FUSION
the energy of the 3rd millenium

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PART I:
PEOPLE AND ENERGY

What is it, the energy?

- **in physics:** a scalar quantity <u>subject to conservation law</u>, measured originally as a potential to do work (in Joules) leading to many consequences in theory, including

$$\boxed{E = mc^2}$$

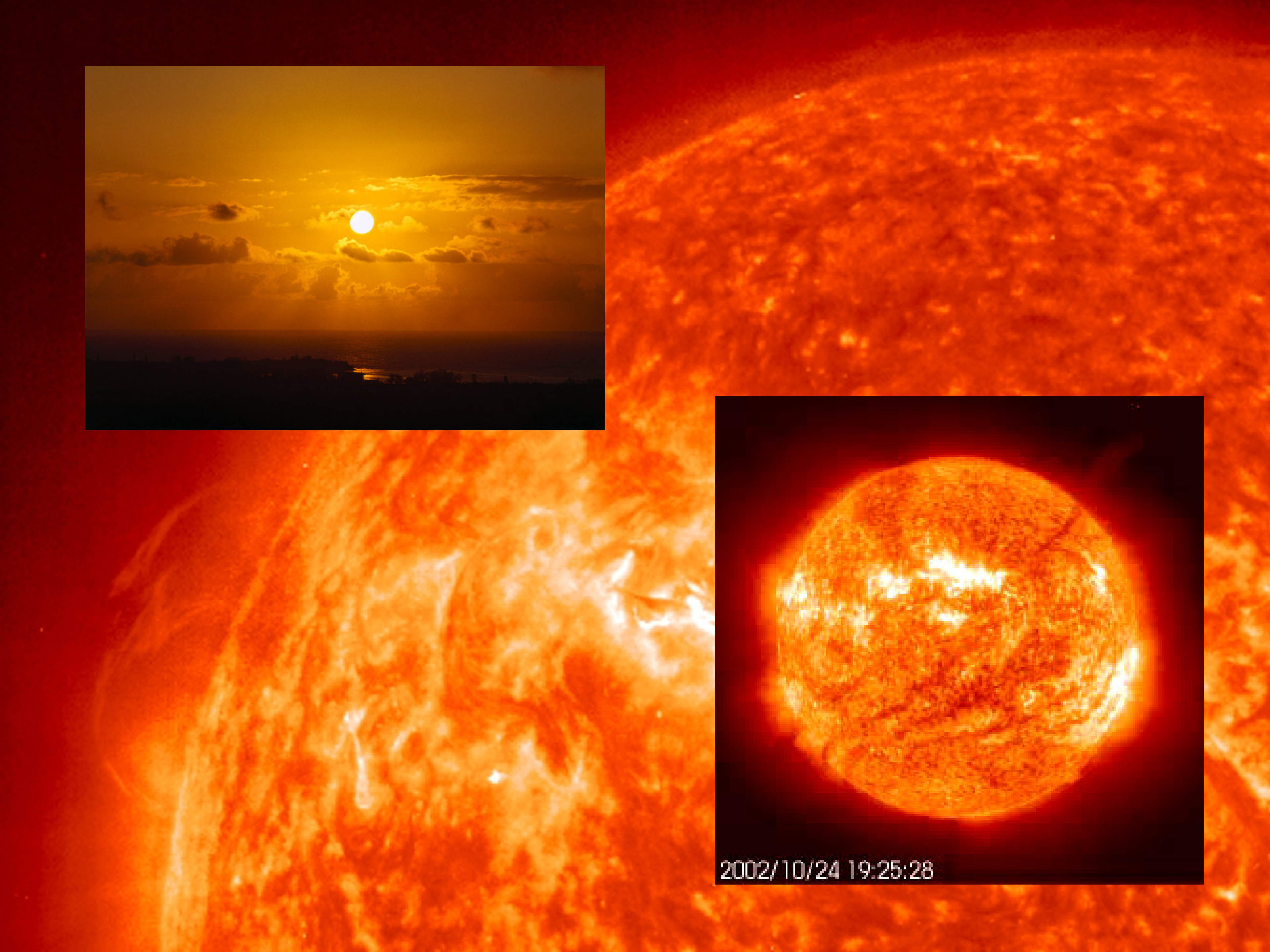
- **in common sense:**

  1. vitality i.e. capability to act, or even a spirituality in esotericism, life force (beyond the scope of this talk)

  2. "the resource that is spent when something is done", often measured (in Joules, kWh or calories) i.e. its **form,** "**quality**" is much more important than the conservation law.

> *energy has **high quality** if its form is easily convertible into other forms (compare electricity – heat – rest energy)*

Where does it come from, the energy?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Solar deity

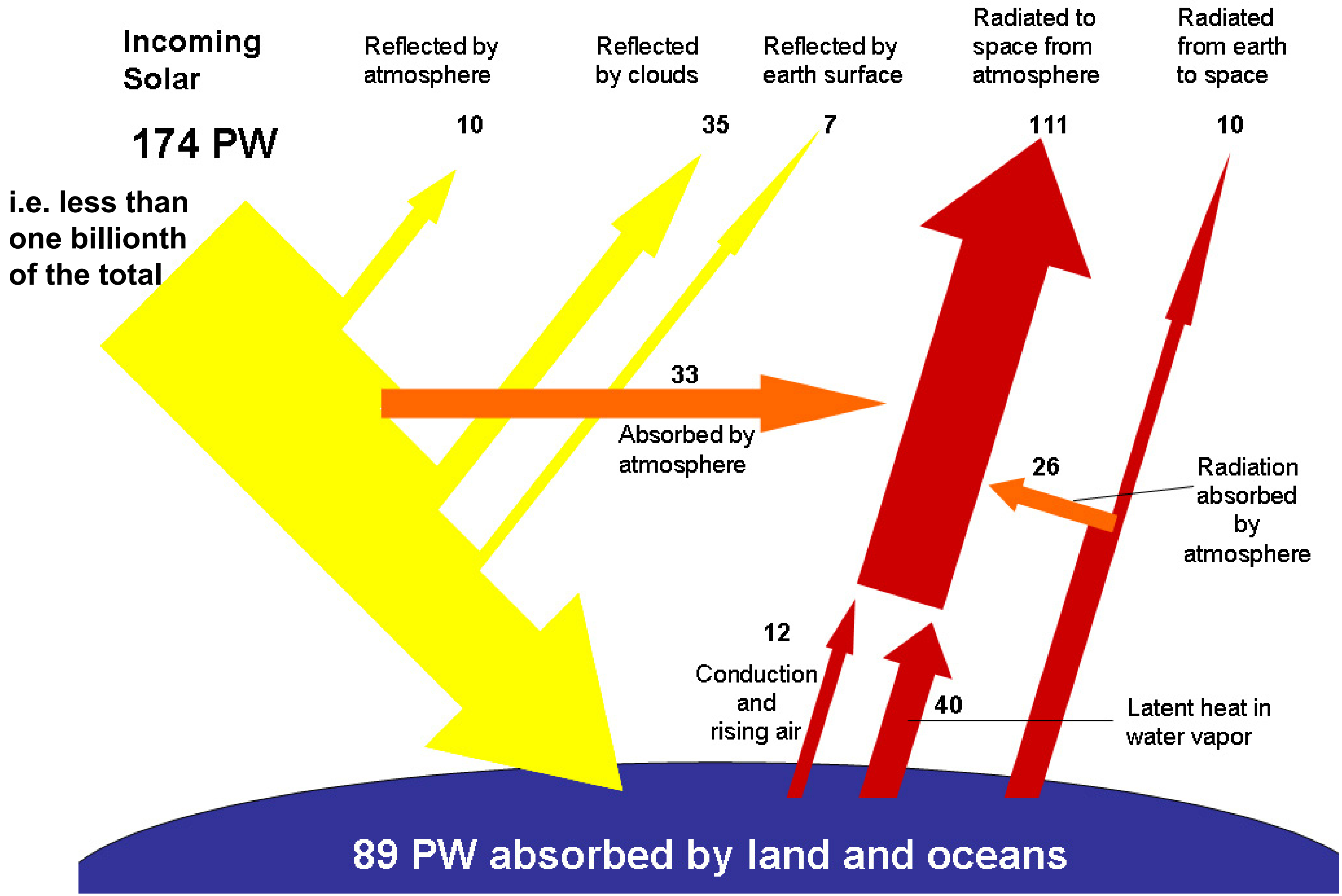
Egypt:: God Ra

Slavic paganism: God Radegast

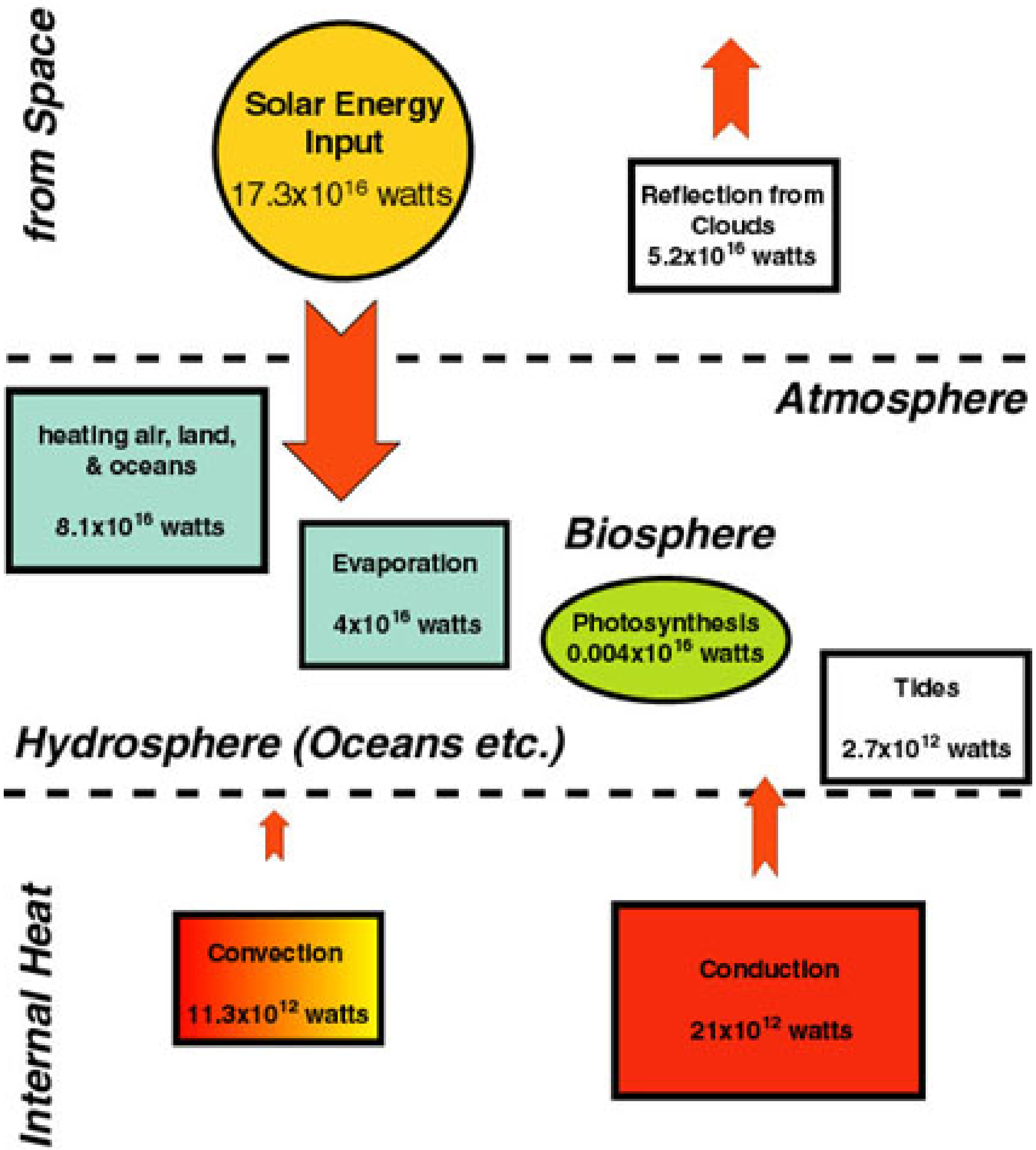
Aztec: God Tonatiuh

Solar power at the Earth

Total power of the Sun is 4.10^{26} W = 4.10^{11} PW



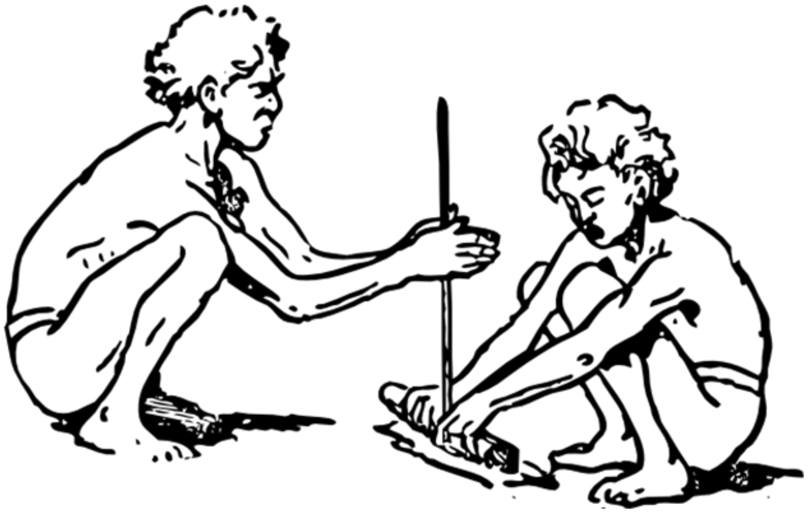
The Earth's Energy Budget

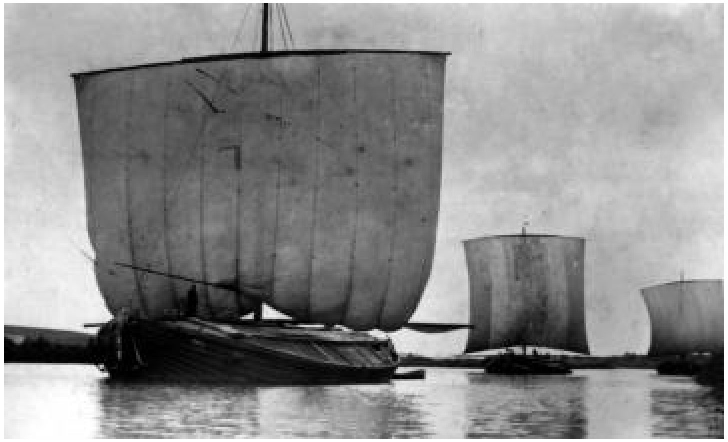


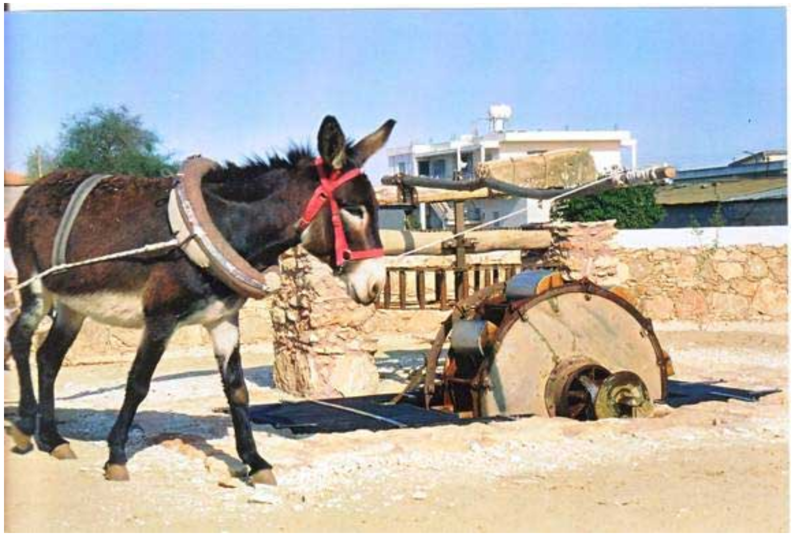
Photosynthesis
4.10^{13} W = 40 TW

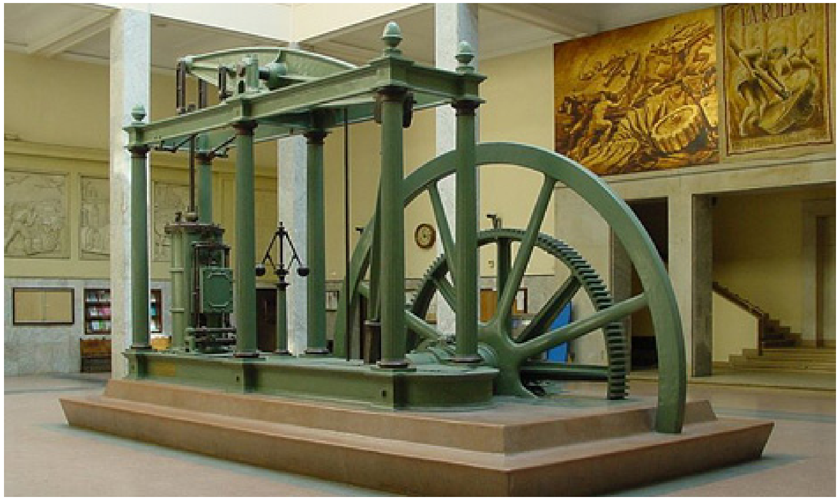
Humankind
total power 16 TW
in renewables ~ 1 TW
in electricity ~ 2 TW

Why do we need energy?



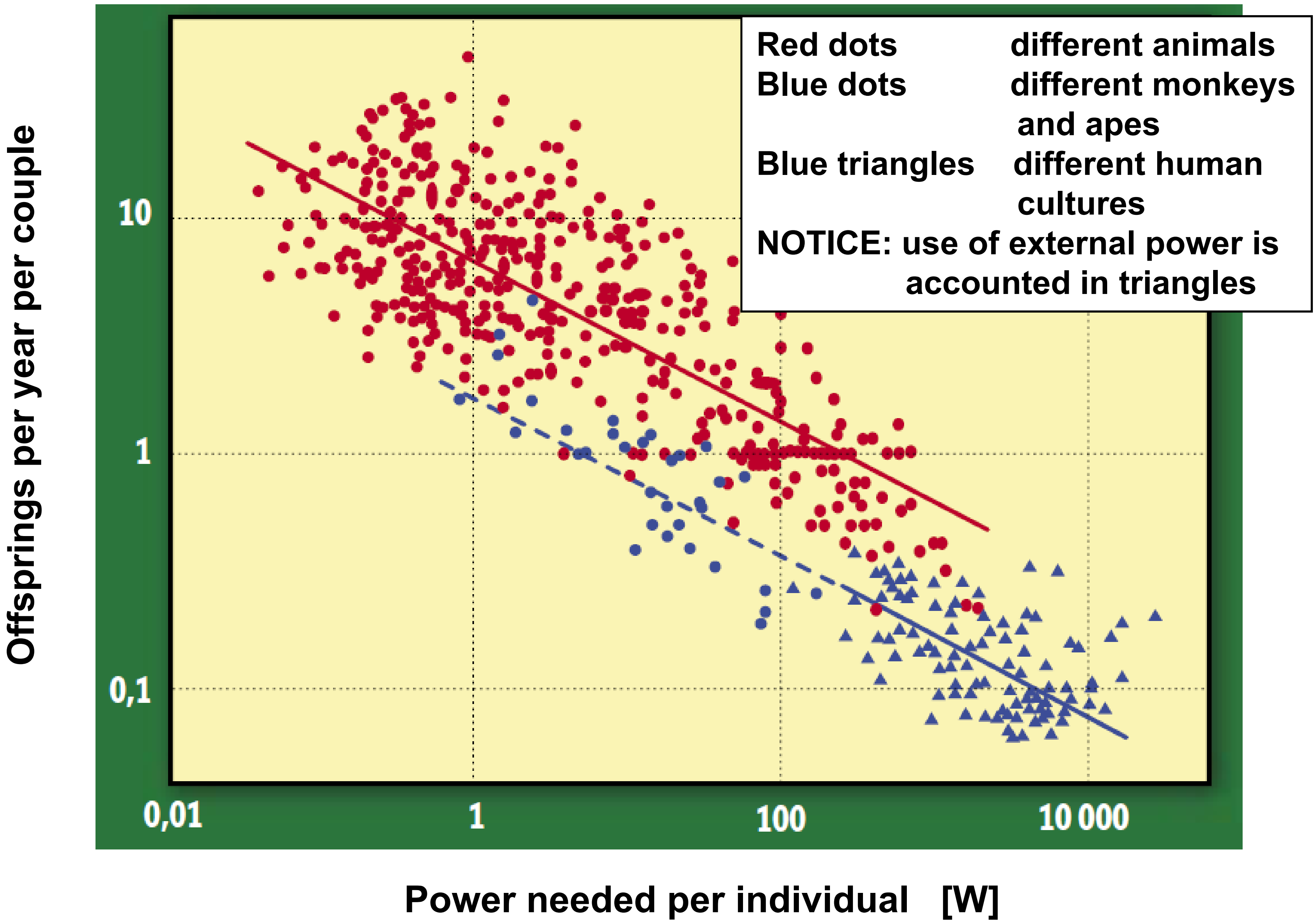






Will we always ask for more energy? No, now rich people ask for <u>better quality</u>.

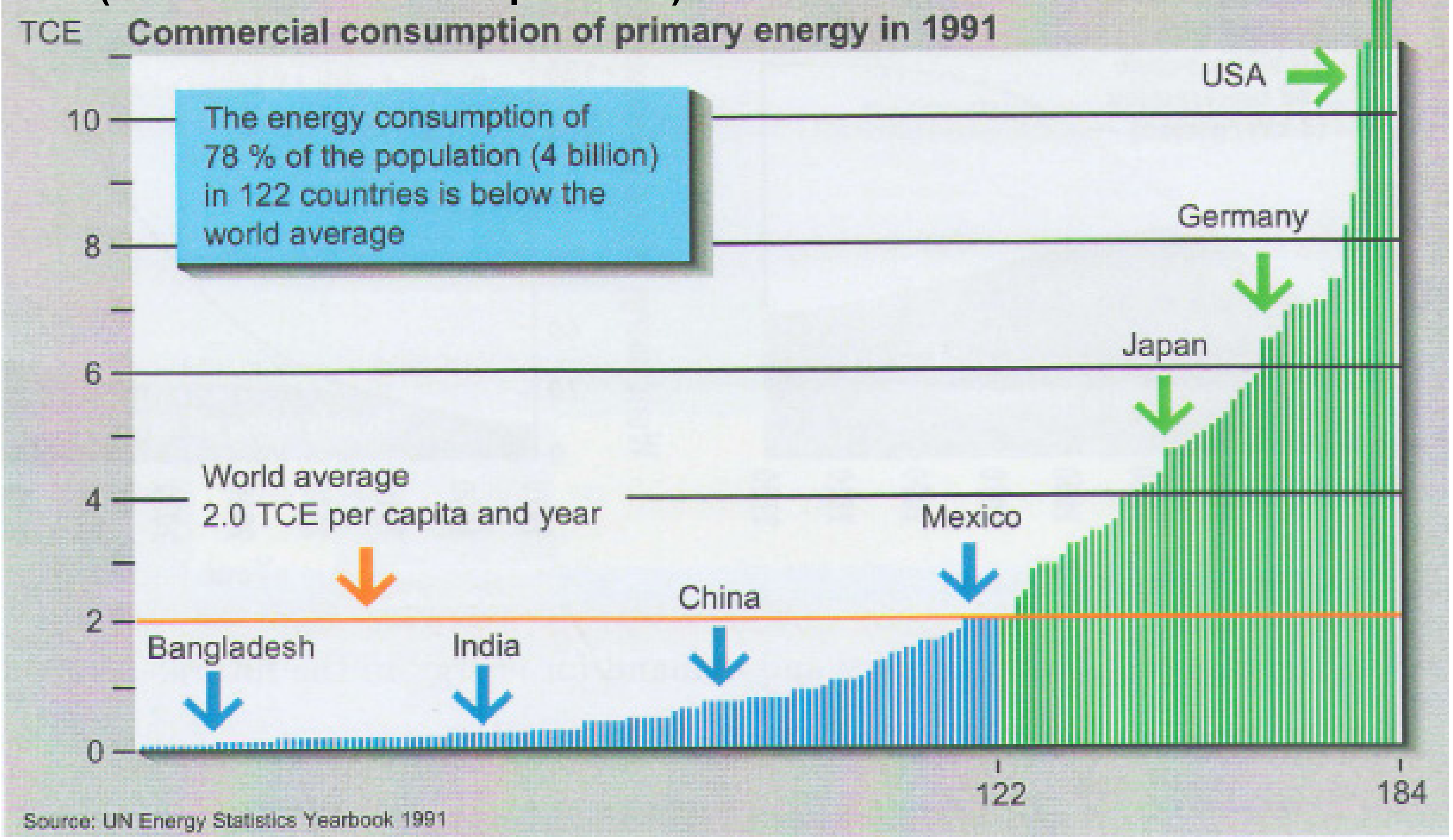
Time for break: a weird link of human and animals



The energy needs of the world

Global energy consumption will increase due to
- population growth
- economic progress in (some) poor countries

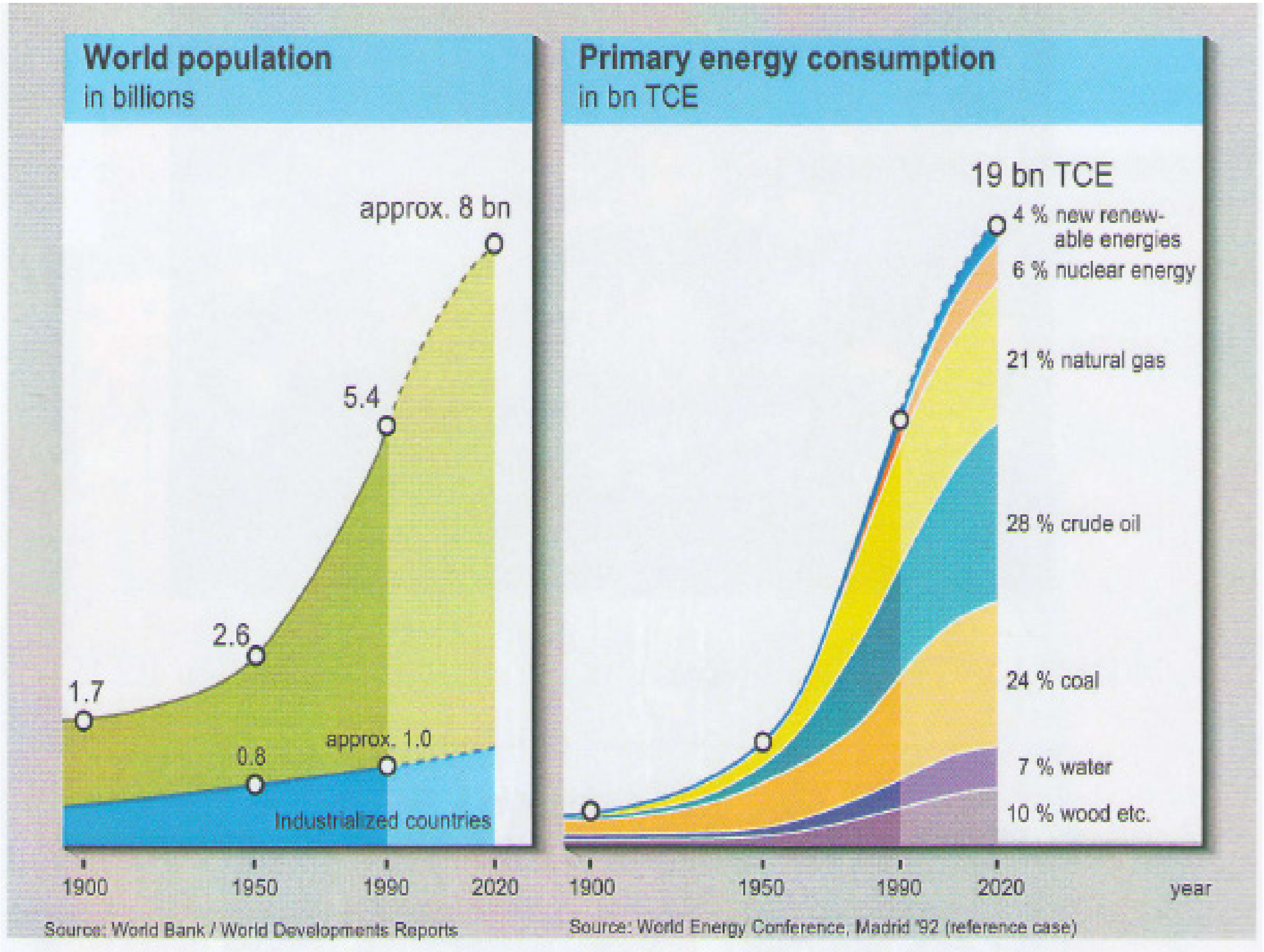
(TCE = tons of coal equivalent)



acceptable quality of life ~ 3 TCE on average.

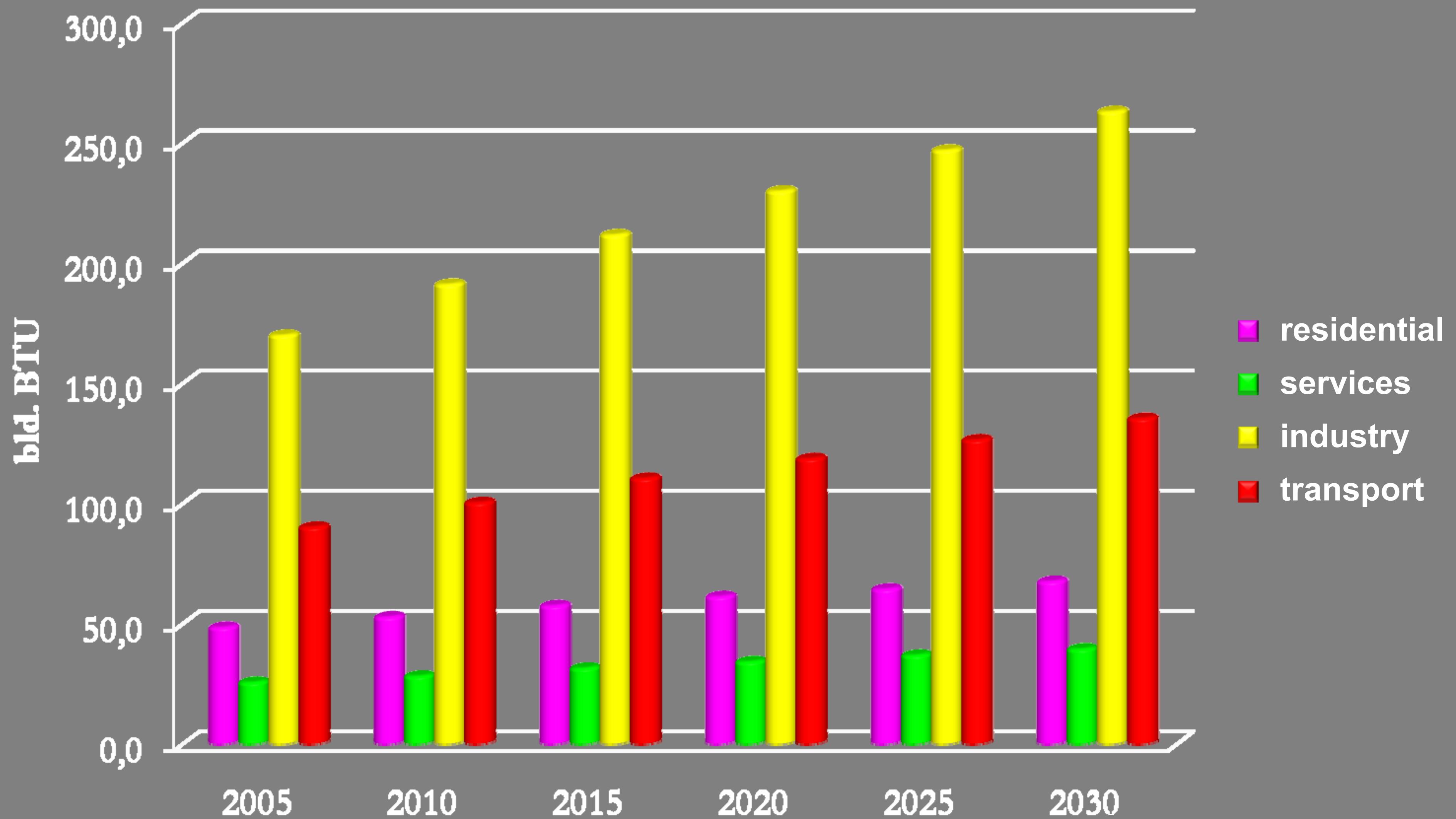
People need more energy and cleaner energy

IEA predicts the global energy consumption will double by 2045.



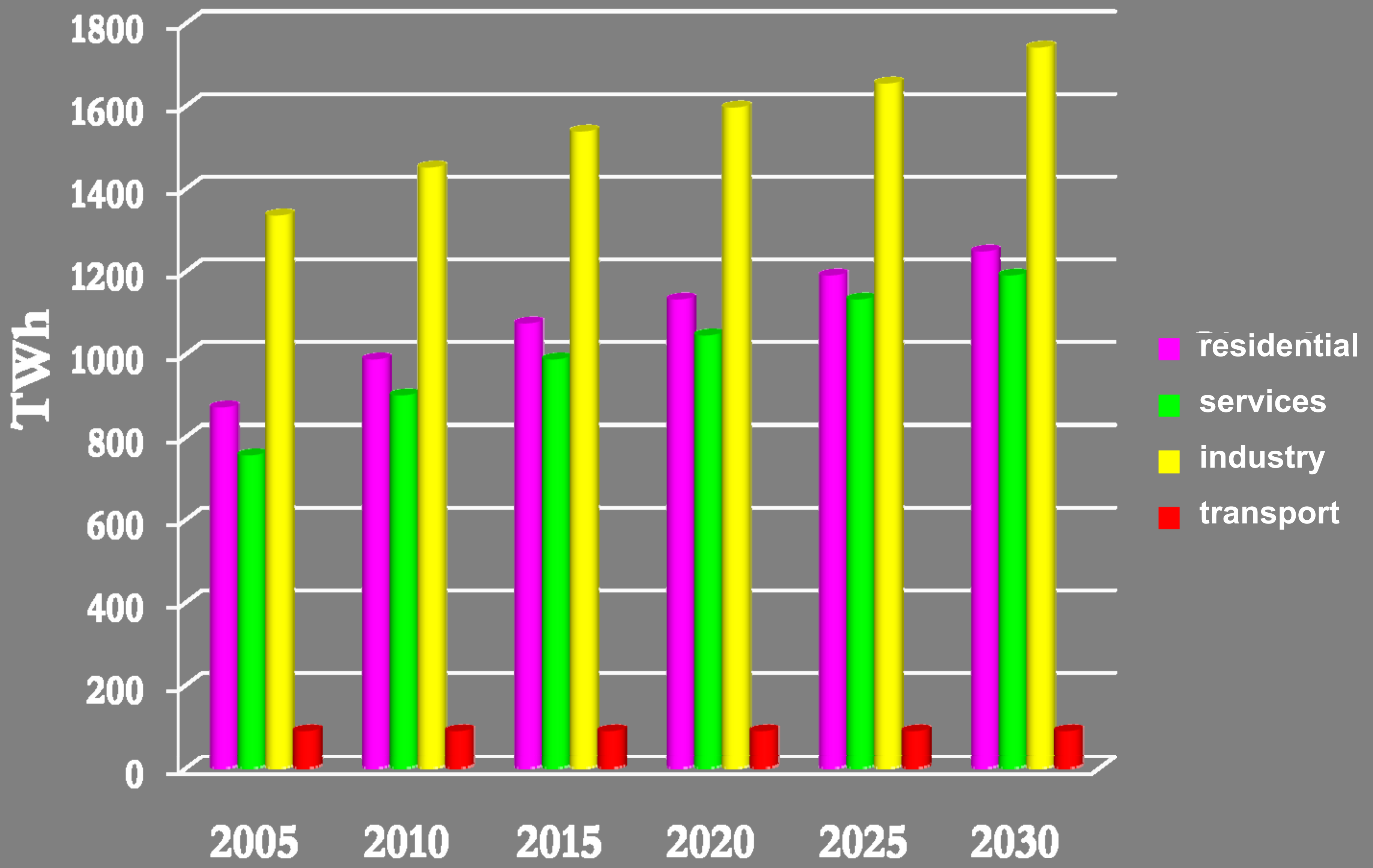
Don't give up! Remind that we still consume much less than the rest of living nature. The challenge is to get a sustainable power source.

Consumption of primary energy



BTU = British Thermal Unit ~ 1055 J

Consumption of electricity



Export and import of electricity in Europe

Fossil fuels: 3/4 of our energy consumptions

Fossil fuels took millions of years to form. Future generations will not appreciate that we depleted their resources.

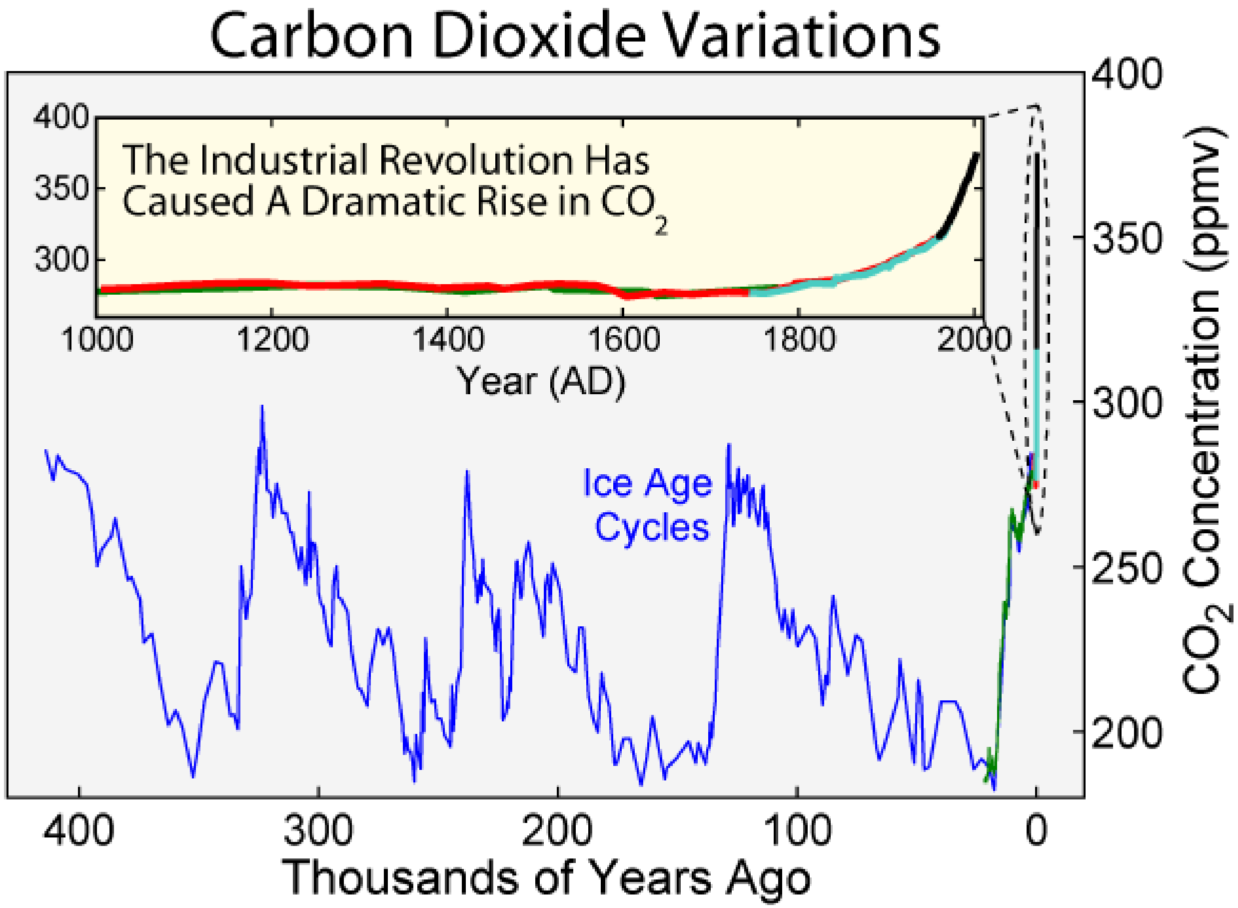
And contributed to…

- climate change

- geopolitical and cultural conflicts

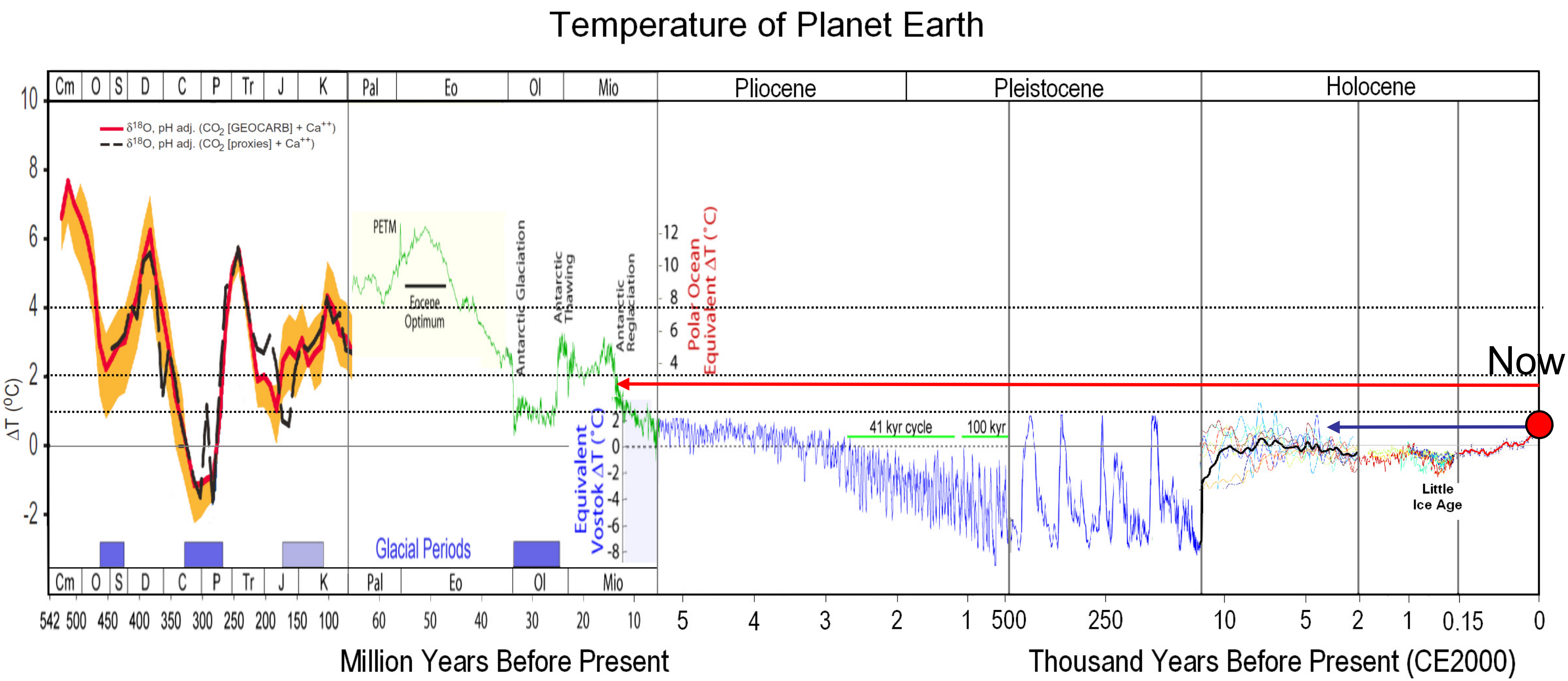
- local pollution

Fossil fuels: Changing the air



Is CO_2 safe??

Greenhouse effect and climate change

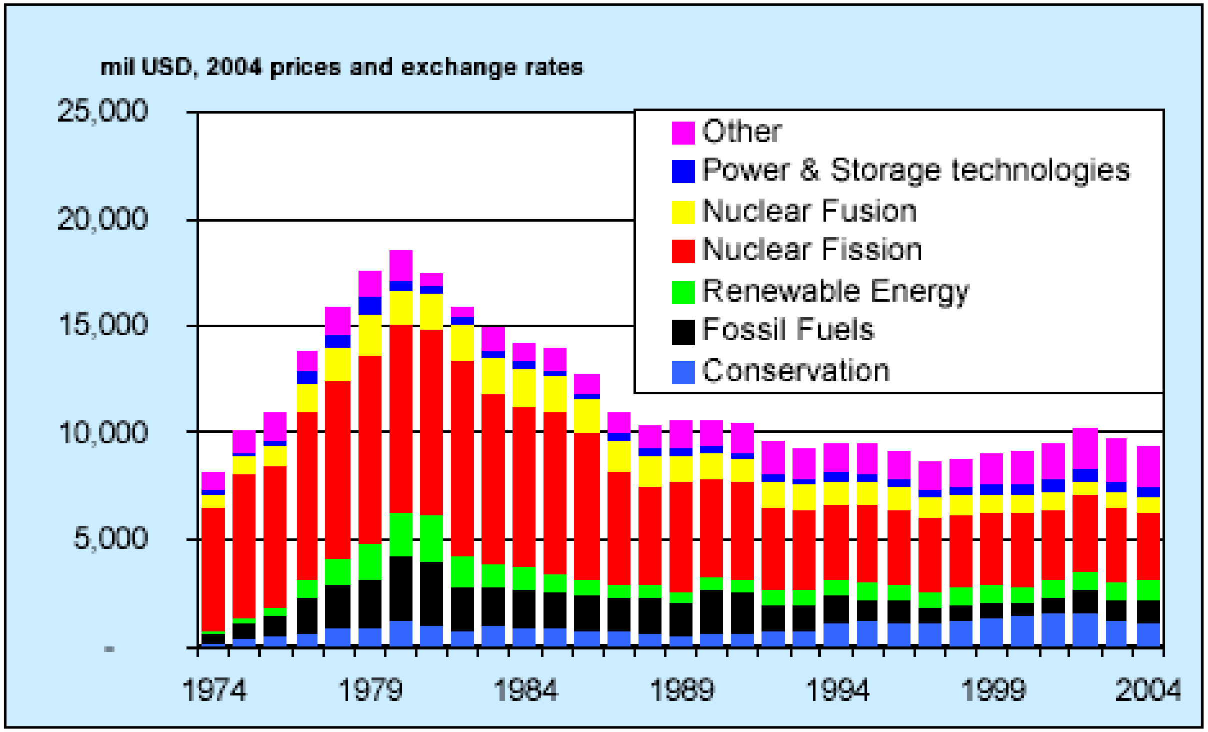


- Global surface temperature increased **0.74±0.18°C** during the last century.
- Projections indicate that the global surface temperature will probably rise a further 1.1 to 6.4 °C during the 21st century,
- Increasing global temperature will cause sea levels to rise.

World energy outlook

„Stern review“
(Independent study for the British government) 2006

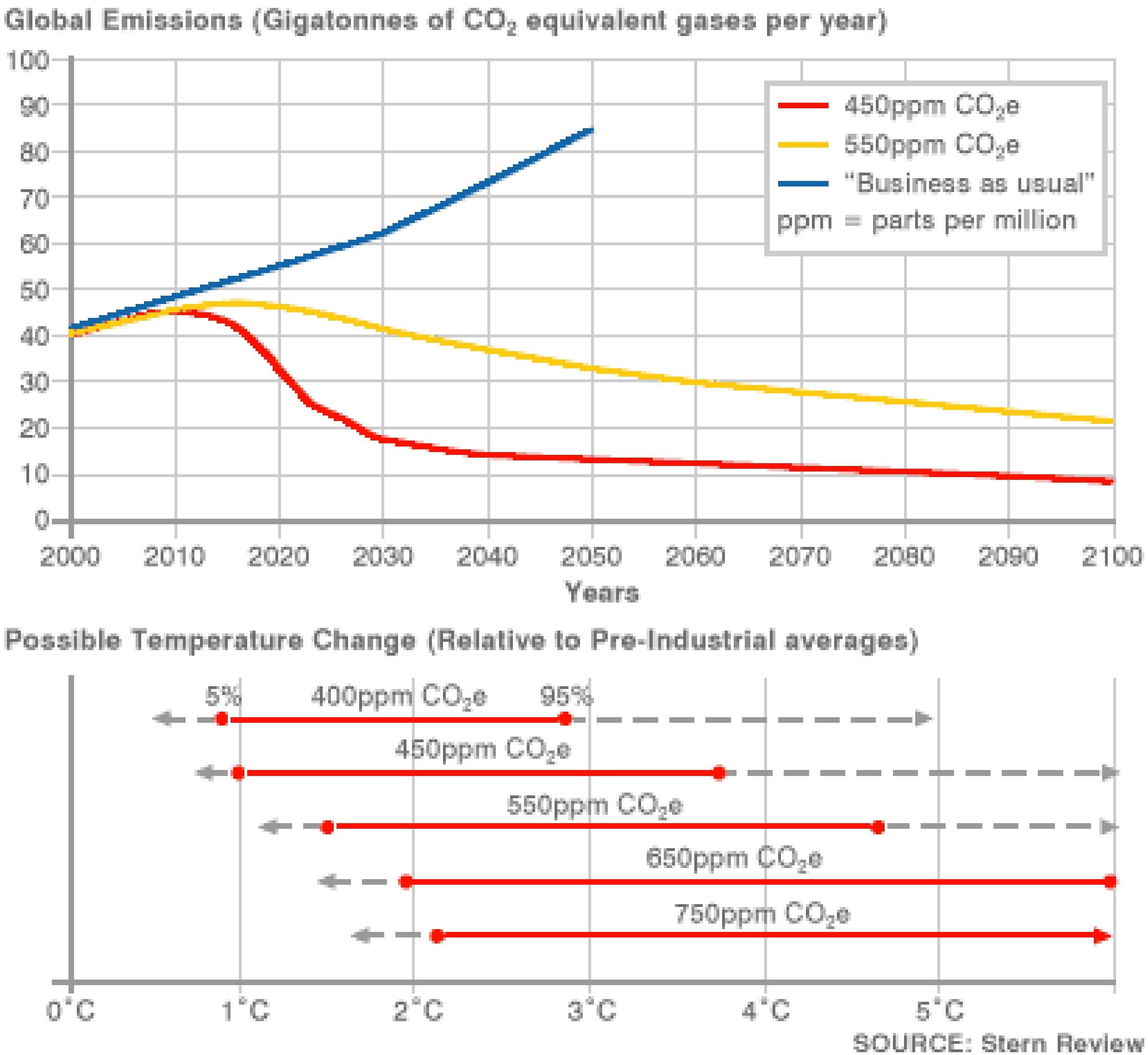
If the climate change is due to the human activities, than we should either invest 1% of the GNP into making these activities sustainable, or get prepared for 20% decrease of the GNP.



Public energy R&D in IEA countries

Unfortunately, the leading economies do not invest much into energy research (neither public nor private bodies) due to long term return of the money invested.

Emission paths to stabilisation



Kyoto protocol 1997

in force since 2005

Mission:based on 1990 data cut 7% emissions of greenhouse gasses incl. CO_2 by 2012

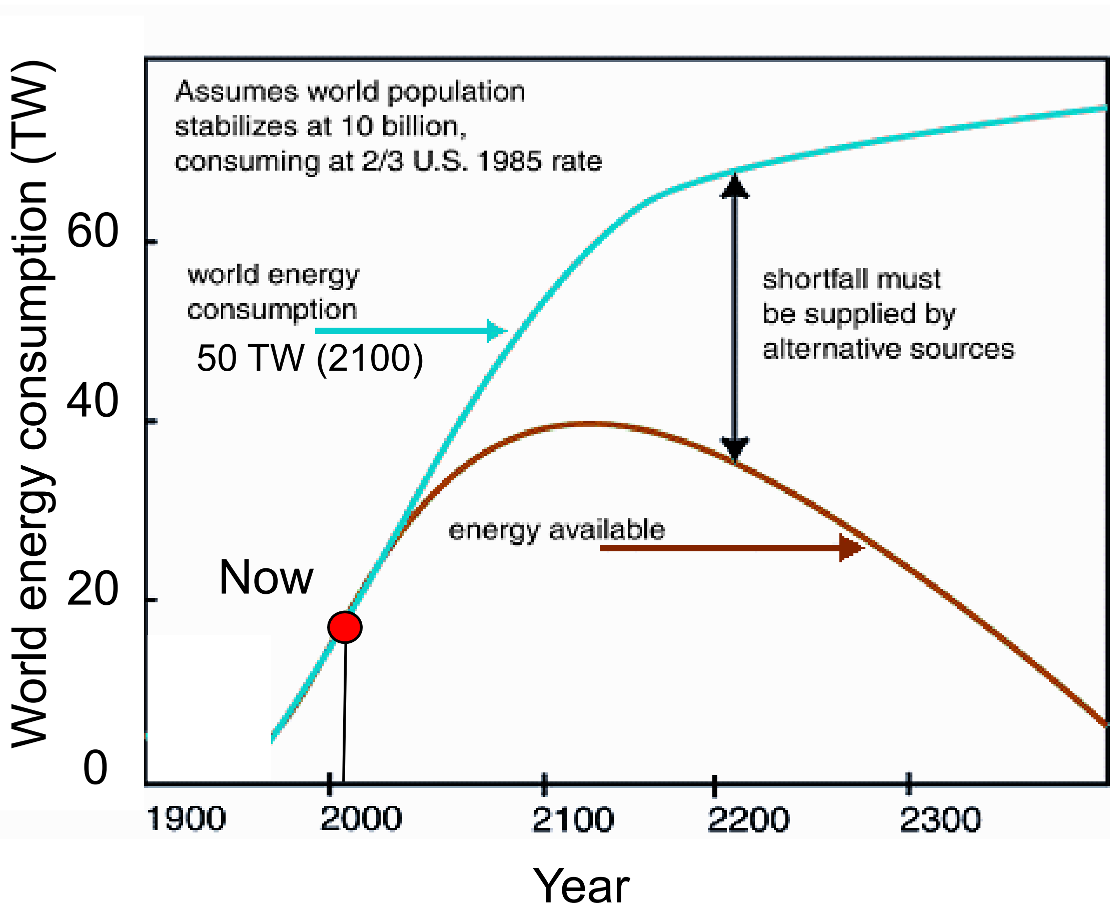
Europe

"20 20 by 2020"

Cut 20% of CO_2 by 2020, and produce 20% of electricity from renewables.

World energy outlook

Even if climate change was untrue (or if CO_2 sequestration worked fine) there is still a major issue regarding available sources (reserves of fossil fuels).



What are the options to fossil fuels?

Nuclear fission

- At present covers less than 7% of energy demand
- **Negligible CO_2 release** → rennaisance
  (notice fission saved more CO_2 than Kyoto protocol aims at)
- **Potential for a long-term solution**
  (however not with the current once-through fuel cycle)
- at present the spent fuel is long-term highly active
- proliferation – danger of abuse of fissile materials
- public concerns regarding safety of the operation

NPP Temelin, PWR 2x1 GWe

NPP Dukovany, PWR 4x450 MWe

Renewables

- ever increasing importance, at present renewables cover approx. 7% of the world energy demand
- low power density and poor reliability – the power grid still requires major backup (peaking) power plants and base load plants
- renewables not immune to the „NIMBY“ and geopolitical problems
- Sufficient potential available only in the solar power but our present knowledge is too limited to exploit it efficiently

But what is the energy source of the Sun?

Thermonuclear fusion.

What is it, fusion?

By definition: **nuclear fusion is an exoergic reaction of light nuclei.**

Some very important examples:

$$p + p \rightarrow d + e^{+} + \bar{\upsilon}_e + 1.44 \text{ MeV}$$

$$\begin{aligned} D + D &\rightarrow {}^{3}He + n + 3.27 \text{ MeV} \\ &\rightarrow T + p + 4.04 \text{ MeV} \end{aligned}$$

$$D + T \rightarrow \alpha + n + 17.6 \text{ MeV}$$

In brief: $D(d,n)^3He$ and $D(d,p)T$

$$p + {}^{11}B \rightarrow 3\alpha + 8.68 \text{ MeV}$$

What is it, thermonuclear fusion?

In fusion reactions, the two reacting nuclei are subject to long distance electric repulsion. This "**Coulomb barrier**" is overruled by much powerful "**strong interaction**" only at a very short distance. High kinetic energy of the reacting nuclei is the typical vehicle to get over the barrier.

We speak of **thermo**nuclear fusion if this high kinetic energy is due to high temperature of the fuel.

Both fusion and fission release energy

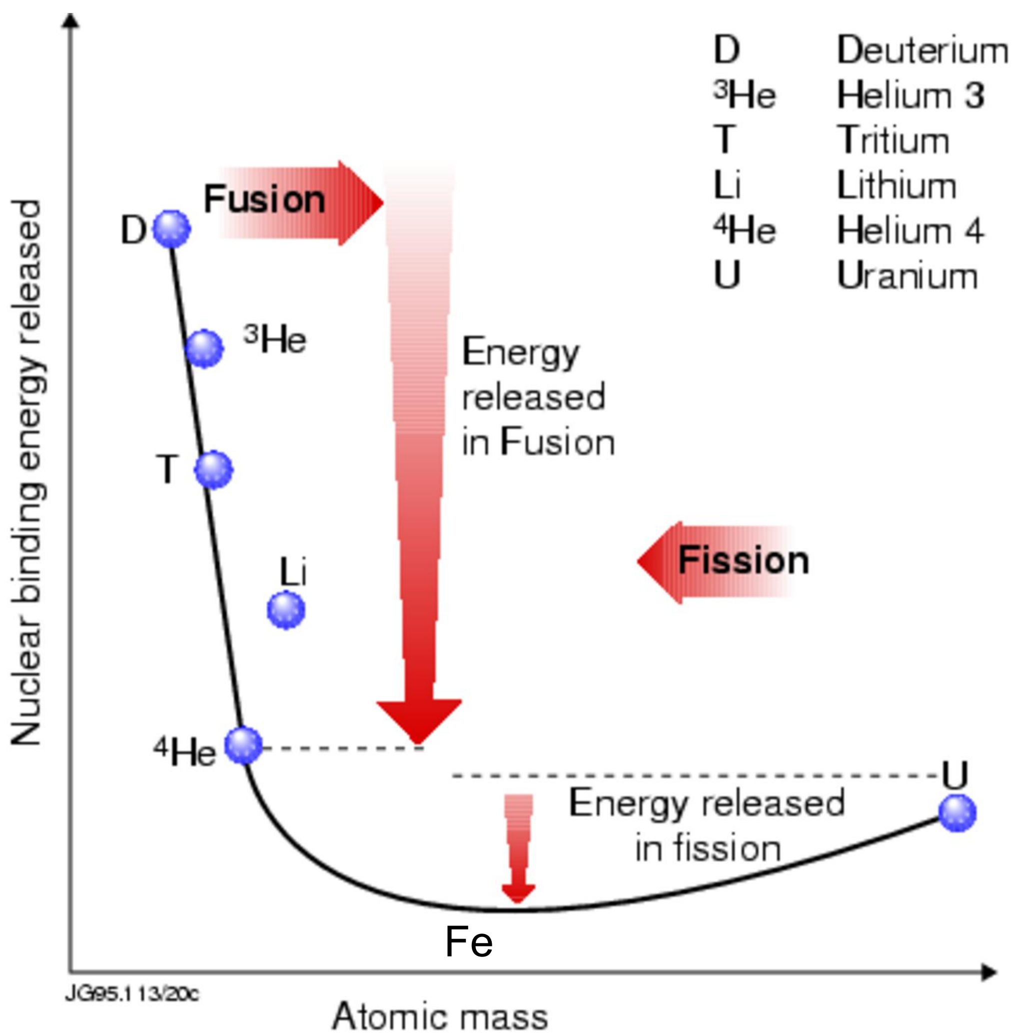
How comes?
Simple explanation is given
by **liquid drop model** of nucleus

• strong nuclear interaction acts at a short range. It is therefore advantageous to form a sphere (to minimise surface)

• electrostatic interaction act on distance. Not only it causes a barrier to fusion, but also it means that for large nuclei it is advantageous to split (protons repulse each other)

• extremes like He are beyond this model, nuclear shell model required.

…but fusion is (even more) efficient



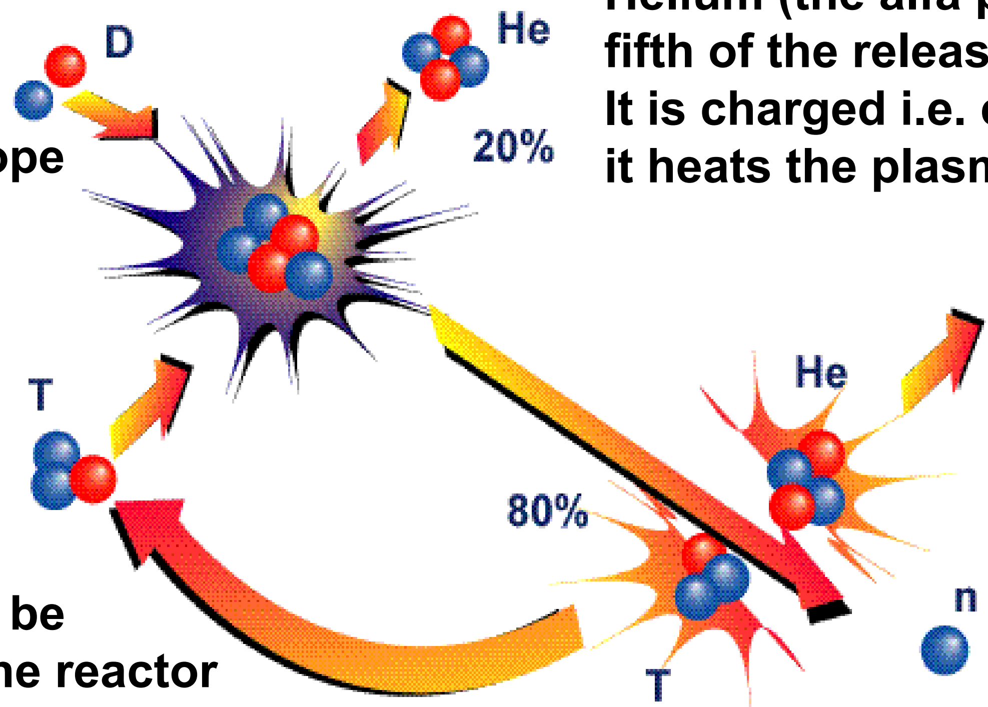
A more detailed look on the D-T fusion reaction

D-T fusion reaction has by far the highest probability

$D + T \longrightarrow {}^{4}He + n + \text{Energy}$

Deuterium is a natural isotope of hydrogen (0.015 % of H)

Helium (the alfa particle) carries one fifth of the released energy (2.5 MeV). It is charged i.e. confined → it heats the plasma.



Neutron has no electric charge and carries four fifths of the released energy (14.1 MeV)

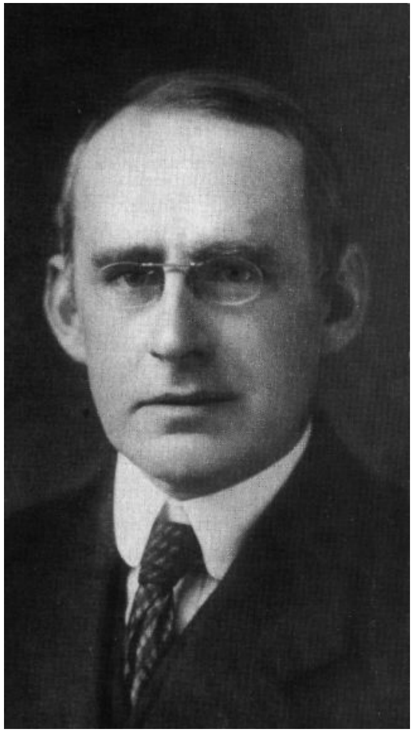
Tritium has to be produced in the reactor from lithium

„Tritium breeding“ to be demostrated and detailed in ITER

${}^{6}Li + n \longrightarrow T + {}^{4}He + 7.7 \times 10^{-13}$ Joules

${}^{7}Li + n \longrightarrow T + {}^{4}He + n - 4.0 \times 10^{-13}$ Joules

Famous quotes



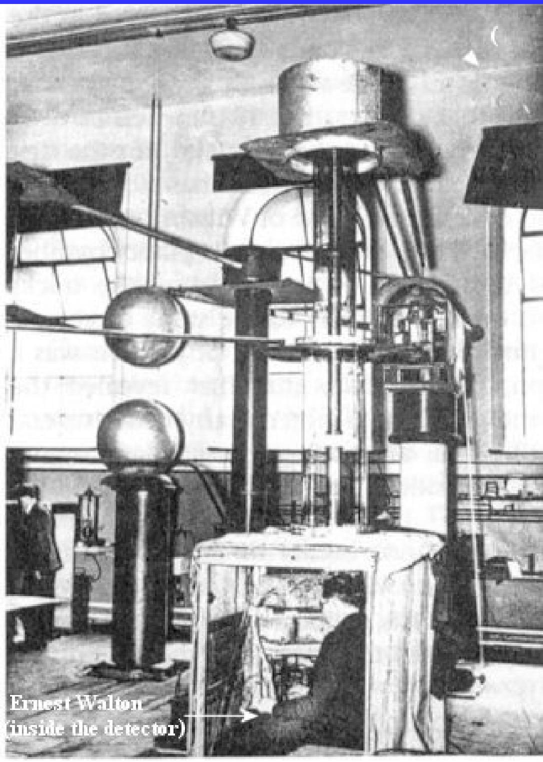
Sir Arthur S Eddington (1920):

« If, indeed, the sub-atomic energy in the stars is being freely used to maintain their great furnaces, it seems to bring a little nearer to fulfilment our dream of controlling this latent power for the well-being of the human race – or for its suicide. »

John D. Lawson (1955):

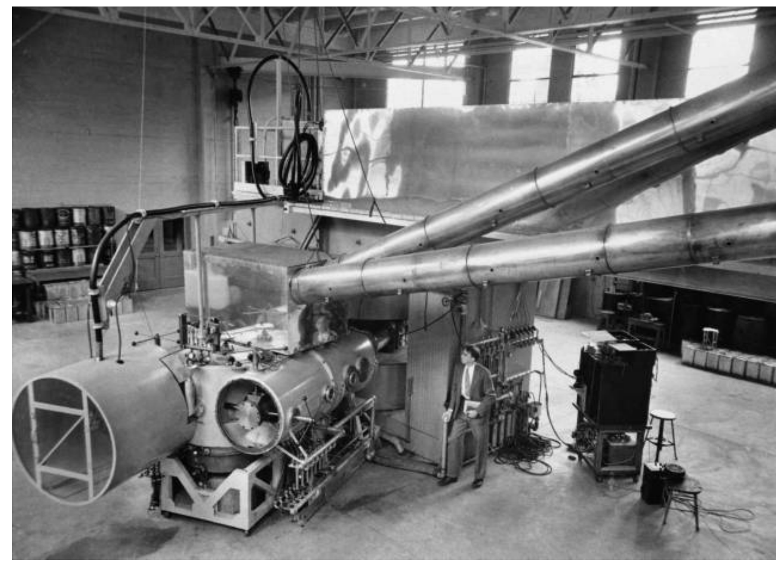
« It is seen that for a useful reactor T must exceed 10^8 degrees and nt must exceed 10^{16}. These conditions are very severe. Conditions for a T-D-Li reactor (...) are easier though still severe. The corresponding values of temperature and nt are $T=3x10^7$ degrees, $nt=10^{14}$. »

A brief historical note



<u>The first nuclear reaction</u> 1932, Cockroft & Walton, 100 keV accelerator in the Cavendish laboratory $^{7}Li(p,\alpha)\alpha$ and $^{6}Li(p,\alpha)^{3}He$ → Nobel prize 1951

<u>D-D fusion</u> discovered (!) 1934, Oliphant, Harteck, Rutherford, Cavendish laboratory... $D(d,p)T$ and $D(d,n)^{3}He$



Both T and ^{3}He isotopes were isolated and tested by Alvarez in Berkeley (first cyclotron) only in 1939
→ Surprise that ^{3}He is stable and T is not
→ Nobel prize 1968

Properties of the D-T fusion were studied for the first time during the World War II in the Purdue University. Large (resonant) cross-section came as a surprise.

Energy density in different fuels

Energy Source	Energy Density (MJ/kg)
Deuterium-Tritium Fusion (breeding Tritium out of Lithium)	187,000,000
Natural uranium (99.3% U-238, 0.7% U-235) in fast breeder reactor	24,000,000
Enriched uranium (3.5% U235) in light water reactor	3,456,000
Natural gas, Crude Oil and Derivates, Coal and similar (burned in air)	~40

Current fusion research aims at converting a breakthrough fraction of rest energy into high quality heat (that we can convert into electricity or fuel)

Conclusion of part I

In near future there is no magic solution to resolve increasing mismatch in energy demand and sustainable supply. Therefore

(i) a broad mix of power sources must be maintained

(ii) None of the potential sources can be ignored