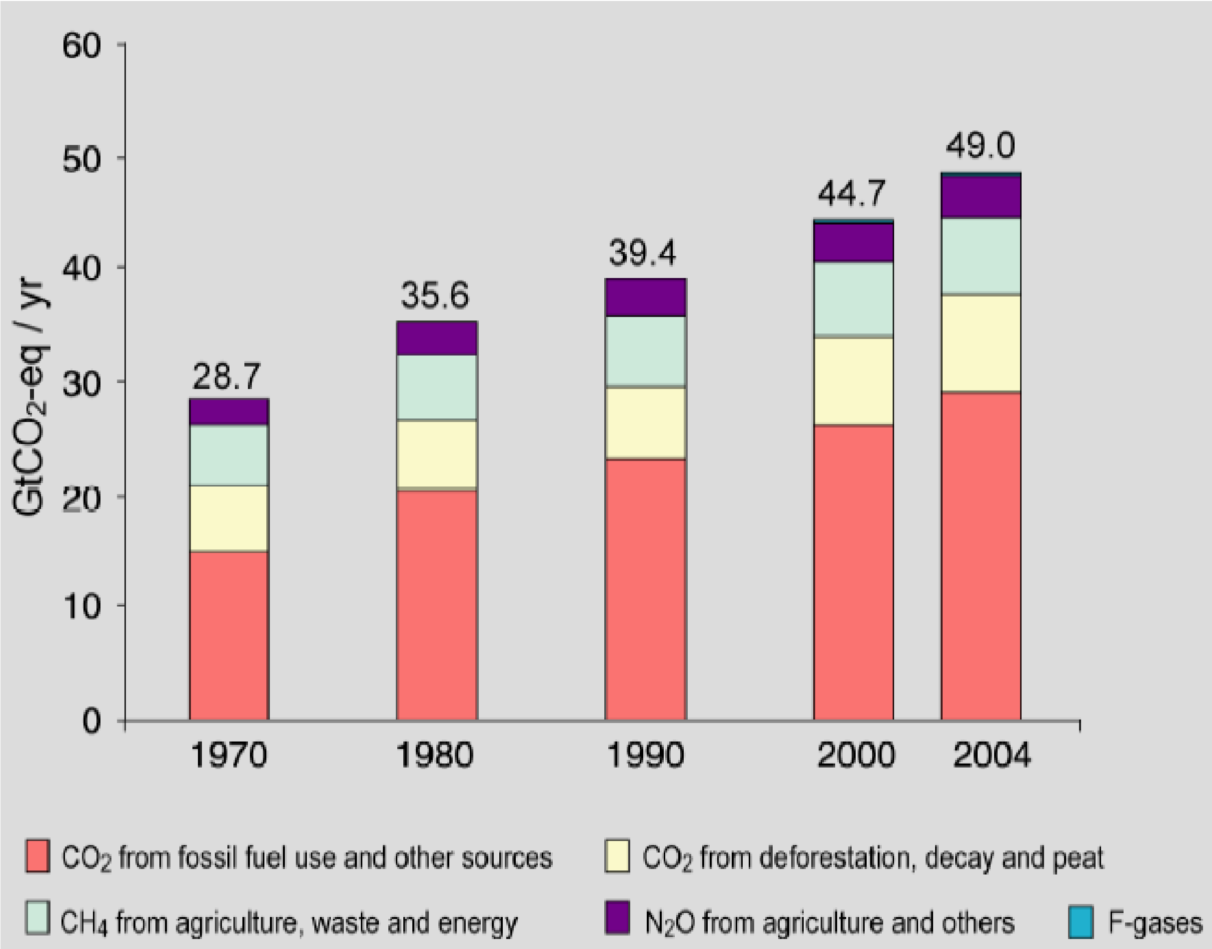


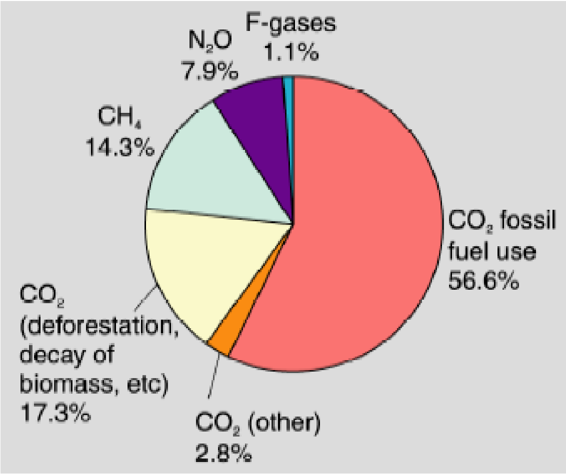


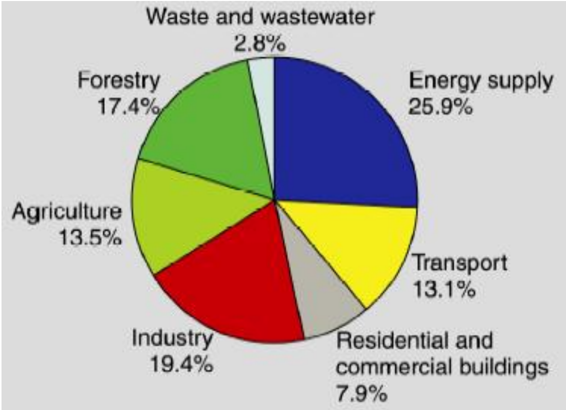
CO_2 absorbs IR radiation in its vibration states. The vibrating molecule re-emits the radiation which is absorbed by another GHG molecule. This absorption - emission - absorption cycle keeps the heat near the surface, effectively insulating the Earth from cold Space.

relative importance of anthropogenic greenhouse gases

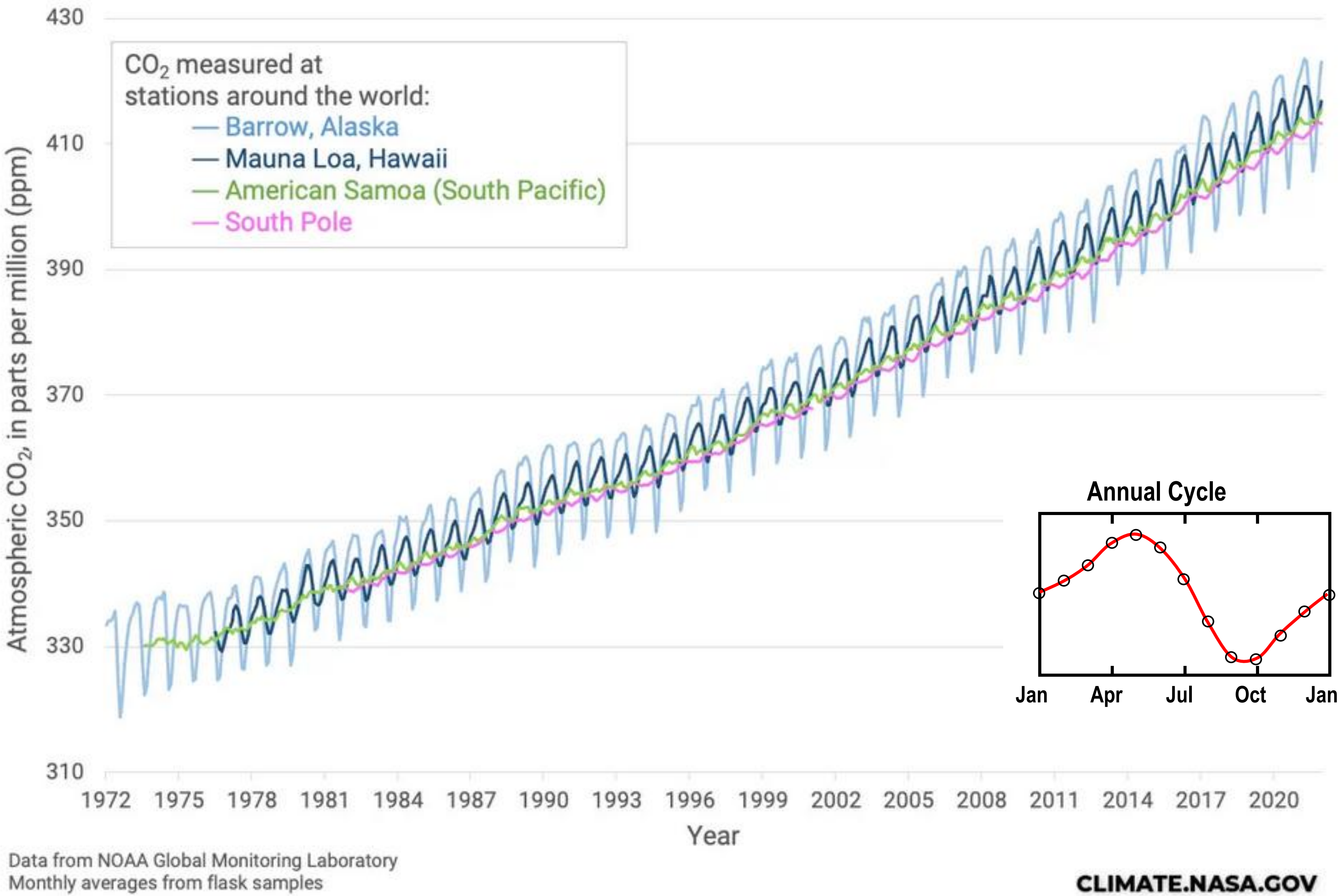
Global warming is for at least half due to energy use



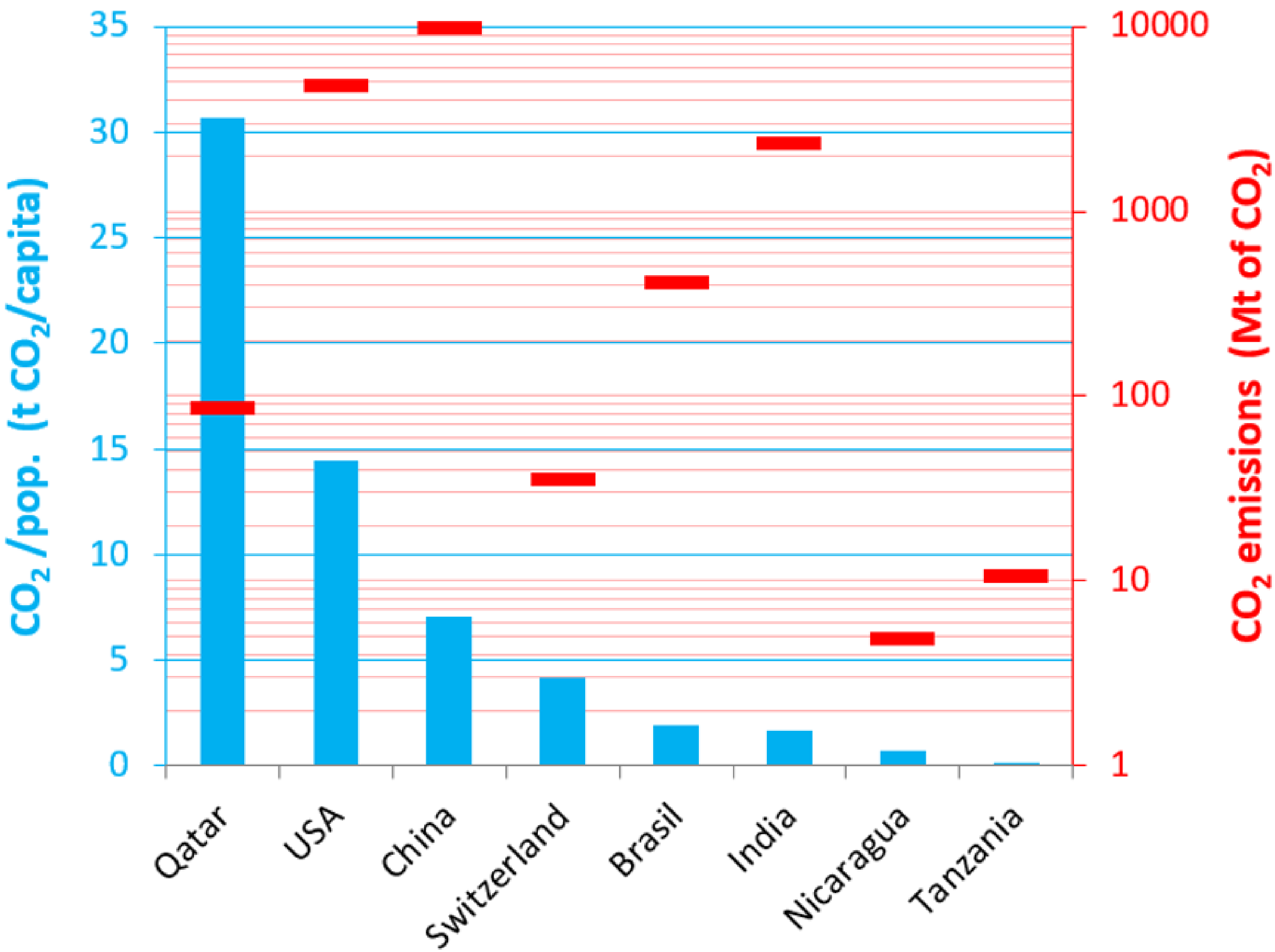




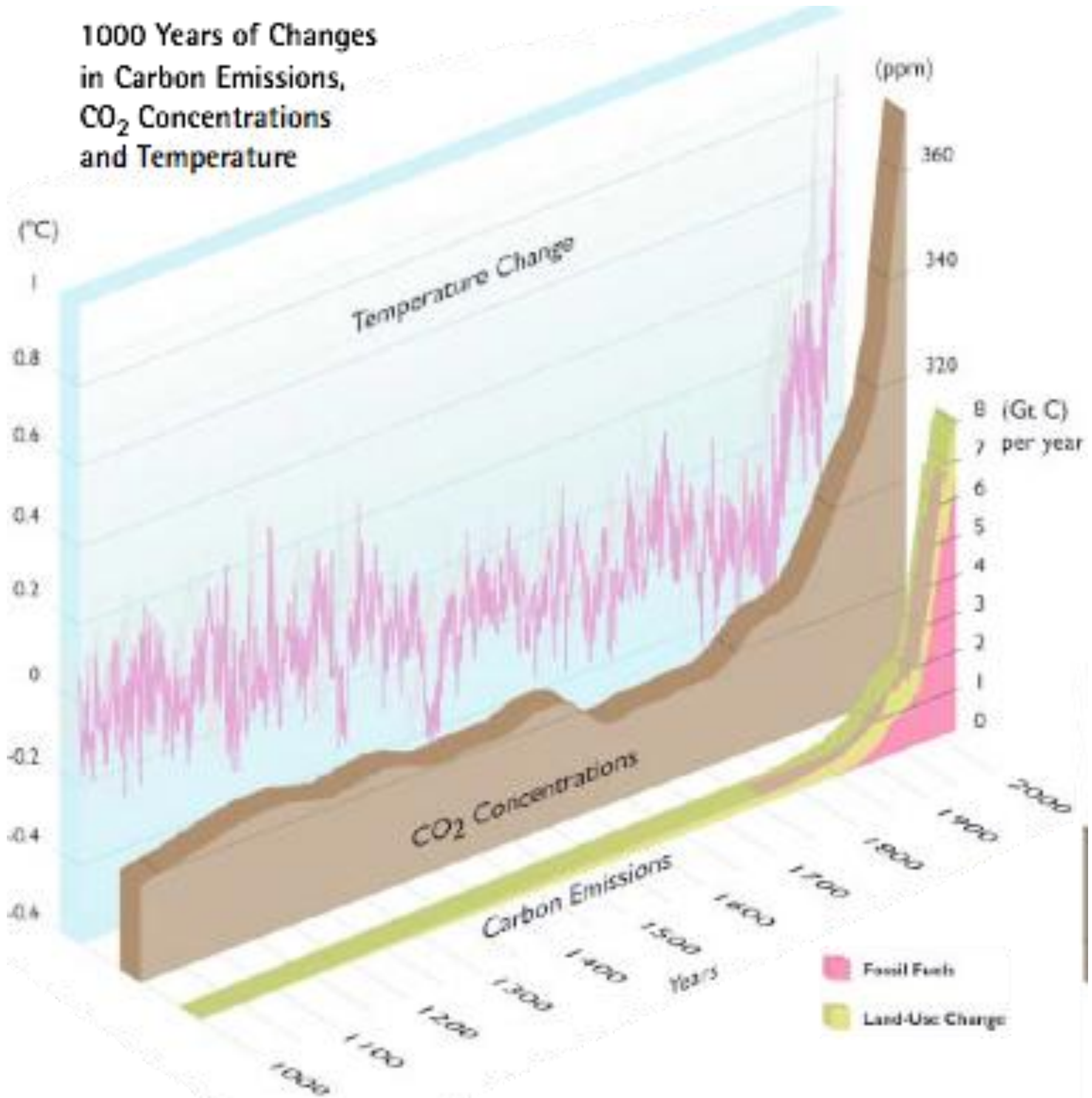
Measured data



CO_2 emissions per capita



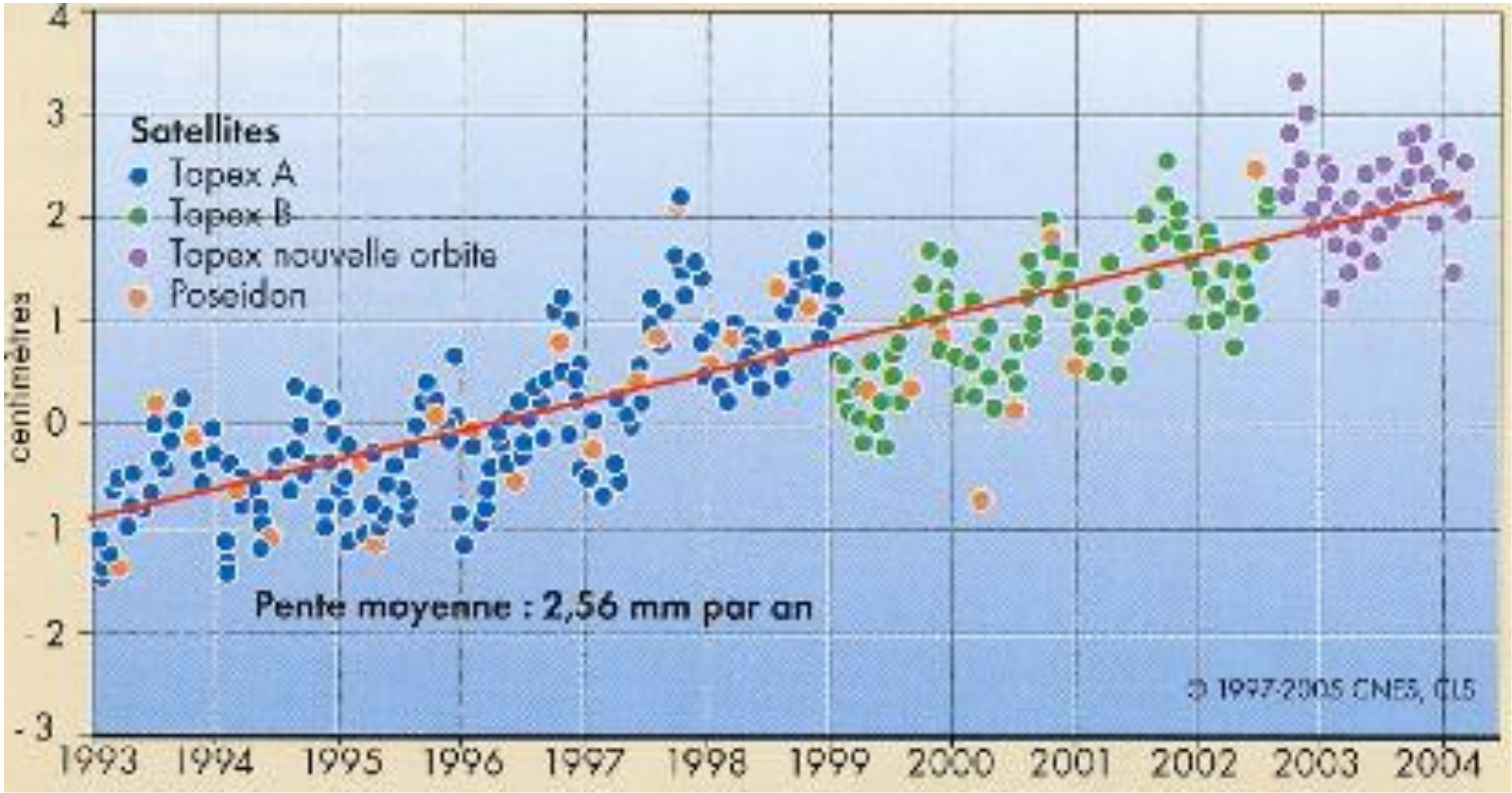
Carbon emissions, CO_2 conc. and temperatures variation



Hassol, 2004

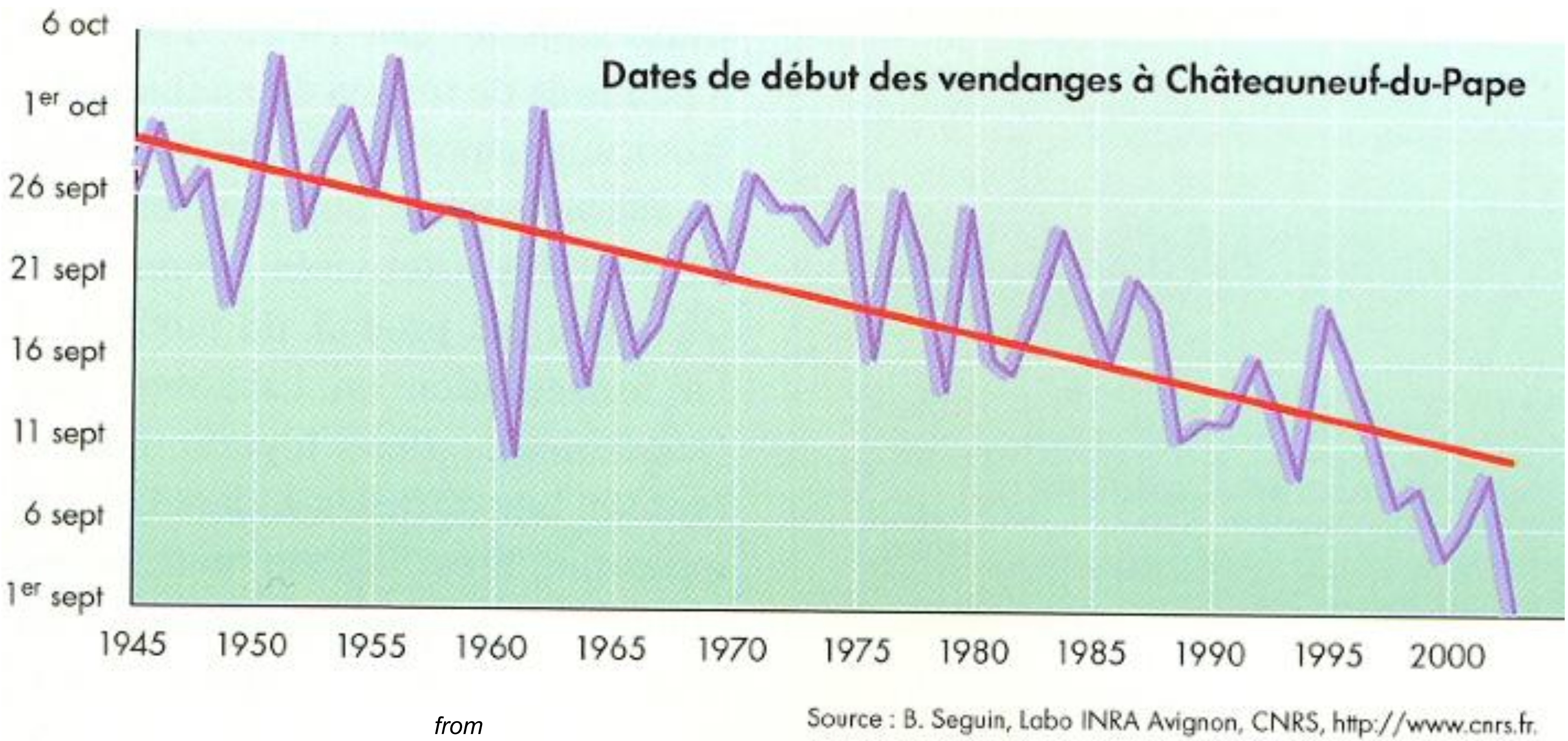
Variation of the sea level (measured by satellite)

- Islands may disappear
- Inland saline water penetration underground



from Denhez,2005

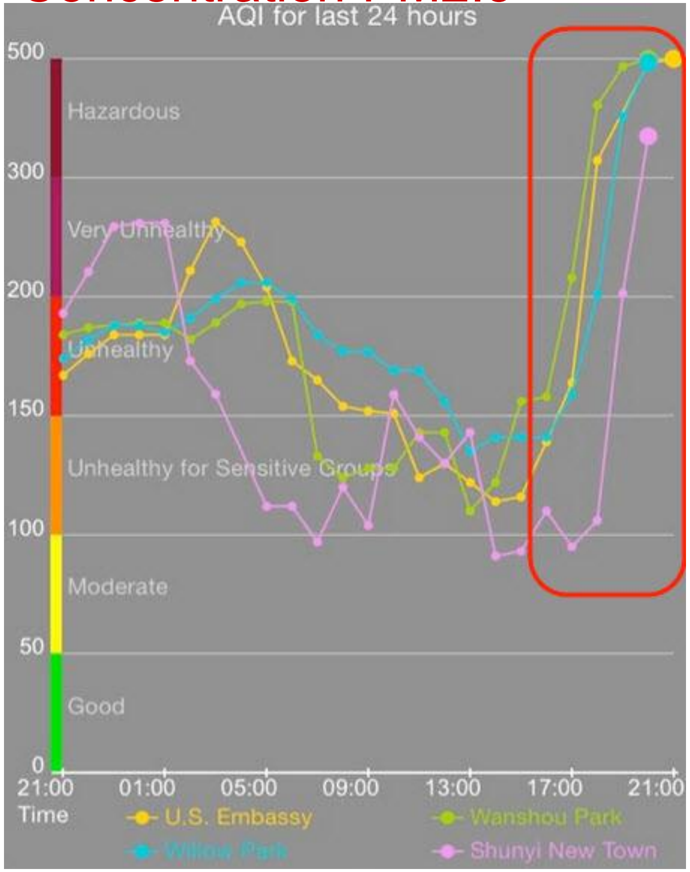
Earlier grape collection!



from Denhez,2005

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.*

Environmental impact

Marcellus field (US)

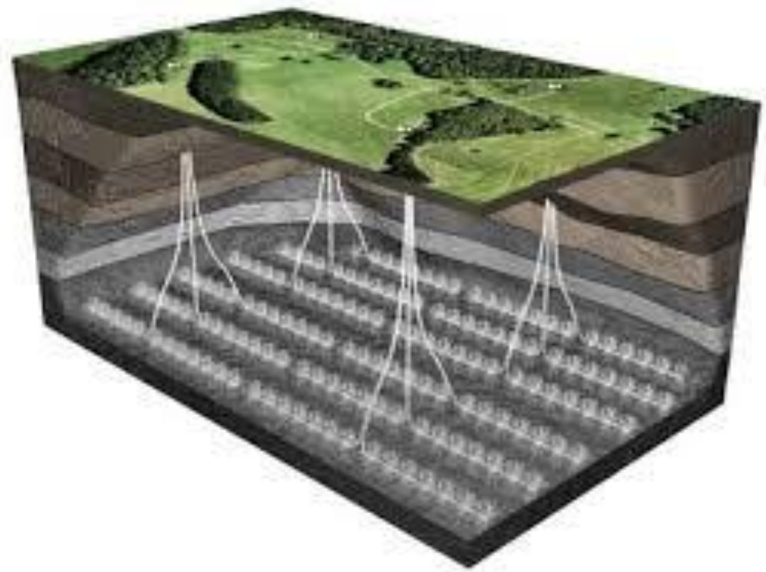
Land occupation
7-10 years of exploitation

Eau de Fracking

Waste mineralised water

Leakage in the aquifer

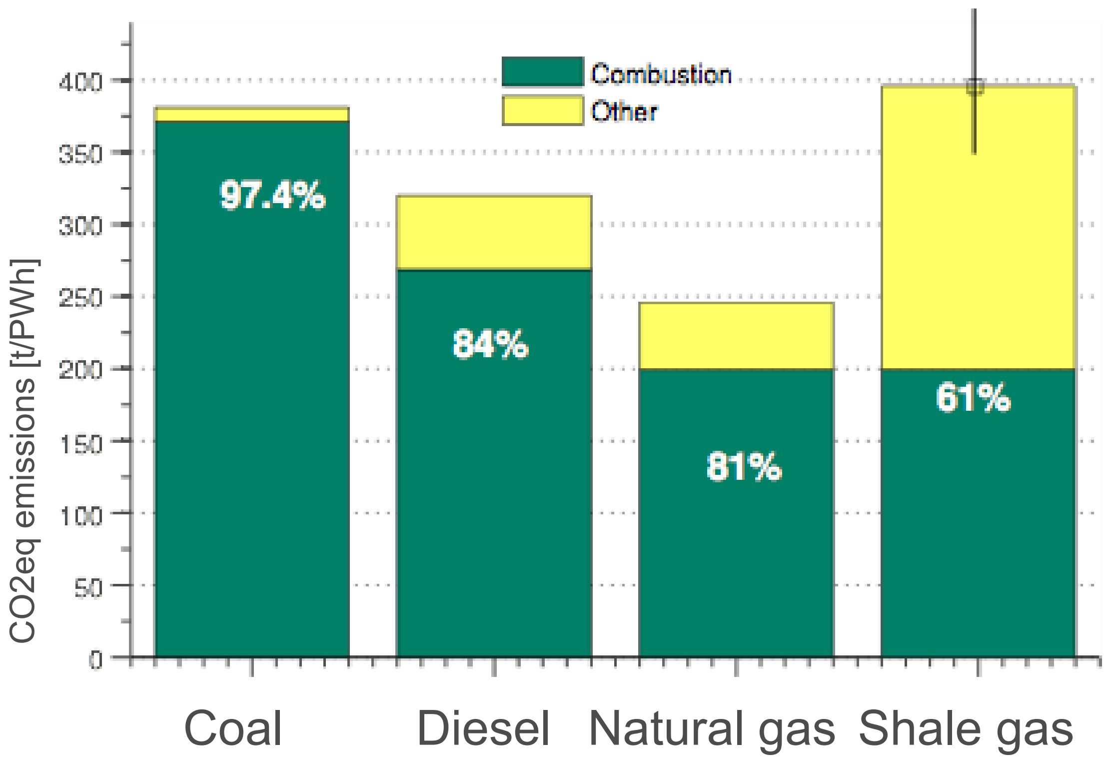
Leakage in the atmosphere



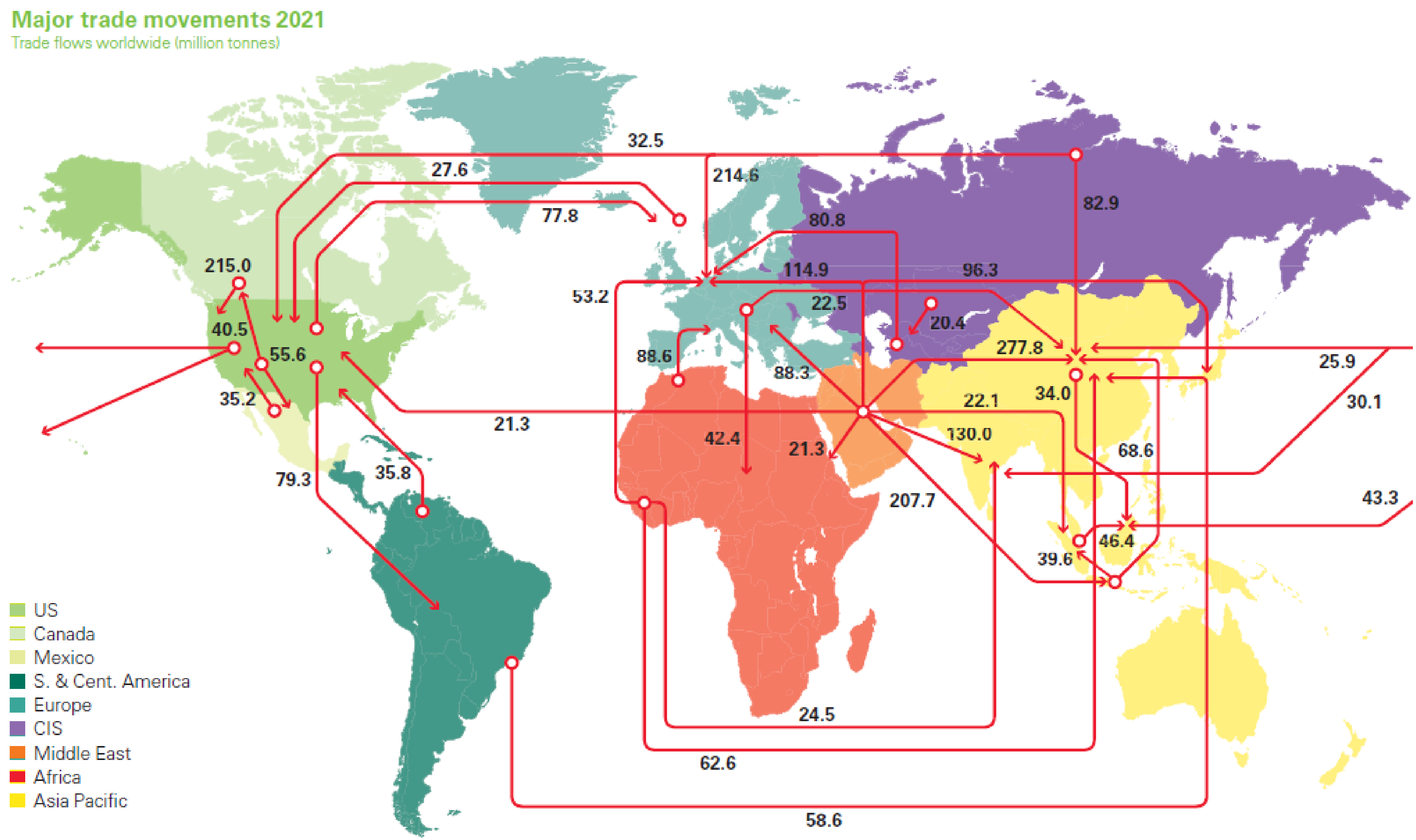
Under ground ? -> Earthquake

Environmental impact

- Importance of life cycle
  - Extraction
  - Treatment
  - Transport
  - Refinery
  - Distribution
  - Combustion



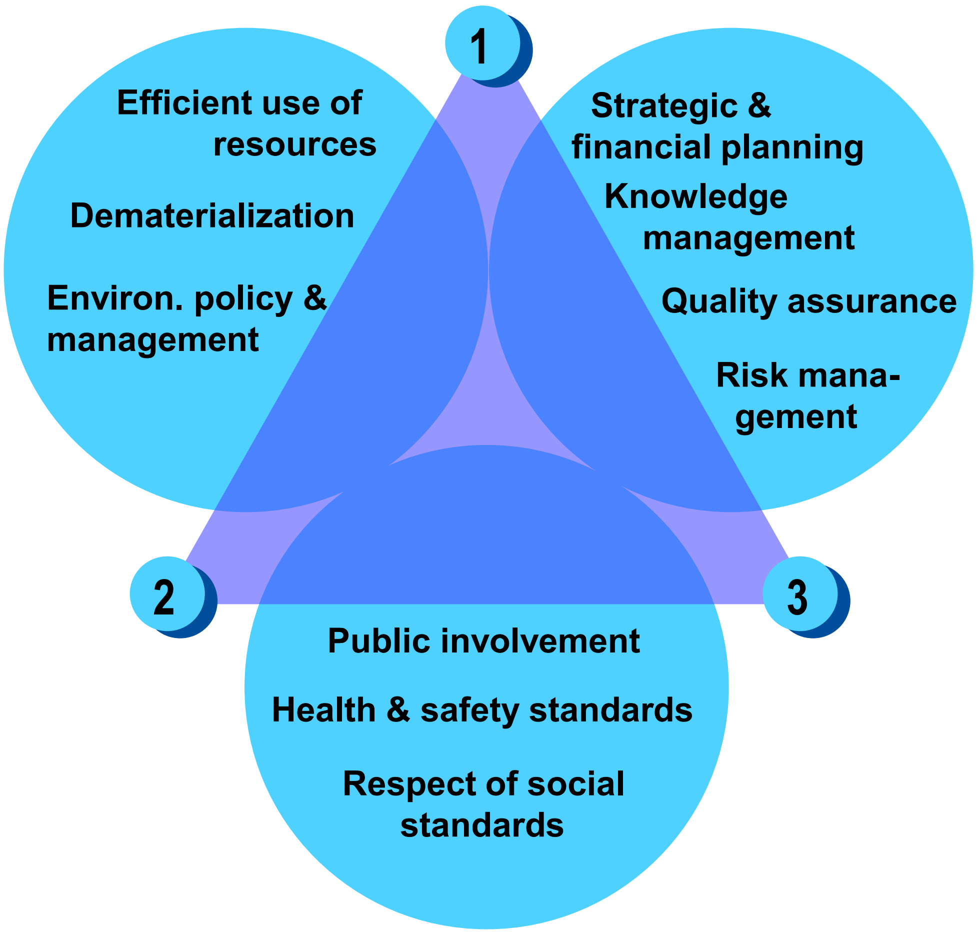
Geopolitical impacts (flows)



How to mitigate emissions and climate, while keeping the services

Sustainable development: meets needs of present without compromising ability of future generation

Sustainability



1. Economy
2. Environment
3. Society

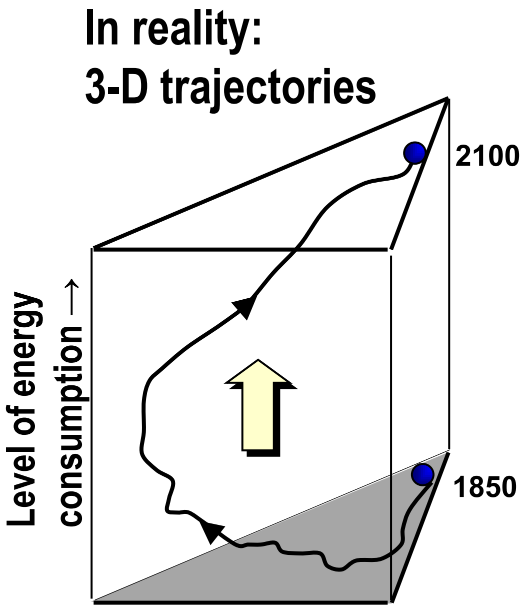
→ Need for efficient, economical, renewable, and environmentally friendly energy technologies

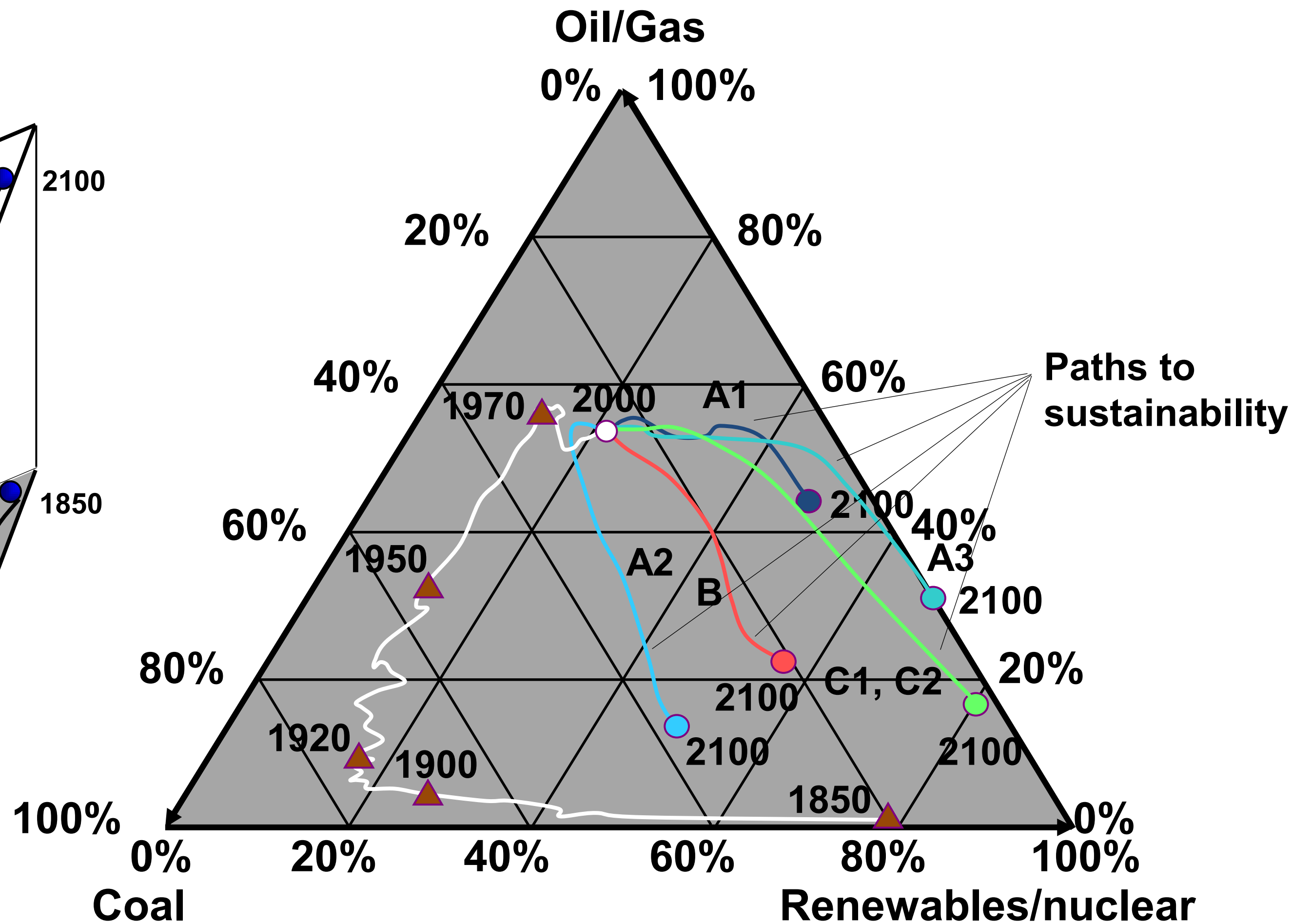
Principal measures

1. Efficiency remains important
   - **ALL** technologies
   - Process integration and optimization
2. Decaronization of energy services
3. Increase of renewable enegry utilization
4. Electrificiaton of services
5. Address the storage issue (seasonal; esp. for renewables)
6. Grids (development, management)
7. Consumer awareness; incentives

All are interconnected!

Pathways


In reality:
3-D trajectories
2100
1850
Level of energy consumption →


Oil/Gas
0%
100%
20%
80%
40%
60%
60%
40%
80%
20%
100%
0%
0%
20%
40%
60%
80%
100%
Coal
Renewables/nuclear
1970
2000
A1
1950
A2
B
A3
C1, C2
1920
1900
1850
2100
2100
2100
2100
2100
Paths to sustainability

Summary

1. Energy supply is still strongly fossil fuel based
2. Economic fossil reserves suffice for ca. 100 yrs, but the climate issue is more urgent
3. Transition to a sustainable energy economy needed