Quelles sources d’énergie pour répondre aux besoins futurs ?

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

technological
sociological
political
economic
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 !

Energy: basic principles

Efficiency, units, conventions, energy conversion
Orders of magnitude

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

$$\left.\begin{array}{l} C \\ (CH_2)_n \\ CH_4 \end{array}\right\} + O_2 \rightarrow CO_2 + \text{heat} + \ldots$$

energy stored in bounding energy between nucleons

natural uranium

nuclear reactor

fission reaction

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

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

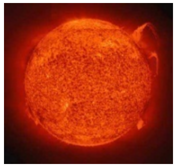
hydropower

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**

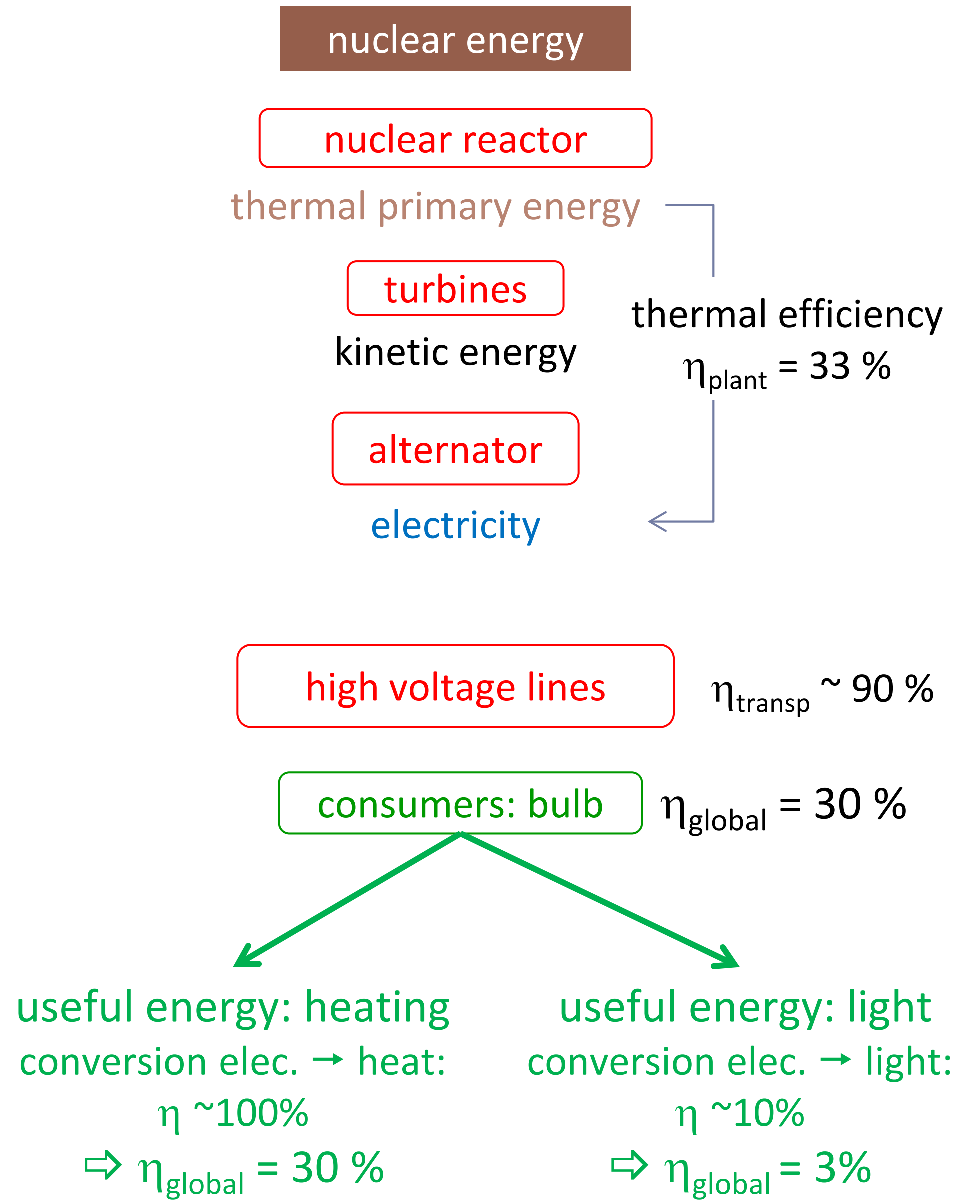
✓ the energy initially available (chemical, light, nuclear, …) is succevely converted in different forms to end in a useful form to consumers (mechanical, thermal, light, …)

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

$$\eta_{conversion} = \frac{E_{useful}}{E_{available}}$$

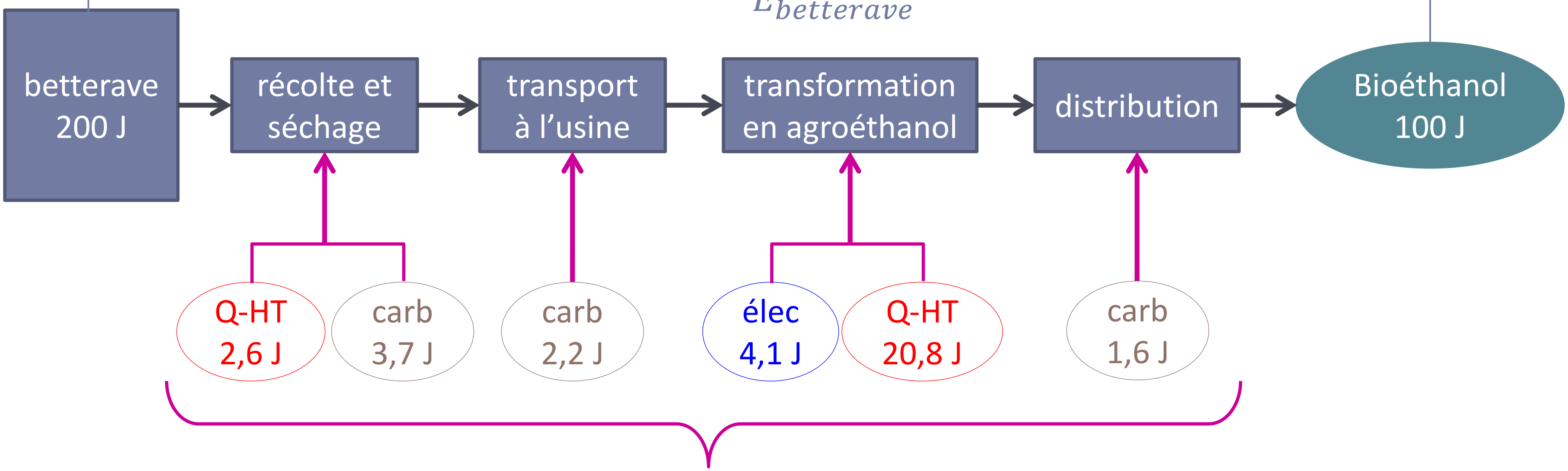
	conversion	η
coal or gas thermal plant	heat → elec.	30 – 50 %
individual gas-fired boiler	heat → heat	60 – 90 %
engines	heat → mech.	25 – 35 %
battery	elec. → elec.	80 %

Ex: conversion of fission to light/heating



- The definition of the efficiency has to be clearly explained by precising
  - useful energy and available energy (electricity, primary energy, ...)
  - losses due transport
- In some cases the « extra » energy consumed to convert energy is taken into account in the efficiency

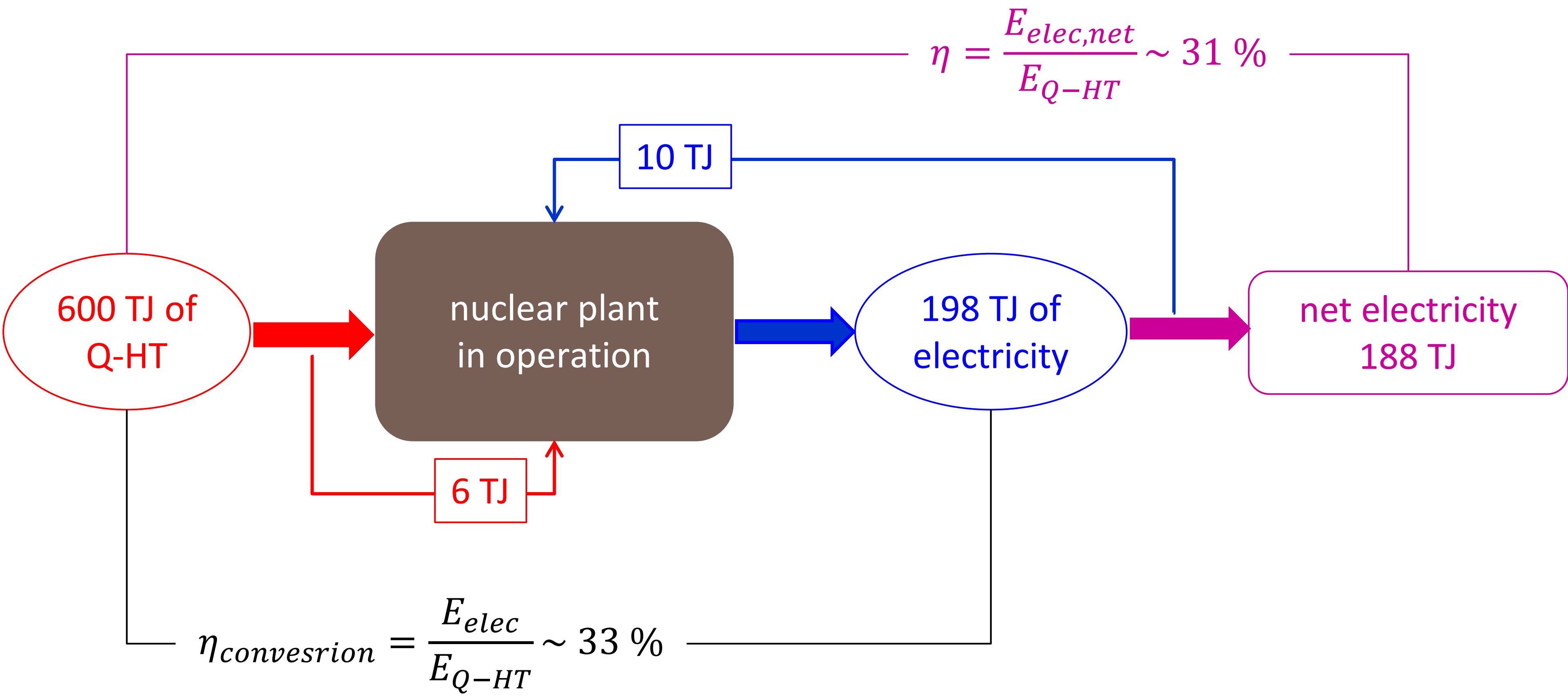
$$\eta_{conversrion} = \frac{E_{bioéthanol}}{E_{betterave}} \sim 50\ \%$$



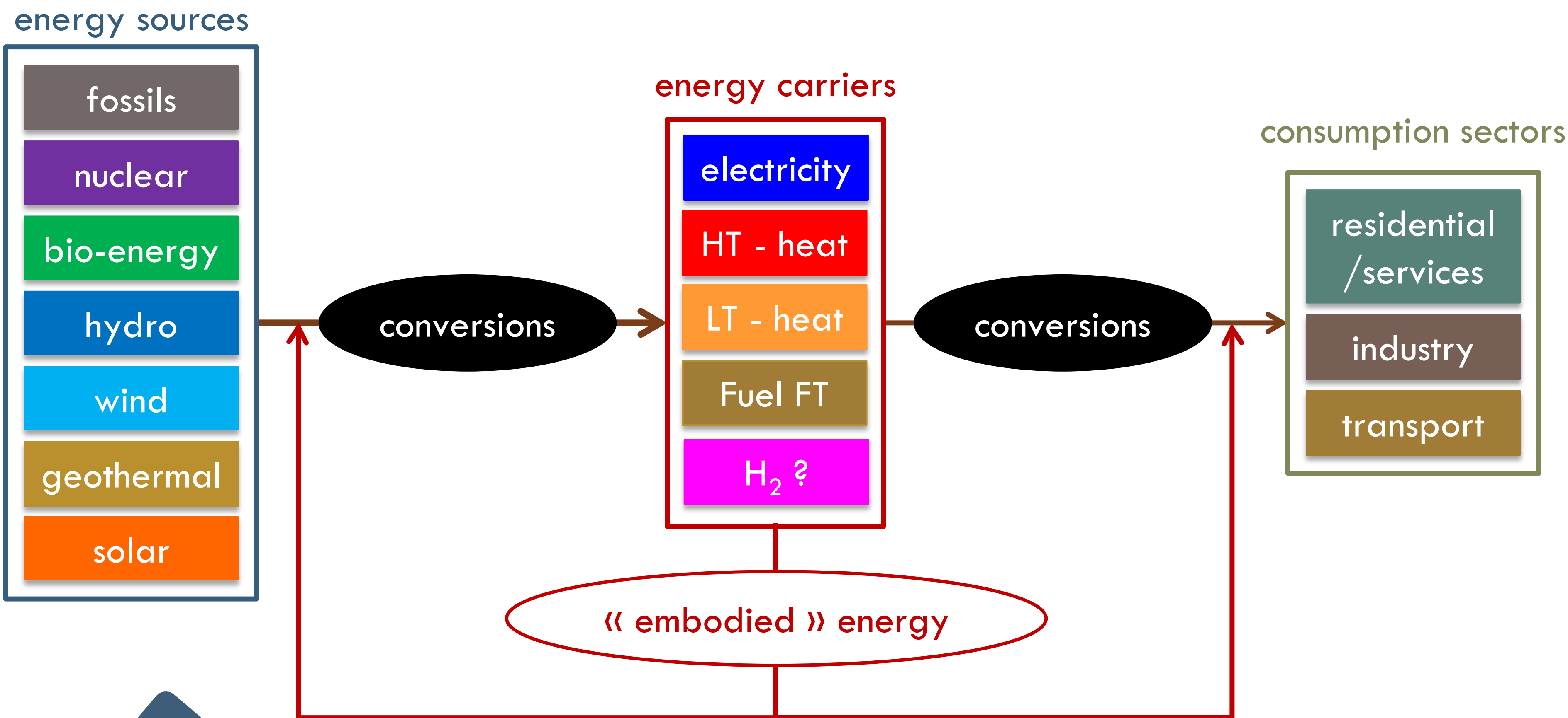
« extra » energy = available energy = 35 J

$$\Rightarrow \eta = \frac{E_{bioétahnol}}{E_{betterave}+E_{extra}} \sim 42\ \%$$

- In some cases, a part of the energy produced is self-consumed by the plant and is taken into account in the efficiency



- primary energy sources – energy carriers – energy end-use

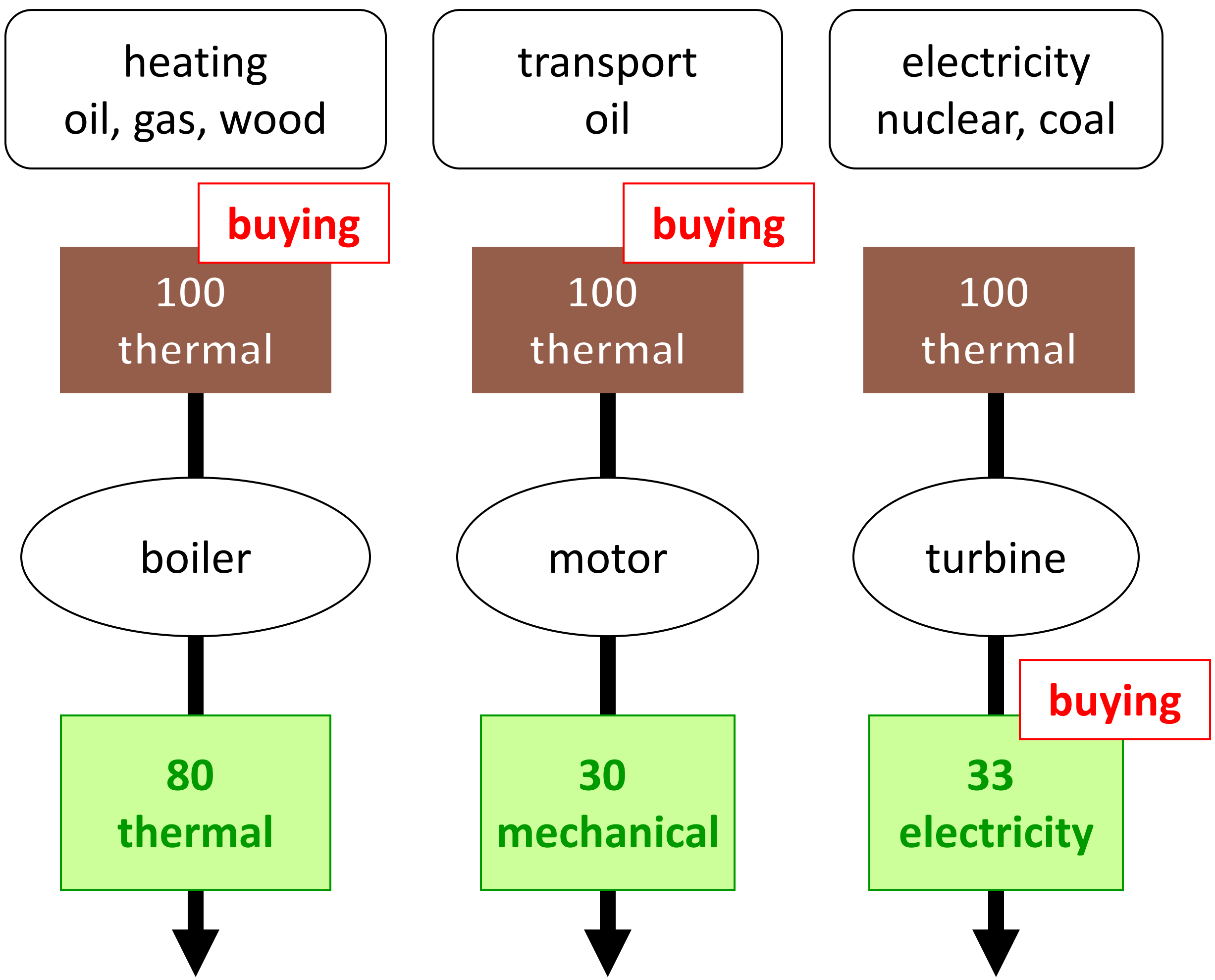


Projet APESE

- Embodied energy taken into account in scenarios ?
- Energy finally available for the economy ?

- 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?



Part of the electricity in the total consumption?

primary energy
electricity: 100/300 = 33%

« final » energy
electricity: 33/230 = 14%

useful energy
electricity: 33/143 = 23%

Nuclear in France

Final electricity

nuclear: 80 %

Total primary energy

nuclear: 39%

Total useful energy

nuclear: 26 %

Total final energy

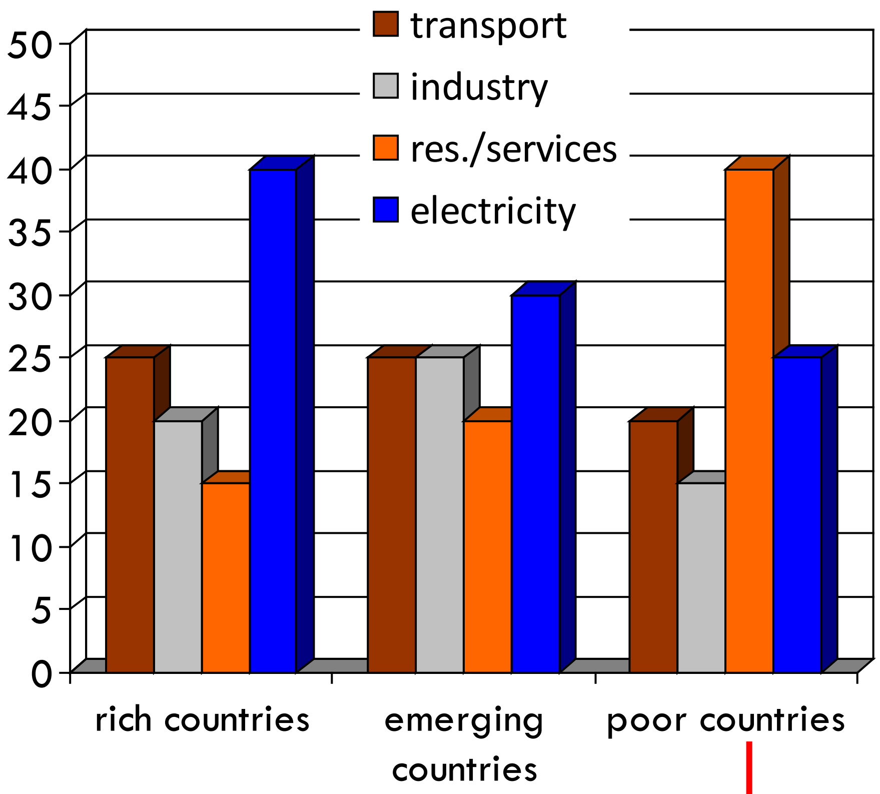
nuclear: 17%

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

- 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 ~ 3 Gtoe/year
→ oil (~ 95 %)
→ biofuel

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

- residential/services ~ 2,5 Gtoe/year
heat at low temperature (< 100°C)
→ domestic fuel and gas (~ 70 %)
→ biomass

- electricity ~ 5 Gtoe/year

- grids not enough deployed
- more than 1 billions of human beings have no access to electricity …

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

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 used:

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

✓ 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

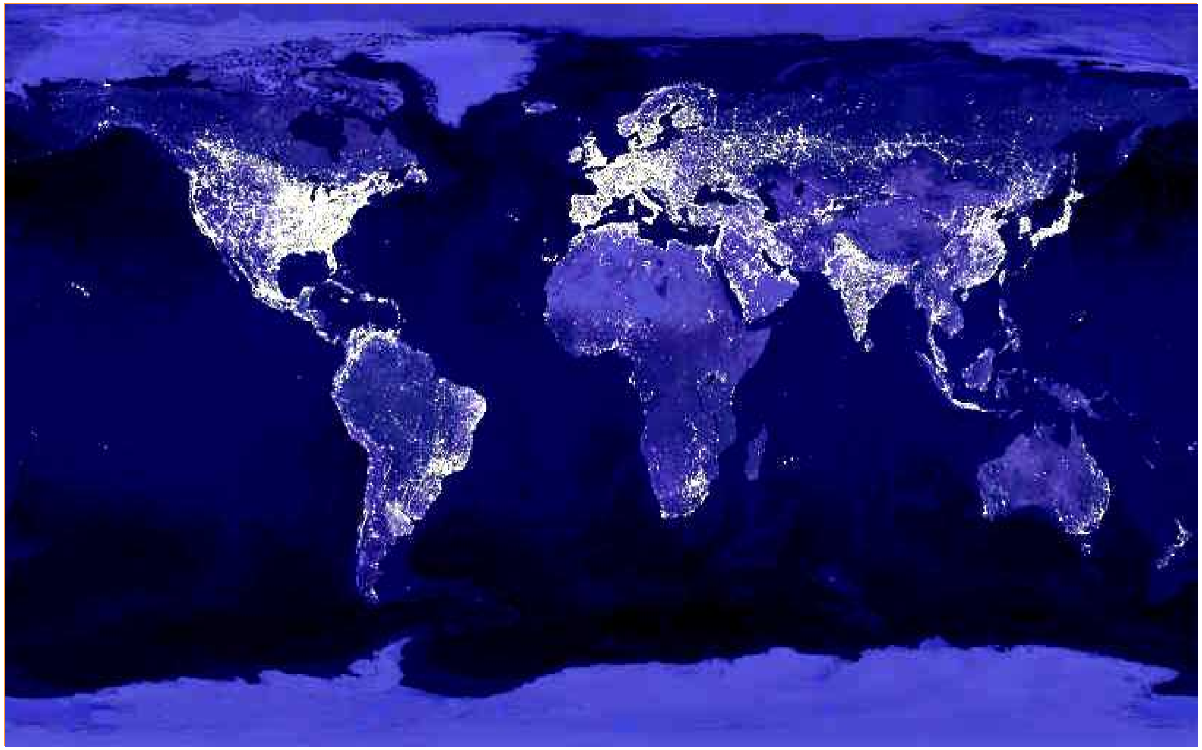
For a same quantity of electicity (1 MWh_{elec}), the mass of oil is different
This is not anymore a « ton oil equivalent » …

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

The world energy context

Today in the world

Total consumption	~13 billions of toe/year
Population	~7 billions of inhabitants
Average consumption/cap.	~1,9 toe/year (2500 W)



- energy consumption distribution according different geographical regions

geographical regions	total consumption (Gtoe/year)	population (Minhab.)	consumption toe/cap/y
North America	2,47	354	7
Pacific	0,15	38	4
Ex-USSR	1,06	286	3,7
Europe	1,77	616	2,9
Middle-East	0,74	232	3,2
Latin America	0,85	622	1,4
Asia	5,52	3 926	1,4
Africa	0,75	1 152	0,65
total	**13,65**	**7226**	**1,9**

- rich countries ~5,5 Gtoe/year
  ~4,2 toe/inhab./year
  ~20 % of the world population
  ~40 % of the world consumption

- emerging countries ~7,2 Gtoe/year
  ~1,2 toe/inhab./y
  ~65 % of the world population
  ~55% % of the world consumption

- poor countries ~ 0,75 Gtoe/year
  ~ 0,65 toe/inhab/year
  ~15 % of the world population
  ~5 % of the world consumption

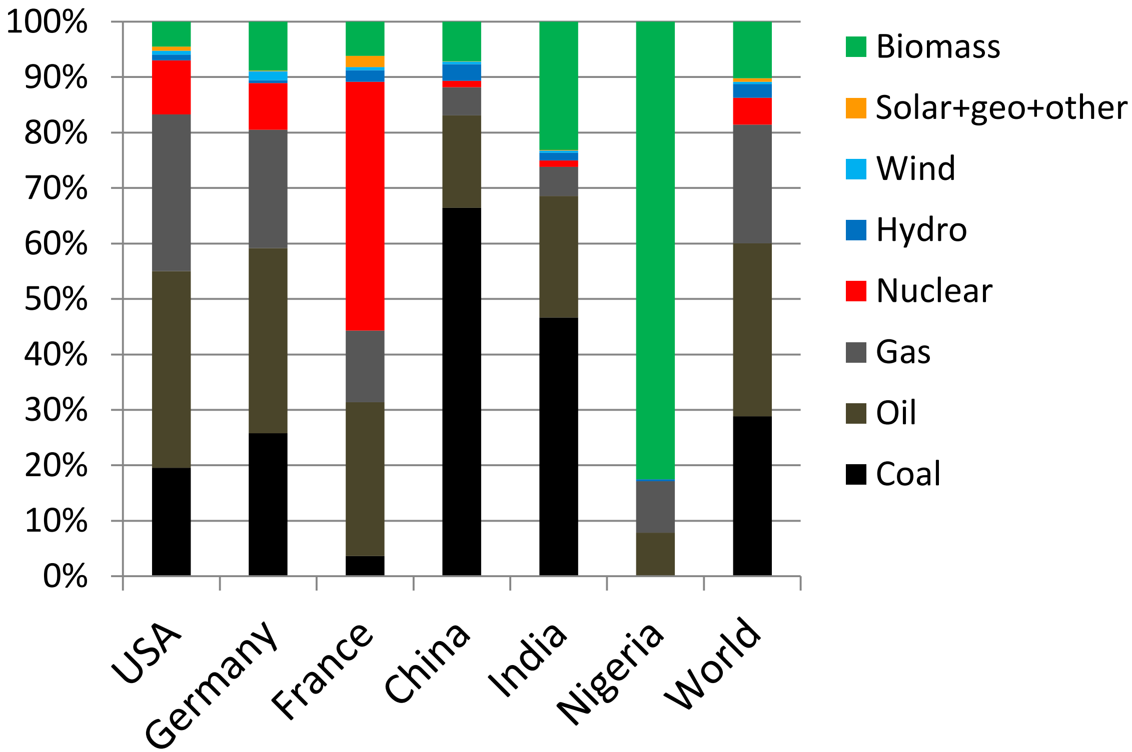
Huge consumption inequalities…

- distribution of energy sources to satisfy the world demand

Source	Gtoe/year	%
fossil fuels oil / gas / coal (conventional)	10,5 4 / 2,8 / 3,7	80 30 / 20 / 30
wood	0,6 – 1,2	7
hydropower	0,8	6
nuclear	0,6	5
new renewables (solar, wind, new biomass)	0,3	2
Total	13,2	

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

- 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

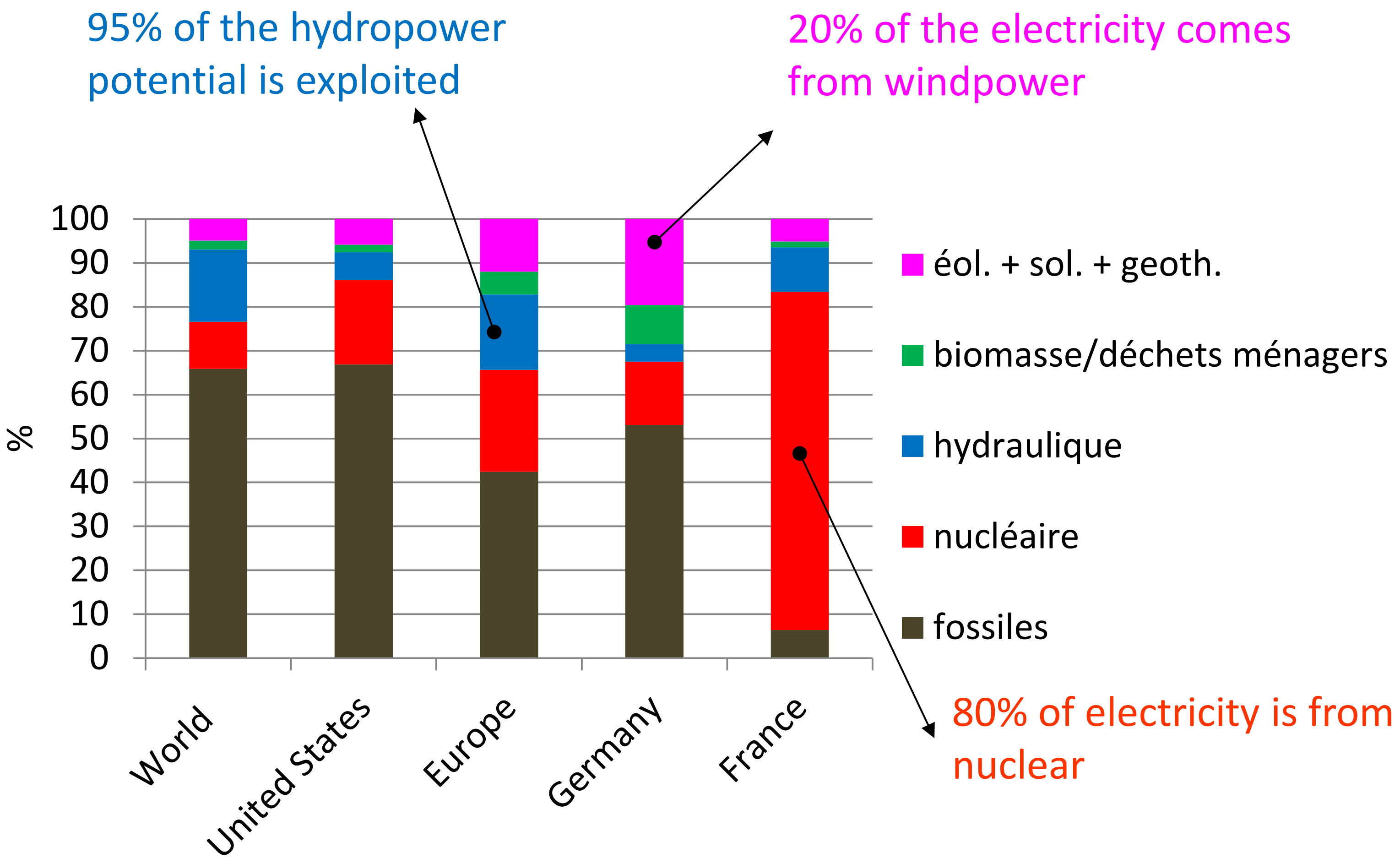
✓development of Asia is mainly based on coal

Rich countries: fraction of fossil fuels > 80 %
fraction of new renewables (solar, wind) < 2 %

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

- electricity mix for different geographical regions

➡ 60% of the electricity generation comes from coal and gas



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**

Orders of magnitude

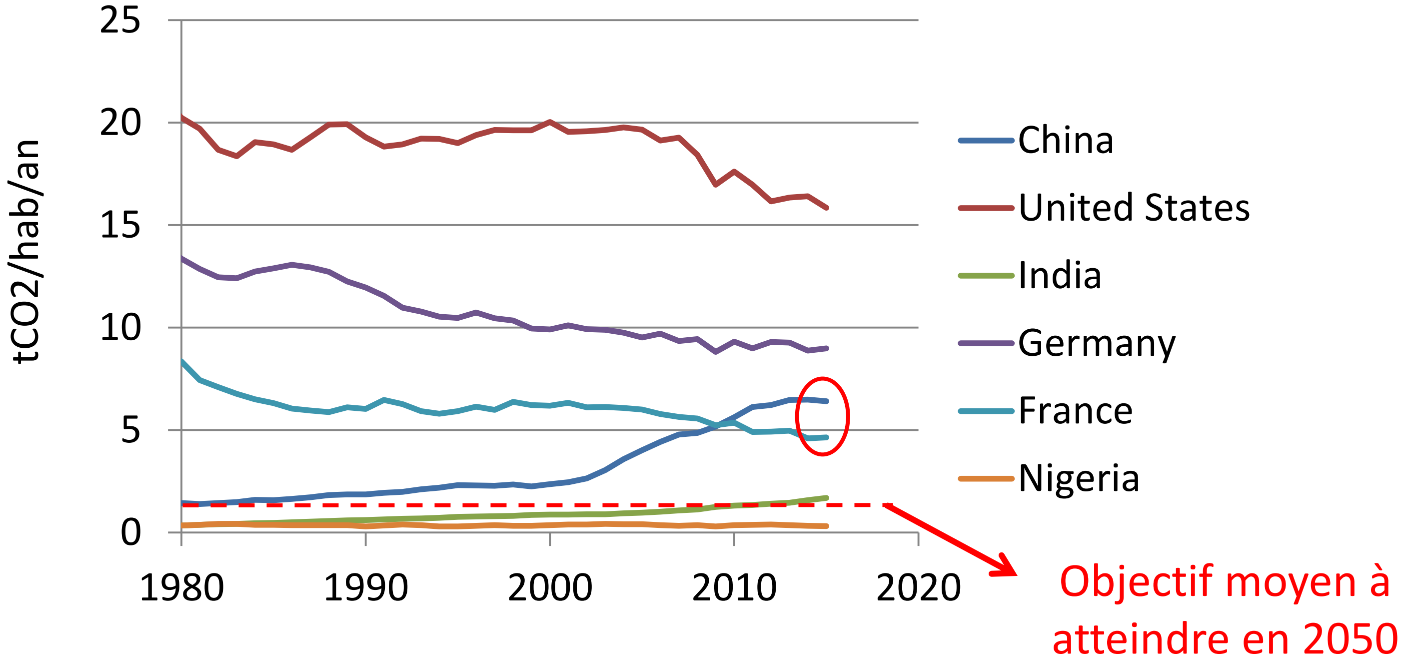
✓ electricity generation η_{therm} = 35 – 50 %

- 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 $CO_2/kWh_{élec}$

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

- Case of a reduction by a factor 2 of CO_2 emissions by 2050 ↔ $\Delta T < 2°C$
  - ✓ 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 !

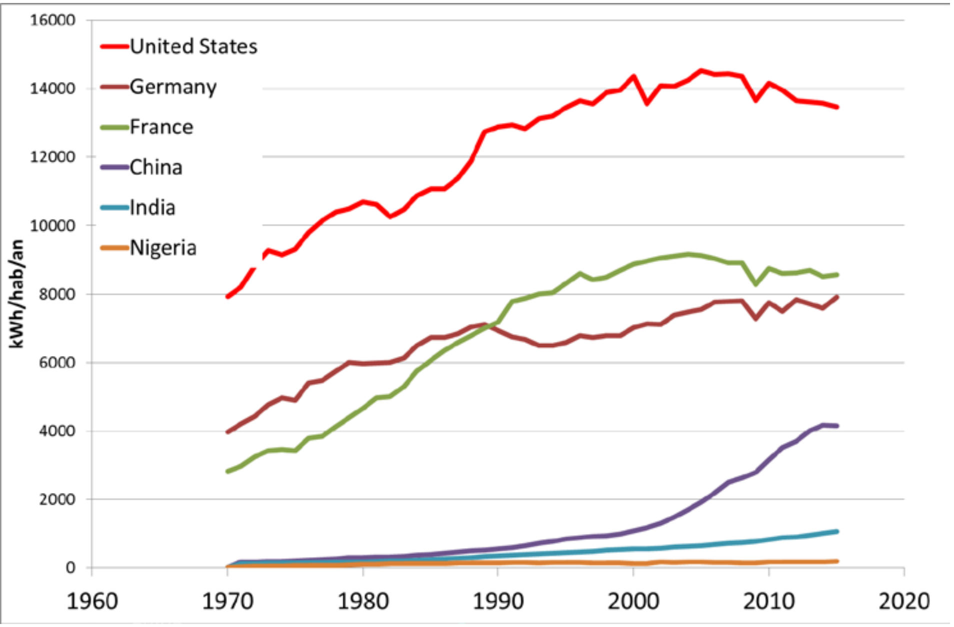
- evolution of the world energy demand

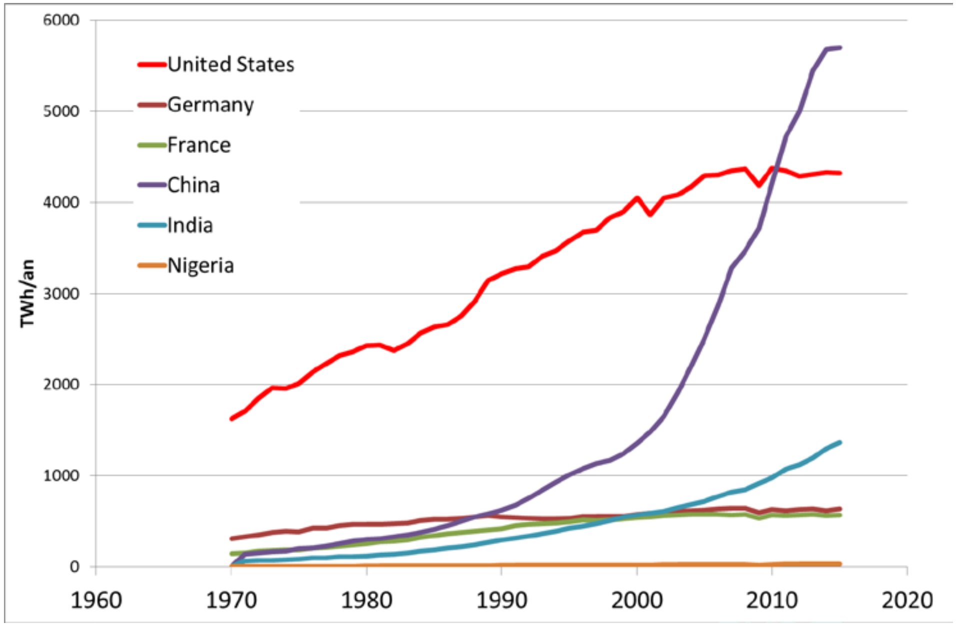
Globally the energy consumption is steadily increasing

Evolution of the electricity consumption in different countries up to 2015

electricty consumption per capita

total electricity consumption





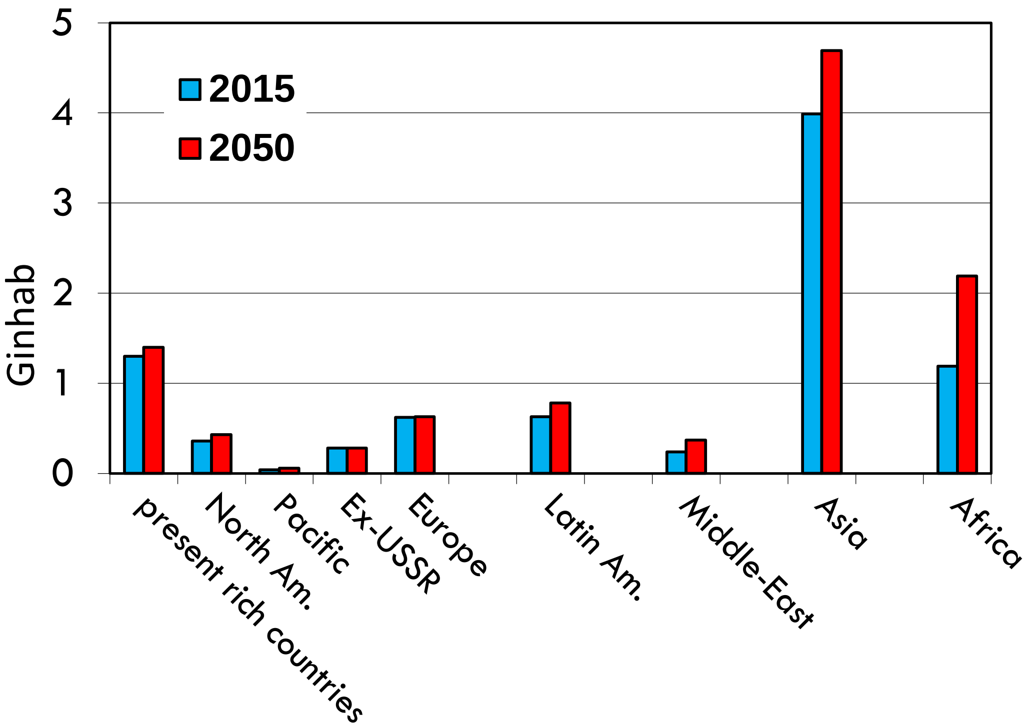
Present electricity consumption in the world ~ 24 000 TWh/year

- 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} = 1,9 toe/cap/year x 9 Ginhab ~ 17 Gtoe/year

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

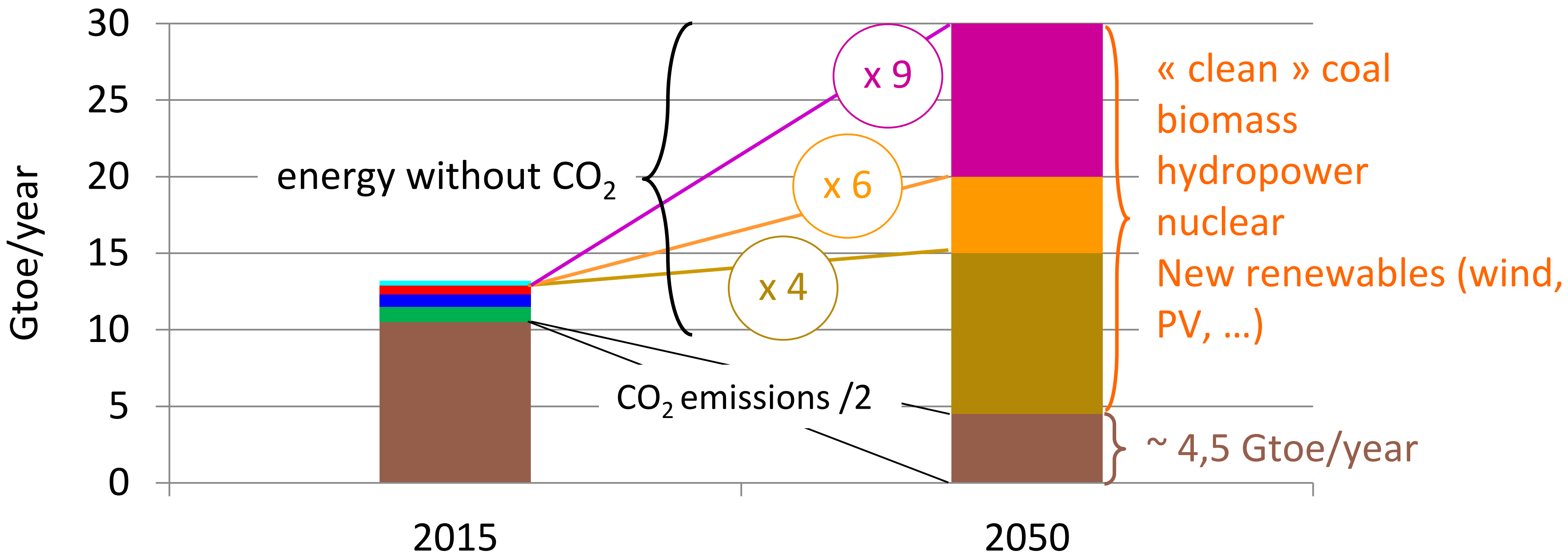
⇨ E_{world} = 4,2 toe/cap/year x 9 Ginhab ~ 40 Gtoe/year

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

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

⇨ a mean and realistic value: 20 Gtoe/year (?)

- 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)

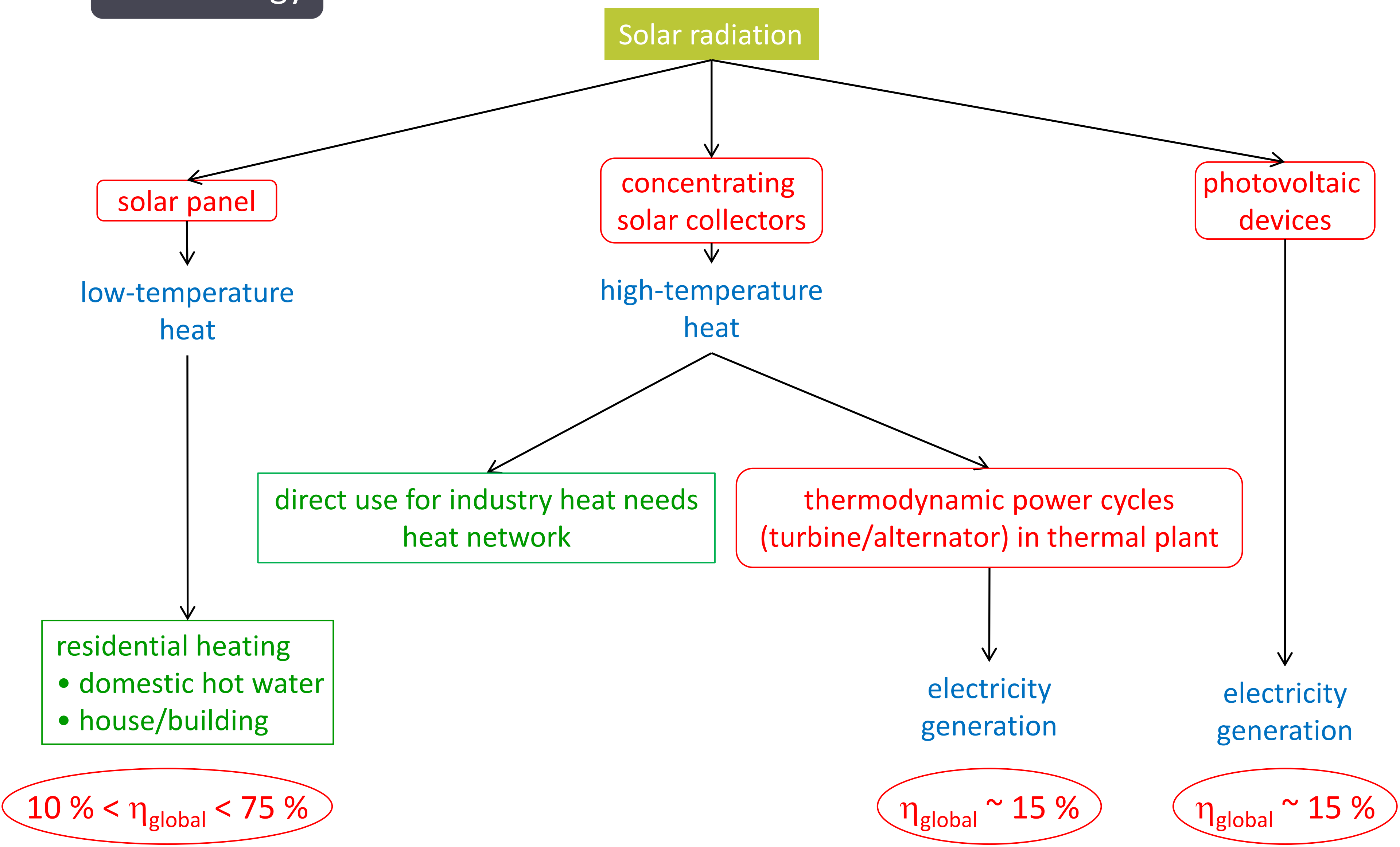
The energy source considered must have a potential ~ 1 Gtoe/year

Survey of energy sources

Focus on renewable energy sources

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

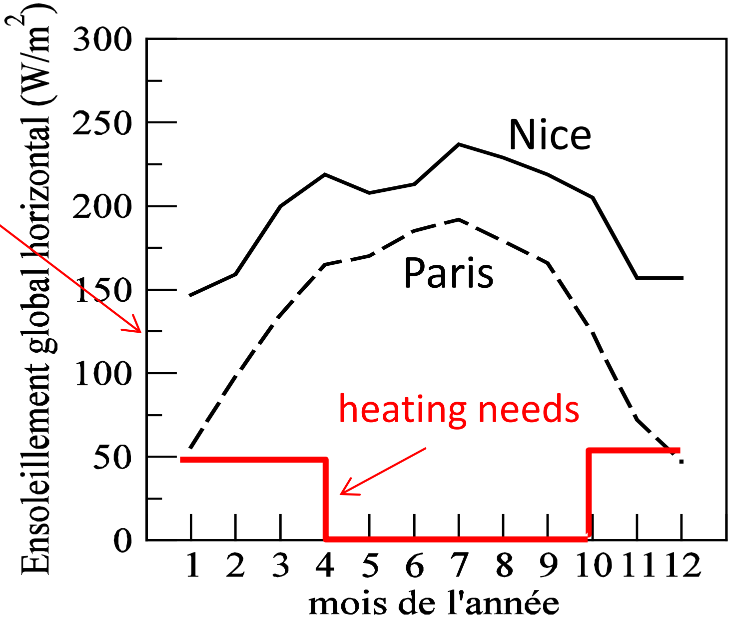
Solar energy



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%) ➡ 0,6 kWh/day/m^2

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

- In Germany, installed capacity ~ 43 GW$_{elec}$
  - ➡ average electric power 4,3 GW$_{elec}$ (~38 TWh$_{elec}$/year)
- residential electricity needs (without heating): ~ 3 kWh$_{elec}$/cap./day
  - ➡ panel area ~ 5 m^2/capita
- efficient way to provide electricity when grids are missing

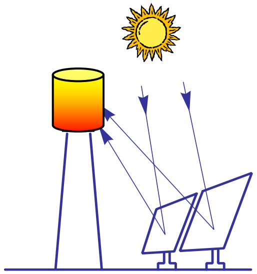
Concentrating Solar Power

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

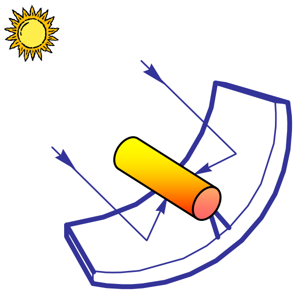
Solar Power Tower



- ✓ 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

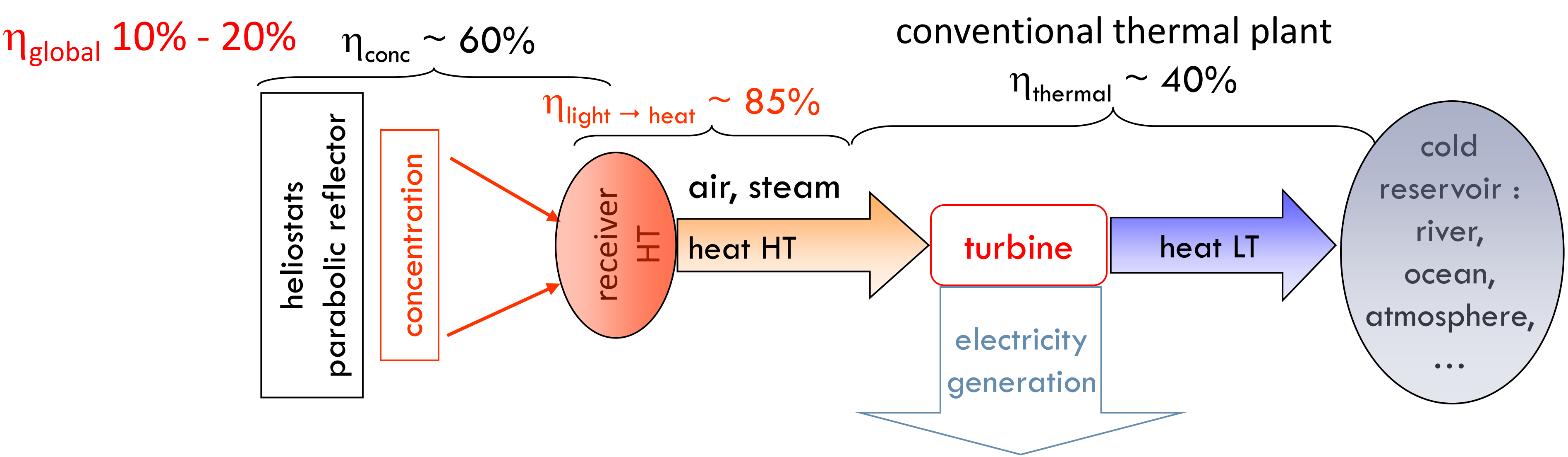
Concentrating Solar Power

Paraboloic trough



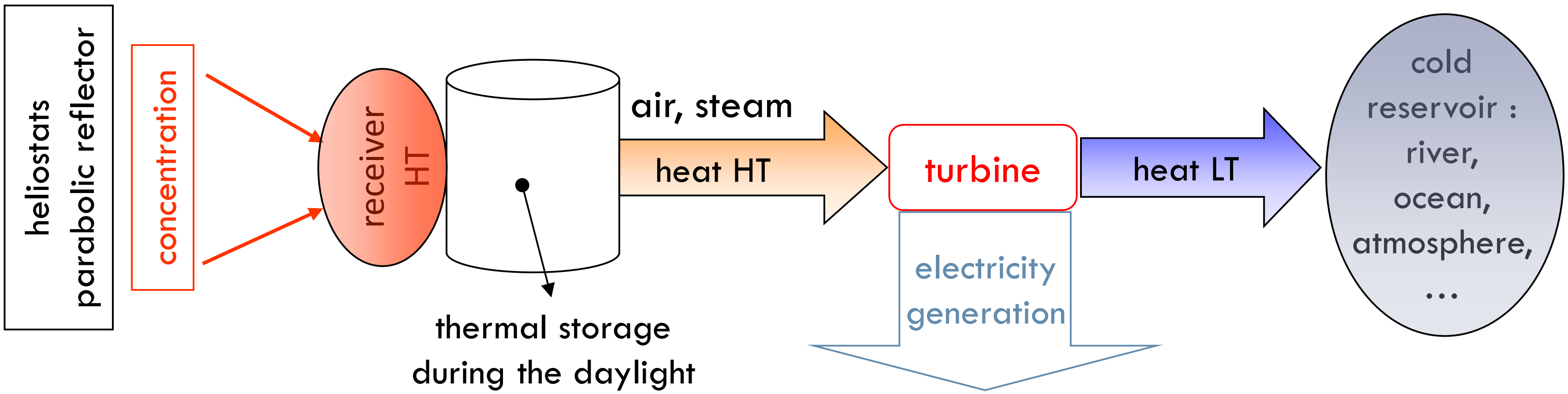
- ✓ linear parabolic reflector concentrates sunlight onto a receiver positioned along the focal line
- ✓ reflector follows the sun during the daylight hours by tracking
- ✓ the receiver is a tube located along the focal line in which a fluid flows
- ✓ fluid is heated to 250°C – 400°C
- ✓ fluid used: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

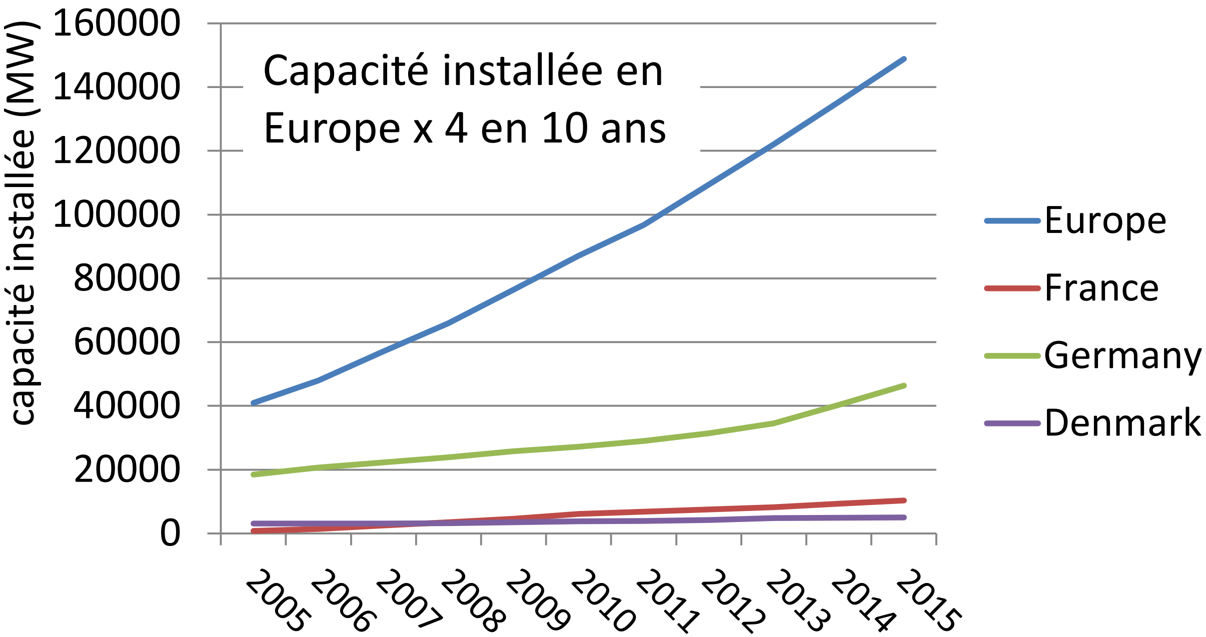


- CSP mainly set up in Spain and California

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 %

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 150 GW_{elec} of capacity installed (420 GW_{elec} in the world)
  - In Germany ~ 56 GW_{elec} ➡ average electric power 12 GW_{elec} (~103 TWh_{elec}/year)
- development offshore for a centralized electricity generation



☺ mature technology

☹ intermittent and random generation which limit the part of wind power (and PV also) in the electricity generation

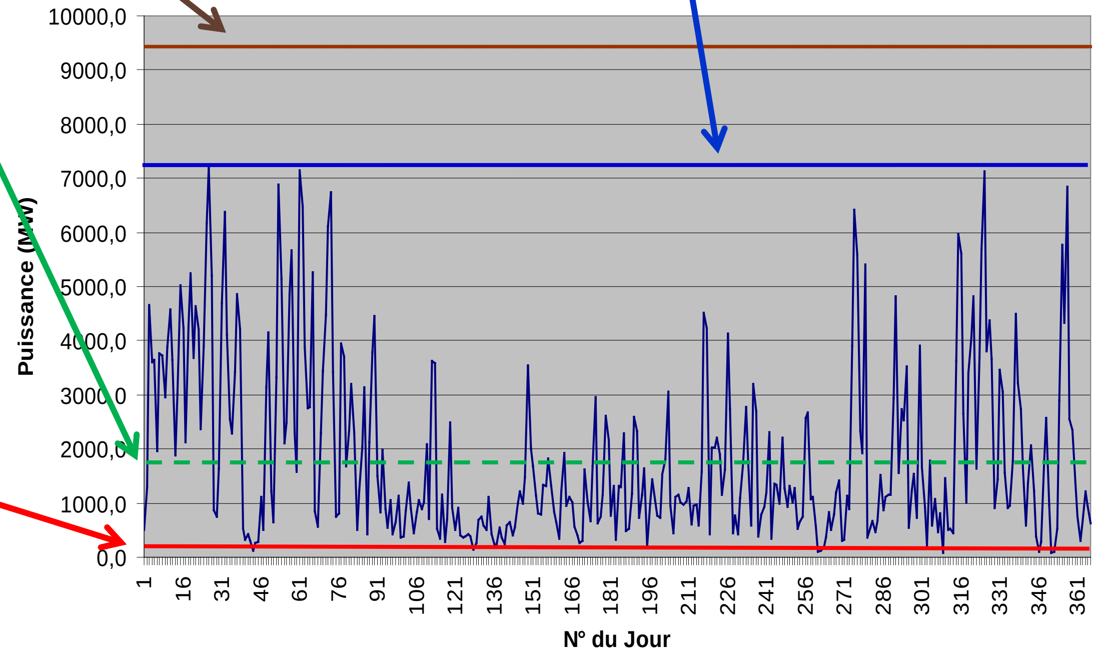
Case of a fleet of several thousands wind turbines (Germany – EON)

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 match with the electicity demand

✓Not very interesting from CO_2 emission point of wiew in developed countries having few coal- or gas-fired plants (France)

✓When electricity is produced by coal and gas (many countries in the world) wind energy is efficient to reduce CO_2 emissions

Hydropower

Conversion of potential energy (dam), $E_p = mgz$, into kinetic energy (turbine) converted in electricity (alternator) – $\eta_{global} \sim 85\%$

- present generation in the world
  - Installed capacity: 1200 GW_{elec}
  - Effective power: 450 GW_{elec} (~ 4000 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, possible important environmental and human impacts

Ex : 3 gorges dam in China
installed capacity: 18 GW_{elec}, effective power: 8 GW_{elec} (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

☹ 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 ~ 80 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

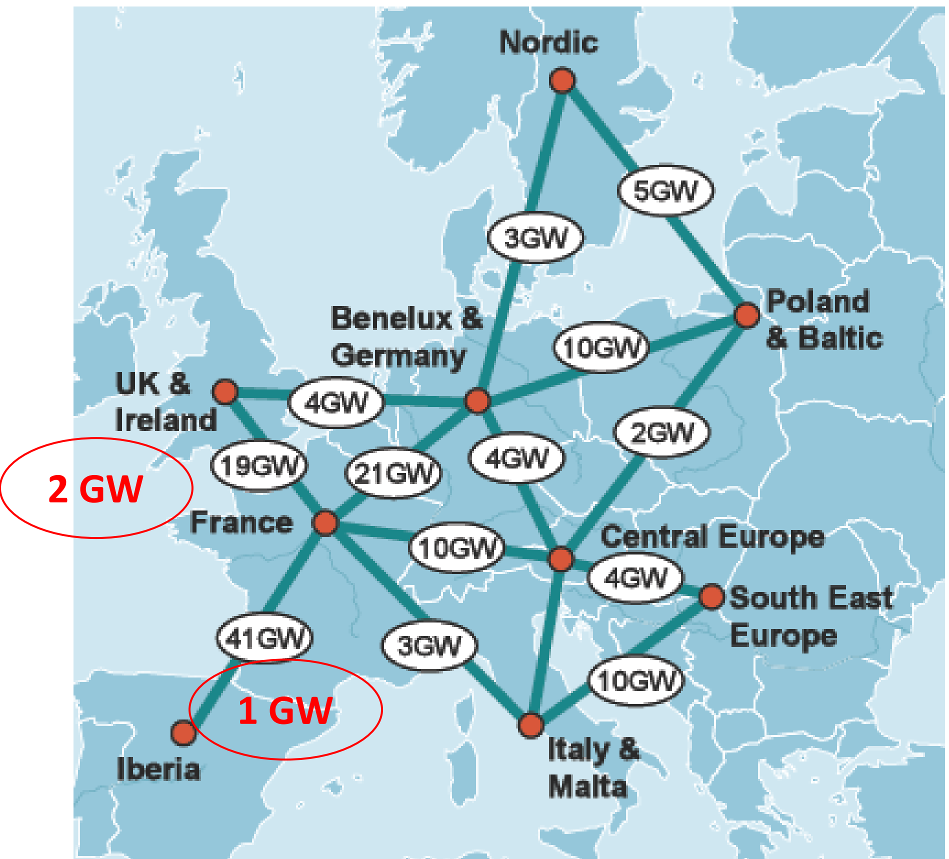
- How to manage intermittency and spread units of production of windpower and PV ?
  - improve the performance of grids and use flexible sources as back up
  - enlarge electricity storage capabilities at very large scale

- 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 !

PV/windpower electricity	H_2 production	conditionning transport	fuel cell or combustion	electricity	motor
100	50	40		20	15

⇨ 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



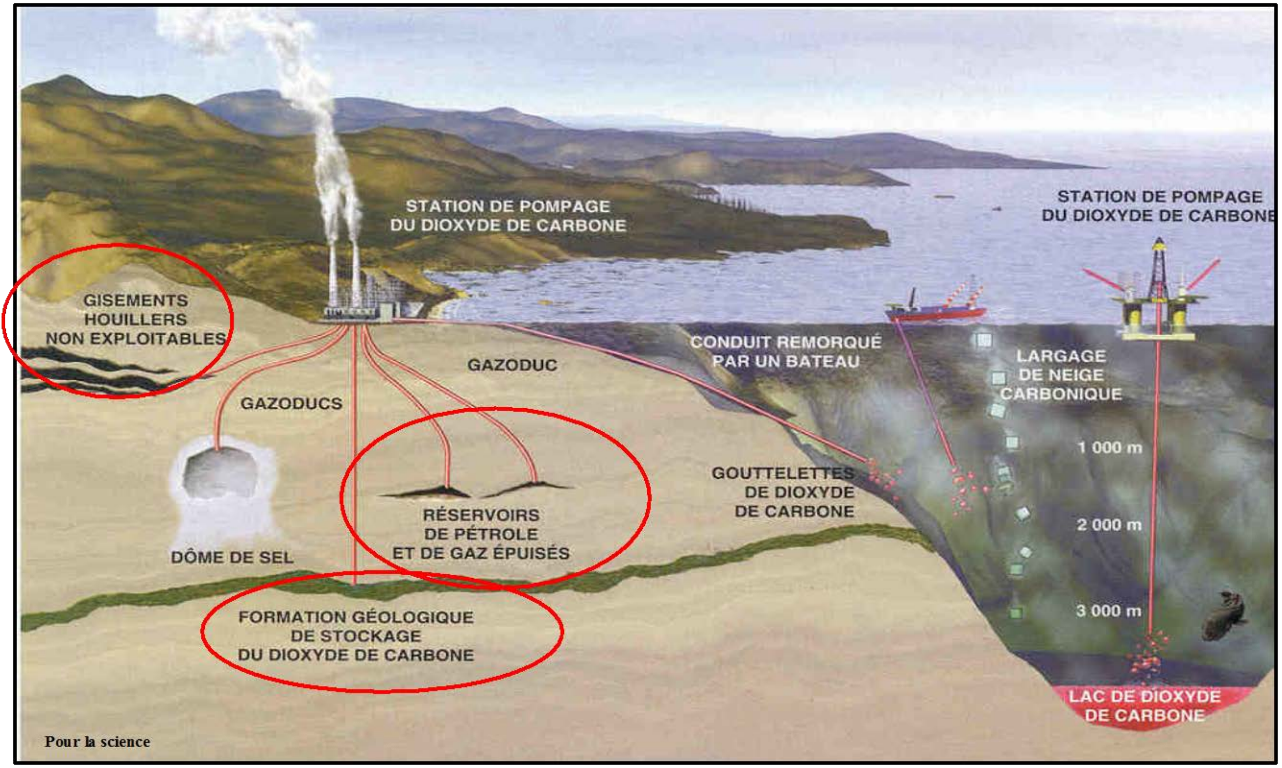
Ex: study for a 60% renewable electicity generation in Europe (http://www.roadmap2050.eu)
⇨ electrical power to transport by high voltage lines between Europe's countries

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

	hydropower	biomass		solar energy			geothermal	wind	total
		biofuels	wood	water heat	PV	CSP			
2014 (Gtoe/y)	0,9	0,1	1,2	0,04	0,04	-	0,02	0,2	~2,5
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 »)

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



<u>R & D needed</u>:
- on separation, capture and storage
- to found appropriate storage sites
- to study the long-term evolution of the CO_2 stored

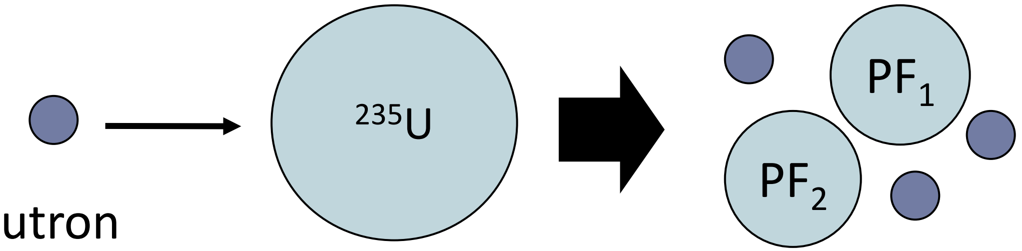
- Cost ? Storage capabilities? Acceptability?
- only used for centralized electricity generation (not possible for transport)
- Very optimistic estimate: 10 to 15 $GtCO_2$/year

  ⇨ ~ 4 Gtoe/year of fossil fuels

Nuclear energy

Heat production → Electricity

fission



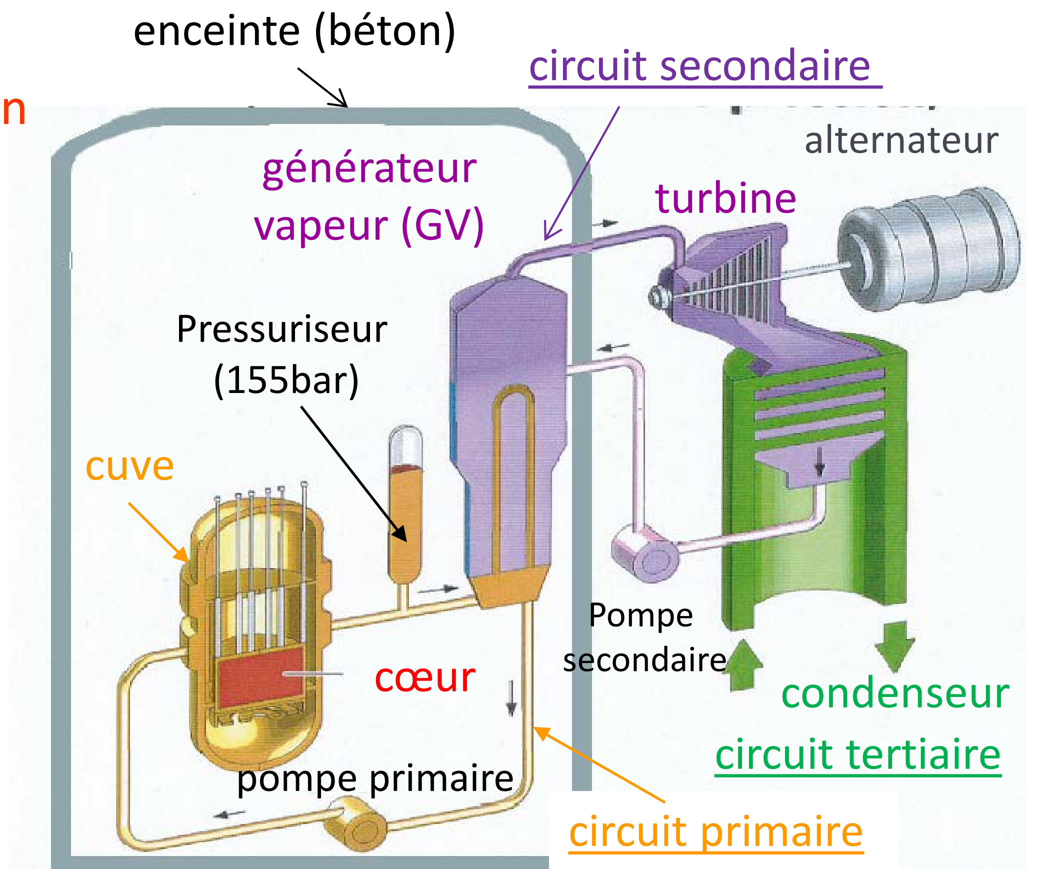
neutron
meV-MeV

E = 200 MeV/fission
→ 10^{14} J / kg

1 reactor ~ 1GWe
1 ton of fission /year

- 15% of the world electricity production

- Present reactors
  - Use of ^{235}U as fissile material (only fissile nucleus available on Earth)
  - U natural : 0,7 % ^{235}U + 99,3 % ^{238}U
  - Cooled by water
    - PWR : liquid water in the core
    - BWR : boiling water in the core
    - Candu : liquid heavy water



Nuclear energy

- In France: 58 reactors
- In the world
  - 440 reactors
  - Installed capacity: 350 GW
  - Electricity production: 2 400 TWh/year

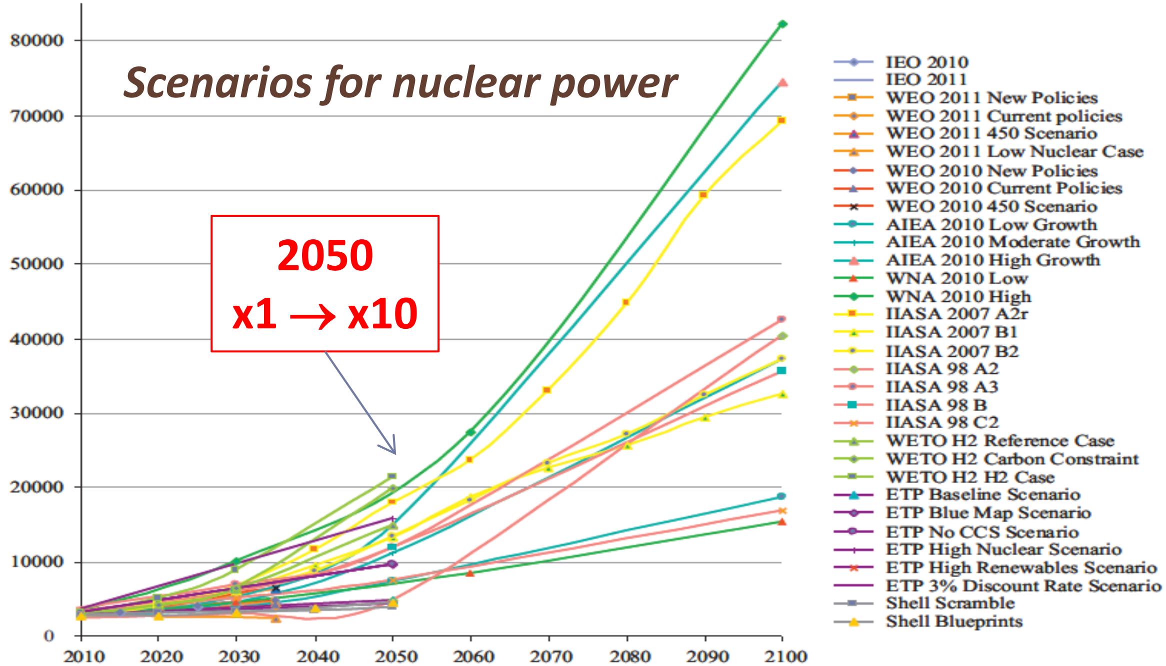
- Power of PWR in France
  - from 900 MWe (oldest) to 1450 MWe
  - Load factor ~ 80 %

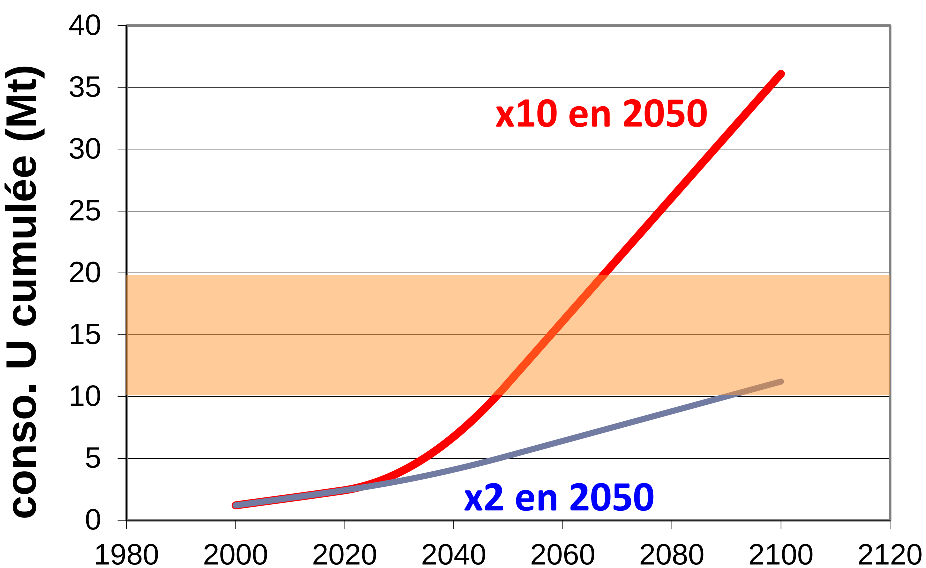
- EPR (gén. 3) power = 1650 MWe
- AP1000 power = 1000 MWe

☺ Very high energy density
☺ Fuel cost negligible in the price of electricity
⇨ Stability of the price of electricity produced
☹ Specific issues of nuclear power: safety, waste management, proliferation, social acceptance
😐 But nuclear power remains a non-emitting energy source with significant potential

Nuclear energy

- It is highly likely that nuclear power will develop in the coming century at the world scale (mainly Asia, South America)





- A significant deployment of nuclear power requires a transition towards Generation 4 reactors
- U consumption divided by 200

Simplified construction of an energetic world in 2050

- motivations
  - Many scenarios exist to predict the energy demand evolution up to 2050
    - complexe « technico-economic » models for non experts
    - many unexplained parameters and hypotheses
  - ⇨ propose a simple approach with fully explained hypotheses and few parameters
    - ✓ to make possible discussions between different disciplines (scientific, economic, philosophic, …)
    - ✓ to be opened to critics
  - 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

- initial hypotheses for 2050

  - world population ~ 9,5 billions of inhabitants

  - energy consumption fixed to E_{tot} = 20 Gtoe/year

  - inequalities of energy consumption still exist but they are considered inside emerging and poor countries

⇨ the population of these countries is distributed 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:

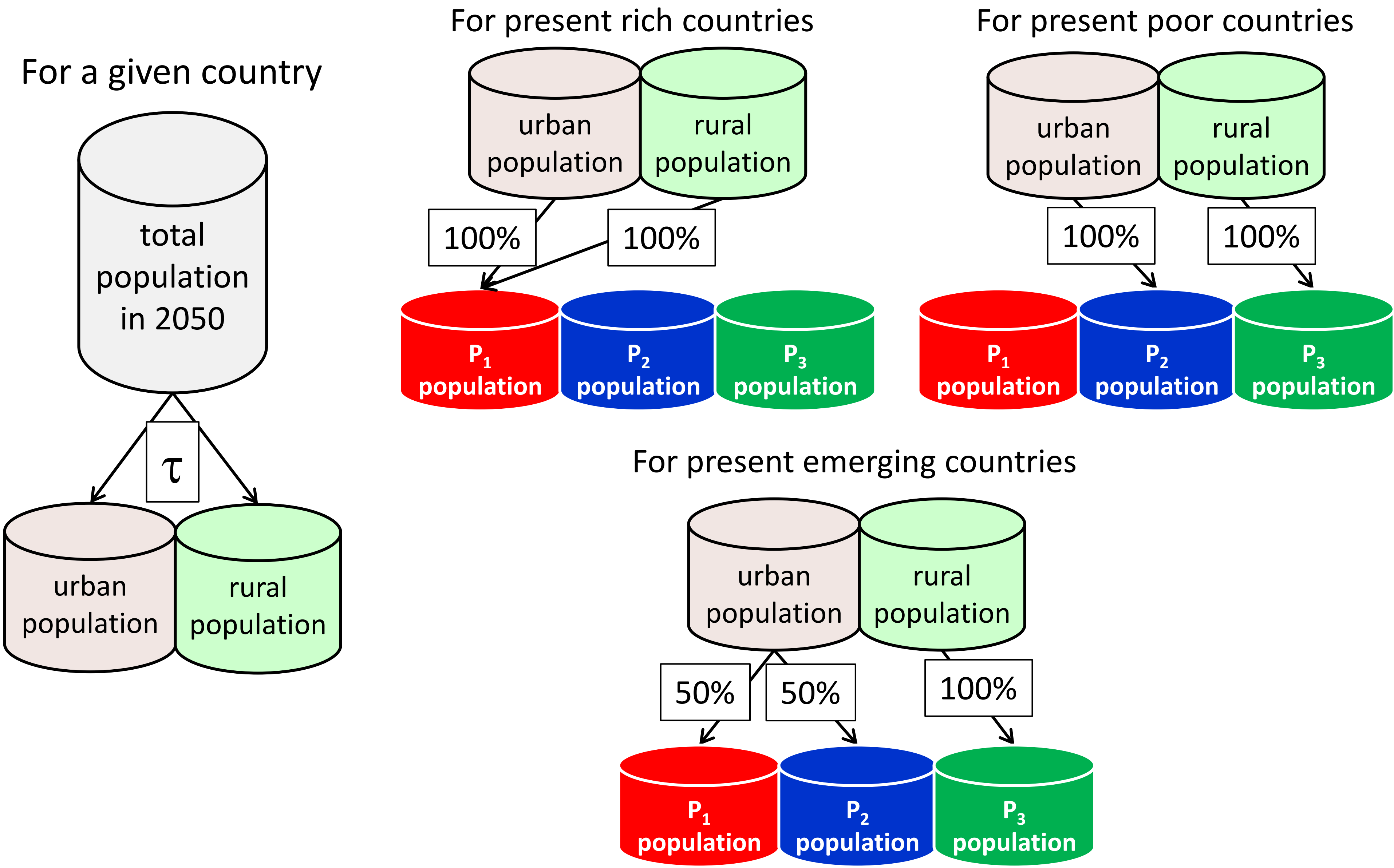
$$C_1/C_3 \text{ and } C_2/C_3$$

  - 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

- P_1, P_2 and P_3 fixed by the rate of urbanization
  - 6,5 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

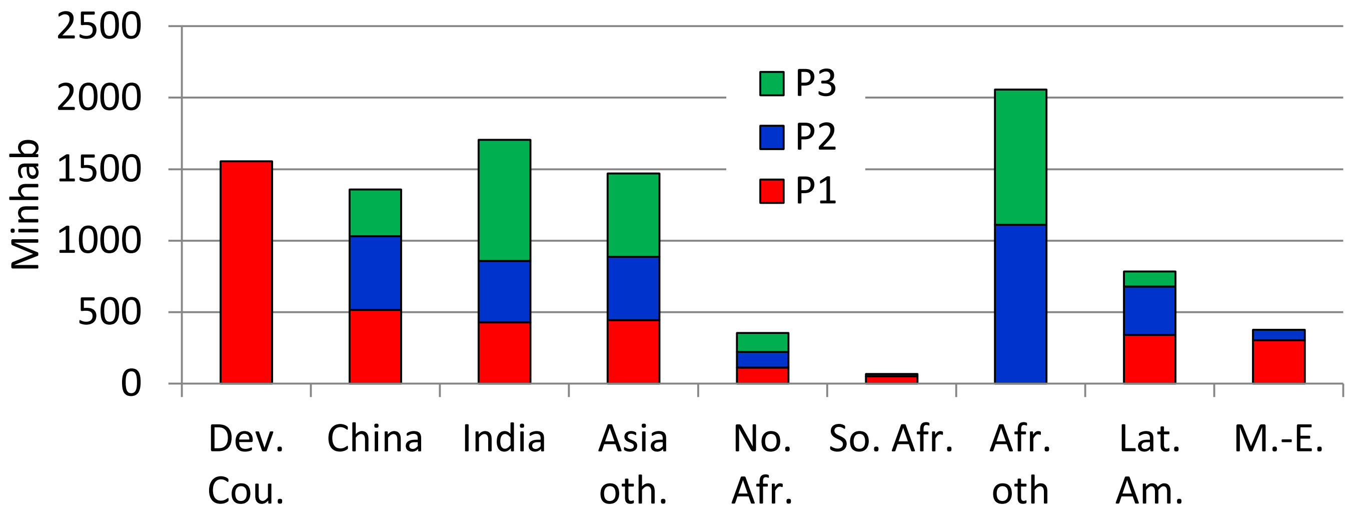


- distribution of populations P_1, P_2 et P_3 in 2050

$P_1^{world} = 3{,}75\ Ginhab$

$P_2^{world} = 3\ Ginhab$

$P_3^{world} = 2{,}95\ Ginhab$

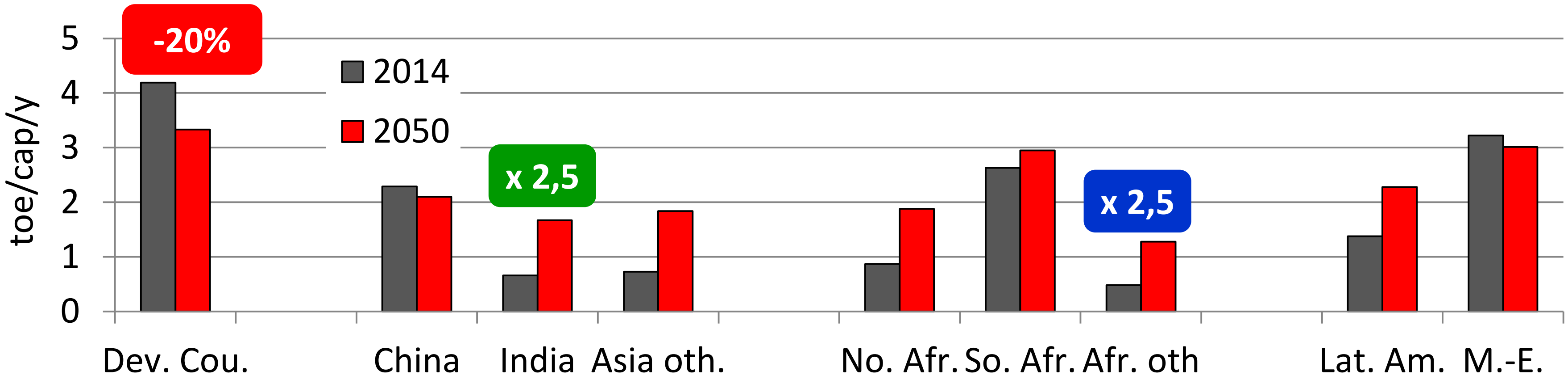


- Choice of inequality ratios
  - Reduction by a factor 4 between the energy consumption of the reachest population (C_1) and the poorest population (C_3) (today ~ 9)

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

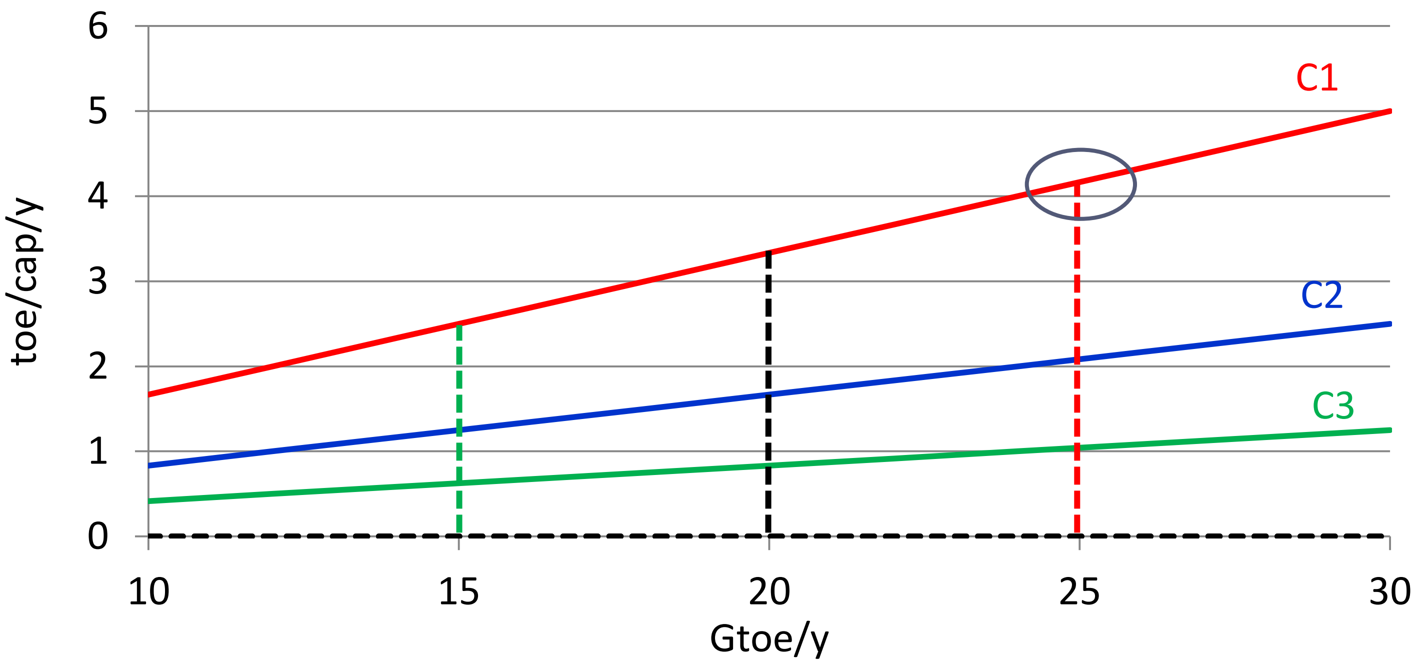
➨ C_1 = 3, 33 toe/cap/year C_2 = 1,67 toe/cap/year C_3 = 0,83 toe/cap/year

Energy demand in 2050



- present rich countries have to reduce their energy consumption from 4,2 toe/cap/year to 3,3 toe/cap/year
  ⇨ strong constraint as the tendency is rather a continuous increase of the level of consumption of rich countries
- For the reachest emerging countries (China & Middle-East), consumption is rather constant
- 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

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

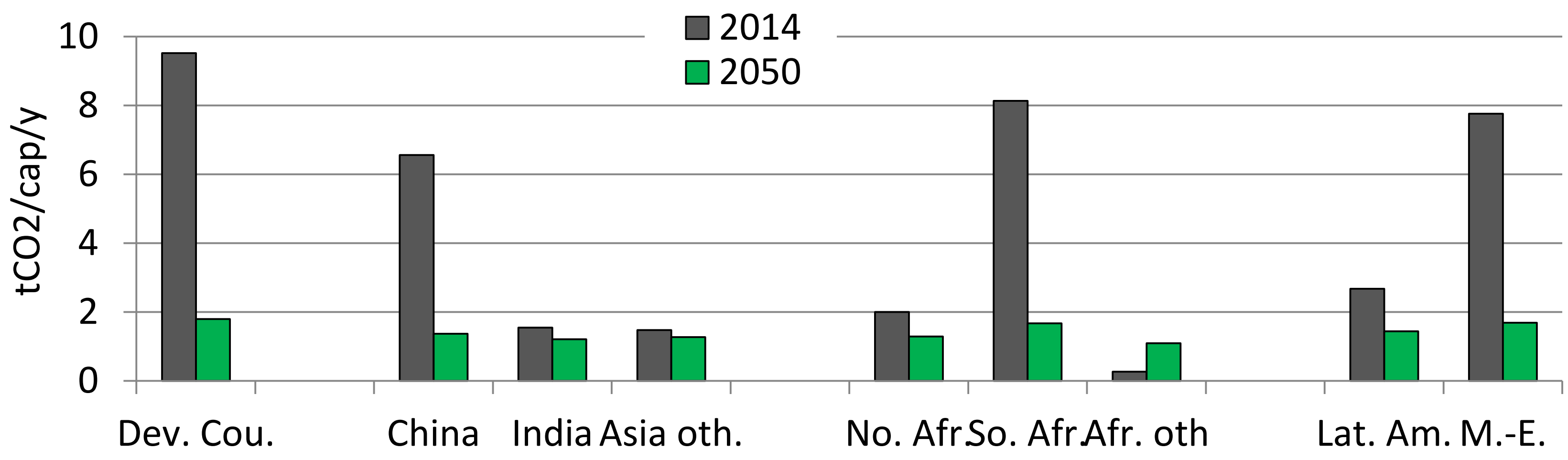
Drastic reduction of inequalities …

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 = 0,4 toe/cap/year F_3 = 0,3 toe/cap/year

Energy consumption with CO_2 emissions in 2050



- In rich countries, CO_2 emissions have to be reduced by a factor 5

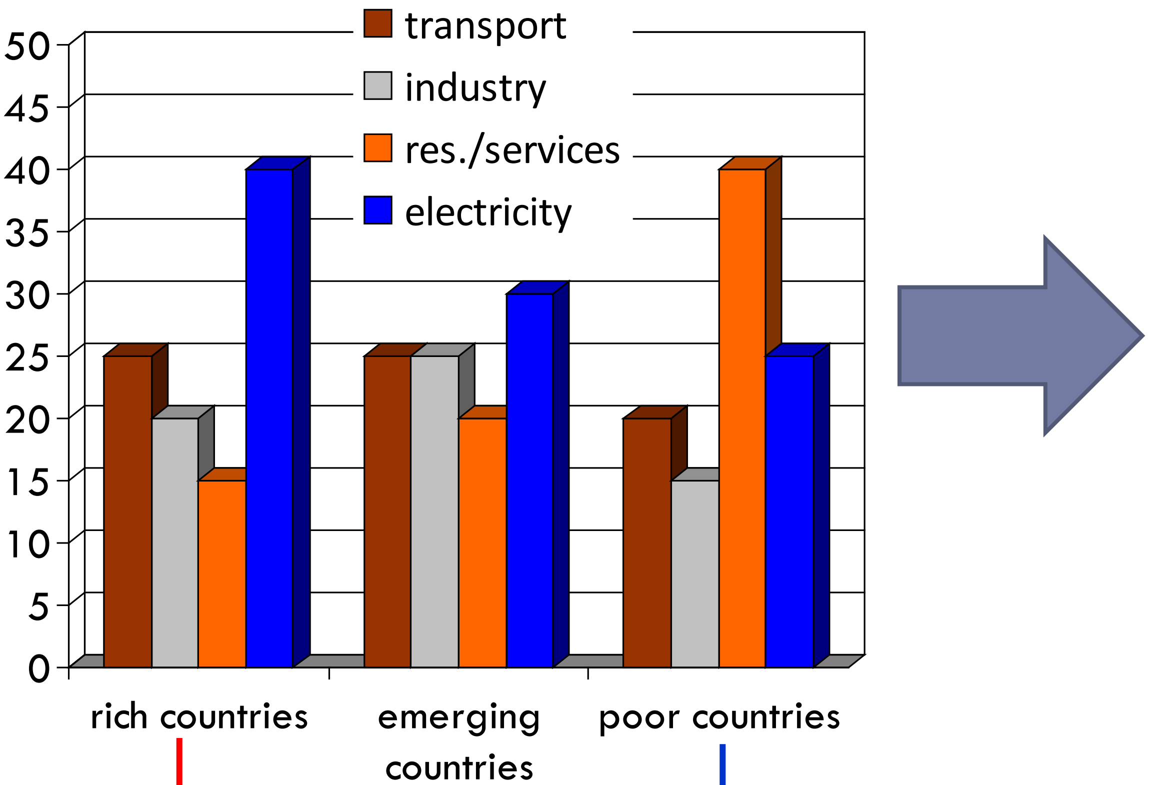
⇨ CO_2-non emitting sources represent 80% of the total energy consumption while it is 20% today

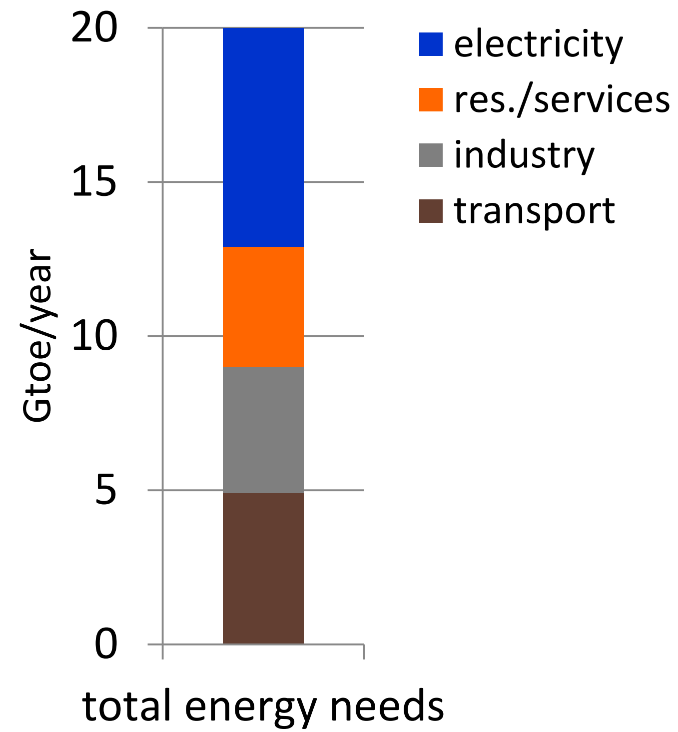
- China has already overshot « allowed » CO_2 emissions
- the increase of energy consumption in present emerging countries is based on CO_2-non emitting sources
- In poorest countries, CO_2 emissions increase only by a factor 3

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

- construction of the energy mix in 2050

Fraction of the total energy consumption in %



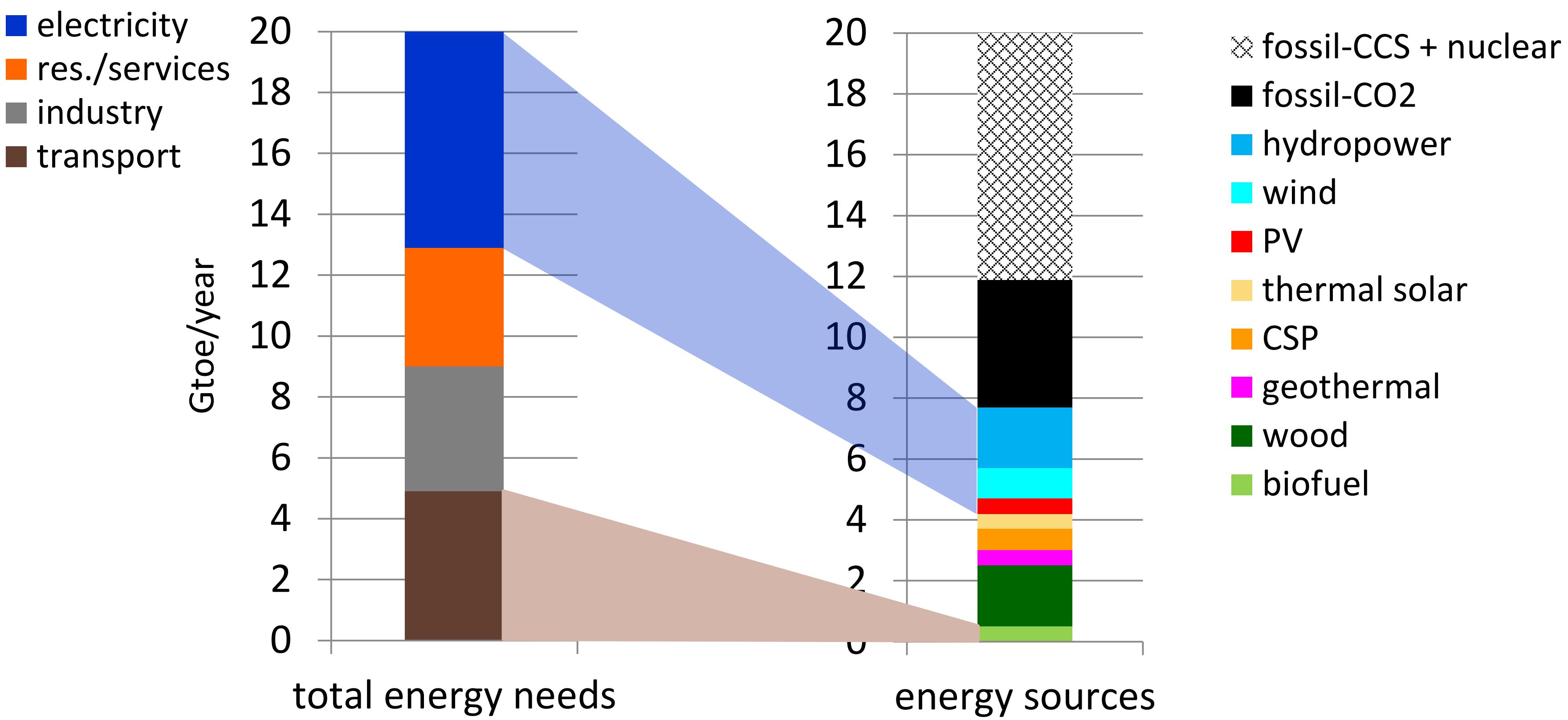


profil consumption of population P_1

profil consumption of population P_3

profil consumption of population P_2

- Matching between energy needs and energy sources

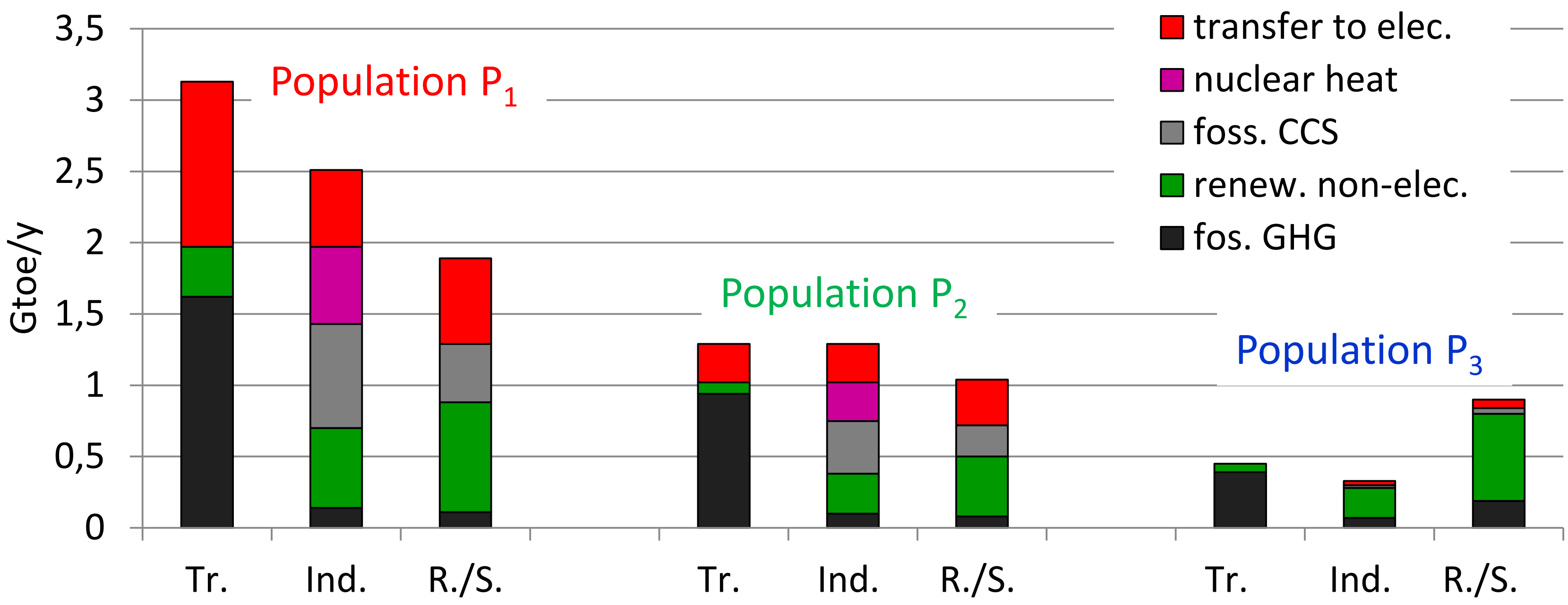


- method to construct energy mix in 2050
  - use of fossil fuels with CO_2 emissions fixed by climate constraint ~ 4,2 Gtoe/year
    - use first for transport
  - renewable energy sources able to provide heat for industry and residential/services sectors: wood, CSP, solar water heat, geothermal
  - fossil fuels with CCS fixed at 3,7 Gtoe/year (12 $GtCO_2$ stored/year)
  - renewable energy sources dedicated to electricity generation
  - nuclear energy is used as adjusting variable to fill the needs

- Construction of the mix for each type of population P_1, P_2 and P_3
  - energy sources are globally distributed in proportion of the needs
  - with some exceptions:
    - wood still remains the main energy source for rural populations (P_3)
    - nuclear energy exclusively used for urban population (P_1 and P_2)

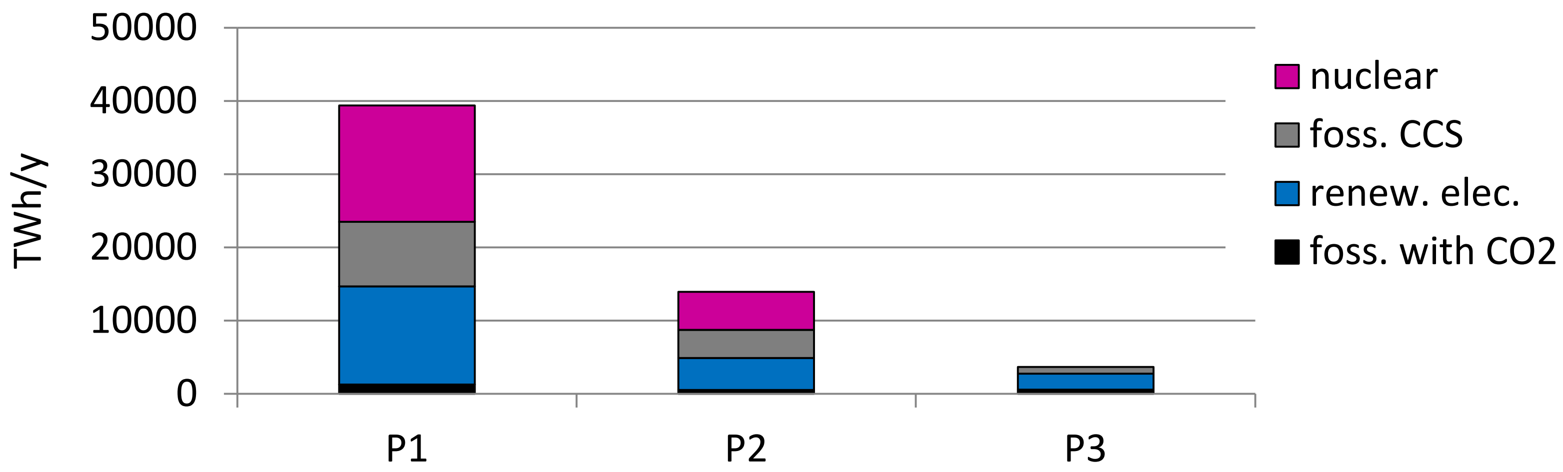
- Some results
  - 50% of transport and heat needs are missing (~ 6 Gtoe/year) and have to be transfered to electricity

    ⇨ use of cogeneration, use of nuclear energy for heat only

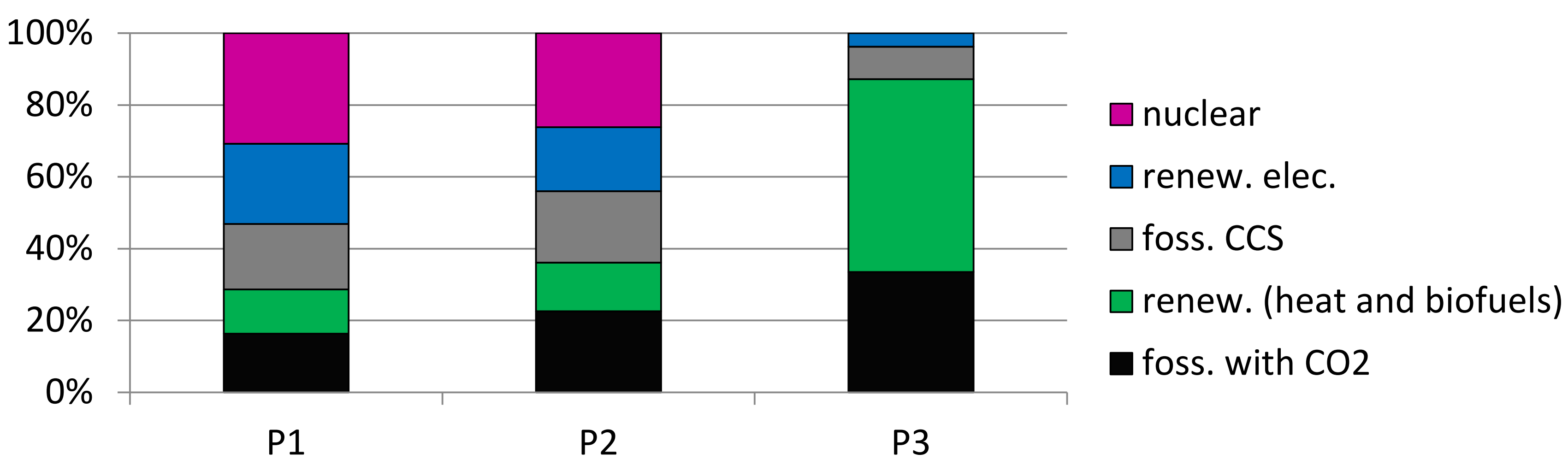


Some results

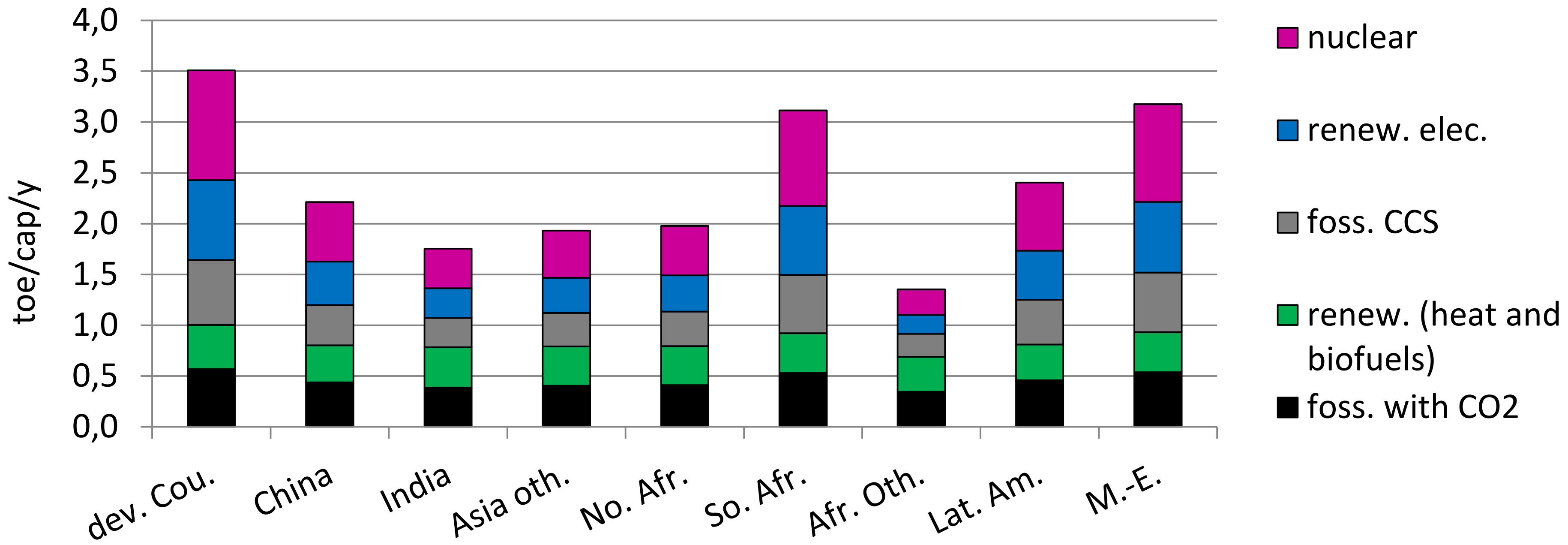
Electricity mix



Energy mix



energy mix of different geographical regions

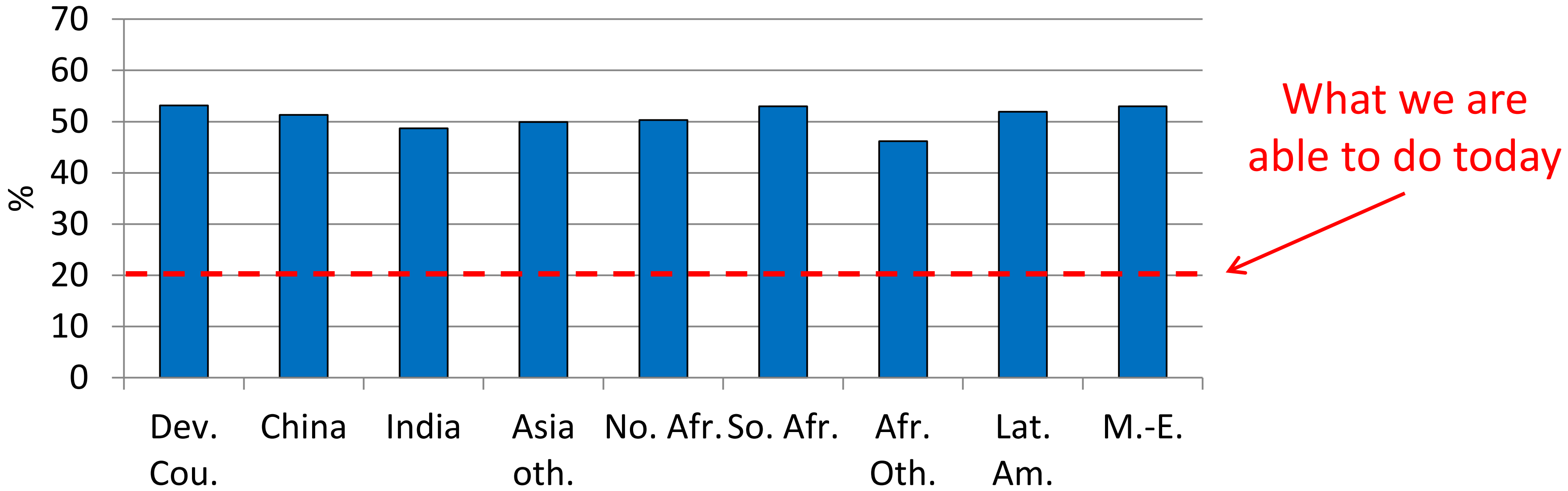


- the use of fossil fuels are leveled around 0,5 toe/cap/year except in poorest regions

⇨ CO_2 emissions ~ 1,6 tCO_2/cap/year

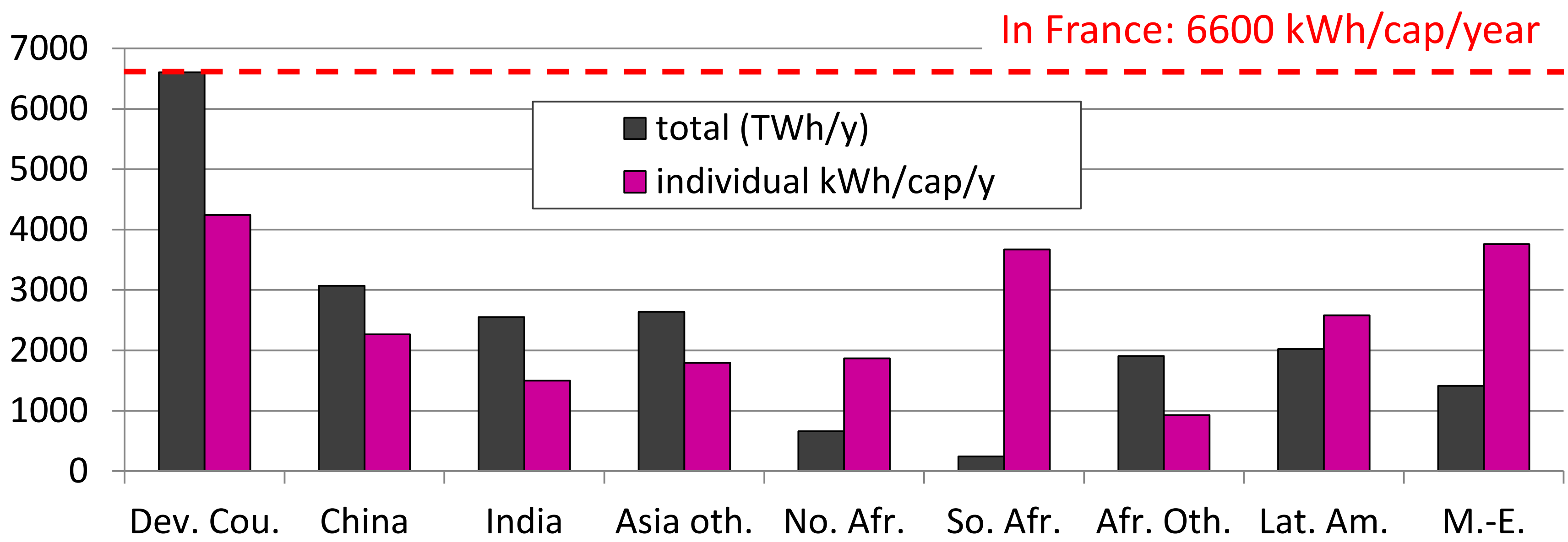
- CCS technology is developed in all regions
- homogenous distribution of renewable energy sources for heat and transport needs
- part of CCS technology, renewable energy sources for electricity generation and nuclear energy increase with the fraction of population P_1

- 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 ~ 8 300 TWh/year
- 1 nuclear reactor = 7,45 TWh/year → ~ 2800 reactors in the world (x 6 / today)
- mainly urban populations concerned ~ 6,5 Ginhab → 1 reactor / 2 Minhab
- French case : 60 nuclear reactors built in 20 years for 60 Minhab

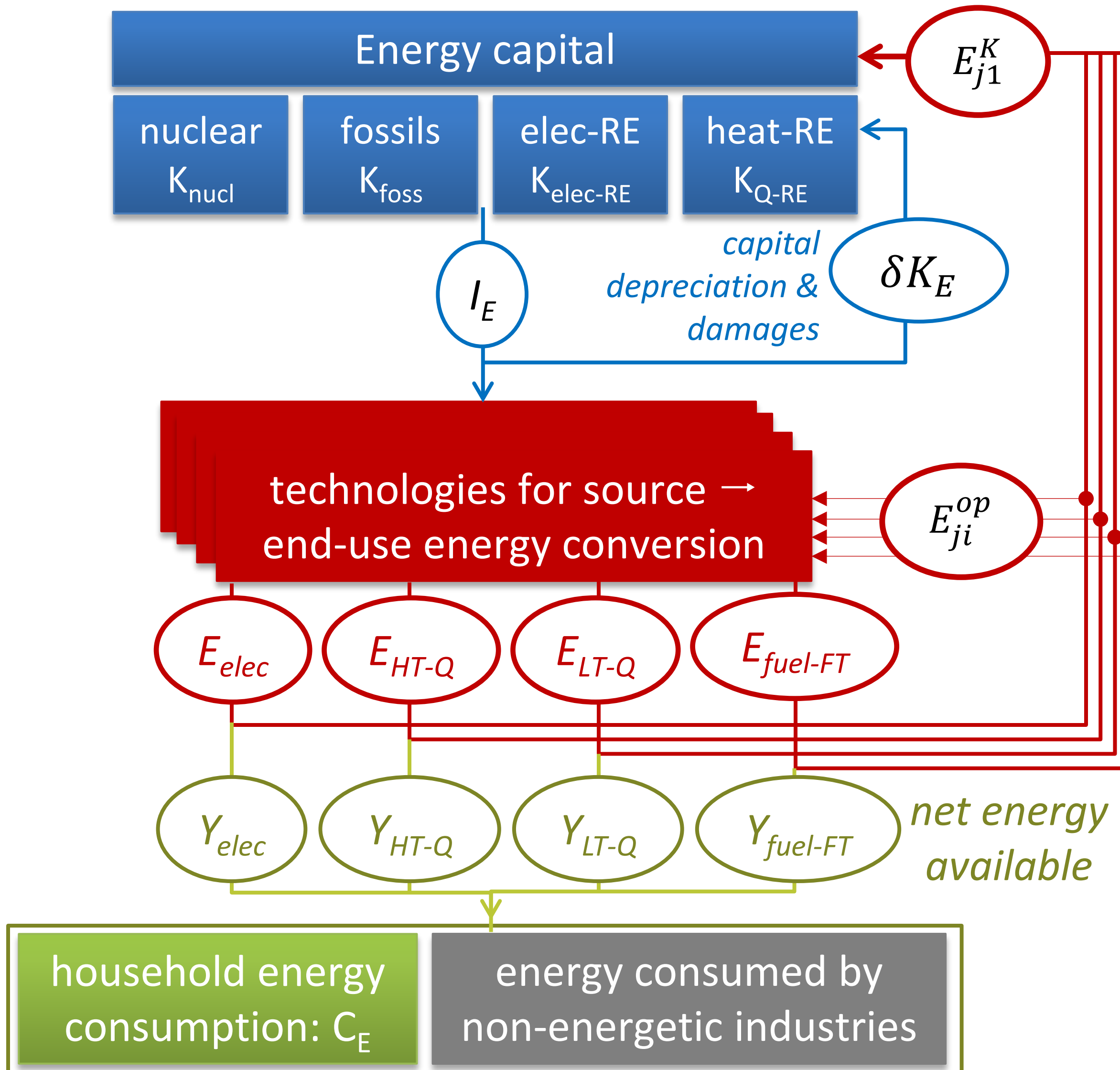
An attempt of interdisciplinary approach to assess energy transition scenarios

Analyse Physique et Economique des Scenario Energétique

- Modélisation du secteur énergétique inspirée d'une approche économique

Economy	Energy
n sectors of commodities production	technologies called by scenarios to operate the energy transition fossil fuels → electricity biomass → fuel for transport solar → low-temperature heat
Capital K	energy facilities (K_E) running at full capacity to produce the gross total final energy (E) $E = \frac{K_E}{\nu_E}$ with $\frac{1}{\nu_E}$: energy produced / capital unit
Investment I	energy required (I_E) to construct new energy facilities $\left(\dot{K}_E\right)$ to increase the gross energy production and/or to replace the old ones (δK_E) $I_E = \dot{K}_E + \delta K_E$
Net prod. Y	net energy (Y_E) produced by the capital K_E once the energy consumed for the energy production itself deducted

- Energy sector modeling inspired by the economic model



- Energy transition scenario
- Energy sector modeling inspired by the economic model

Energy facilities evolution

- ✓ decline: $K_i \searrow$
- ✓ renewal: K_i = Cte
- ✓ deployment: $K_i \nearrow$

input parameter

Energy investment fixed by the scenario for each type of source i (= nucl, foss, elec-RE, Q-RE)

Energy carriers produced/source

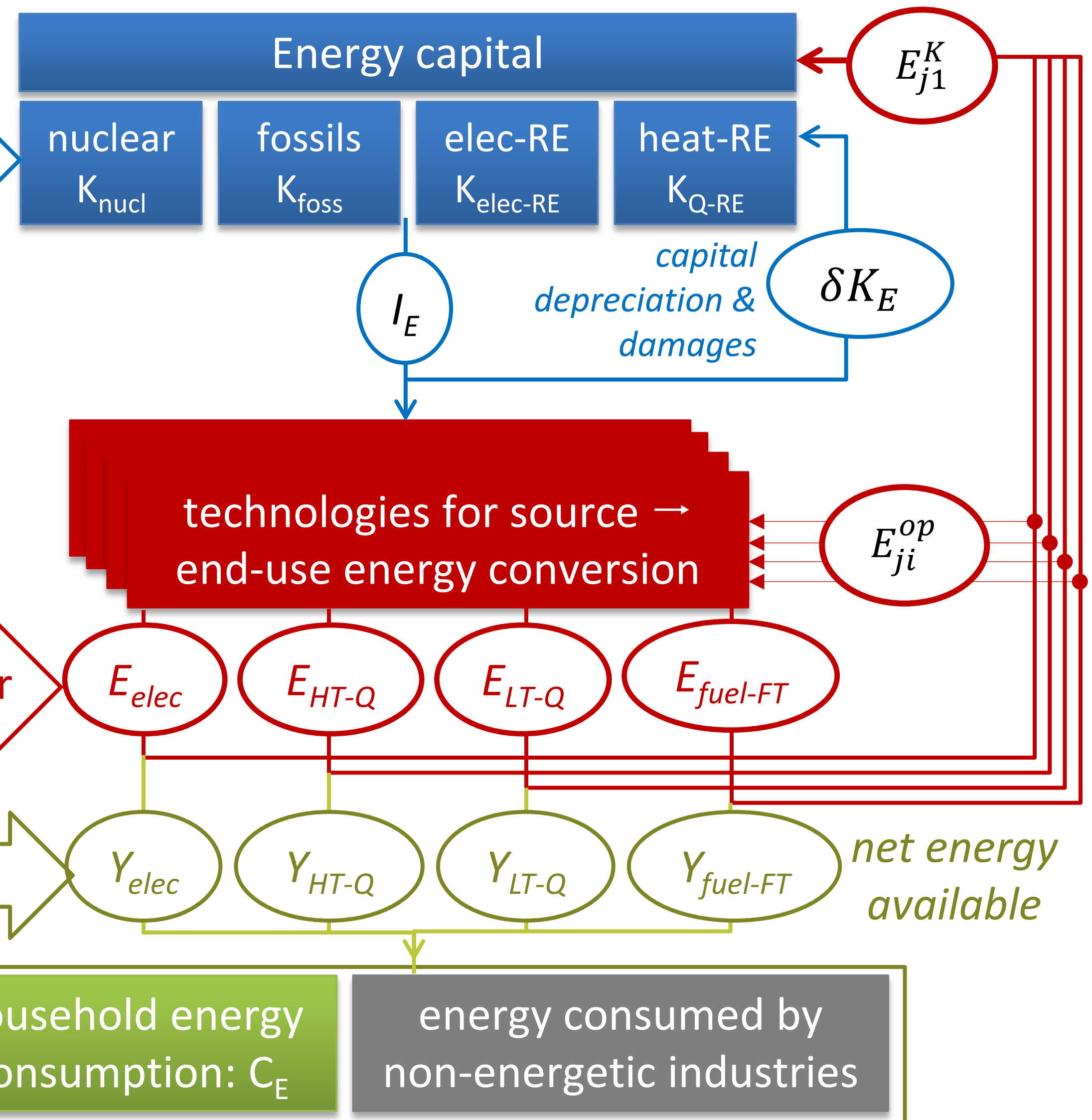
Quantity of energy carriers j produced by each type of source i fixed by the scenario

$$E_j = \sum_i \eta_{ji} E_i$$

input parameter

Energy consumption by household and non-energetic industries

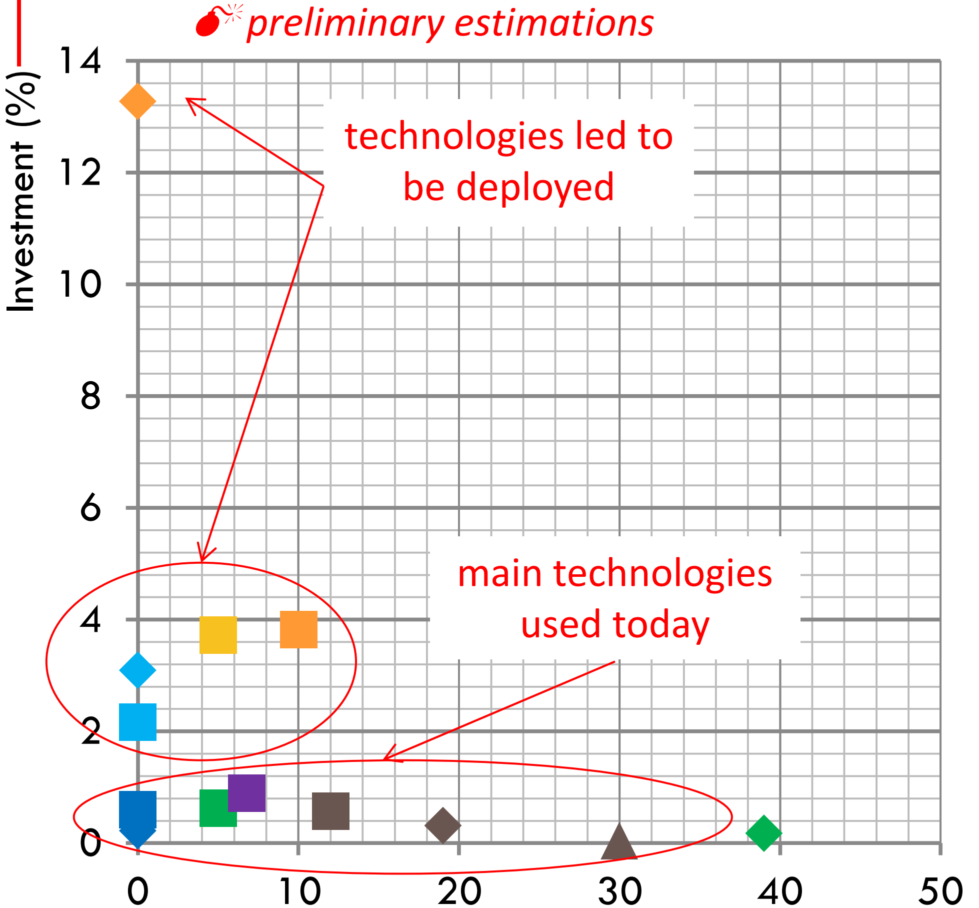
= ?



$$\text{Investment (\%)} = \frac{\text{energy investment/capital unit}}{\text{total energy produced/capital unit}} = \frac{E^{K_i}_{consumed}}{E^{tech_i}_{produced} \times life\ time} = \frac{1}{\text{EROI}}$$

Electricity production

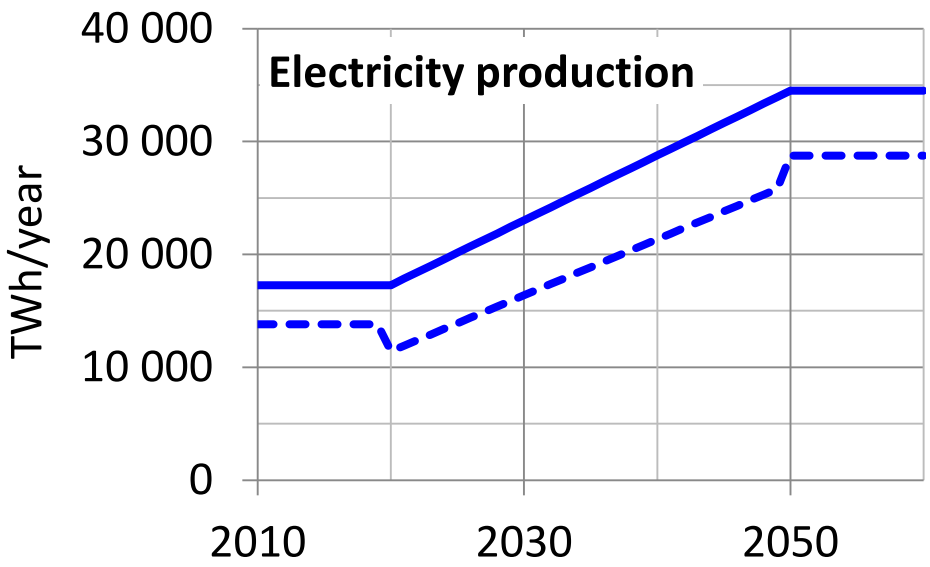
preliminary estimations

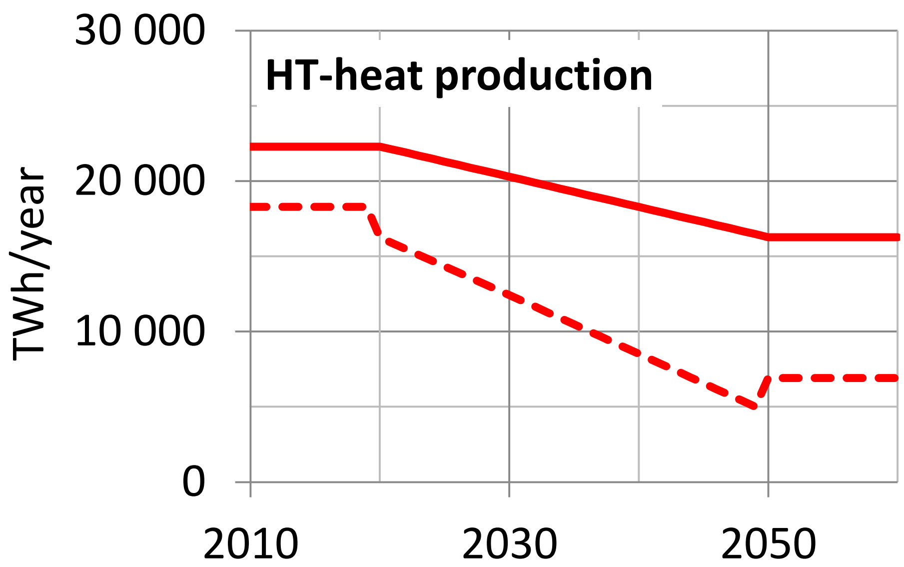


$$\text{Operation (\%)} = \frac{\text{energy consumed for energy production}}{\text{energy produced}} = \frac{E^{Op_i}_{consumed}}{E^{tech_i}_{produced}}$$

	Life time (year)	Load factor (%)
coal	20	85
oil	20	85
gas	20	85
wood	20	85
bio-waste	20	85
hydro dam	80	30
hydro river	80	85
nuclear	40	85
wind onshore	20	20
wind offshore	20	20
geothermal	20	85
conc. sol.	20	40
PV	20	20

- Results for ECOFYS-scenario: gross & net total production / energy carrier

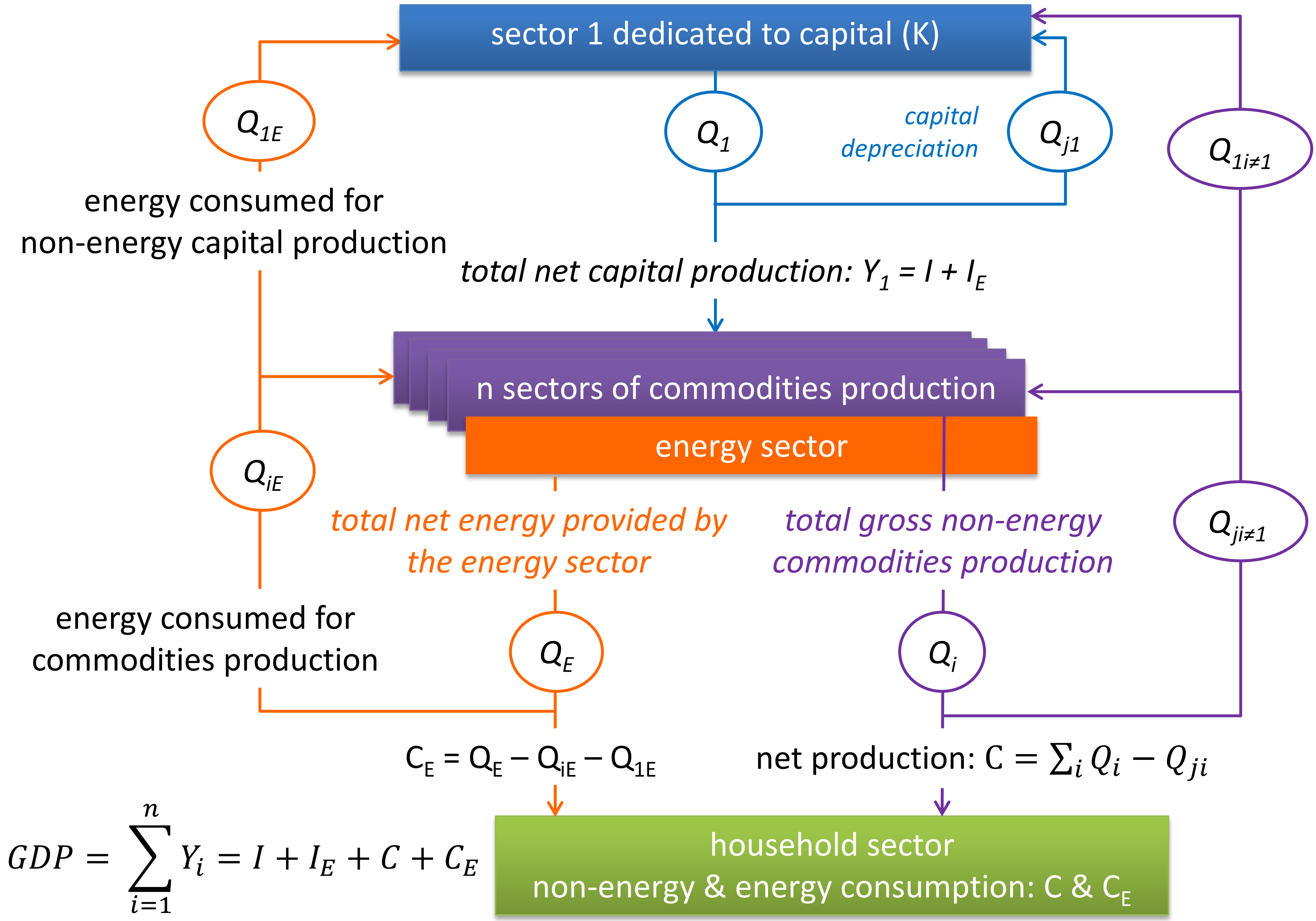




✓ Electricity and HT – heat are the most important energy carriers consumed during the transition (initial hypothesis/energy investment)

➡ gross and net electricity follow the same trend

➡ HT – heat is strongly consumed during the transition and after the transition the net production remains very low


sector 1 dedicated to capital (K)
Q_{1E}
Q_1
capital depreciation
Q_{j1}
$Q_{1i\neq 1}$
energy consumed for non-energy capital production
total net capital production: $Y_1 = I + I_E$
n sectors of commodities production
energy sector
Q_{iE}
total net energy provided by the energy sector
total gross non-energy commodities production
$Q_{ji\neq 1}$
energy consumed for commodities production
Q_E
Q_i
$C_E = Q_E - Q_{iE} - Q_{1E}$
net production: $C = \sum_i Q_i - Q_{ji}$
$GDP = \sum_{i=1}^{n} Y_i = I + I_E + C + C_E$
household sector
non-energy & energy consumption: C & C_E