Energy challenge for the 21st century

Sandra Bouneau
Institut de physique nucléaire d'Orsay
bouneau@ipno.in2p3.fr

UNIVERSITÉ PARIS SUD FACULTÉ DES SCIENCES D'ORSAY

IPN INSTITUT DE PHYSIQUE NUCLÉAIRE ORSAY

- The question about energy challenge is difficult to deal with because it contains many different aspects

technological
sociological
political
economical
environmental
ideological

- find alternative sources to nuclear energy considered as dangerous for humanity by a large part of citizens
- improve significantly the energy efficiency and/or reduce the energy consumption
- make the cost of energy as low as possible
- provide to the world the energy it needs
- reduce the energy consumption inequalities in the world
- preserve the climate change by reducing the green-house gas emissions
- deploy massively renewable energy sources
- ….

All these aspects are inter-connected and not always easy to conciliate

⇨ Some choices have to be made !

- 1st part Present world energy context
  - distribution of energy consumption in the world
  - fossil fuels ressources
  - climate constraint
  - evolution of the world energy consumption

- 2nd part Survey of energy sources
  - their main characteristics
  - their uses
  - their estimate for 2050

- 3rd part A simplified construction of the energetic world in 2050
  - hypotheses
  - approach and main steps of the construction
  - some results

Some precautions have to be taken to discuss about energy

- What is the energy we are talking about ? the available, primary, final or useful energy ?
  - the **available energy** is the form of the energy at the primary source level
  - ➡ 2 types of primary source
    - ✓ **« stock energy »**: stock is limited as fossil fuels (oil, gas, coal) and uranium

chemical energy storage

coal

oil

gas

combustion reaction

C, $(CH_2)_n$, CH_4 } $+ O_2 \rightarrow CO_2 +$ heat + …

energy stored in bounding energy between nucleons

natural uranium

nuclear reactor

fission reaction

$^{235}U \rightarrow$ nucleus1 + nucleus2 + heat

✓**« flow energy »**: energy arrives continuously (flux) wether it is exploited or not for our needs

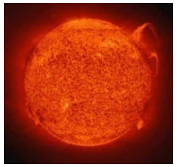
hydropower

kinetic energy of water in dam

windpower

kinetic energy of wind on wind turbine paddles

sun



light energy

biomass

chemical energy released into heat by combustion

- the **primary energy (PE)** depends on the type of the primary source and is defined according to a **convention**

« stock energy » sources
PE = **heat** released by combustion and fission reactions

« flow energy » sources
PE = **energy provided by the installations**
- dam, wind turbines and photovoltaic cells: PE = **electricity**
- solar panel and biomass: PE = **heat**

- the available energy has not the right form to be used directly for our needs and has to be converted in **useful energy**

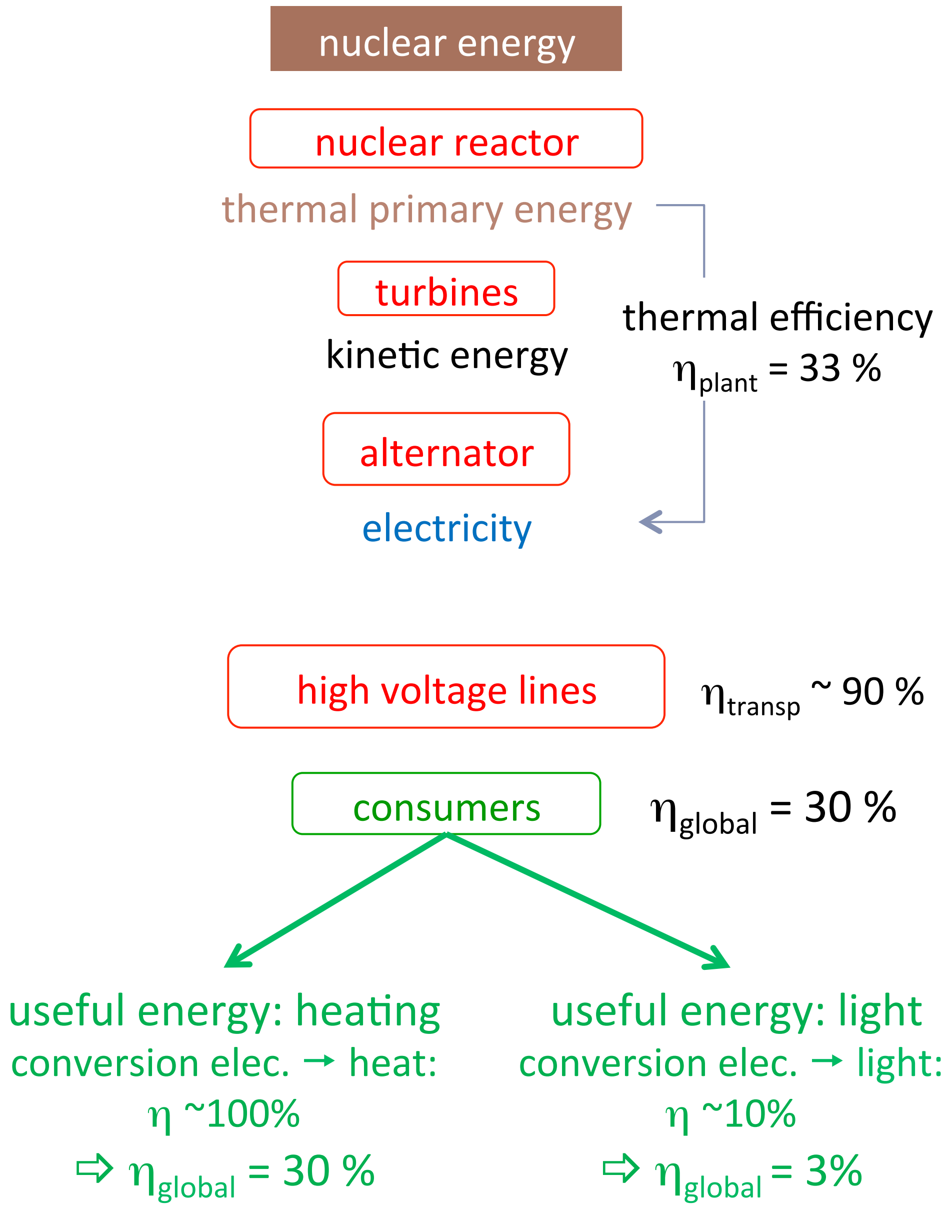
- ✓ the energy initially available (chemical, light, nuclear, …) is succevely converted in different forms to end in a useful form to consumers (mechanical, thermal, light, …)

- ✓ for each conversion, the recovered energy in the right form is quantified by the efficiency

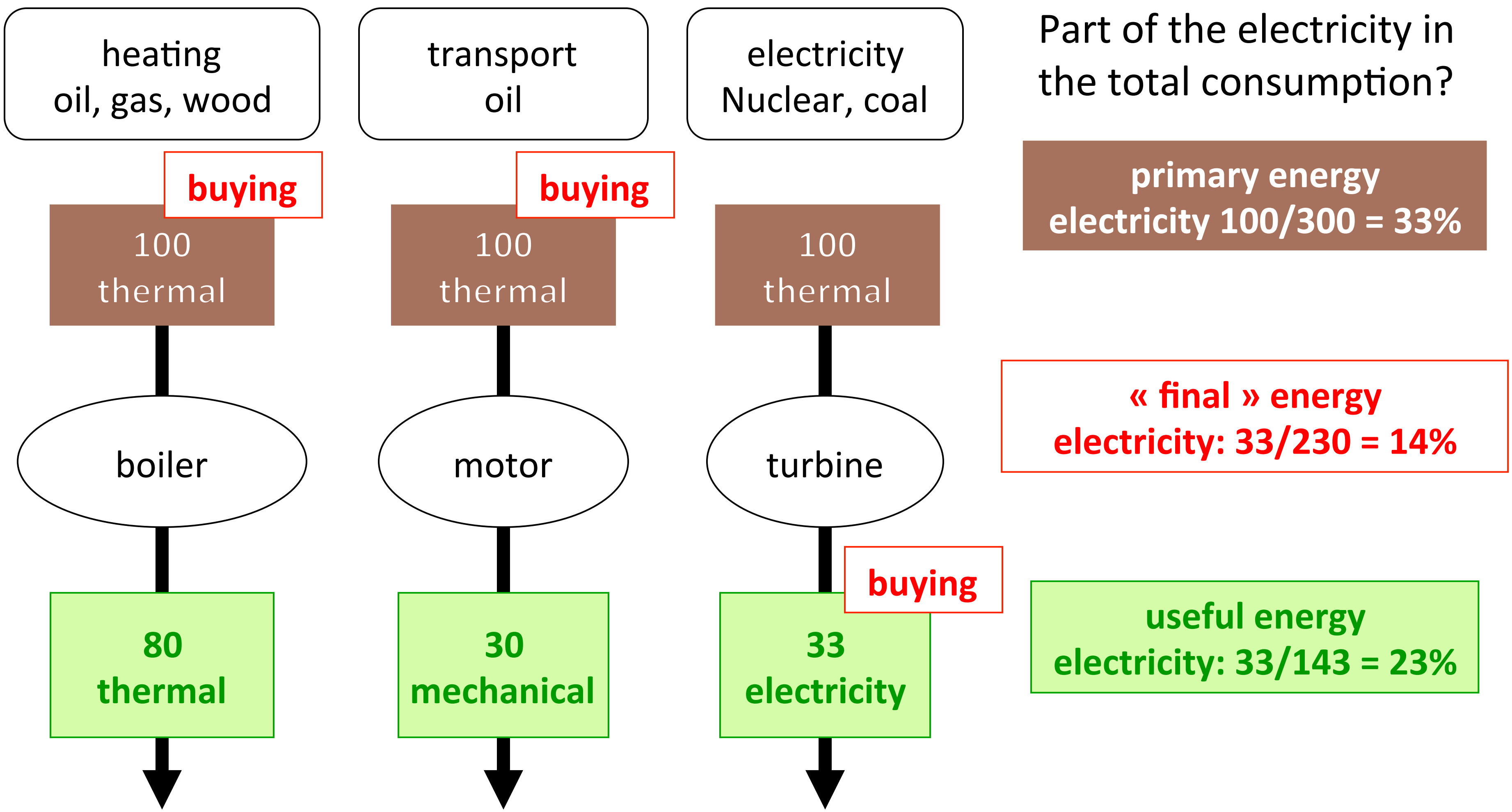
$$\eta = \frac{E_{useful}}{E_{available}}$$

	conversion	η
coal or gas thermal plant	heat → elec.	30 – 50 %
individual gas-fired boiler	heat → heat	60 – 90 %
engines	heat →mech.	25 – 35 %
battery	elec. → elec.	80 %

Ex: conversion of fission to light/heating



- the « **final** » **energy** used by economist is the energy the consumers buy: electricity, gasoline, gas, domestic fuel, …
- Major difficulty: what is the best way to count energy?



Nuclear in France

Final electricity

nuclear: 80 %

Total primary energy

nuclear: 39%

Total useful energy

nuclear: 26 %

Total final energy

nuclear: 17%

Just choose the value which confirms what you want to prove…

units for energy – power and orders of magnitude

Physics

[energy] = Joule (J) ; [power] = Watt (W) = J/s

- chemical processes ~eV, 1 eV = 1,6 10^{-19}J: combustion C + O_2 → CO_2 + 4 eV
- nuclear process ~MeV, 1 MeV = 1 million eV : fission ^{235}U → nucleus 1 + nucleus 2 + 200 MeV
- thermal power steadily dissipated by a human being ~ 120 W

Electricity

1 kWh = 1000 W x 1 hour (= 3600 s) = 3,6M J

energy consumption in Wh = power consumption in W x number of hours

- electrical power consumption of a refrigerator in working ~ 100 W working 8h/day ⇨ 800 Wh/day ⇨~290 kWh/year
- average residential electricity consumption (without heating) ~ 3 kWh_{elec}/cap/day
- lead battery storage capacity ~ 50 Wh/kg

Frequently used unit

[energy] = Toe Ton Oil Equivalent = 42 GJ (heat)

- consumption of a car traveling 20 000 km/year ~1 toe/year

- equivalence electricity ↔ toe
  - convention used before 2002

Toe = mass of oil that should be used in a virtual oil-fired plant to produce electricity with a fixed thermal efficiency: η_{therm}=38, 7%

To produce 1 MWh_{elec}: $$E_{primary} = \frac{1\,MWh_{elec}}{0{,}387} = 2{,}58\,MWh_{therm} = 2{,}58\,\frac{3600\,10^6}{42\,10^9} = 0{,}22\,toe$$

1 MWh_{elec} = 0,22 $toe_{<2002}$: whatever the primary source used

  - Since 2002 …

Toe = unit to express the primary energy really used in the installation to produce electricity

✓ For primary sources providing heat (coal, gas, geothermal, nuclear), the effective thermal efficiency of the plant is taken:

To produce 1 MWh_{elec}: $$E_{primary} = \frac{1\,MWh_{elec}}{\eta_{thermal}} = \frac{1}{\eta_{thermal}} \times \frac{3600\,10^6}{42\,10^9} = \frac{0{,}086}{\eta_{thermal}}\,toe$$

✓ For the other primary sources (PV, hydro., wind) : η = 100%!

		nuclear	coal, gas, biomass	geothermal	hydropower, wind, PV
toe convention before 2002	thermal efficiency of the virtual oil-fired plant	38,7 %			
	toe/MWh_{elec}	0,22			
toe convention since 2002	mean effective efficiency	33%	40%	10%	100%
	toe/MWh_{elec}	0,26	0,21	0,86	0,086

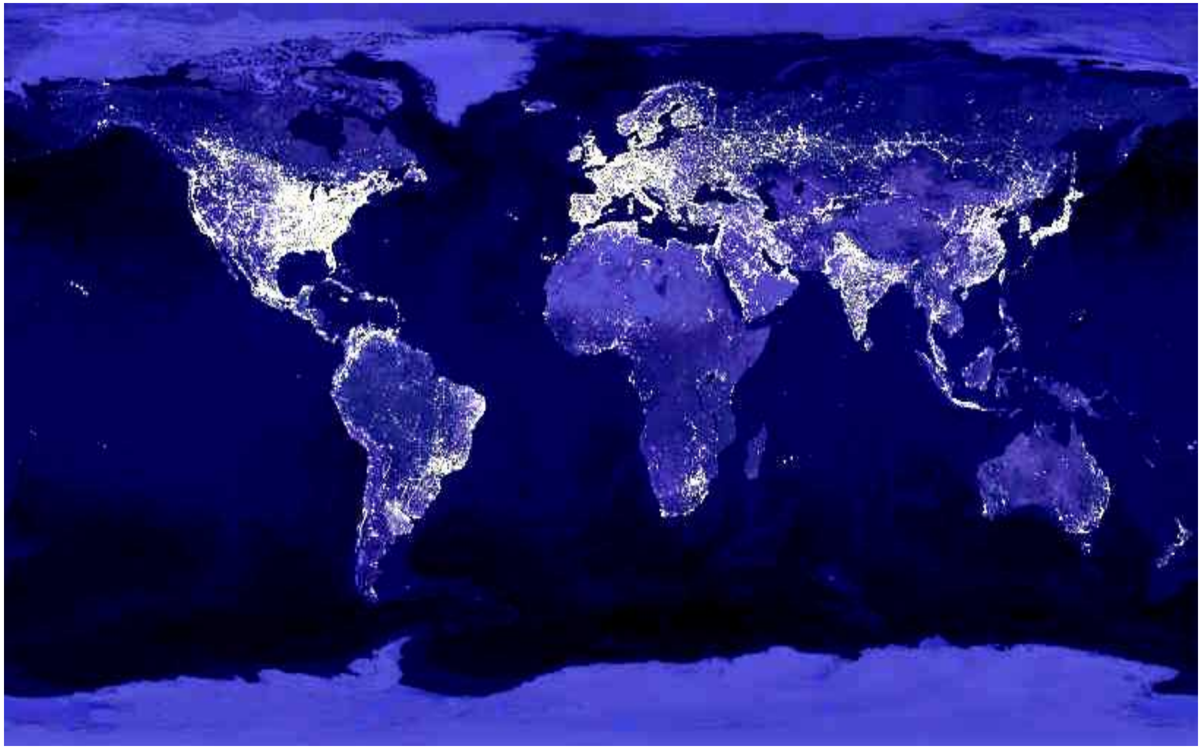
For a same quantity of electicity (1 MWh_{elec}), the mass of oil is different
This is not anymore a « ton oil equivalent » …

In the following, production and consumption of electricity are giving in « toe – before 2002 » or in Wh

1st part
The world energy context

Today in the world

Total consumption	12 billions of toe/year
Population	7 billions of inhabitants
Average consumption/cap.	1,7 toe/year (2300 W)



Present world energy context

- energy consumption distribution according different geographical regions

geographical regions	total consumption (Gtoe/year)	population (Minhab.)	consumption toe/cap/y
North America	2,4	341	7,1
Pacific	0,65	162	4,0
Ex-USSR	0,95	279	3,4
Europe	1,75	534	3,3
Middle-East	0,5	210	2,4
Latin America	0,75	583	1,3
Asia	4,1	3 707	1,1
Africa	0,75	999	0,75
total	**11,85**	**6816**	**1,73**

- rich countries ~6 Gtoe/year
  ~4,4 toe/inhab./year
  ~20 % of the world population
  ~50 % of the world consumption

- emerging countries ~5 Gtoe/year
  ~1,2 toe/inhab./y
  ~65 % of the world population
  ~45% % of the world consumption

- poor countries ~ 0,75 Gtoe/year
  ~ 0,75 toe/inhab/year
  ~15 % of the world population
  ~5 % of the world consumption

Huge consumption inequalities

- distribution of energy sources to satisfy the world demand

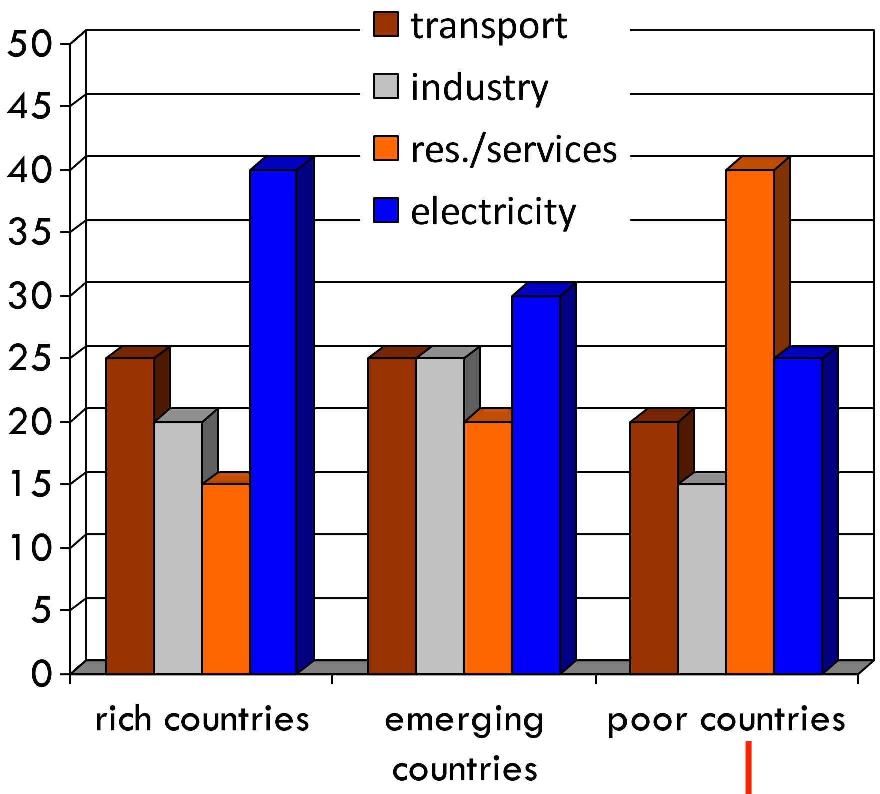
Source	Gtoe/year	%
fossil fuels oil / gas / coal	9,6 3,5 / 2,7 / 3,4	80 30 / 20 / 30
wood	0,6 – 1,2	8
hydropower	0,7	6,2
nuclear	0,6	5,3
new renewables (solar, wind, biomass)	0,1	0,8
Total	12	

Today, 80% of the world energy production is insured by fossil fuels
Since 2000, the use of fossil fuels increases at a rate close to 3%/year

- energy distribution according the four consumption sectors

Average consumption profile determined from sample of rich, emerging and poor countries

Fraction of the total energy consumption in %



- transport ~ 2,8 Gtoe/year
→ oil (~ 95 %)
→ biofuel

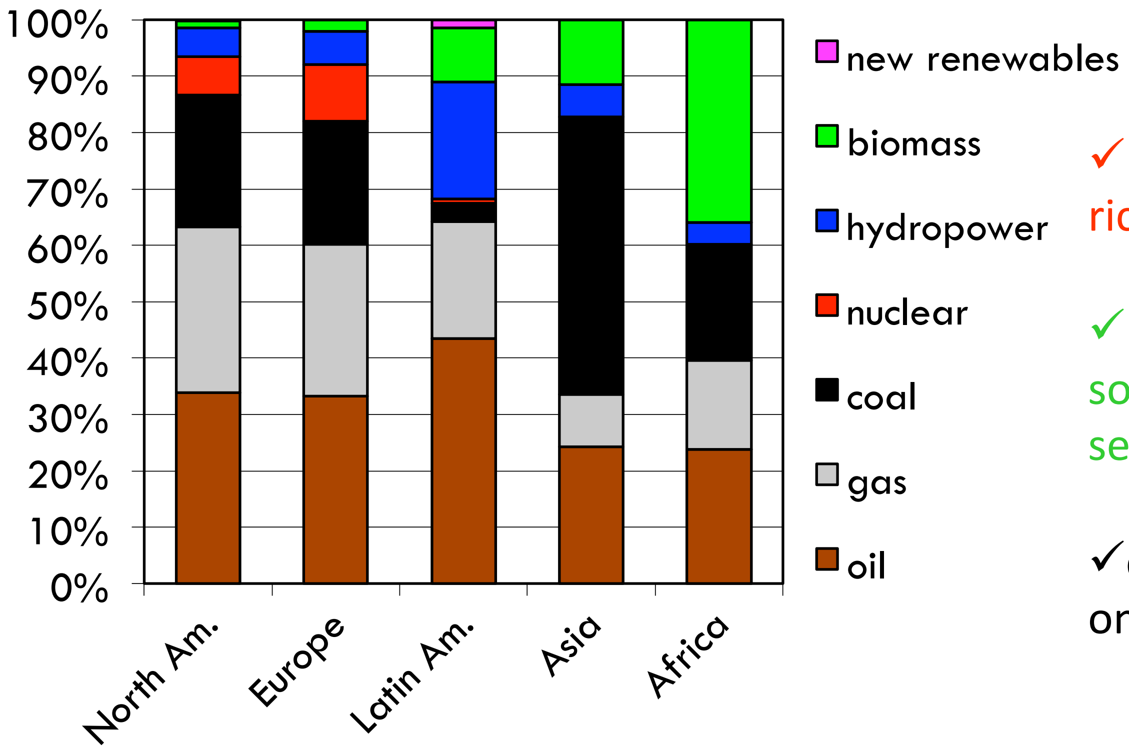
- industry ~ 2,3 Gtoe/year
heat at high temperature (150°C – 1000°C)
→ coal and gas (~ 100 %)

- residential/services ~ 2 Gtoe/year
heat at low temperature (< 100°C)
→ domestic fuel and gas (~ 70 %)
→ biomass

- electricity ~ 4 Gtoe/year

• grids not enough deployed
• 1,5 billions of human beings have no access to electricity …

- energetic mix for different geographical regions



✓ nuclear power mainly deployed in rich countries

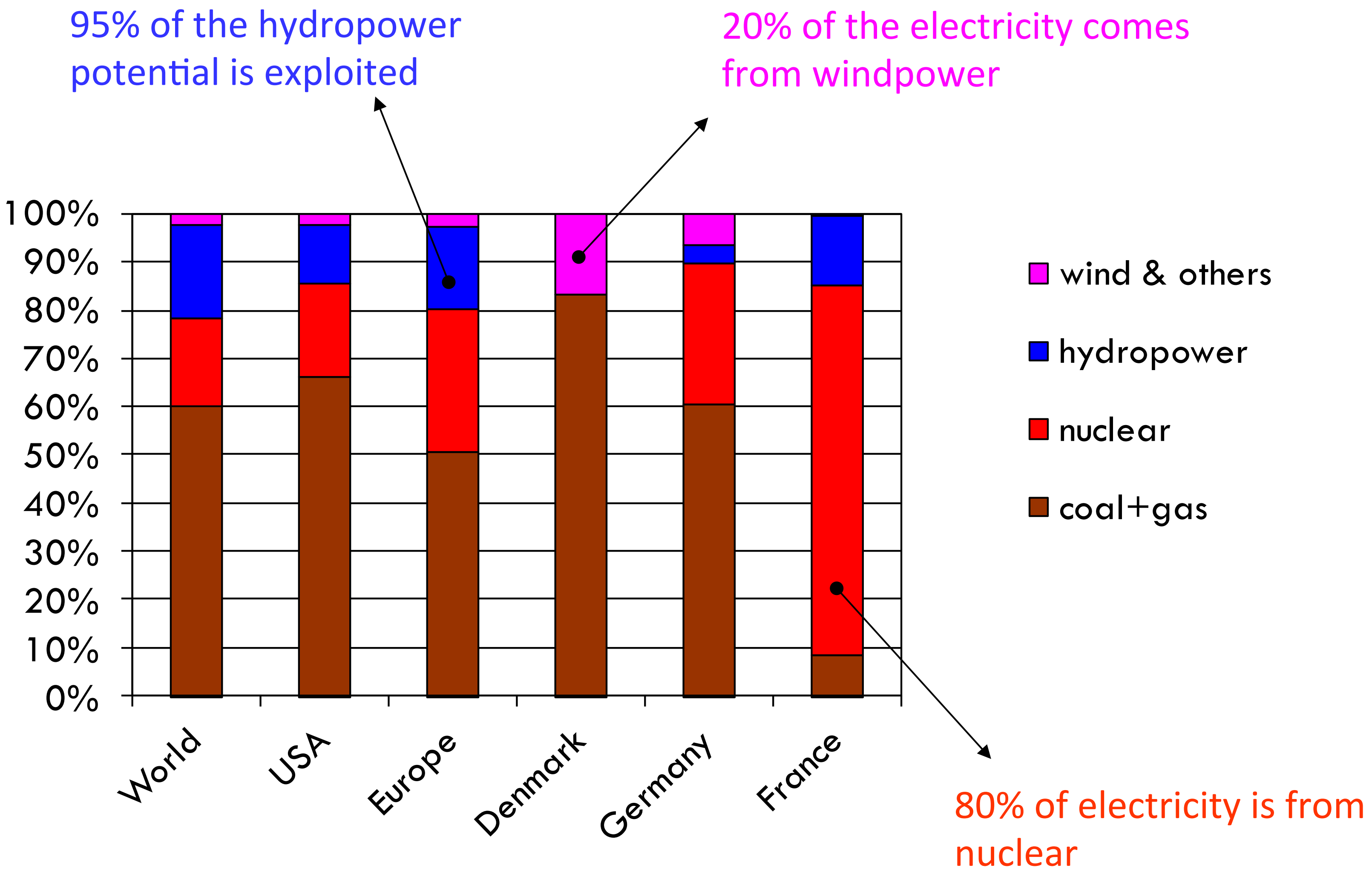
✓ in poor countries, wood is the first source used for the residential/services sector

✓development of Asia is mainly based on coal

Rich countries: fraction of fossil fuels > 80 %
fraction of new renewables (solar, wind) < 1 %

Africa : strong potential of hydropower but not exploited, deployment of grid is necessary

- electricity mix for different geographical regions



Why is it so hard to manage without the use of fossil fuels ?

☺ all the energy needs can be satisfied: transport, heat and electricity generation
☺ energy can be produced at all power scales: from individual boiler to power plants
☺ easy to transport and to store
☺ important heat supplied by combustion

coal (C) ~ 35 MJ/kg
oil $(CH_2)_n$ ~ 42 MJ/kg
gas (CH_4) ~ 55 MJ/kg

Ex: we fill the car up with 50 liters of gasoline in 2 minutes, corresponding to a power of 15 MW !! and we can travel 1000 km

☺ very competitive cost
☺ maturity of technologies
☺ coal- and gas-fired plants are very flexible to be adjusted to variations of electricity demand

⇨ Difficult for the other sources to compete with ....

☹ « stock energy » and then not renewable at our time scale ⇨shortages of resources
non conventional fuels (oil shale, bitumen, extra-heavy oil) release the pressure on resources
☹ unequally distributed (geopolitical tensions, wars)
☹ environmental impacts and CO_2 emissions (GHG) which lead to a major climate change

fossil fuels and CO_2 emissions

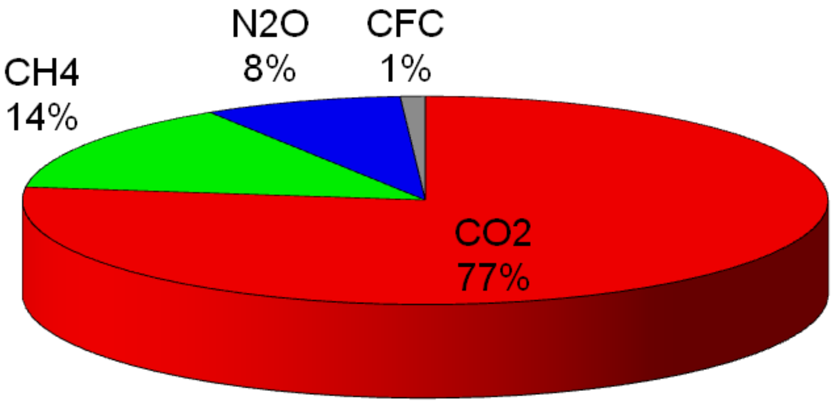
	Coal (C)	Oil $(CH_2)_n$ -C-C-C-C-...	Gas (CH_4) -C-
energy	~35 MJ/kg	42 MJ/kg	55 MJ/kg
$m_{fossil\ fuel}$ for 1 toe (=42 GJ)	~1200 kg/toe	1000 kg/toe	765 kg/toe
combustion reaction	$C + O_2 \rightarrow CO_2$	$CH_2 + 3/2\ O_2 \rightarrow CO_2 + H_2O$	$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$
$M_{molar}^{fossil\ fuel}$	12 g	14 g	16 g
$m_{CO_2} = m_{fossil\ fuels} \times \frac{M_{molar}^{CO_2} (= 44g)}{M_{molar}^{fossil\ fuel}}$	**4 400 kg/toe**	**3142 kg/toe**	**2100 kg/toe**

<u>Orders of magnitude</u>

✓ electricity generation η_{therm} = 35 – 50 %

- coal-fired plant of 1 GW_{elec} ~ 8,5 $MtCO_2$/year ➡ ~ 1 kg CO_2 /kWh_{elec}
- in average
  - in Europe ~ 600 g $CO_2/kWh_{élec}$
  - in France < 60 g $CO_2/kWh_{élec}$

- the climate constraint
  - human activities increase the quantity of GHG in the atmosphere leading to an increase of the mean temperature on earth
  - main anthropogenic GHG
    - CO_2 from fossil fuels
    - CH_4 from natural gas extraction (leakage), wastes from agriculture, decay of organic matter
    - N_2O from chimical processes and fertilizer for agriculture
  - contribution of each GHG on the climate warming



Presently, the total GHG emissions are equivalent to 50 Gt CO_2/year
30 Gt CO_2 come from the use of fossil fuels for energy production

- the target to achieve by 2050
  - ✓ The Intergovernmental Panel on Climate Change reports propose various stabilization scenarios according to different level of CO_2 emissions
  - ✓ the corresponding temperature rise varies from 2°C to 6°C
  - ✓ scenario of category II: stabilization of the increase of the mean temperature between 2,4°C and 2,8°C
    - ⇨ decrease of CO_2 emissions by 30% to 60% (with respect to 2000)

- Case of a reduction by a factor 2 of CO_2 emissions by 2050

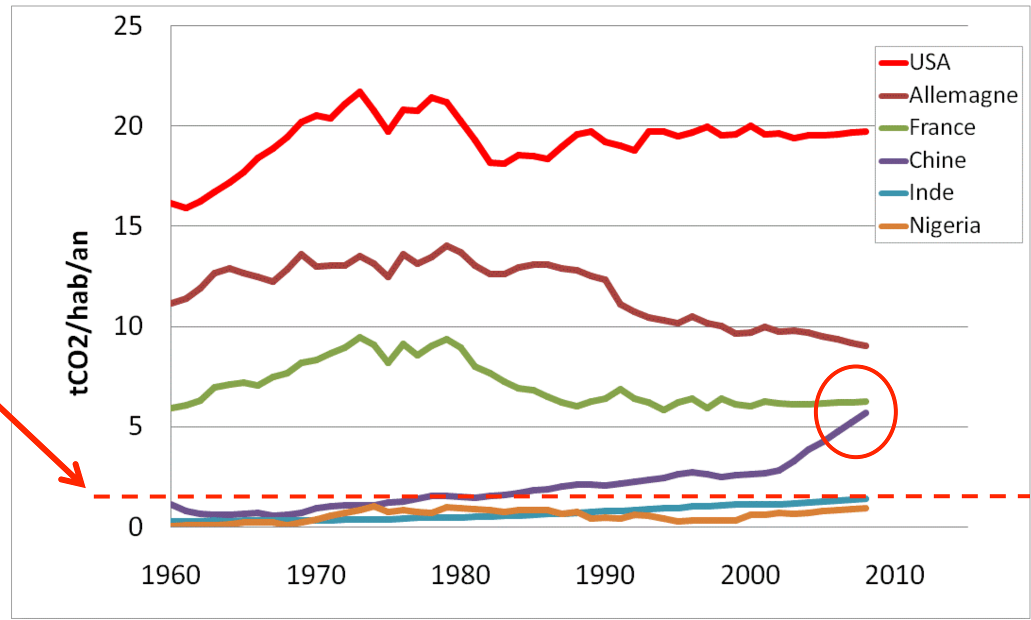
✓ bring back the CO_2 emissions from 30 Gt/year to 15 Gt/year

⇨ reduce the use of fossil fuels from 9 Gtoe/year to 4,5 Gtoe/year

✓ world population in 2050

~ 9 billions of inhabitants

⇨ CO_2 emissions per capita ~ 1500 kg/year



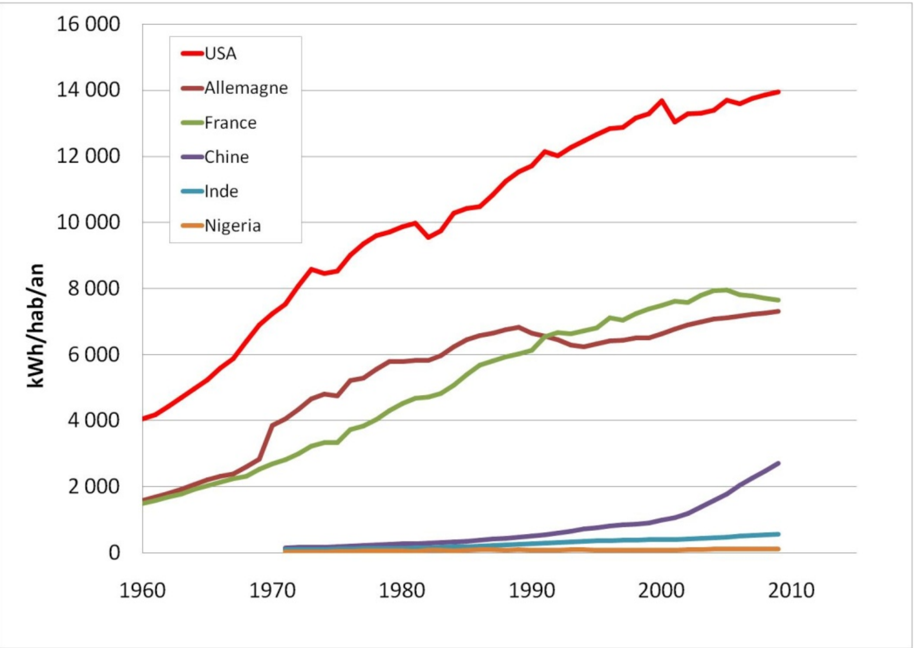
The efforts to make are tremendous !

- evolution of the world energy demand

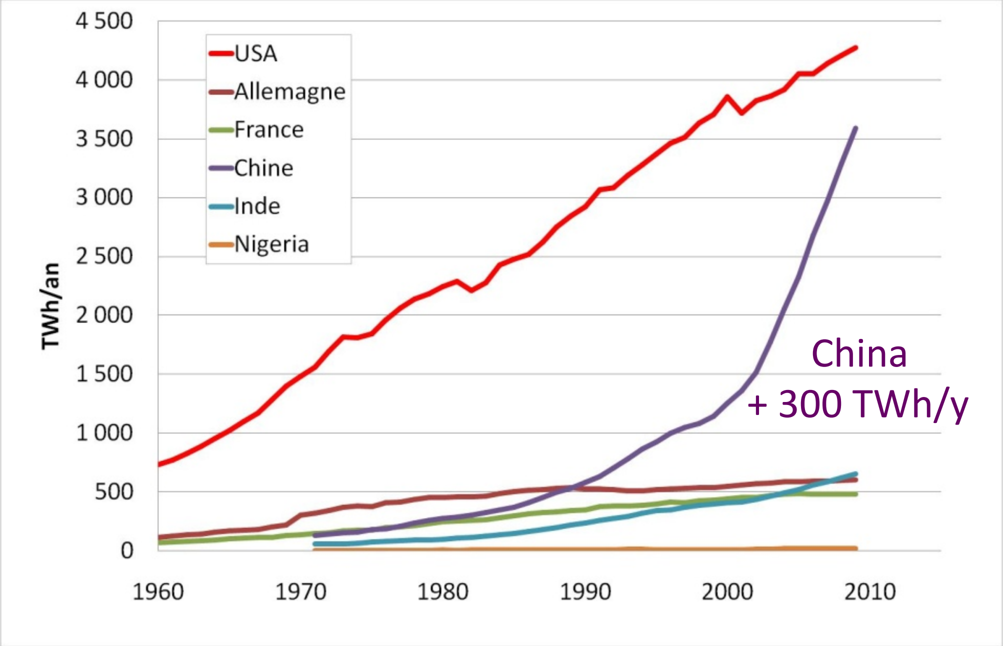
Globally the energy consumption is steadily increasing

Evolution of the electricity consumption in different countries up to 2010

electricty consumption per capita



total electricity consumption



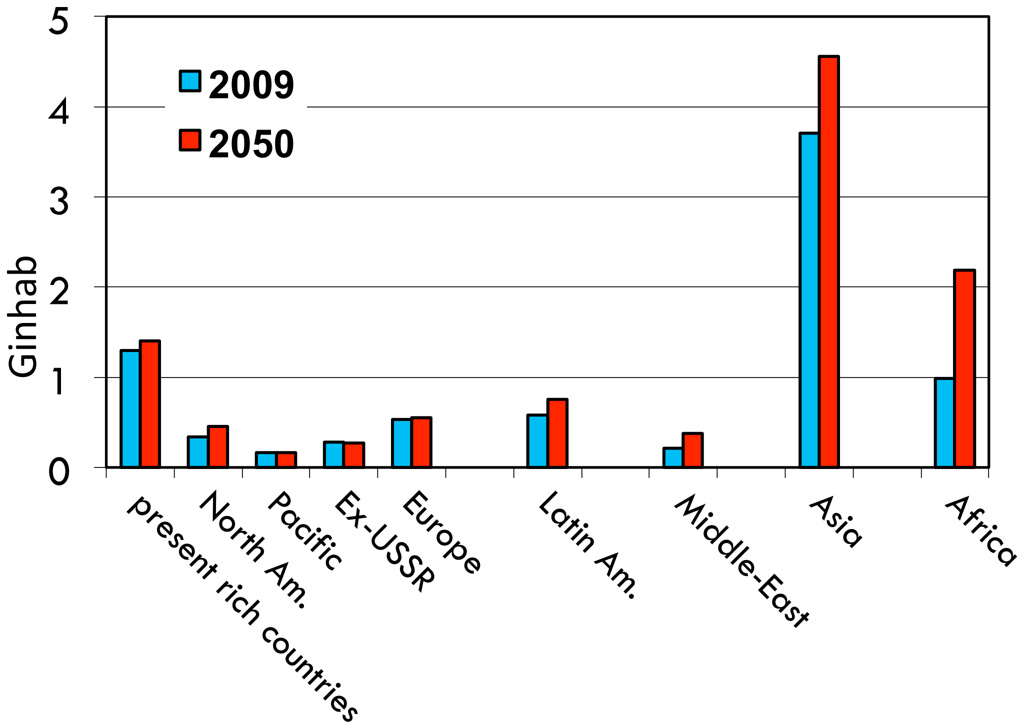
Present electricity consumption in the world ~ 20 000 TWh/year

- evolution of the world energy demand by 2050?
  - world population in 2050

Projections of population of each country up to 2050 given by UN demographic data

⇨ ~9 billions of inhabitants

- Stabilization of the population of present rich countries to ~ 1,4 Ginhab.
- 50% of the world population will be in Asia, as today
- population in Afrique x 2



That is likely to happen:

→ present developped countries will maintain their level of life

→ present emerging and poor countries want rightfully to improve their level of life

➡ the world energy demand will probably increase faster than the population

- estimation of the world energy consumption in 2050

✓a lower estimate : the present average energy consumption will remain unchanged

⇨ E_{world} = 1,7 toe/cap/year x 9 Ginhab = 15 Gtoe/year

✓an other extreme estimate : the whole population will have the same level of present rich countries

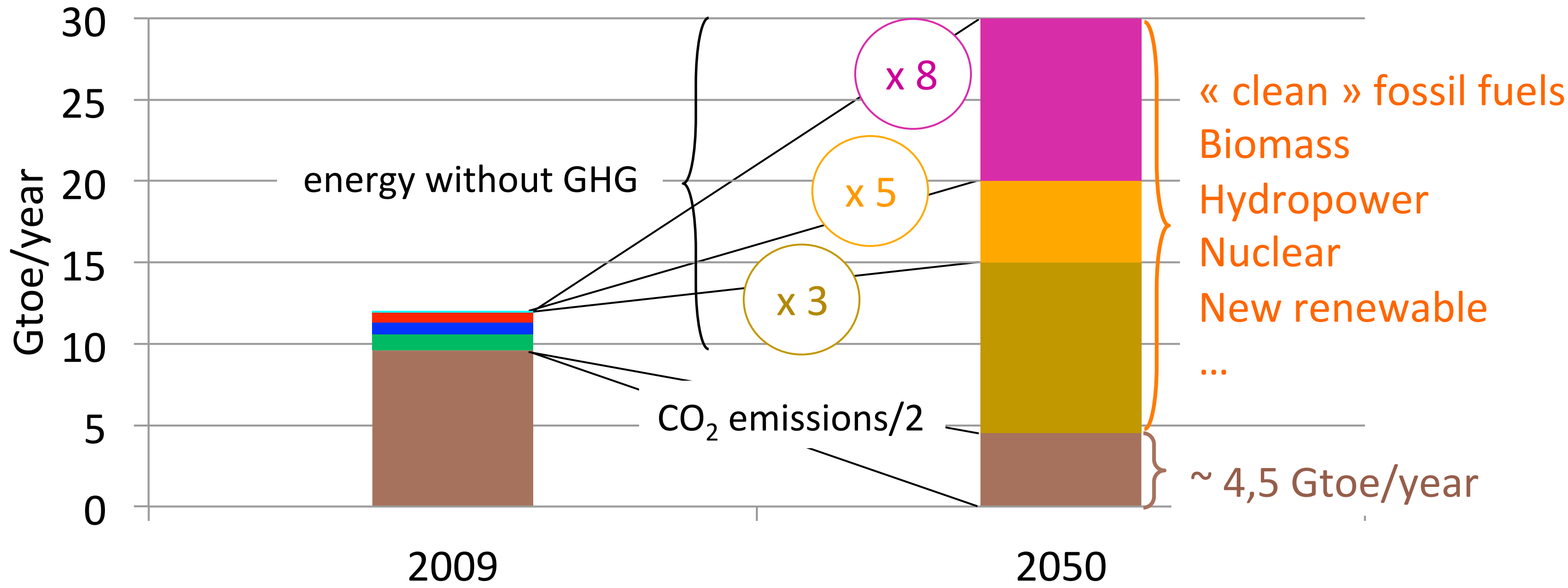
⇨ E_{world} = 4,4 toe/cap/year x 9 Ginhab = 40 Gtoe/year

✓different technico-economical studies (IIASA, WEC, IEA, …) predict

15 Gtoe/year < E_{world} < 30 Gtoe/year

⇨ a mean and realistic value: 20 Gtoe/year (twice higher as 2000 !)

- How to meet a growing energy demand of an increasing population while reducing GHG emissions?



What are the potentials of CO_2-non emitting sources? Are they sufficient to satisfy the energy demand? Do these sources match with needs ?

- technology maturity?
- cost ? (investment, operation, fuels, …)
- environmental impacts (used aeras, polluted emissions, risks, …)
- acceptability (nuclear, wind turbines, storage of CO_2)

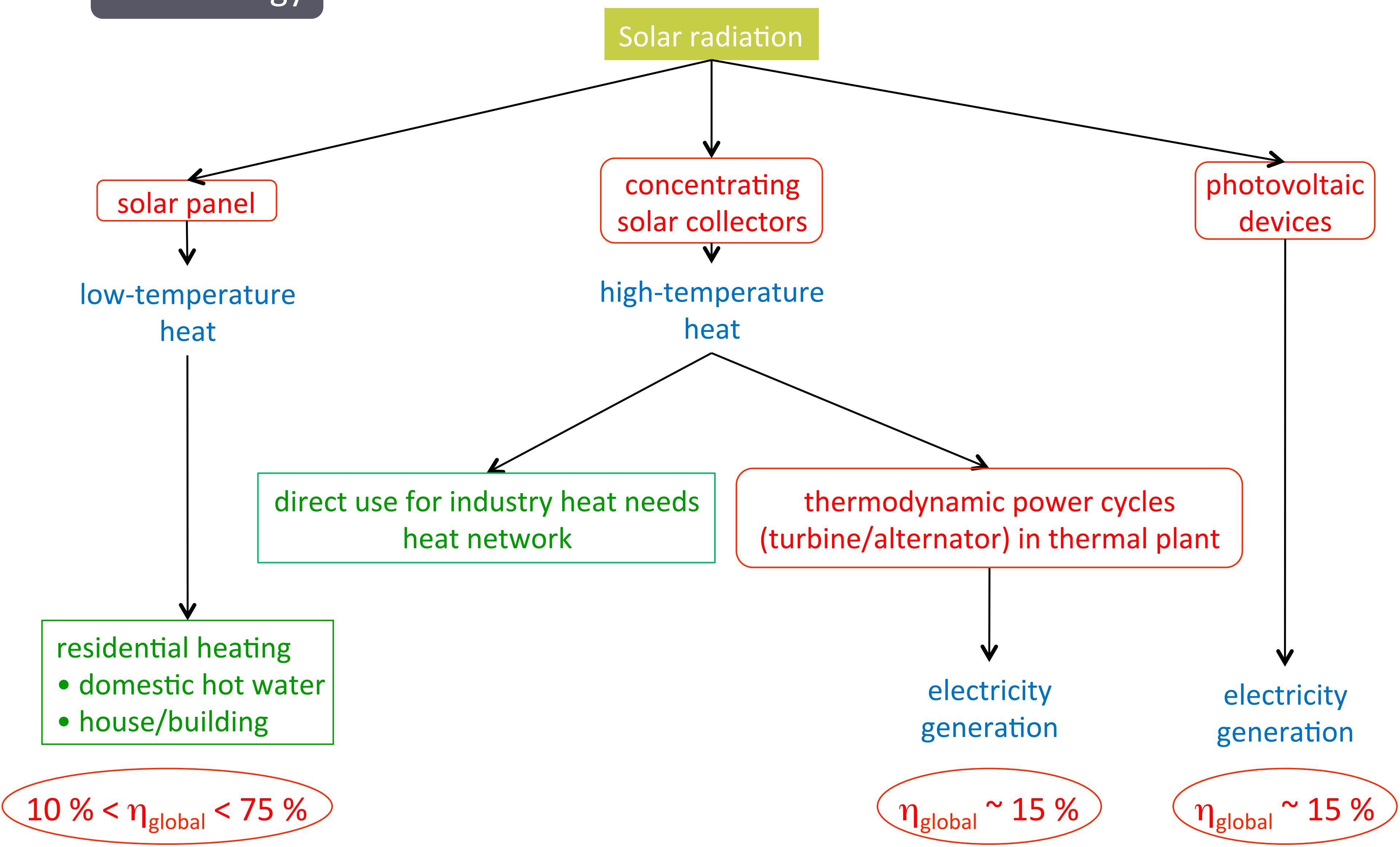
The energy source considered must have a potential ~ 1 Gtoe/year

2nd part
Survey of energy sources

Focus on renewable energy sources

solar, wind, hydropower, biomass, geothermal
Characteristics, uses and capabilities

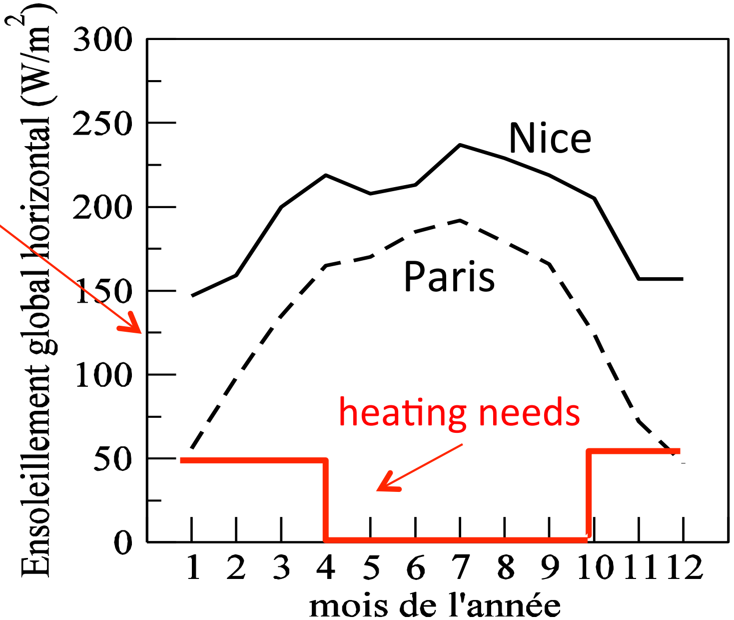
Solar energy



Solar water heating

Panel heated by solar radiation

- domestic hot water – orders of magnitude
  - daily needs over the whole year
  - amount: 50 l/cap./day at 60°C ~ 3 kWh/cap./day (~125 W)
  - panel area ~ 2 m^2/cap.
  - 30 to 70% of needs are covered, depending on the location



- heating house/building – orders of magnitude
  - total heating power to provide = K (T_{out} - T_{in}) [W]
    - K (W/°C): global thermal losses coefficient specific of the house (surface and insulation)

      200 < K < 400 (W/°C) for an house of 120 m^2
  - heating during winter ~ 50 W/m^2
  - panel area ~ 0,25 m^2/ m^2 of house
  - fraction of needs covered by solar energy, depending on the location
    - « traditional » house/small heat exchanger (T_{water} ~ 60°C): 20 to 40 %
    - « solar » house/large heat exchanger (T_{water} ~ 30°C): 40 to 60 %

☺ domestic fuel, gas or electricity saving

☺ cost-effective investment < 10 ans (with subventions)

☹ extra heater is necessary

☹ intermittent, thermal storage difficult on several days

Photovoltaic systems

direct conversion of sunlight into electricity (photoelectic process)

- silicon solar cells are the most common today,
  - effective efficiency: η_{conv} de 10 % à 20 % (η_{theo} = 45 %, η_{labo} = 40 %)

- Peak of solar power (clear day at noon) ~ 1000 W/m^2

  ➡ peak of electricity generation ~ 150 W/m^2 (η_{conv} ~ 15%)

- Intermittent (day/night) + changing during the day

  ➡ solar power in average~ 150 W/m^2

  ➡ average electric power ~ 25 W/m^2 (η_{conv} ~ 15%), given 0,6 kWh/day/m^2

⇨ ratio between effective and maximum electricity generation=load factor: $f = \frac{E_{eff}}{E_{max}} \approx 15\%$

- residential electricity needs (without heating): ~ 3 kWh_{elec}/cap./day

  ➡panel area ~ 5 m^2/capita

- mainly developed in rich countries for individual uses

- efficient way to provide electricity when grids are missing (poor countries)

Photovoltaic systems

See presentation of ISE

☺ important subventions in Europe (in France, buy-back~ 50cts€/kWh$_{elec}$ during 20 years !)

☺ long life ~ 25 years

☺ development of flexible thin-film PV panels to be better integrated in building design

☺ performance improved by the use of multijunction cells (increasing the absorption of solar spectrum) and concentrating PV (concentrating optics focus light on a smaller area)

☹ high cost ~ 20 cts €/kWh$_{elec}$

☹ ~ 800 kg CO_2/m^2 of PV panel constructed➡[100 – 200] g de CO_2/kWh$_{elec}$

☹ energetic cost to construct 1 m^2 of PV panel~ 5 years of PV panel production

☹ intermittency

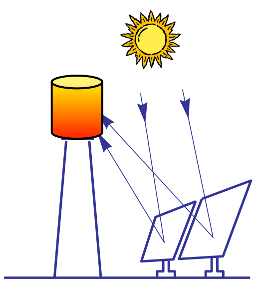
Concentrating Solar Power

Mirrors with tracking system concentrate solar radiation on a receiver which contains a fluid heated at high-temperature 200°C to 1000°C

- many applications
  - direct use of heat for industry processes
  - supply heat networks for urban heating
  - centralized electricity generation with thermal power plant

- mainly 2 technologies

Solar Power Tower



✓a field of heliostats surround a tower and focus sunlight on a central reiceiver atop the tower

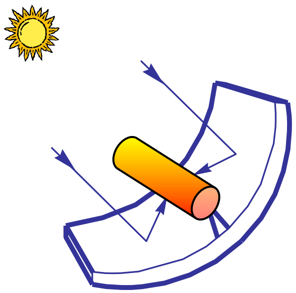
✓ heliostats follow the sun during daylight hours by tracking

✓the fluid in the receiver is heated to 400°C – 1000°C

✓ fluid used: molten salt, water, air, liquid metals

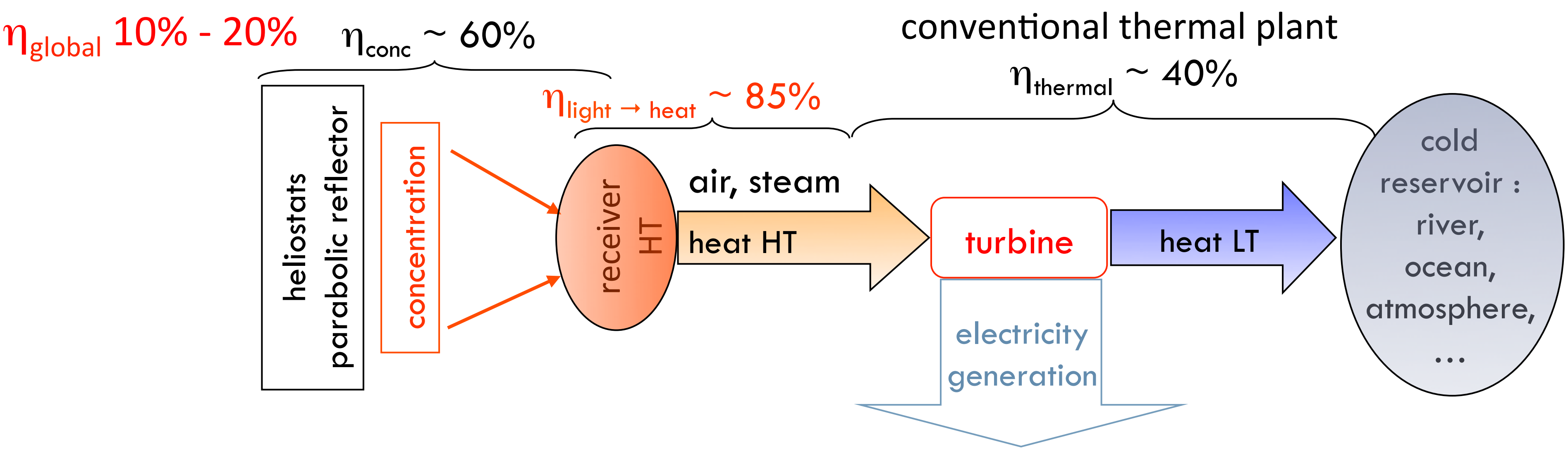
Concentrating Solar Power

Paraboloic trough



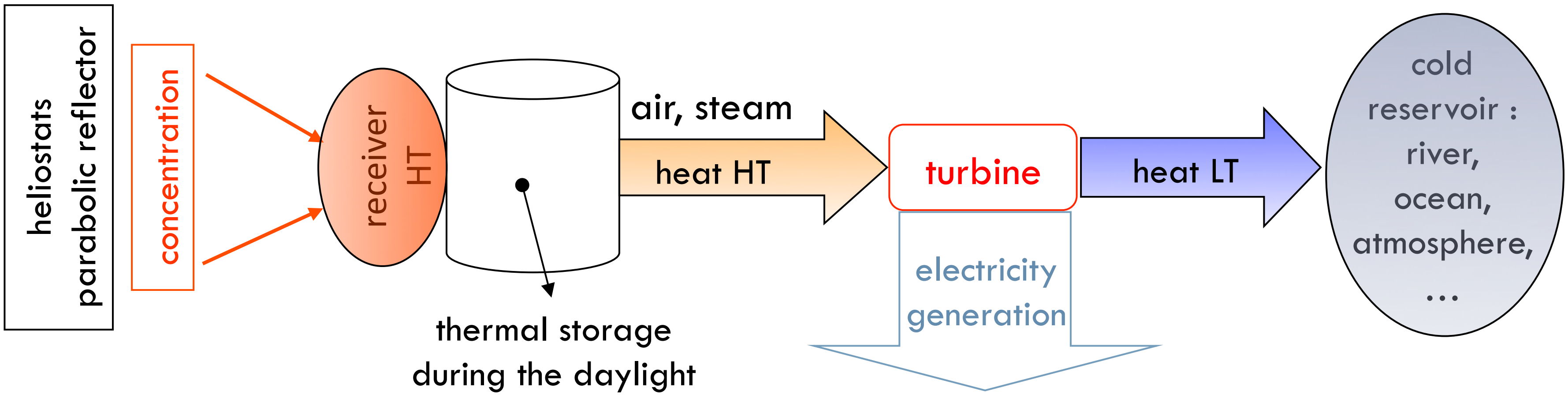
✓linear parabolic reflector concentrates sunlight onto a receiver positioned along the focal line
✓ reflector follows the sun during the daylight hours by tracking
✓ the receiver is a tube located along the focal line in which a fluid flows
✓ fluid is heated to 250°C – 400°C
✓ fluid used: water, oil

- the heated fluid can be used as a heat source for conventional power plant to generate electricity from 10 to 40 MW_{elec}



- intermittency easier to manage by storing high-temperature heat

⇨ electricity generation can be extended to several hours when hours of sunshine are over



- CSP mainly set up in Spain and California

Ex: Solar Power Tower project in Spain « solar 3 »

2493 héliostats → 240 000 m^2

installed power 15 MW$_{éléc}$

thermal storage capability ~ 600 MWh

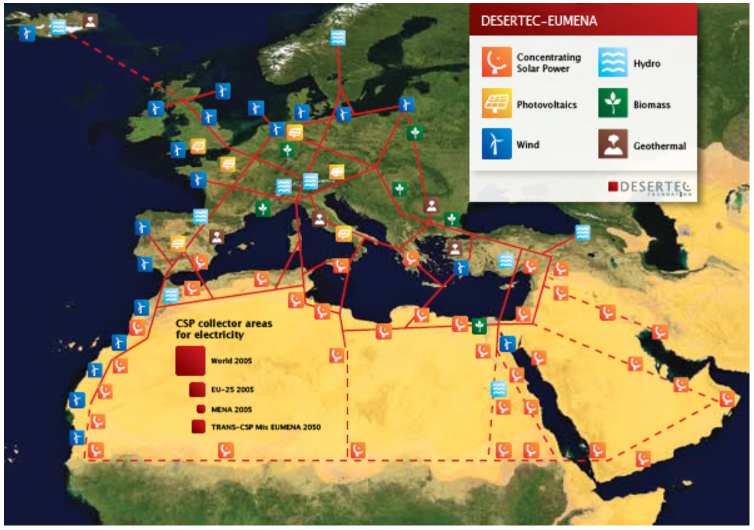
electricity generation~ 85 GWh$_{élec}$/an ⇨ f$_{charge}$ 65 %

Ex: projet « DESERTEC - EUMENA »

1 800 TWh$_{elec}$ /year generated by solar thermal plants

600 TWh$_{élec}$ for Europe, 600 TWh$_{élec}$ for local consumption

600 TWh$_{élec}$ desalination of ocean water



Concentrating Solar Power

For centralized electricity generation

- ☺ cogeneration is feasible: combined production of heat and electricity according needs
- ☺ hybrid system = CSP coupled with a conventional coal or gas fired-plant as back-up to manage intermittency (without thermal storage)

☺ technological maturity

☺ CO_2 emissions < 20 g/kWh_{elec}

☹ cost < 20 cts €/kWh_{elec}

Wind Power

- typical wind turbine power: 2 MW_{elec} (122 m high)
- the wind turbine works at the maximum of its capacity 15% to 25% of the time
  ⇨average power ~ 0,4 MW_{elec}
- surface used: 8 ha/MW installed ➡ generation < 10 W/m^2 (< solar energy)
- Europe is the leader with 72 GW_{elec} of capacity installed (120 GW_{elec} in the world)
  - In Germany ~ 20 GW_{elec} ⇨ average electric power 3,5 GWelec (~30 TWh_{elec}/year)
- development offshore for a centralized electricity generation

☺ mature technology
☺ reasonnable cost ~ 2 x higher than nuclear or gas

☹ noise, visual aspect, …
☹ intermittent and random generationwhich limit the part of wind power (and PV also) in the electricity generation

Maximum potential in Denmark: 20 % of the electricity consumption
Beyond, difficult problem to manage grids

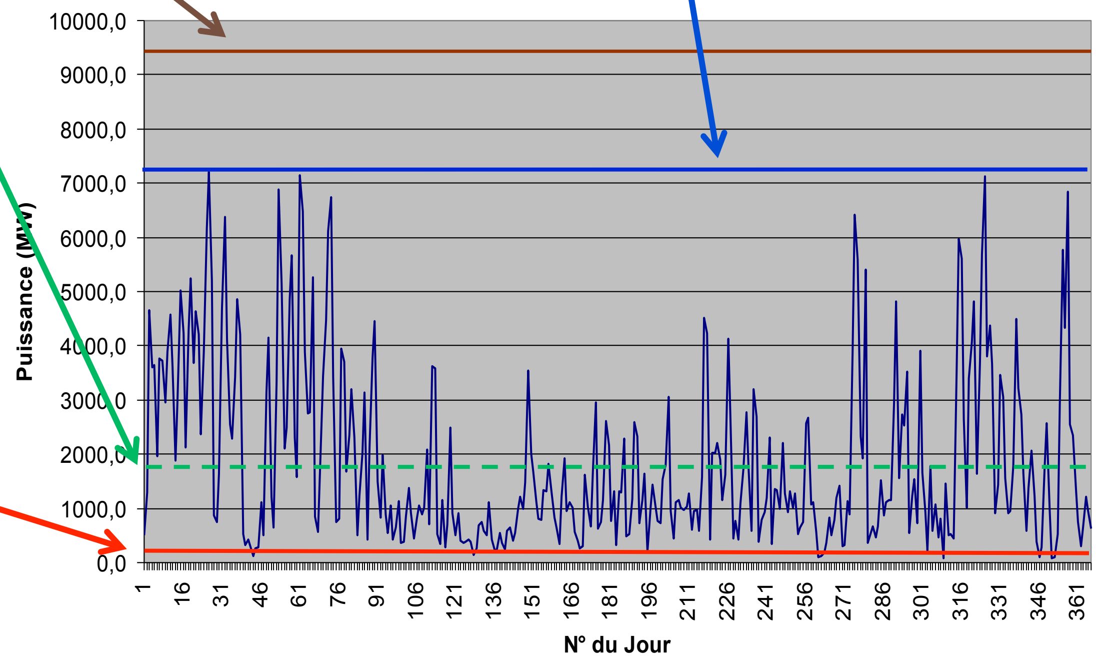
Case of a fleet of several thousands wind turbines (Germany – EON)

installed power $P_{installed}$ ~ 9300 MW_{elec}
related to the investment cost

maximum electricity power deliverd by the fleet, should not exceed the electricity consumption

average electric power (17% $P_{installed}$): amount of electricity generated in average over a year
⇨ quantify the fuel savings of the fired-plants

minimum electric power delivered by the fleet
⇨ quantify the number of coal- or gas-fired plants that the fleet can definitly replace



✓Wind turbines have to be coupled with flexible sources as hydropower, coal- or gas-fired plants to satisfy the electicity demand

✓Not very interesting from CO_2 emission point of wiew in developed countries having few coal- or gas-fired plants (France)
✓ In Germany, 6% of coal and gas are saved with wind energy but no significant reduction of fired-plants

Hydropower Conversion of potential energy (dam), E_p = mgz, into kinetic energy (turbine) converted in electricity (alternator) – η_{global} ~ 85%

- present generation in the world
  - Installed capacity: 875 GW_{elec}
  - Effective power: 365 GW_{elec} (3 200 TWh_{elec}/year) = 16% of the total electricity consumption
- 2 types of production
  - dams: very flexible to be adjusted to a varying demand (peak) or to variations of intermittent sources
  - « run of river » equipment: electricity is supplied continuously and can be little or slowly adapted to needs

☺ reduce the consumption of fossil fuels
☺ centralized (if grids are available) or local electricity generation

☹ favourable sites for new projects are far away from areas where the needs are
☹ Large surface used, important environmental and human impacts

Ex : 3 gorges dam in China
installed capacity: 18 GW_{elec}, effective power: 8 GWelec (72 TWh_{elec}/year)
surface of water reservoir behind the dam: 2 km x 640 km ⇨ 6 $W_{élec}$ / m^2
millions of persons have been displaced

Biomass

conversion of solar energy (+ CO_2 absorption) into chemical energy stored in the plants (photosynthesis)

- uses of wood and plants similar to fossil fuels
  - biofuels → transportation
  - biomass → heat generation at low- and high temperature, electricity

☺ renewable energy (not necessarely, depending on forestry management) and CO_2 non-emitting source if uses are well managed

☺ energy stored and transportable

☺ energetic value of wood ~15 MJ/kg

☺ low cost of the wood: 3 cts€/kWh comparing to fuel domestic 9 cts€/kWh

☹ efficiency of the photosynthesis very weak (E_{wood}/E_{solar}) ~ 0,1 % ⇨ 0,15 W/m²

➨ large surface needed

☹ in competition with land currently used for food production

1st-generation biofuels

	energetic value in toe/ha	conversion	energy spent in toe/ha
oil crops	1,5	biodiesel	0,5
sugar crops	4	bioethanol	2,7

CO_2 non-emitting sources needed (nuclear, solar, wind)

Geothermal

heat from radioactivity ^{238}U, ^{232}Th, ^{40}K inside the earth

- total geothermal heat = 22 TW ~ order of magnitude of the power consumed in the world
  ⇨ in average, geothermal flux on the earth's surface = 0,06 W/m^2 (<< solar energy)
  ➨ too weak to be exploited …

- non homogenuous flux: natural heat sources, volcanos, …
  ⇨ local exploitation is feasible (Island)

- deep (~ 5 km) heated rocks (~ 200°C) = thermal energy stored since billions of yers
  ⇨ strong potential but not completly renewable

- uses: dual generation of heat and electricity

Ex : geothermal plant at Soultz-les-forêts (Mulhouse)

heated rocks at 5000 m of deep

thermal power: 13 MW_{therm} à T < 200°C, electric power: 2,1 MW_{elec} among 0,6 are used for the installation working

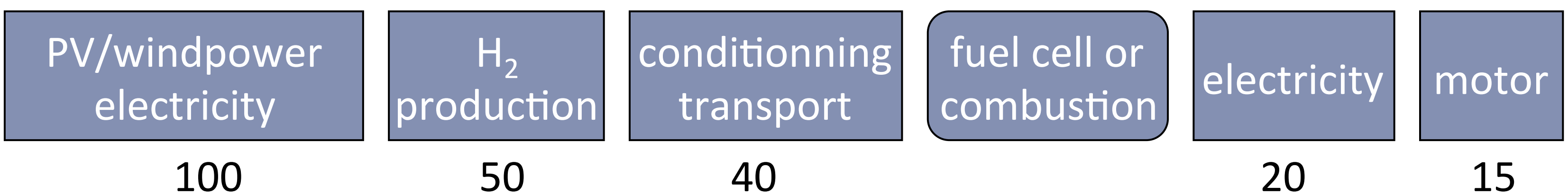
- Total geothermal electricity generation ~ 71 TWh_{elec}/year

To summarize ...

Photovoltaic	35 W_{elec}/ m^2	very diffused sources; intermittent
Wind power	< 10 W_{elec}/m^2	very diffused sources; intermittent
Solar water heating	60 W_{therm}/m^2	very diffused sources; intermittent
Concentrating Solar Power	40 W_{elec}/m^2	very diffused sources; intermittent
Biomass	< 1 W/m^2	very diffused sources
Hydropower	5 – 25 W_{elec}/m^2	very diffused sources
Geothermal	0,06 W_{therm}/m^2	very diffused sources

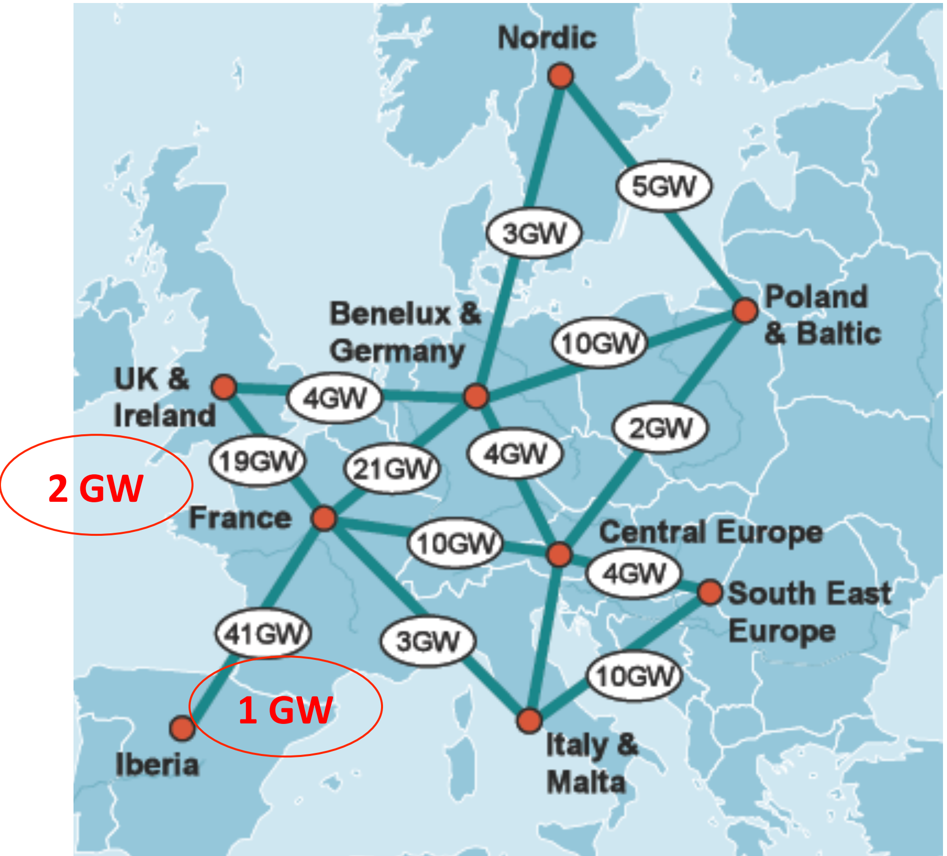
- How to manage intermittency and spread units of production of windpower and PV ?
  - improve the performance of grids and use flexible sources as back up
  - enlarge electricity storage capabilities at very large scale

- examples of electricity storage technologies
  - today, the most efficient way is the pumped-storage: the water released for electricity generation with dam is pumped to the high reservoir when wind turbines or PV plants produce more than the needs
  - chemically-charged batteries at large scale (environmental, recycling, resources, …)
  - hydrogen production by electrolyse: H_2O + electricity → H_2 + ½ O_2 + 120 MJ/kg stored
    ⇨re-use of energy: H_2 + ½ O_2 → H_2 + heat or electricity (fuel cells)
    ⇨use H_2 in coal-to liquid process !



⇨ global efficiency of the storage: 15%

- optimize the PV and windpower generation by sharing the electricity at Europe scale
  - to be sure to consume at some place the electricity produced somewhere in Europe
  - to develop intermittent sources where the conditions are the best
    - solar in Spain
    - off-shore windpower



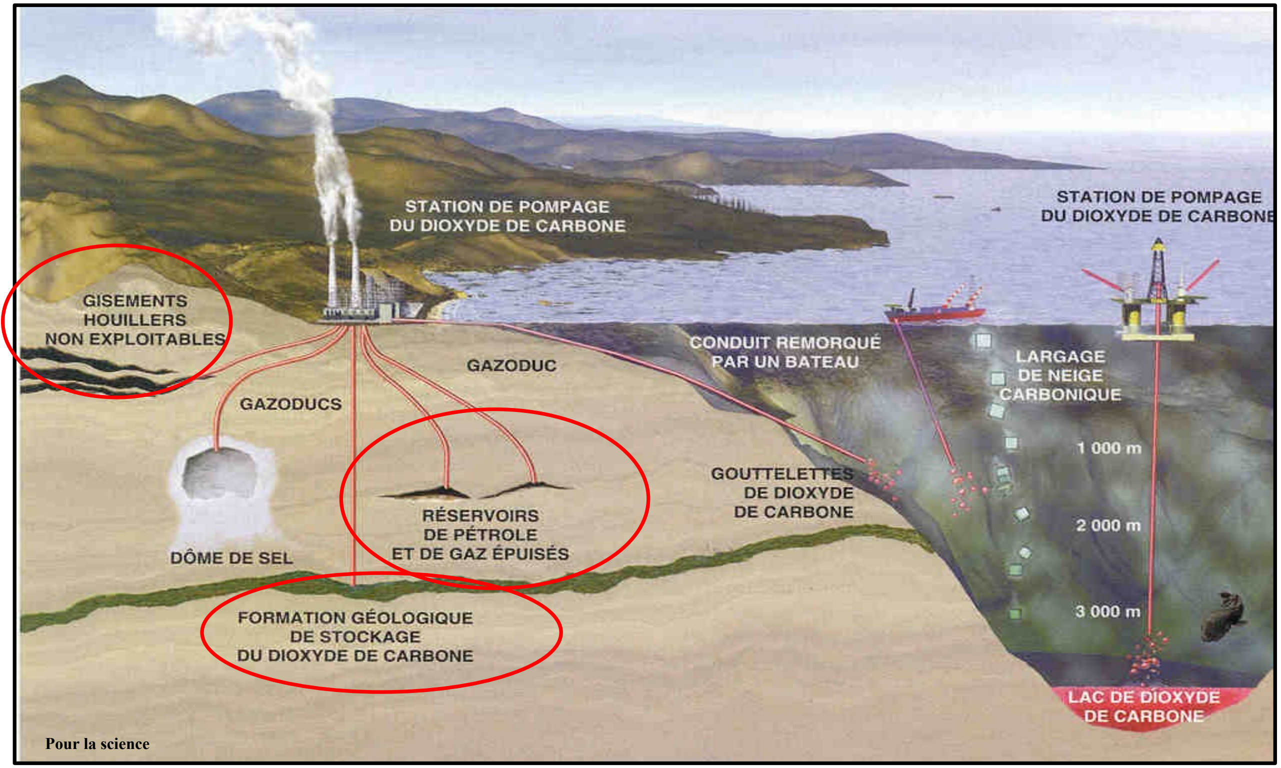
Ex: study for a 60% renewable electicity generation in Europe (http://www.roadmap2050.eu)
⇨ electrical power to transport by high voltage lines between Europe's countries

- estimate of renewable sources potential by 2050 (WEC report)

	hydropower	biomass		solar energy			geothermal	wind	total
		biofuels	wood	water heat	PV	CSP			
2008 (Gtoe/y)	0,7	0,03	0,9	-	0,04	-	0,02	0,05	1,74
2050 (Gtoe/y)	**2**	**0,5**	**2**	**0,5**	**0,5**	**0,7**	**0,3**	**1**	**7,5**
transport									
HT heat									
LT heat									
electricity									

- Total potential estimated in 2050: ~7,5 Gtoe/year
- Many sources are specifically dedicated to electricity generation ~ 3,5 Gtoe/year
- to achieve the target of GHG reduction and release the pressure on the use of fossil fuels: CO_2 Capture and Storage technology (coal « clean »)

- Principle: - extract CO_2 from products of combustion process of power plants
  - storage of CO2 in underground geological formation (declining oil and gaz fields, deep aquifer, coal seams, bottom of the ocean)



R & D needed:

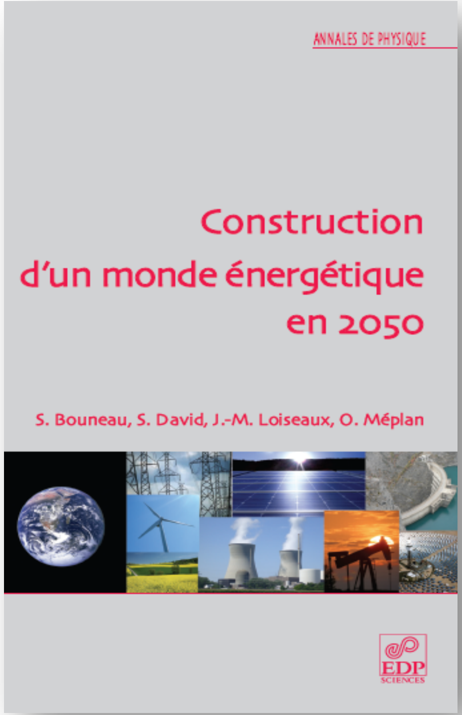
- on separation, capture and storage
- to found appropriate storage sites
- to study the long-term evolution of the CO_2 stored

- Cost ? Storage capabilities? Acceptability?
- only used for centralized electricity generation (not possible for transport)
- Very optimistic estimate: 10 to 15 $GtCO_2$/year

  ⇨ ~ 4 Gtoe/year of fossil fuels

3rd part
Simplified construction of an energetic world in 2050

Motivations, hypothesis, approach and results



- motivations
  - a quantitative description of what could be the world energy landscape in 2050 constrained by:
    - a finite amount of available energy
    - a reduction of GHG emissions
    - a reduction of inequalities of energy consumption in the world
  - What are the impacts of these constraints on:
    - the energy consumption of populations
    - the world energy mix
    - the consistency between available sources and energy needs
  - to propose a simple approach with fully explained hypotheses and few parameters
    - in contrast to predictive « techno-economical » models more complex and using unexplained parameters (for non experts)
    - to make possible discussions between different disciplines (scientific, economic, philosophic, …)
    - to be opened to critics
  - the question of the path to follow is not adressed in this work

- initial hypotheses for 2050

  - world population ~ 9 billions of inhabitants
  - energy consumption fixed to E_{tot} = 20 Gtoe/year
  - inequalities of energy consumption still exist but
    - it is not appropriate to consider each country as homogeneous: in present emerging countries some people have already reached high level of energy consumption whereas some others have level of living as in poorest countries in the world

  ⇨ the population of each emerging and poor country is distibuted into 3 categories of energy consumption per capita: high (C_1), moderate (C_2) and low (C_3)

  - At the world scale, the populations P_1 consume C_1, P_2 consume C_2 and P_3 consume C_3

This approach means that the consumption levels C_1, C_2 and C_3 are the same whatever the emerging and poor country considered

- the approach
  - determine P_1, P_2 and P_3 to deduce the consumption levels C_1, C_2 and C_3 by the simple relation:

$$P_1 C_1 + P_2 C_2 + P_3 C_3 = E_{tot} = 20 \text{ Gtoe/year} \qquad (1)$$

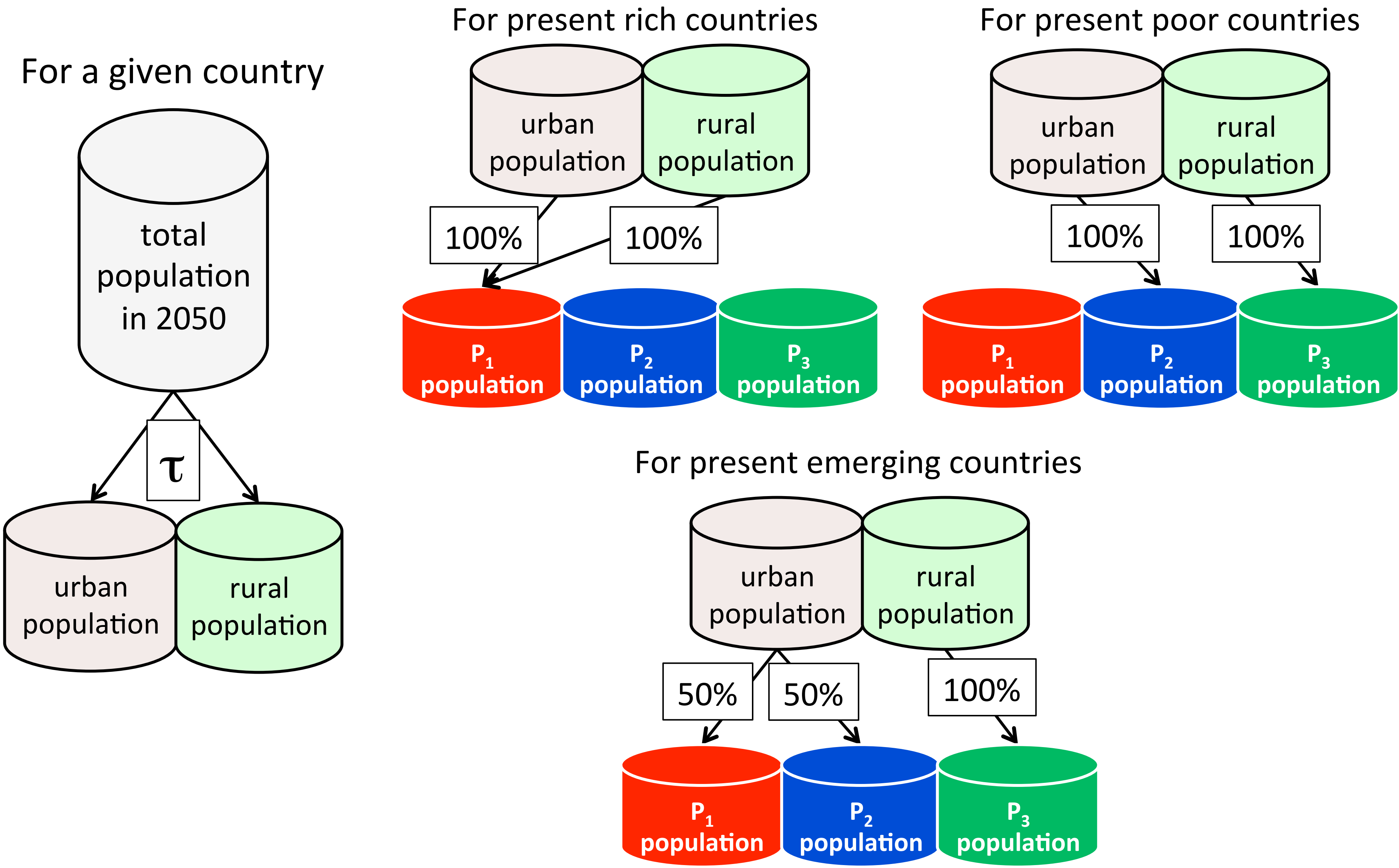
  - to obtain absolute values, we introduce inequality ratios of energy consumption:

$$C_1/C_3 \text{ and } C_2/C_3$$

  - so that (1) becomes: $$\left[P_1\left(\frac{C_1}{C_3}\right)+P_2\left(\frac{C_2}{C_3}\right)+P_3\right]C_3 = E_{tot} \qquad (2)$$
  - by fixing values of C_1/C_3 and C_2/C_3, we deduce C_3 from (2) and then C_1 and C_2

- to determine P_1, P_2 and P_3, we use the rate of urbanization as unique parameter
  - 6,3 billions will be living in cities by 2050
  - socio-economic development of a country takes place in cities
  - to deal with hundred thousand people living together infrastucture for health, transportation, electricity, water and communication must be developped
  - ⇨ Rate of urbanization is a relevant indicator of the energy consumption in emerging and poor countries

- rules to determine P_1, P_2 and P_3 from known rate of urbanization τ in 2050

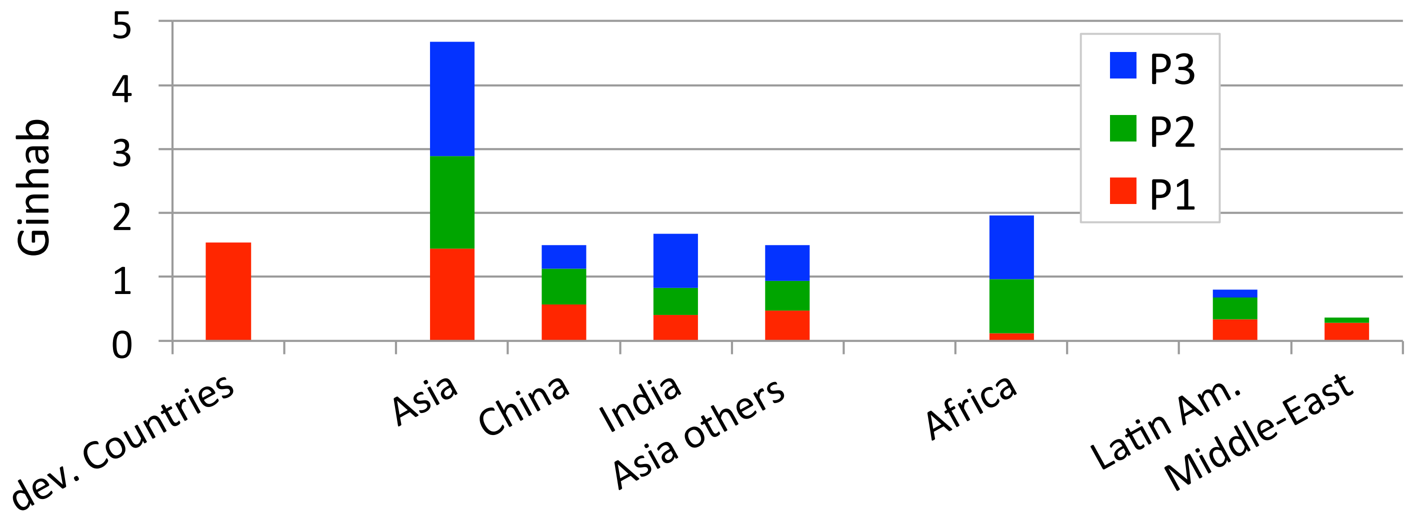


- distribution of populations P_1, P_2 et P_3 in 2050

$$P_1^{world} \approx 3{,}6\,\text{Ginhab}$$

$$P_2^{world} \approx 3{,}0\,\text{Ginhab}$$

$$P_3^{world} \approx 2{,}7\,\text{Ginhab}$$

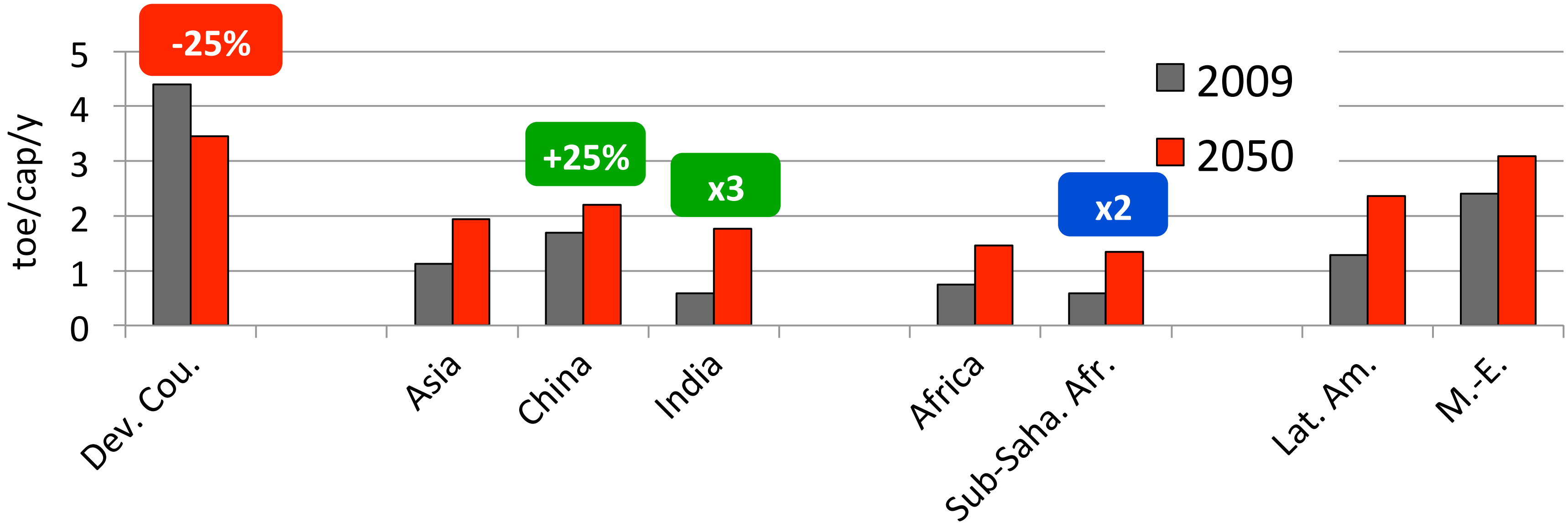


- Choice of inequality ratios
  - we reduce by a factor 4 the inequalities between the energy consumption of the reachest population (C_1) and the poorest population (C_3)
  - we assume that moderate energy consumption (C_2) of urban population is twice as large as in rural zones (C_3)

$$\Rightarrow \frac{C_1}{C_3} \Big/ \frac{C_2}{C_3} \Big/ \frac{C_3}{C_3} = 4/2/1$$

➨ C_1 = 3, 46 toe/cap/year C_2 = 1,73 toe/cap/year C_3 = 0,86 toe/cap/year

Energy demand in 2050

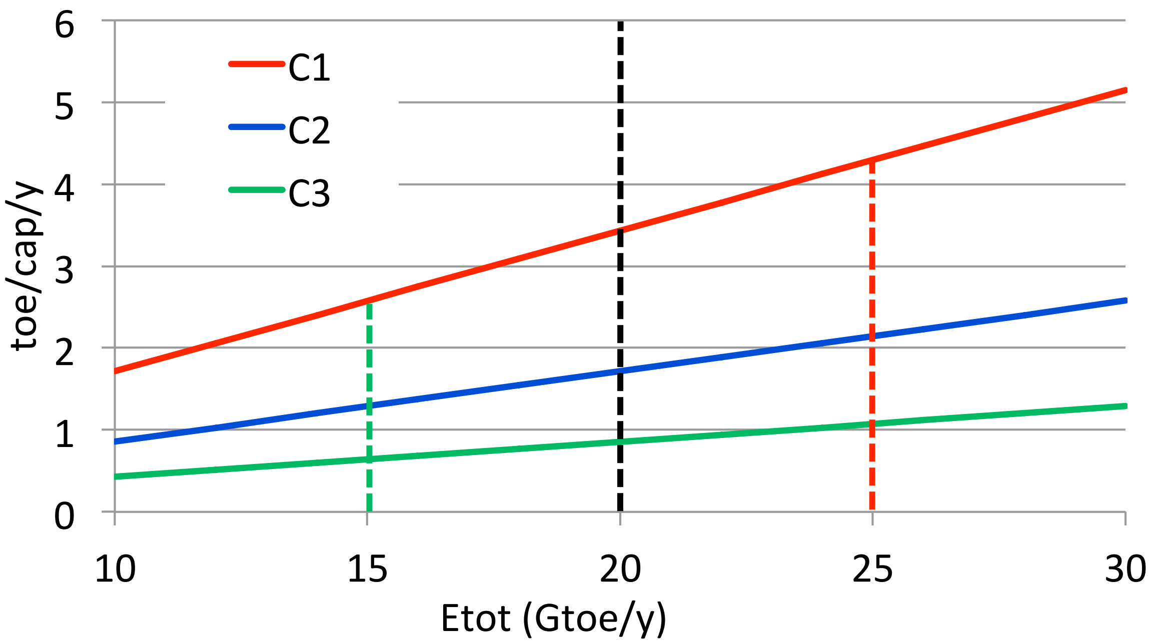


- present rich countries have to reduce their energy consumption from 4,4 toe/cap/year to 3,46 toe/cap/year
  ⇨ strong constraint as the tendency is rather a continuous increase of the level of consumption of rich countries

- the inequality reduction implies that for other entities the increase of their energy consumption is all the more important since their present consumption is low
  - increase of 25% in China, x3 in India

- the mean energy consumption for poorest region has doubled but still remains low

- evolution of C_i's level with total energy consumption E_{tot}



  - an mean energy consumption of present rich countries stabilized to 4,4 toe/cap/year in 2050 with a reduction of inequalities leads to a total energy consumption of 25 Gtoe/year
  - a 15 Gtoe/year scenario does not allow to emerging and poor populations to increase their energy consumption by 2050

⇨ A total energy of 20 Gtoe/year is rather sober and maybe too lower to be acceptable

- the climate constraint
  - to reduce GHG emissions by a factor 2
  - ⇨ total fossil fuesl consumption with CO_2 emissions: F_{world} = 4,2 Gtoe/year

- as previously, we determine the fossil fuels consumption per capita for each category of population, F_1, F_2 and F_3, by fixing the ratios

$$\Rightarrow \frac{F_1}{F_3} \Big/ \frac{F_2}{F_3} \Big/ \frac{F_3}{F_3} = 2/1{,}4/1$$

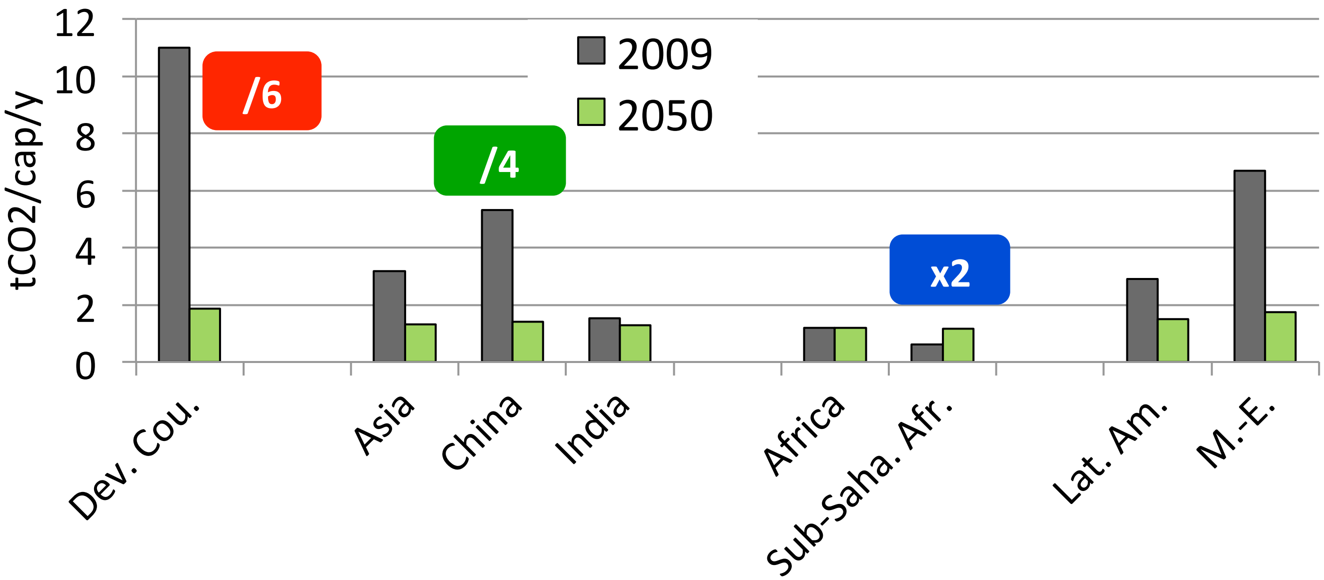
Drastic reduction of inequalities …

We assume that richest populations (P_1) are in better condition, technically and economically, to develop non-CO_2 emitting sources

With $$\left[P_1\left(\frac{F_1}{F_3}\right)+P_2\left(\frac{F_2}{F_3}\right)+P_3\right]F_3 = F_{tot}$$

➨ F_1 = 0,6 toe/cap/year F_2 = 0,42 toe/cap/year F_3 = 0,3 toe/cap/year

- CO_2 emissions in 2050



- In rich countries, CO_2 emissions have to be reduced by a factor 6

⇨ CO_2-non emitting sources represent 80% of the total energy consumption while it is 20% today

- China has already overshot « allowed » CO_2 emissions

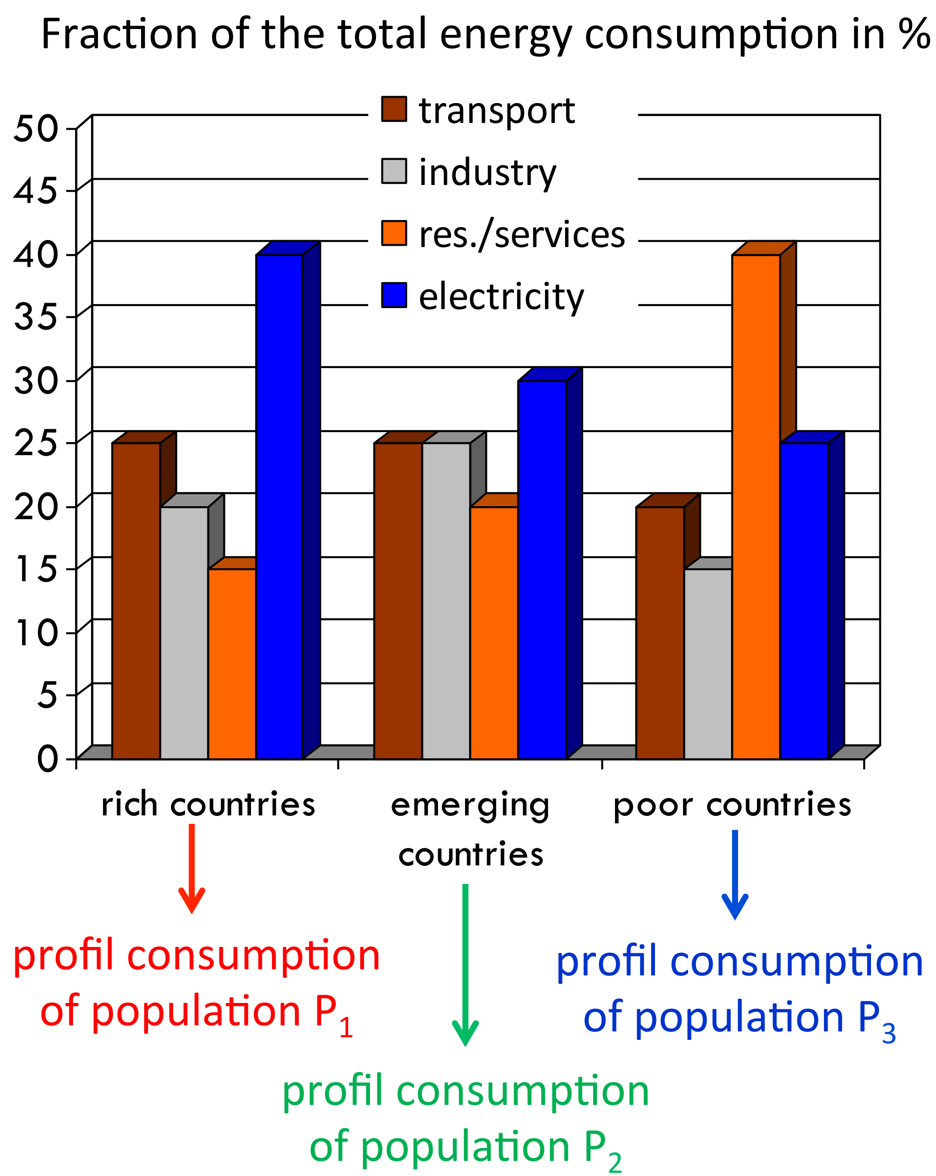
⇨ the increase of energy consumption in present emerging countries is based on CO_2-non emitting sources

- In poorest countries, CO_2 emissions increase only by a factor 2

⇨ The use of fossil fuels is also limited …

⇨ The climate constraint is very demanding, the tendency showing a continuous increase of fossil fuels consumption

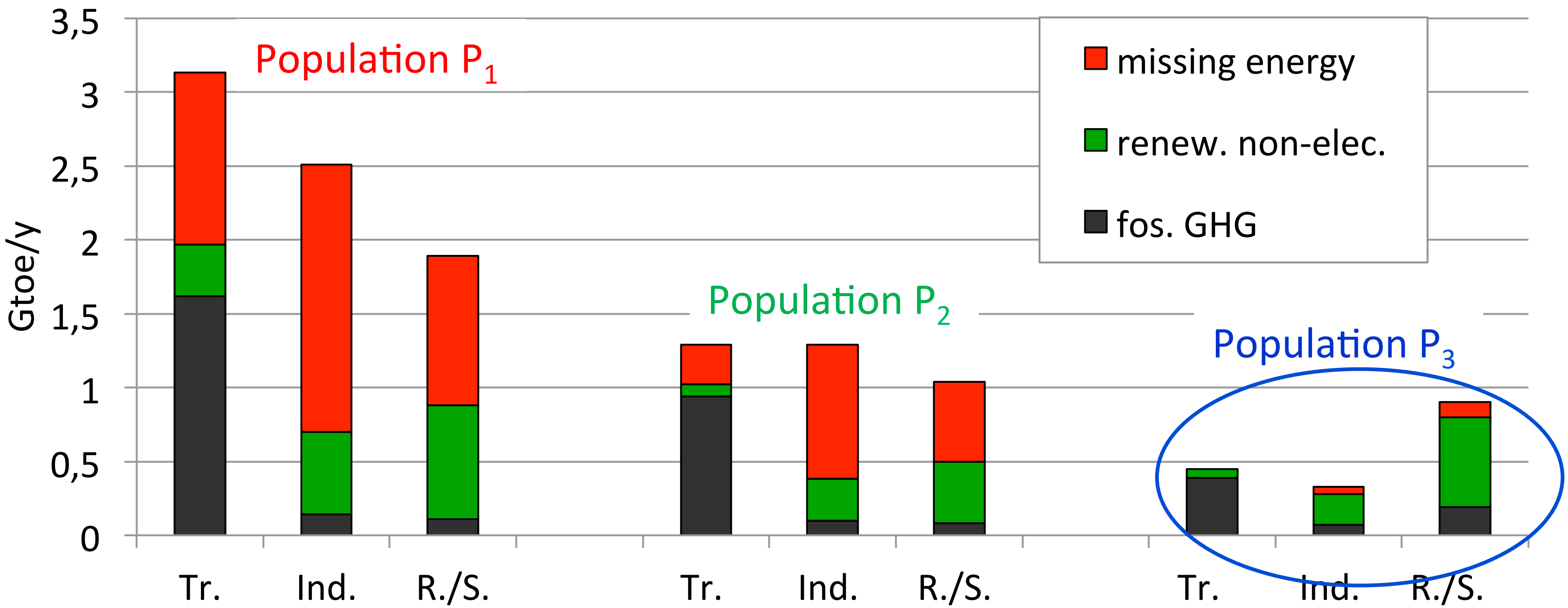
- construction of the energy mix in 2050



- method to construct energy mix in 2050
  - use of fossil fuels with CO_2 emissions fixed by climate constraint ~ 4,2 Gtoe/year
  - potential of renewable energy sources fixed to optimistic values:
    - renewable electricity: ~ 3,5 Gtep/year
    - renewable heat: ~ 3,5 Gtoe/year
    - biofuels: ~0,5 Gtoe/year
  - fossil fuels with CCS fixed at 3,7 Gtoe/year (12 $GtCO_2$ stored/year)
  - nuclear energy is used as adjusting variable to fill the needs

⇨ We start by filling the transport and heat for industry and res./services needs

- method to construct the energy mix in 2050 (1/3)
  - energy needs of each group of population, P_1, P_2 and P_3, are considered
  - we use first fossil fuels with CO_2 emissions mainly for transport and renewable energy sources able to provide heat: wood, CSP, solar water heat, geothermal
    - energy sources are globally distributed in proportion of the needs
    - wood still remains the main energy source for rural populations (P_3)



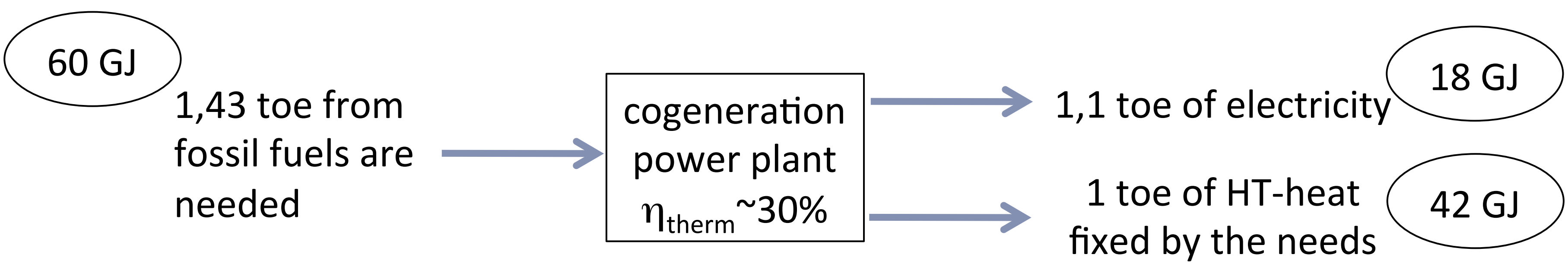
⇨ 50% of transport and heat needs are missing (~ 6 Gtoe/year)

- What are the options to meet heat and transport needs ?
  - transfer these needs (~ 6 Gtoe/year) to electricity which are added to « classical » electric uses (~ 7 Gtoe/year)?

    ⇨ explosion of the electricity demand

  - develop cogeneration: produce electricity and use at the same time the heat rejected by power plants at various temperatures according to specific uses

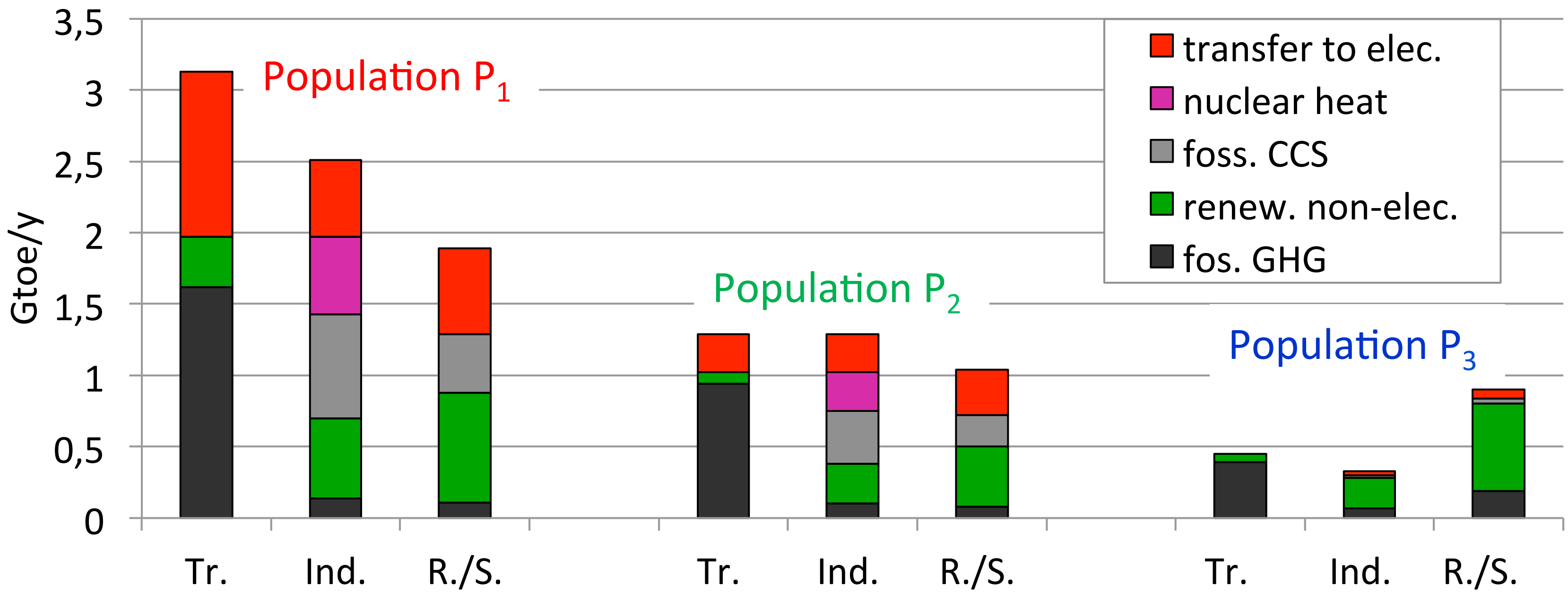
    ⇨ the use of fossil fuels coupled to CCS technology represents an efficient way to produce heat without CO_2 emissions



Convention 1MWhelec = 0,22 toe ➡ 18 GJ = 5 MWh_{elec} = 1,1 toe

  - use nuclear energy to produce directly high temperature heat rather than electricity

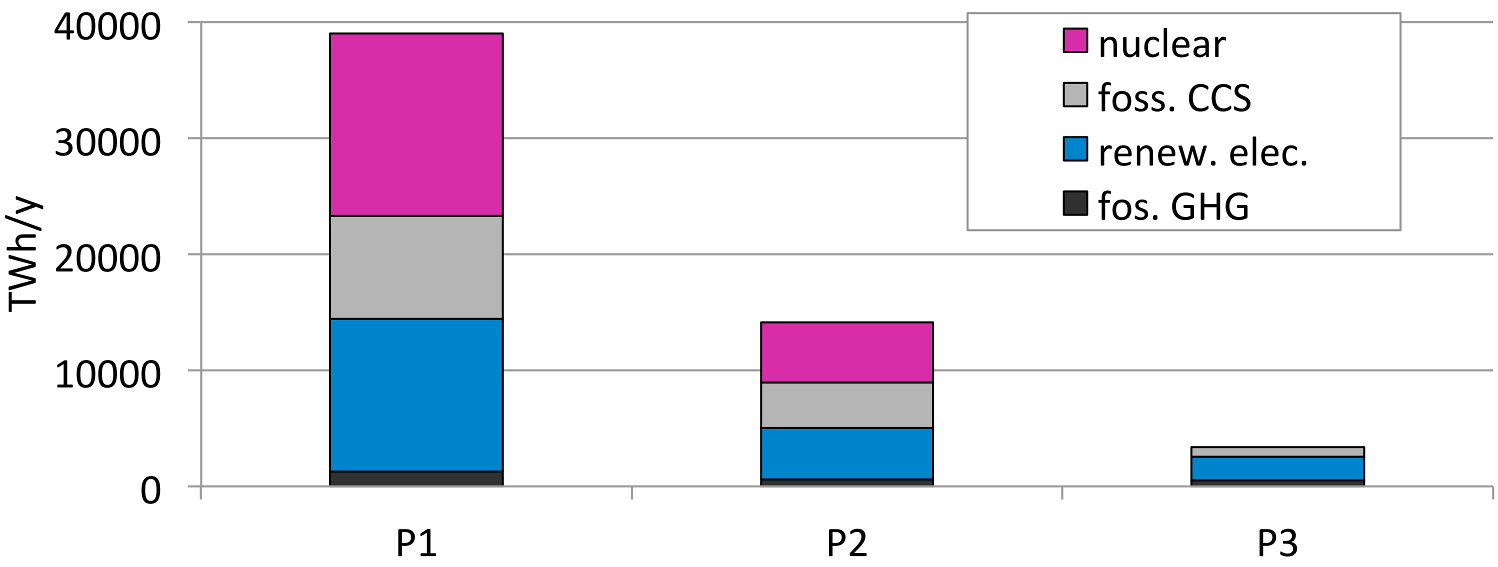
- method to construct the energy mix in 2050 (2/3)
  - 2/3 of the maximum potential of CCS with cogeneration are used to cover heat needs of industry and residential/services sectors
    ⇨ Mainly used for urban population (P_1 and P_2)
  - nuclear heat covers 50% of the missing energy of industry needs and is exclusively used for urban population (P_1 and P_2) ⇨ 0,8 Gtoe/year ~ almost the nuclear power of today



⇨ But energy is still missing (~ 3Gtoe/year) !

method to construct the energy mix in 2050 (3/3)

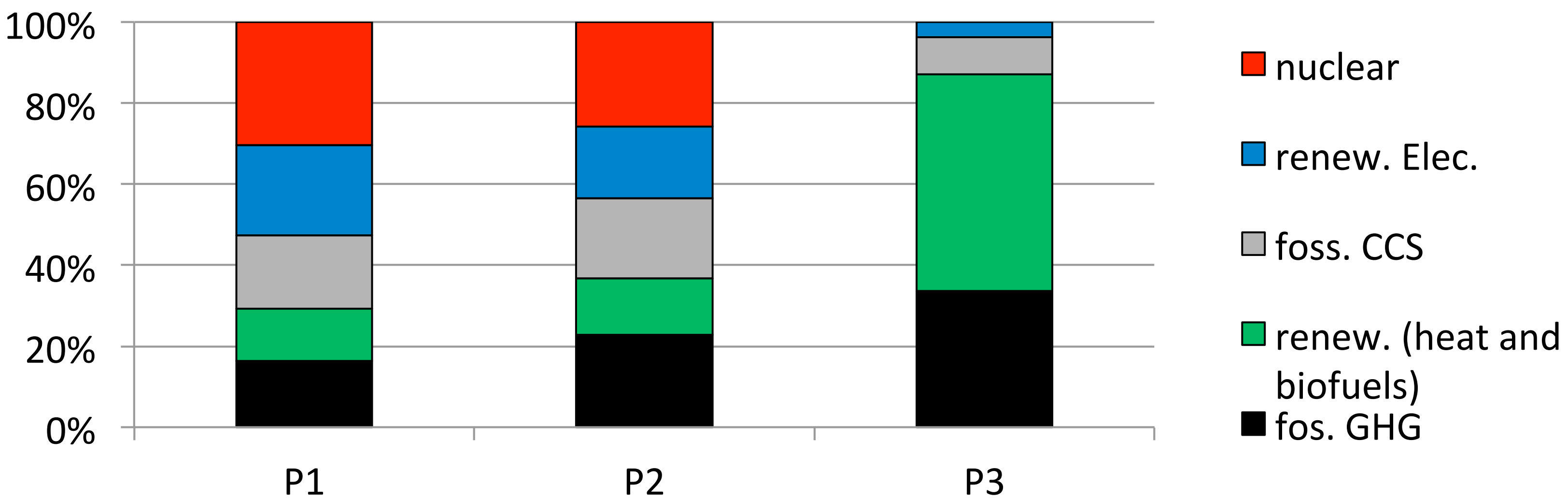
- direct transfer of transport and heat needs to electricty (~ 3 Gtoe/year)
  - 35% of transport are electrical
  - use of heat pumps for electrical heating to minimize the electricity consumption
- electricity mix
  - renewable energy sources are used in priority at the maximum of their potential: hydropower, windpower, PV
  - fossil fuels with CCS and without cogeneration
  - finally, nuclear energy



⇨ maximum of potential estimates of renewable sources and CCS capabilities are used

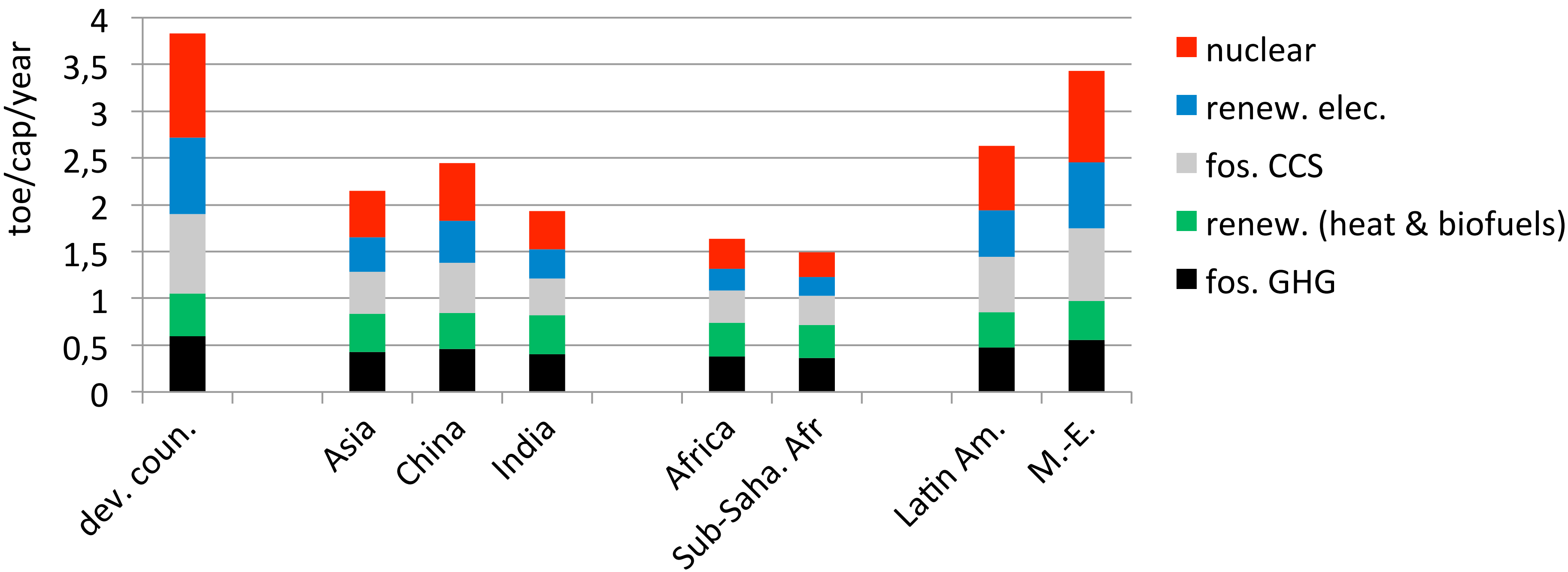
⇨ difficult to get rid of nuclear power ~ 4,6 Gtoe/year (x 8 /today)

- Some results
  - energy mix of population P_1, P_2 and P_3



  - for population having high and moderate level of consumption, the choice of inequality ratios implies:
    - ✓ the use of fossil fuel with CO_2 emissions is the weakest
    - ✓ the deployment of renewable sources for electricity generation is the most important
    - ✓ as well as CCS technology and nuclear power
  - important fraction of CO_2-non emitting for P_3 due to essentially to biomass

energy mix of different geographical regions

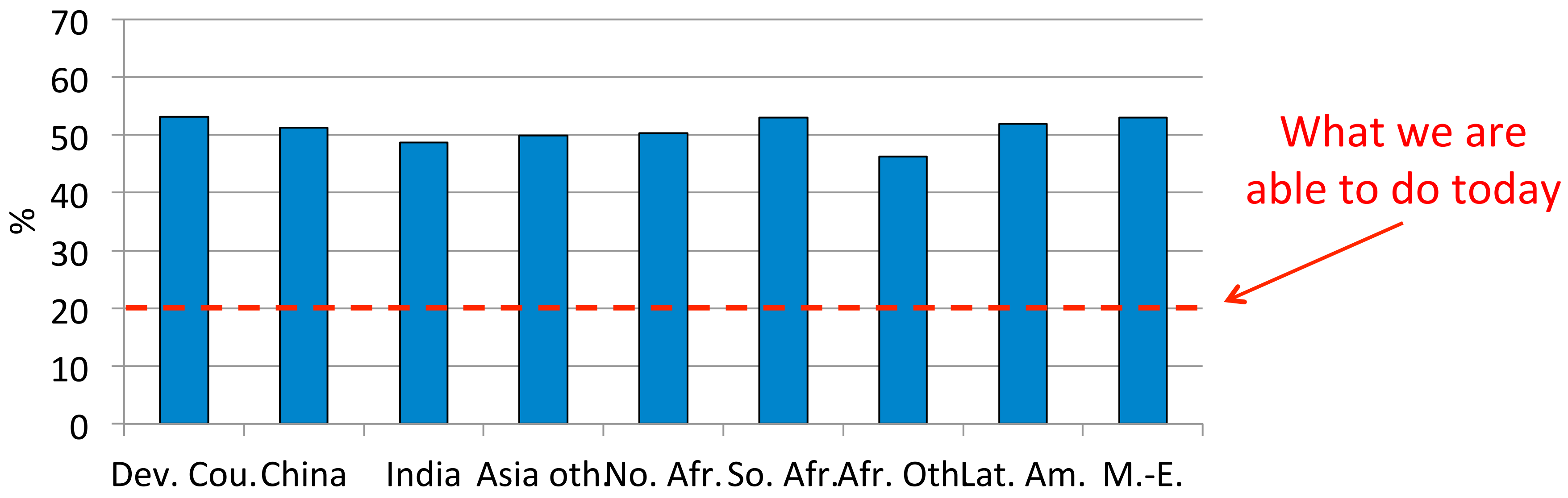


- the use of fossil fuels are leveled around 0,5 toe/cap/year except in poorest regions

⇨ CO_2 emissions ~ 1,6 tCO_2/cap/year

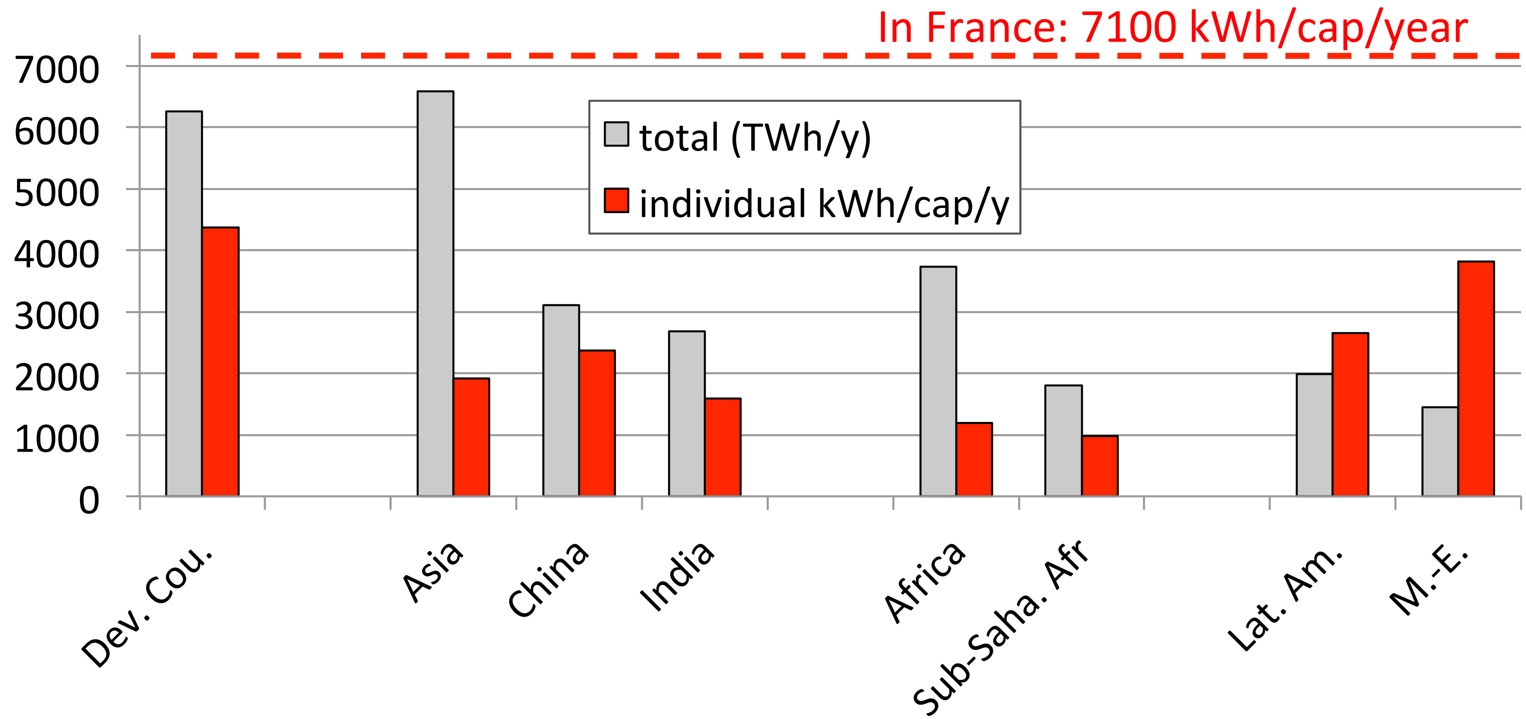
- CCS technology is developed in all regions
- homogenous distribution of renewable energy sources for heat and transport needs
- part of CCS technology, renewable energy sources for electricity generation and nuclear energy increase with the fraction of population P_1

- Focus on electricity
  - fraction: intermittent /(intermittent +flexible)



  - storage at very large scale
  - management of the intermittent electricity with electrical transport
  - make nuclear power flexible
  - ....

- focus on nuclear power



- nuclear heat ~ 0,8 Gtoe/year
- nuclear electricity ~ 21 000 TWh (~ 37% of the total electricity consumption)

⇨ X 9 / today (5,4 Gtoe/year)

- mainly developed in Asia

- some remarks to open the discussion …

  - a total energy demand of 20 Gtoe/year is quite sober and seems to be no consistent whith an economic growth of +2%/year in developed countries

  - lack of CO_2-non emitting sources for heat and transport needs which lead to a massive transfer to electricity

  - the capabilities that new renewable energy sources have to reach are very ambitious

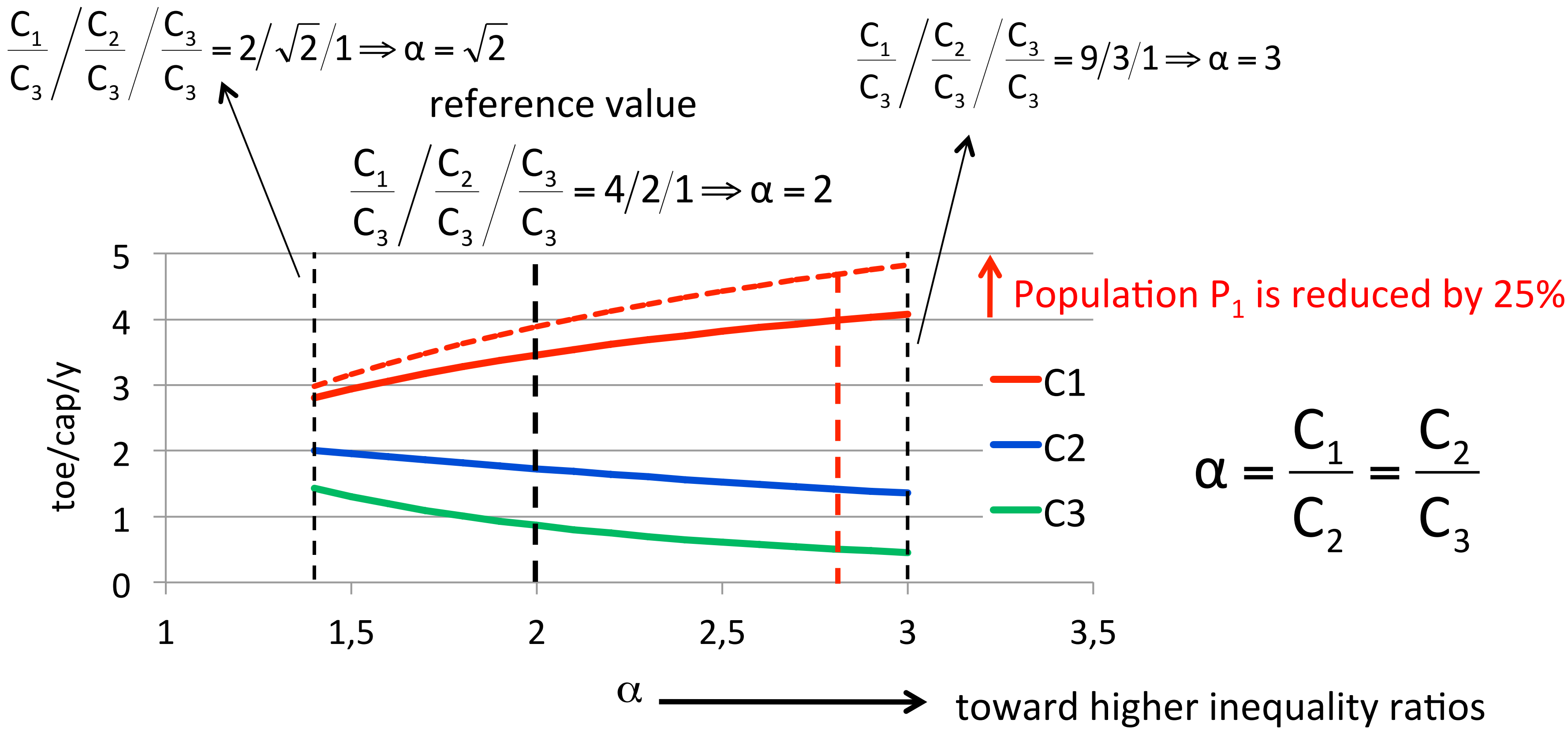
  - how to manage without fossil fuels, cheap, easy to use and available in large amount?

  - how the efforts to make to limit the climate change can be bearable while we will never see their effects in our lifetime?

references

- *World DataBank, http://data.worldbank.org*
- *United Nations Department of economic and Social affairs/Population Division, « World Urbanization prospects : The 2010 Revision ».*
- *Deciding the future : energy policy scenarios to 2050, World Energy Council 2007, http://www.worldenergy.org/publications/energy_policy_scenarios_to_2050/default.asp*
- *World Energy Outlook – WETO H_2, European Commission, EUR22038, http://ec.europa.eu/research/energy/gp/gp_pu/article_1100_en.htm*
- *United Nations – Habitat, « The state of the world's cities report 2006/2007 »*
- *GIEC 2007, Bilan 2007 des changements climatiques. Contribution des Groupes de travail I, II et III au 4ème rapport d'évaluation du Groupe d'experts intergouvernemental sur l'évolution du climat [Equipe de rédaction, Pachauri, R.K. et Reisenger, A]*
- *United Nations, Economic & Social Affairs, « 2004 Energy balances and electricity profiles »*
- *United Nations, Economic & Social Affairs, « 2004 Energy statistics Yearbook »*
- *World Energy Council, « 20010 Survey of energy resources » http://www.worldenergy.org/publications/3040.asp*

- evolution of C_i's level with inequality ratios with E_{tot} = 20 Gtoe/year



- with a 20 Gtoe/year fixed, to stabilize a mean energy consumption of present rich countries to 4,4 toe/cap/year in 2050 requires both inequality ratios higher and a limitation of population P_1

To make possible a development of the level of living of emerging and poor countries, strong reduction of inequalities and reduction of energy consumption of richest populations are both required