Some thoughts about

Energy transition

INSTITUT NATIONAL DES SCIENCES APPLIQUÉES TOULOUSE

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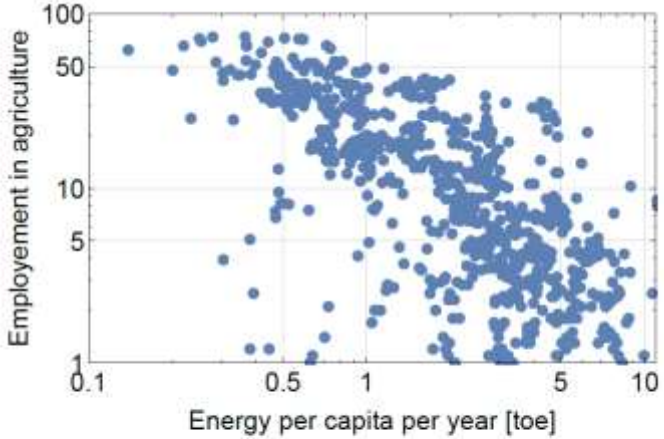
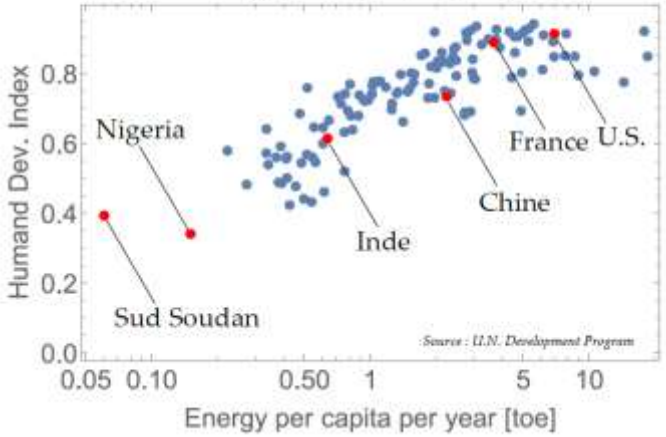
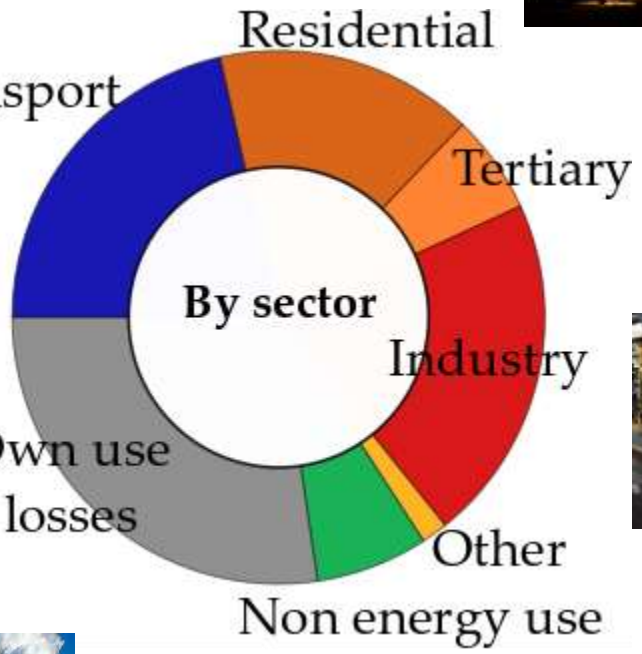
Why energy? A powerful indicator

Energy consumption and society



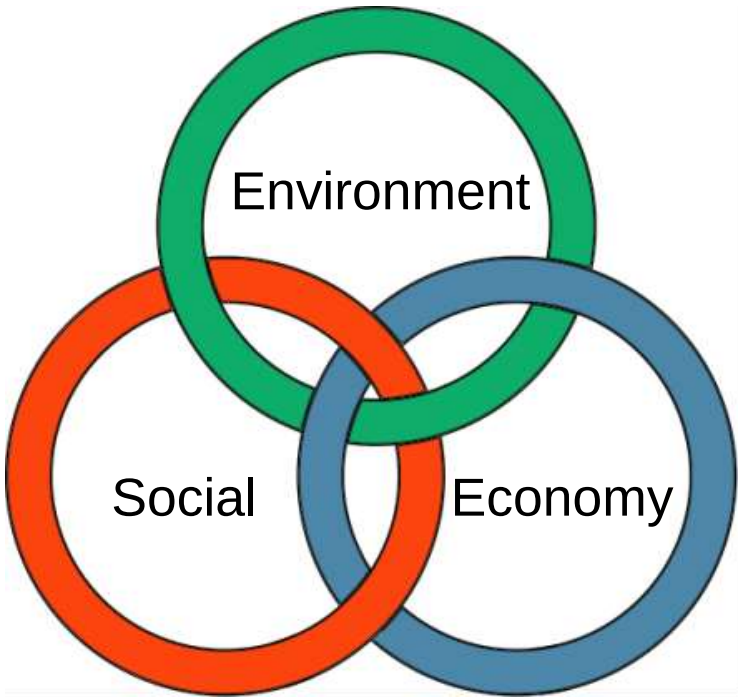


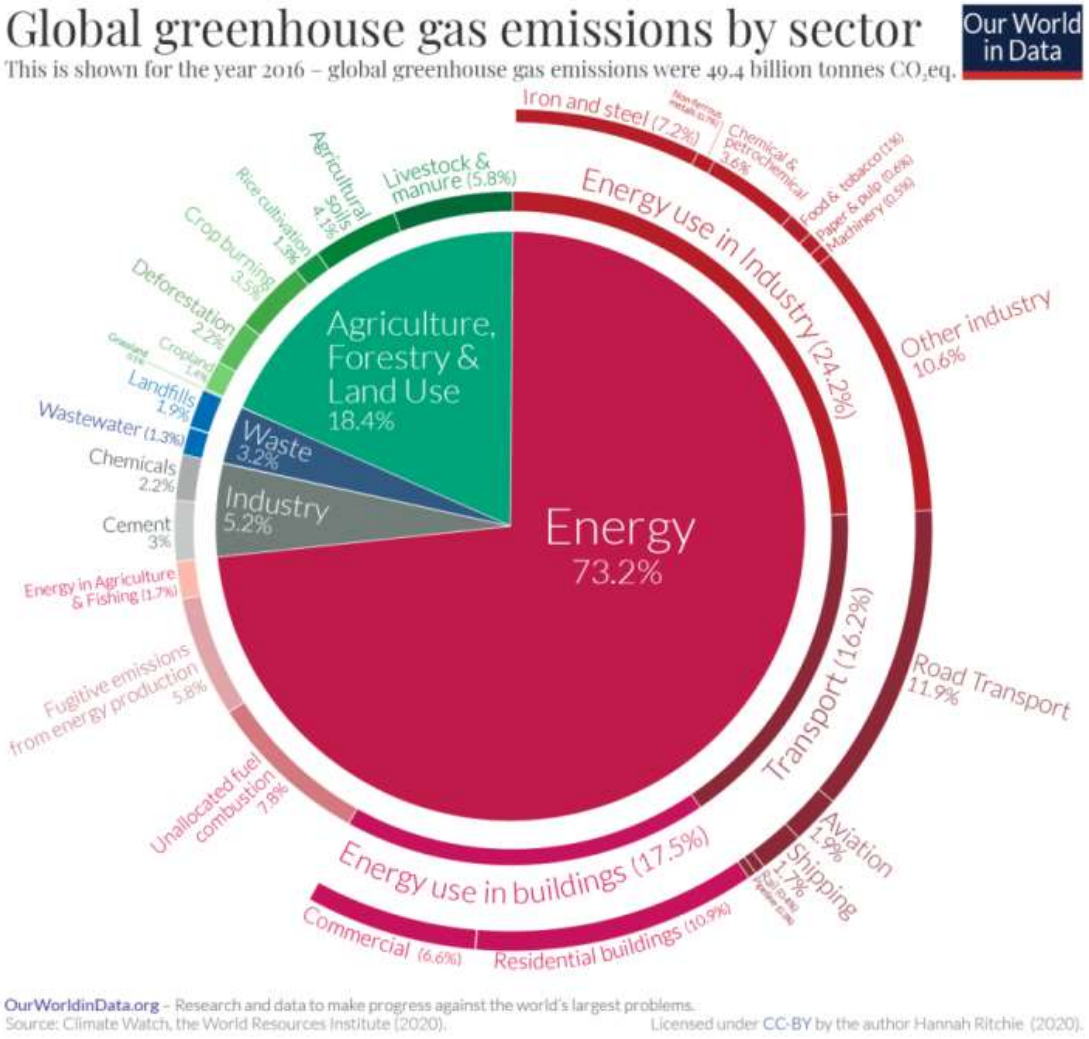


World Total Final Consumption, IEA 2020

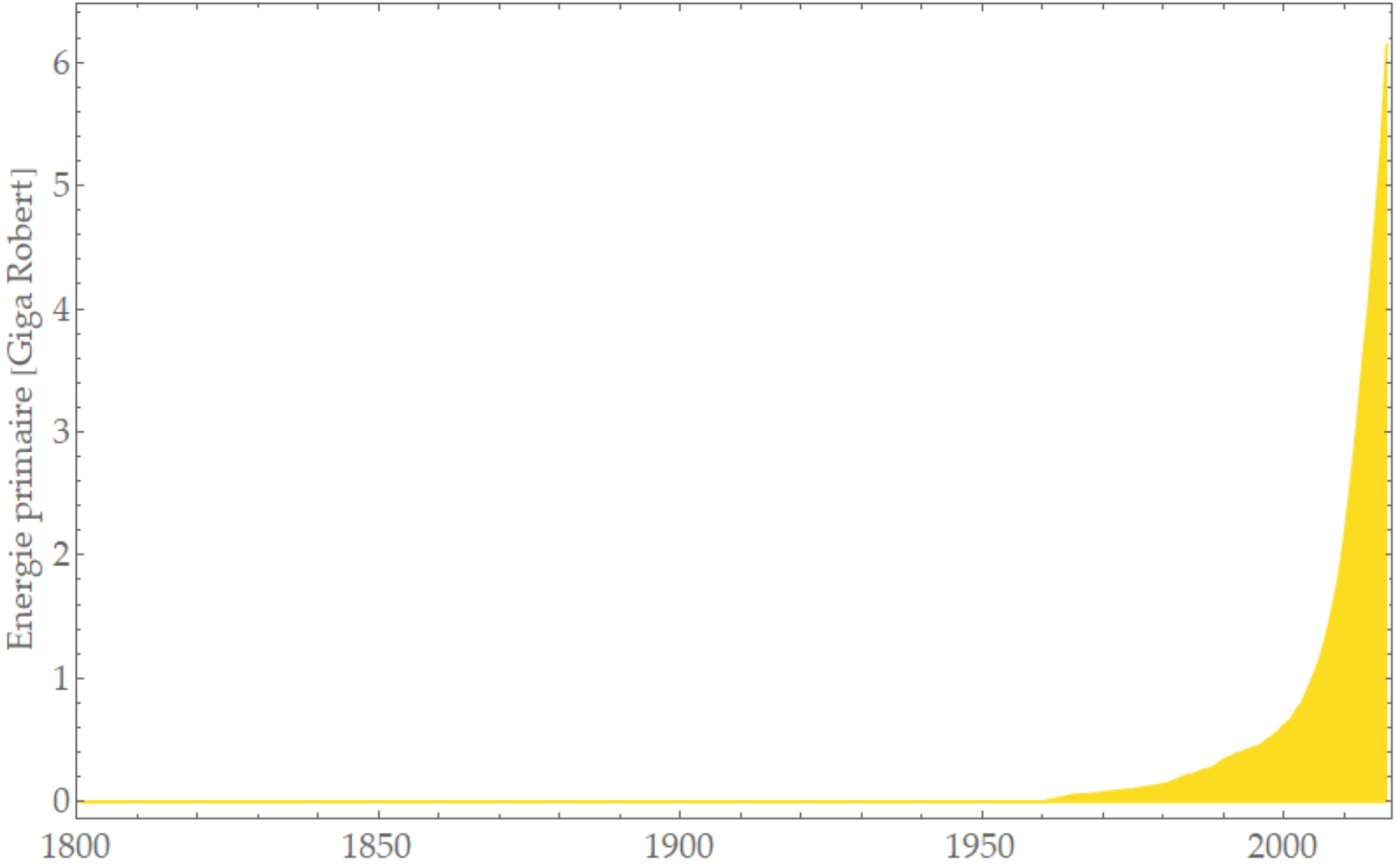
Energy is a powerful concept because it is quite insenstive to technical details

Why energy? An impactful consumption





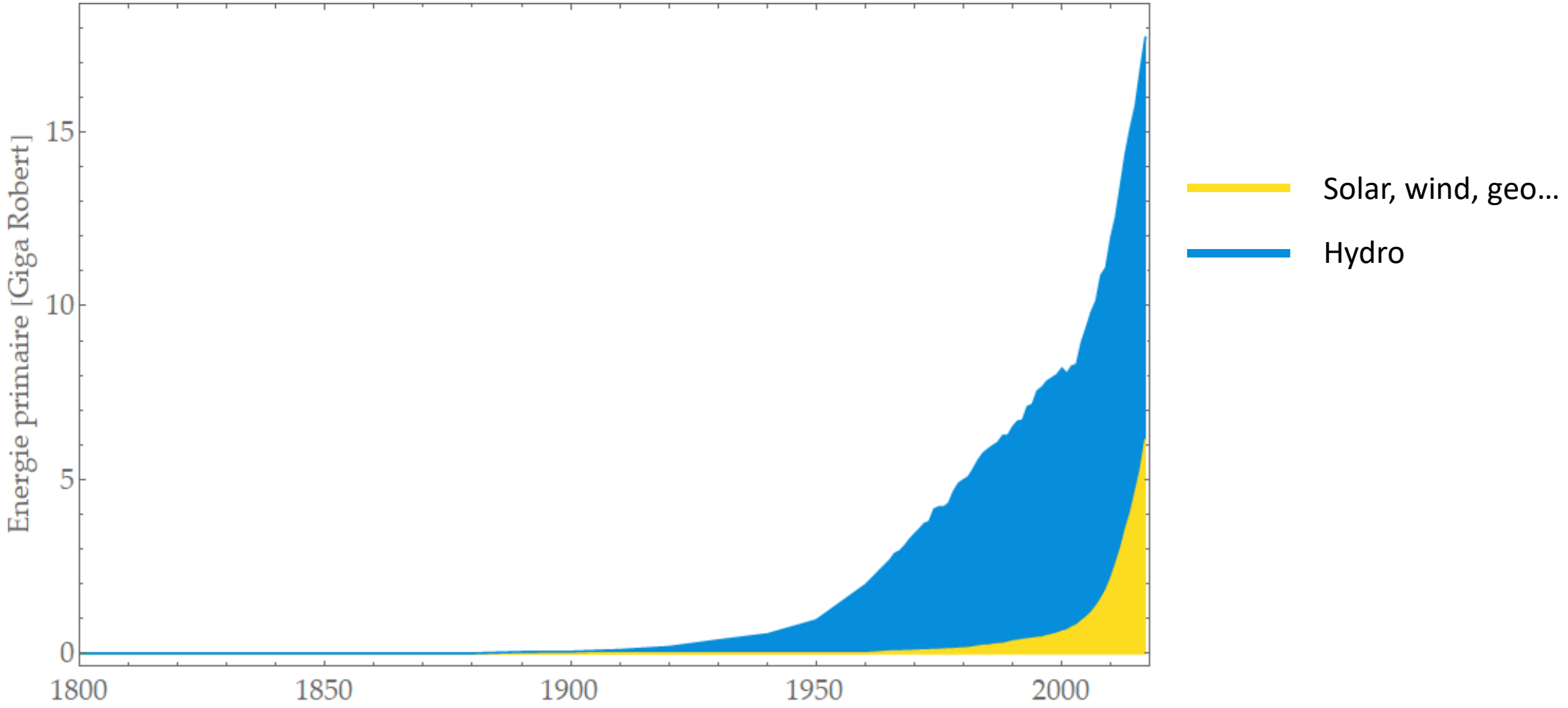
How did we get there?



Solar, wind, geo…

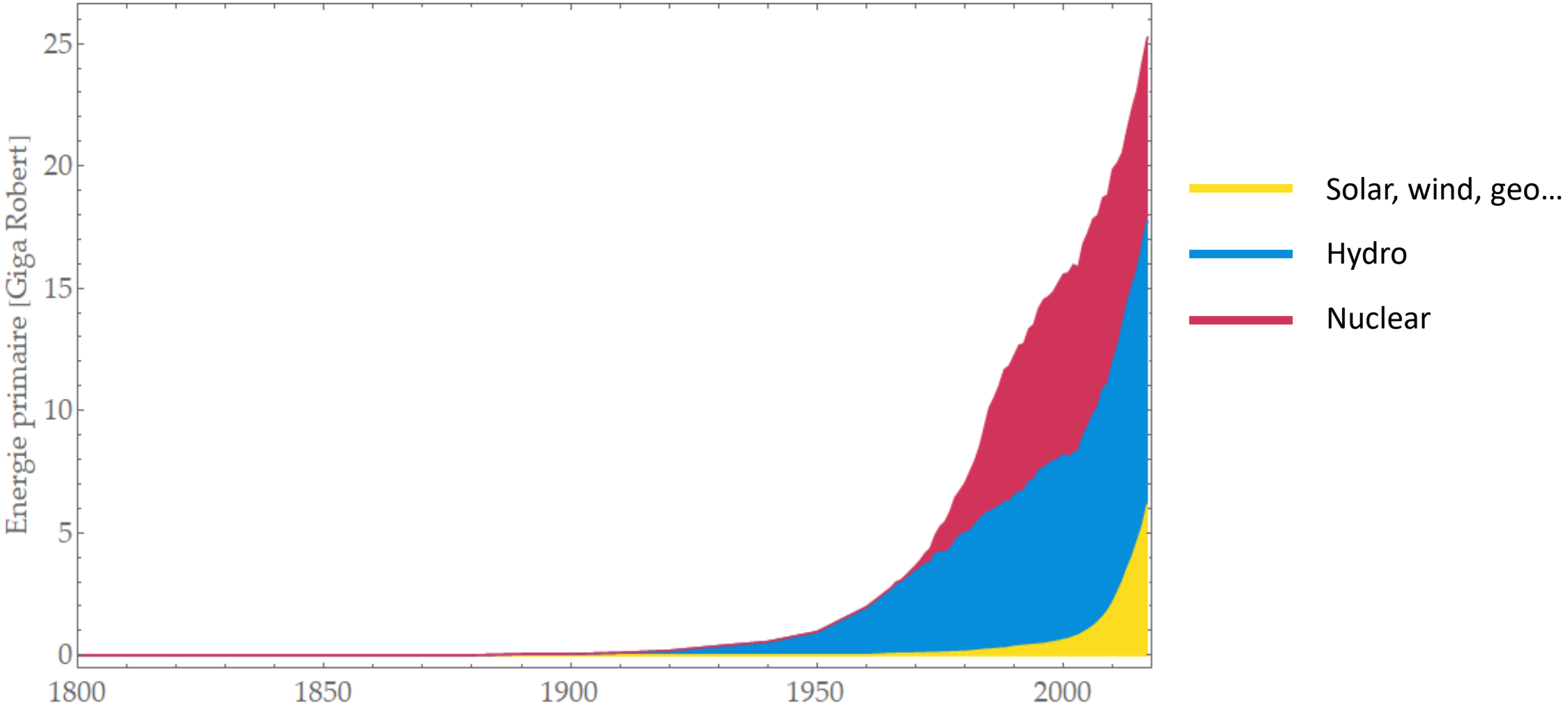
Source International Energy Agency (2014)

How did we get there?



Source International Energy Agency (2014)

How did we get there?



Source International Energy Agency (2014)

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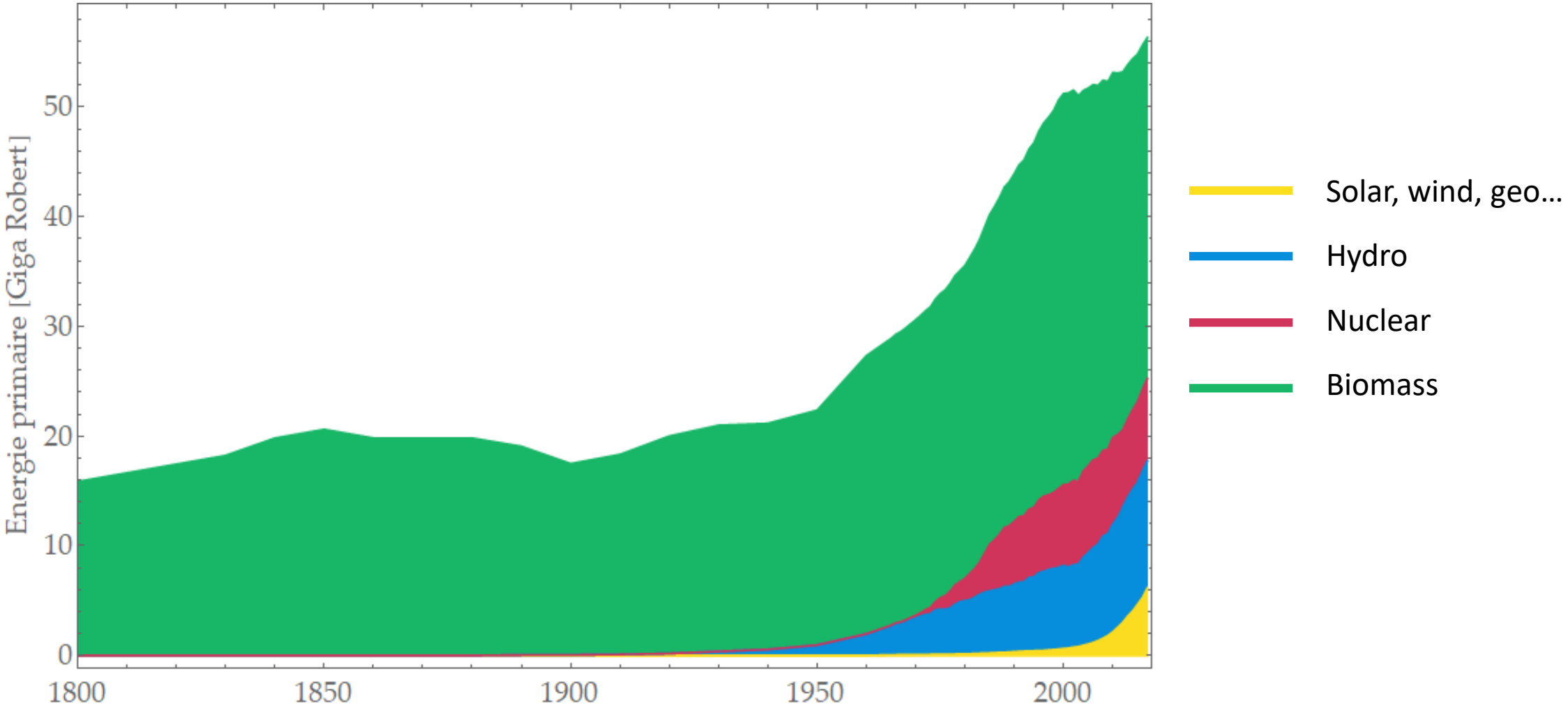

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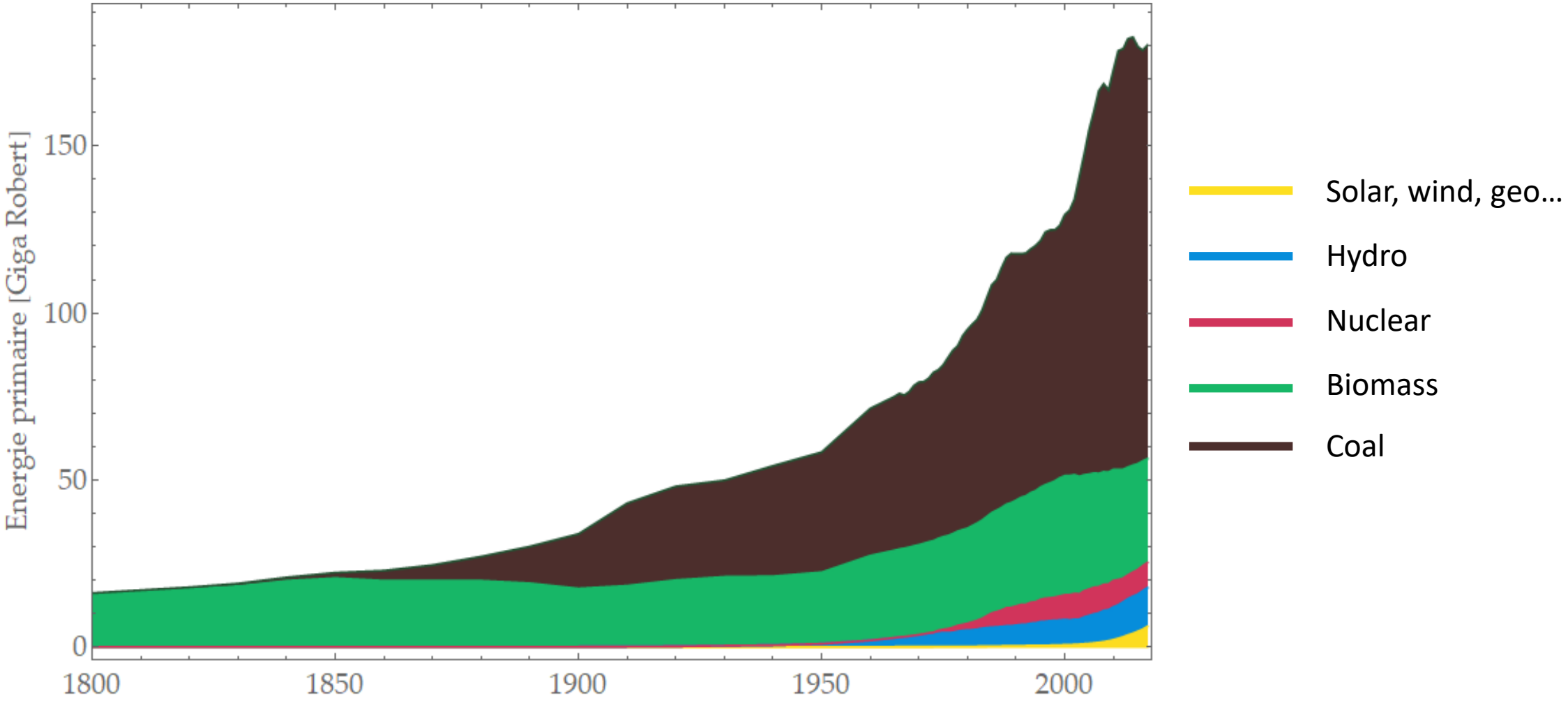

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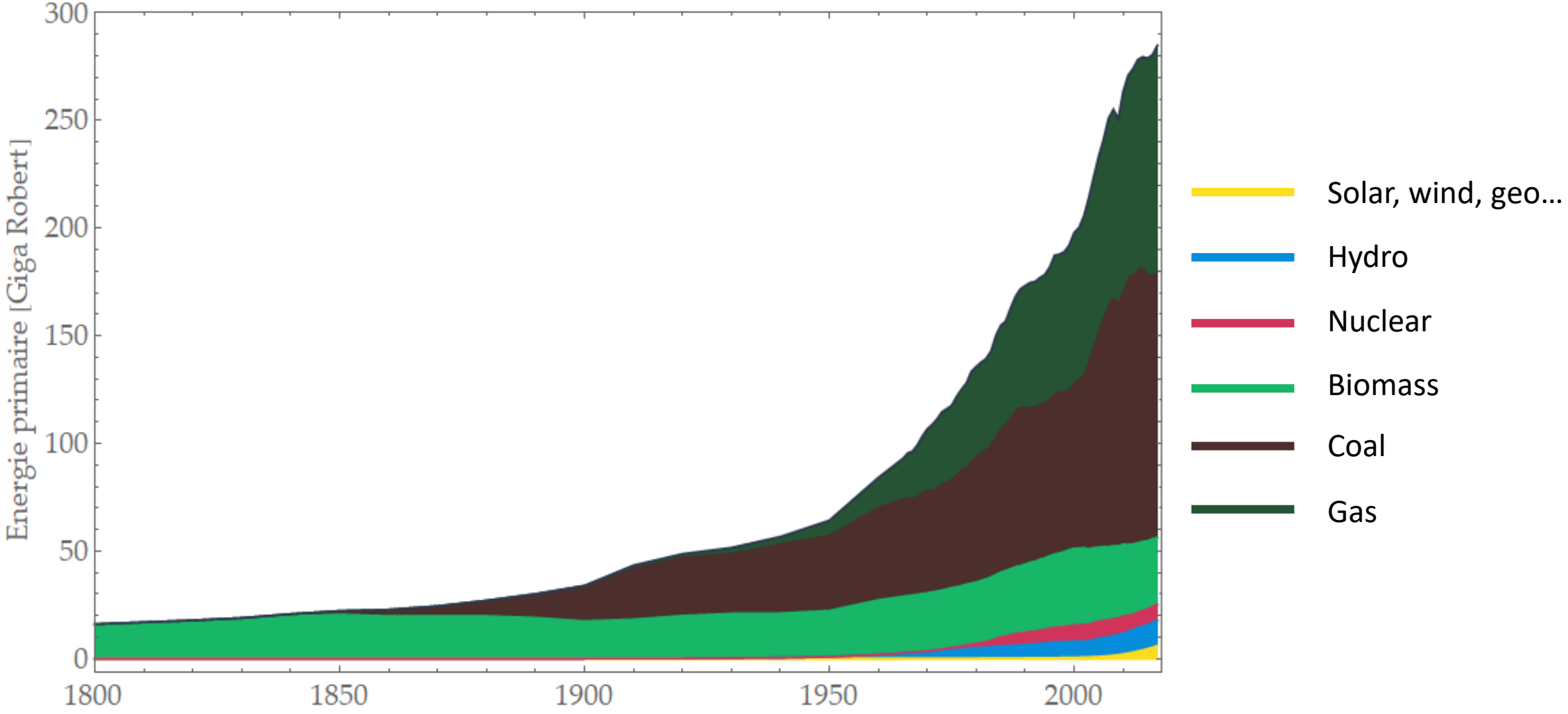
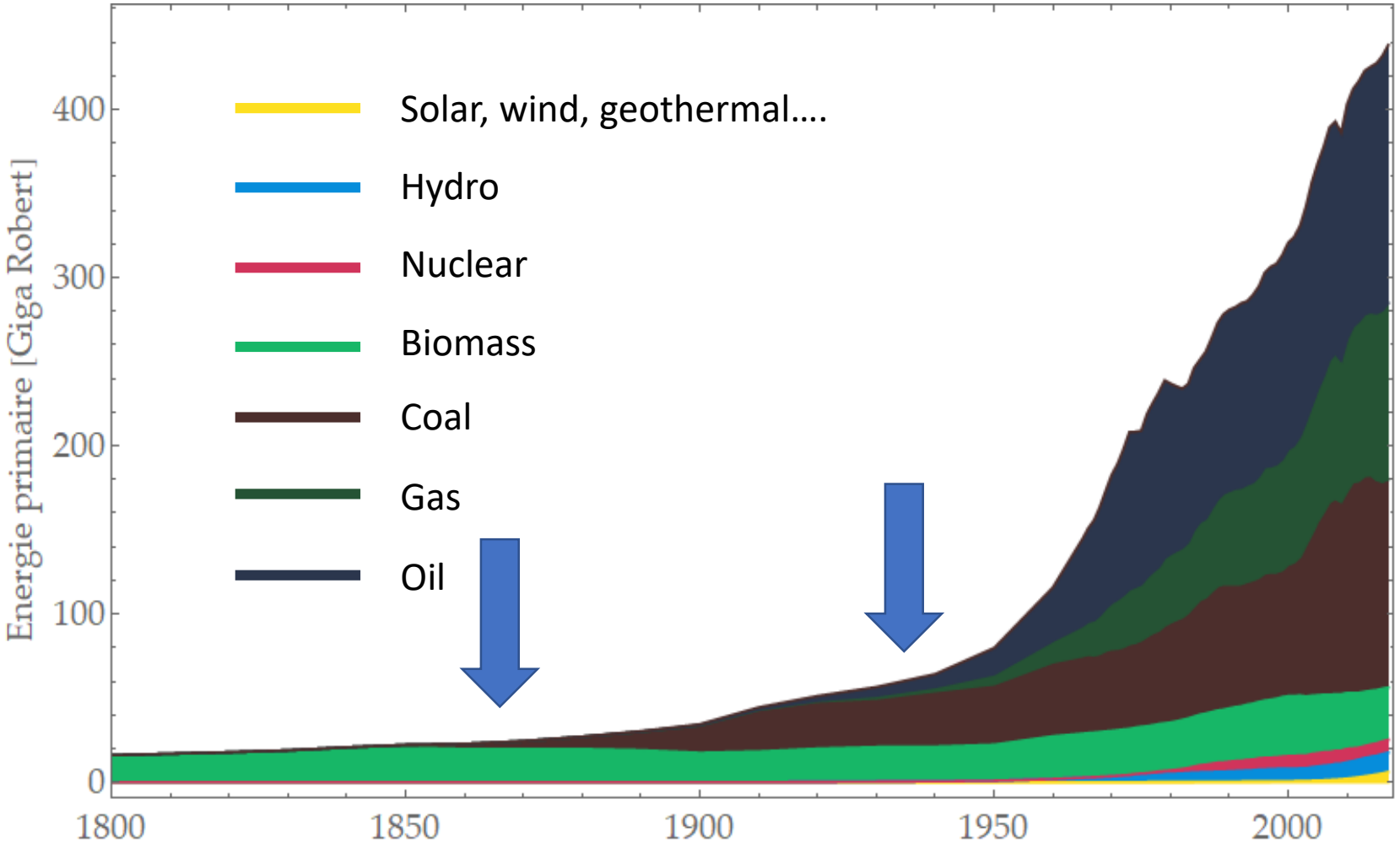


Source International Energy Agency (2014)

How did we get there?



Energy transtions

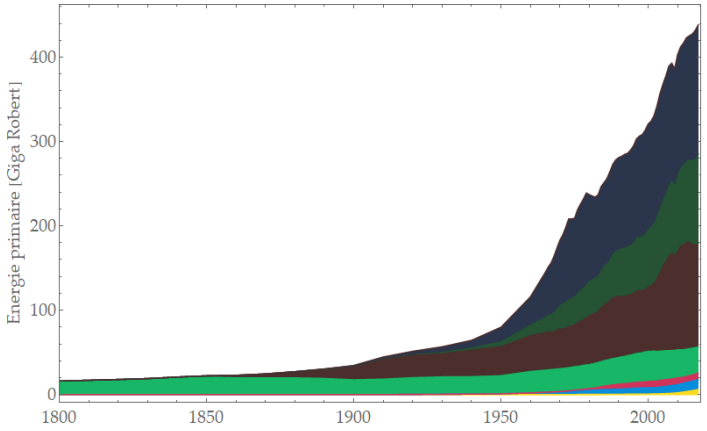
Pile up vs. replace

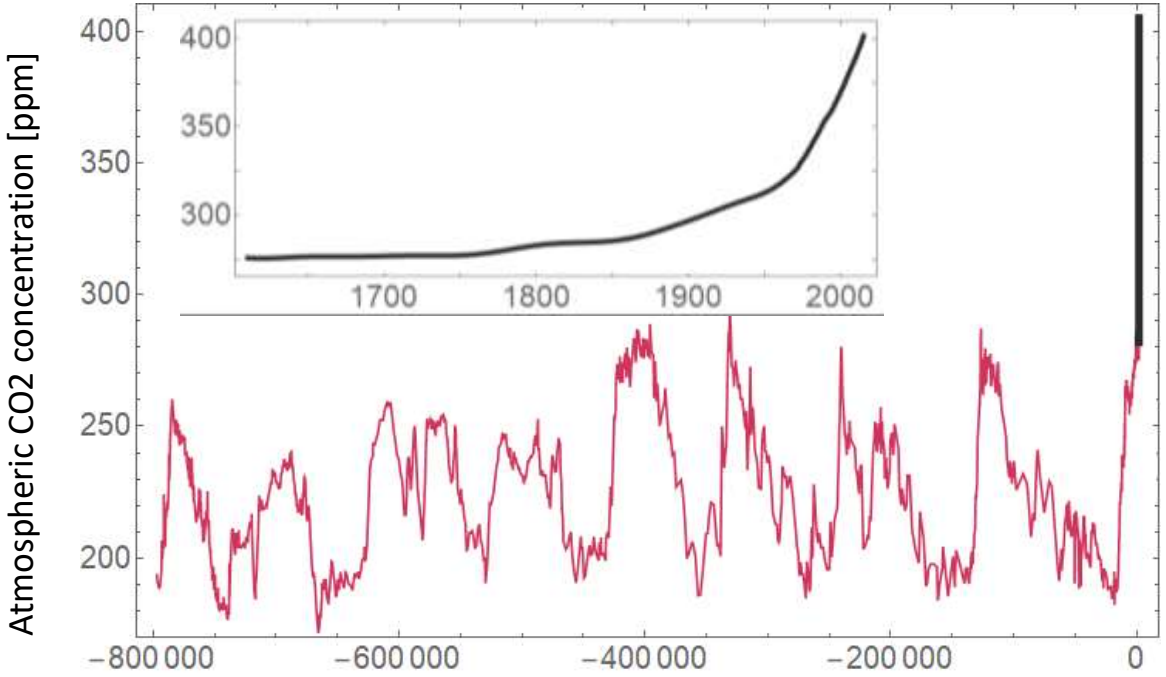
Fossil → Carbon based

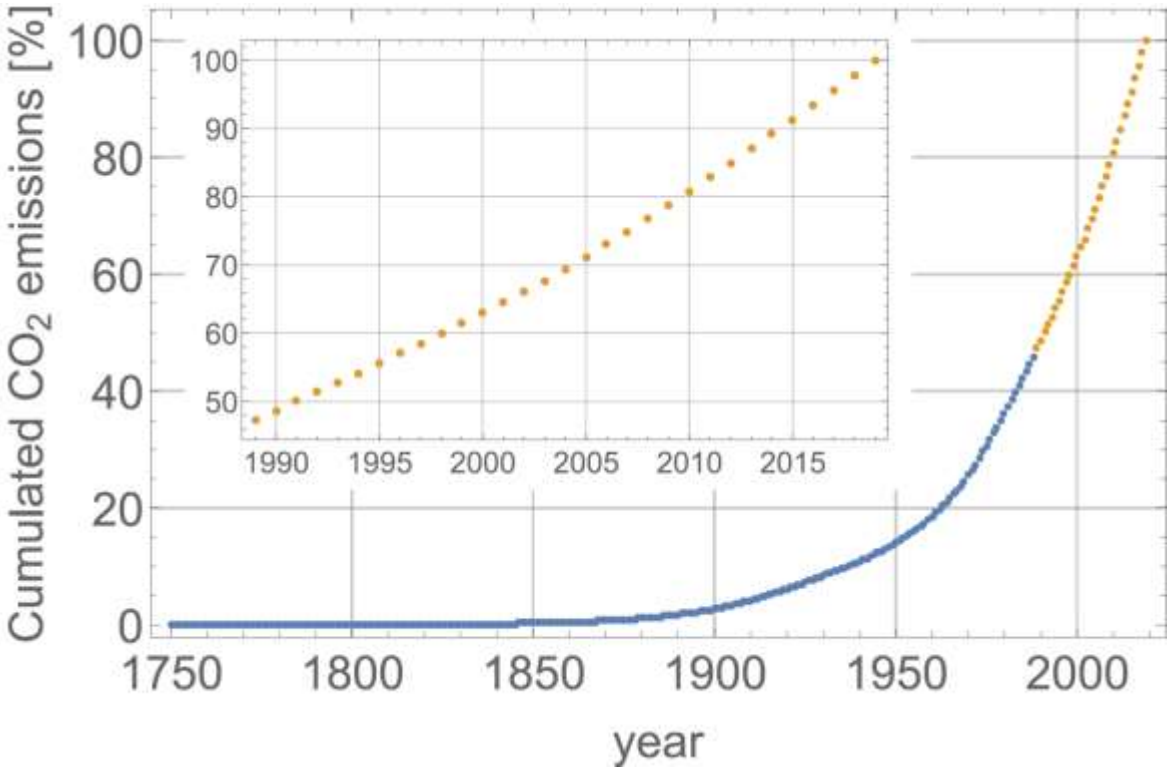
Nuclear
Renewable
} Carbon « free » ?

Source International Energy Agency (2014)

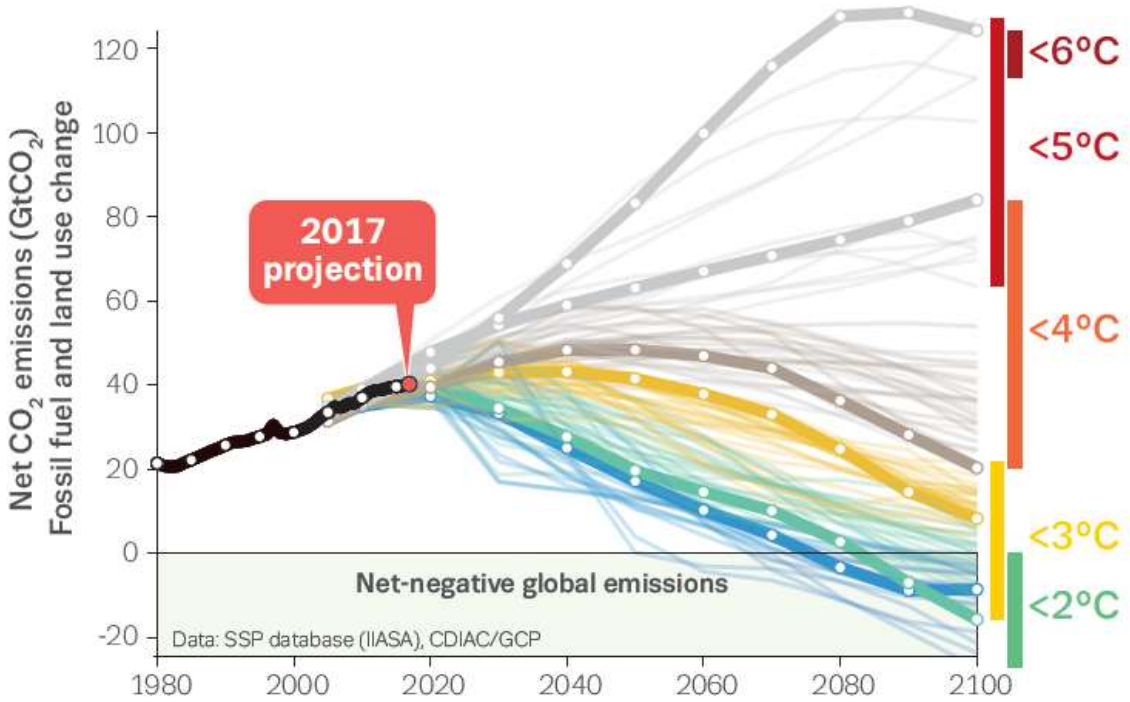
Just a reminder







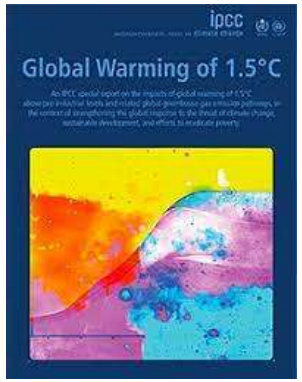
Objective(s)



This Agreement […] aims to strengthen the global response to the threat of climate change[…] by holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels.

PARIS2015
UN CLIMATE CHANGE CONFERENCE
COP21·CMP11

"The current nationally determined contributions, extending only to 2030, do not limit warming to 1.5°C. Depending on mitigation decisions after 2030, they cumulatively track toward a warming of 3°-4°C by 2100, with the potential for further warming thereafter."



Outlook

- 1 What is Energy? – this part you should master…
  - 1.1 Physics is behind
  - 1.2 Conversion of energy
  - 1.3 Key values
  - 1.4 Towards scenario construction
- 2 Energy production (and use) – this won't be exhaustive…
  - 2.1 Fossil fuels
  - 2.2 Electricity
  - 2.3 Hydrogen
  - 2.4 Heat
  - 2.5 Efficient Energy use
- 3 Global considerations– this is a few guidelines to build your scenario…
  - General thoughts and idea of scenarios

1. What is energy ?

1.1 Energy : Physics is behind !

Energy is a conserved quantity

never created or consumed – only exchanged

Energy can be exchanged through heat or work – 1st law of thermodynamics

$$\Delta E = W + Q$$

Energy Work Heat

Heat and work are two ways to exchange energy. A system *does not contains* heat or work, it contains energy.

1.1 Energy : Physics is behind !

Entropy creation – 2nd law of thermodynamics

Entropy measures the disorder of a system.

Every heat transfer comes with an entropy transfert

Entropy can be created, but never destroyed

$$dS_{\text{created}} \geq 0$$

$$dS_{\text{exchanged}} = \frac{\delta Q}{T_{\text{ext}}}$$

Consequences

- Heat cannot flow spontaneously from a cold source to a hot source

  Transfering heat from a cold source to a hot source requires work

- Converting heat into work requires a hot source and a cold source

  The conversion efficiency is limited to Carnot's efficiency

Notion of Exergy : considering the environment

1.1 Energy : Physics is behind !

Does efficiency matters ?

Yes if you compare apples with apples
No if you compare oranges and apples

Wind turbine efficiency vs. coal efficiency vs. nuclear power plant efficiency -> pointless !
Compare evolution of one technology -> Yes, you can

What matters is the output power

1.1 Energy : Physics is behind !

Does efficiency matters ?

Some typical values – Some of them are limited by the law of physics !

Convertisseur	Entrée	Sortie utile	Efficacité
Turbine vapeur	Mécanique	Electrique	40 %
Eolienne	Mécanique	Electrique	(< 59 %)
Turbine hydro	Mécanique	Electrique	90 %
Cellule solaire	Solaire	Electrique	20% (<33 %)

Convertisseur	Entrée	Sortie utile	Efficacité
Moteur combustion	Chimique	Mécanique	10 – 50 %
Moteur électrique	Electrique	Mécanique	30 – 90 %
Photosynthèse	Solaire	Chimique	5 %
Muscles	Chimique	Mécanique	20 %

1.1 Energy : Physics is behind !

Power vs. Energy

$$P = \frac{dE}{dt}$$

Basic unit : **Watt (W)**

1 Watt = 1 J/s

$$\Delta E = \int P dt = P \times \Delta t$$

100 W accumulated during 1s = 100 J

200 W accumulated during 0.5 s = 100 J

1 W accumulated during 1min 40s = 100 J

Currently: mostly energy consideration.
(except in grid stability, where power is critical?)

Tomorrow: power more limiting than energy?

1.2 Conversion of Energy

$$E = \frac{1}{2}mv^2$$

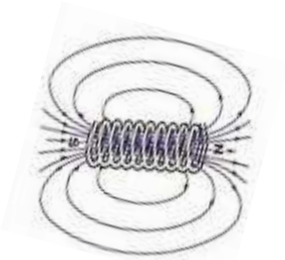
Kinetic

$$E = mgz$$

Gravity

$$E = \frac{1}{2}m\omega^2x^2$$

Elastic

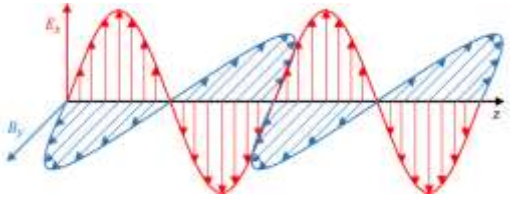


$$E = \frac{1}{2}LI^2$$

Inductance

$$E = \frac{1}{2}CU^2$$

Capacitance

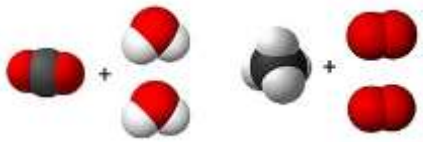


$$\int d^3\mathbf{r}\left(\frac{1}{2}\epsilon E + \frac{1}{2\mu_0}B^2\right)$$

Electromag.

$$\Delta E = C\Delta T$$

Thermal



$$\Delta E = l_{\text{reaction}}\Delta n$$

Chemical

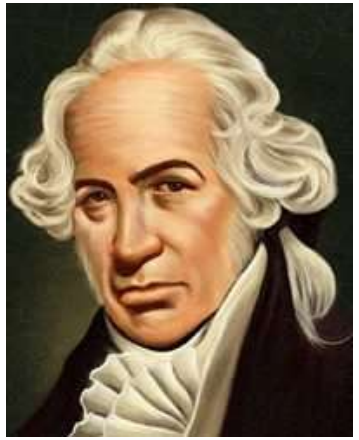
$$\Delta E = L_{\text{fusion}}\Delta m$$

Phase

Very specific, not very generic…

Courtesy from Daniel Suchet

1.2 Conversion of Energy



$$1 \text{ Joule} = 1 \text{ kg.m}^2\text{.s}^{-2}$$

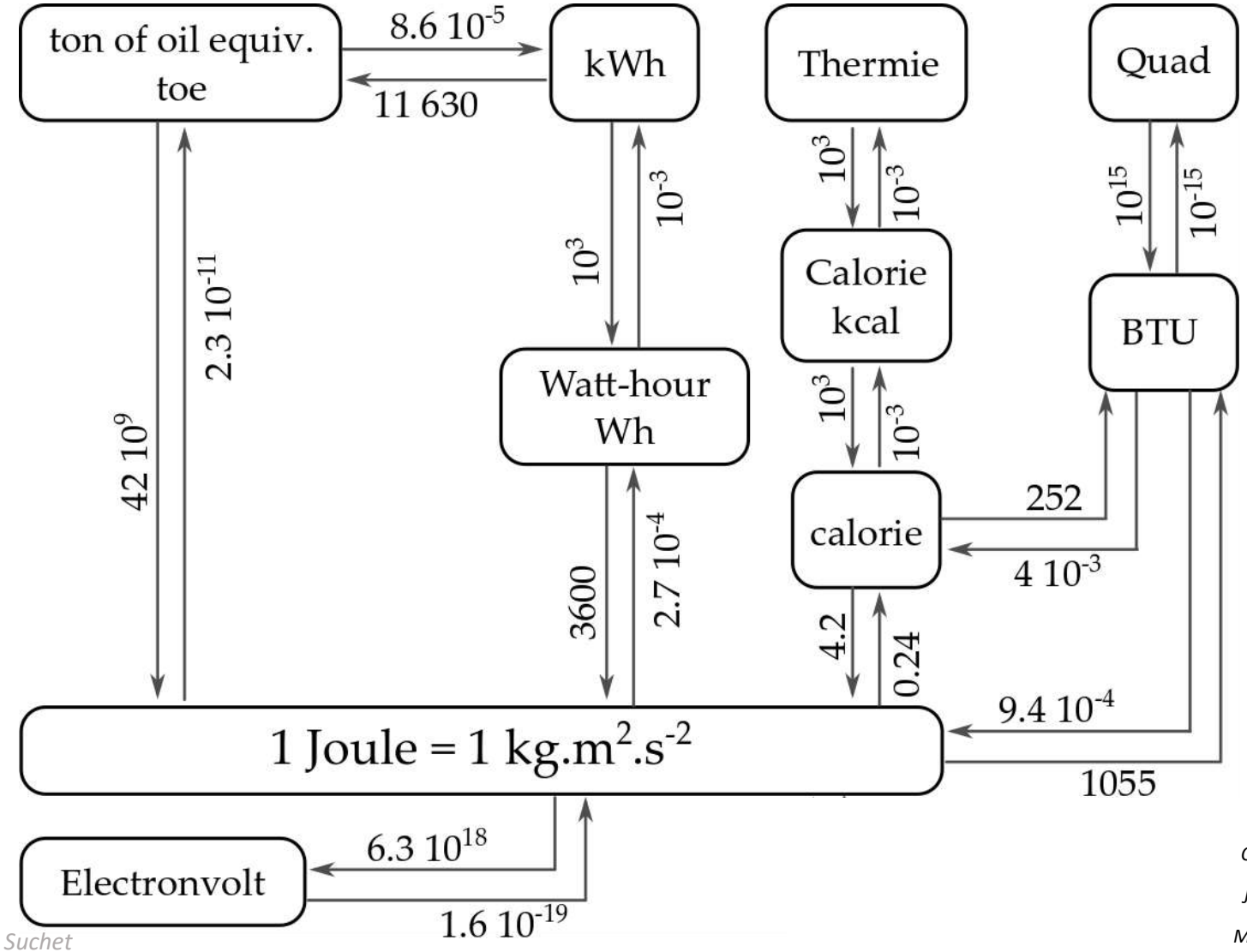
Carl Frederik von Breda.

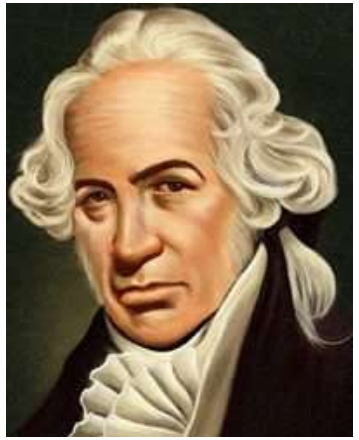
John Maler Collier

Manchester Science Museum Group Collection

Courtesy from Daniel Suchet

1.2 Conversion of Energy





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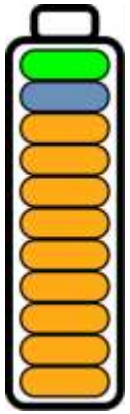
Courtesy from Daniel Suchet

1.2 Conversion of Energy



Usage 10%

Transport 10%

Production 80%

Source : ADEME

+ network, database, ads…

Ex of known conversions

Chemical → → Thermal

Thermal → → Kinetic

Chemical → → Potentiel

Thermal → → Electric

Courtesy from Daniel Suchet

1.2 Conversion of Energy

Primary energy raw commodities directly captured from natural resources

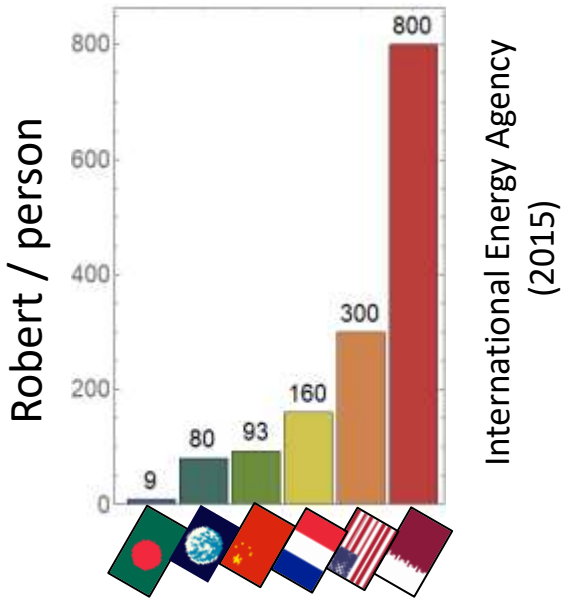
Solar *Wind* *Hydro* *Biomass* *Muscle* *Oil* *Coal* *Gas* *Nuclear* *Geothermal*

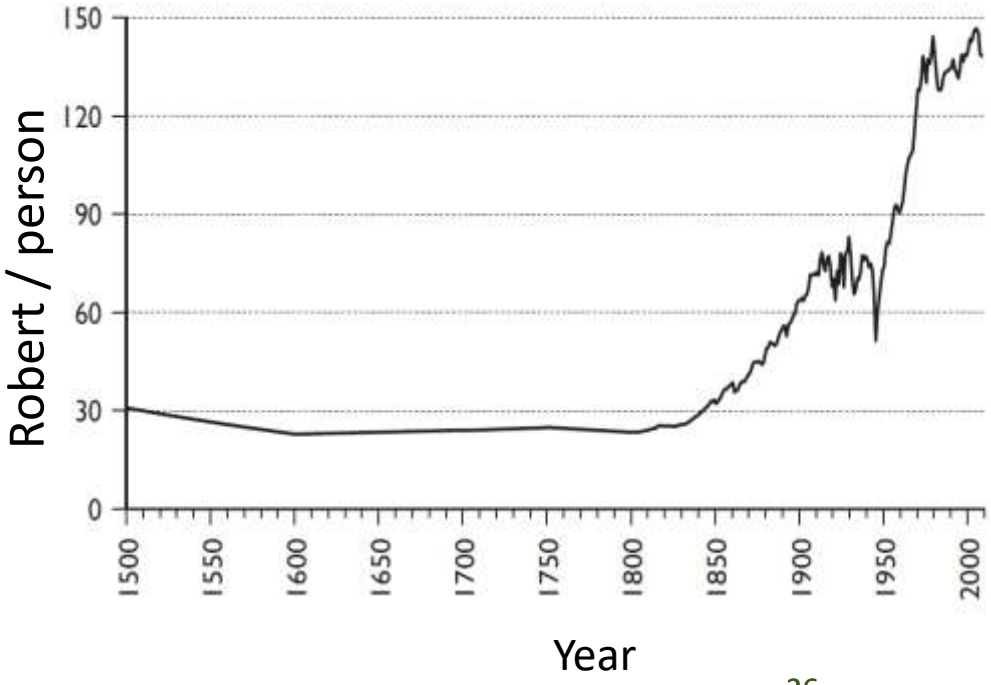
From the Sun

1.2 Conversion of Energy

Muscle

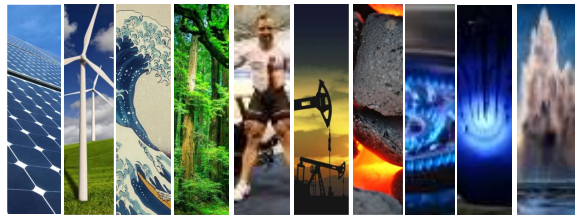
Robert Förstemann





Source Astrid Kander, *Power to the People* (2013)

1.2 Conversion of Energy



Primary energy raw commodities directly captured from natural resources

Crude oil, coal, nuclear heat…
Renewable heat & direct electricity

Transformations

May not be relevant for the requested purpose?

Secondary energy obtained from transformations of primary energies

Oil products, coal products, charcoal
Thermal based electricity

Distribution

Not very useful if remains at the power station…

Final energy commodities which are actually purchased and used by end users

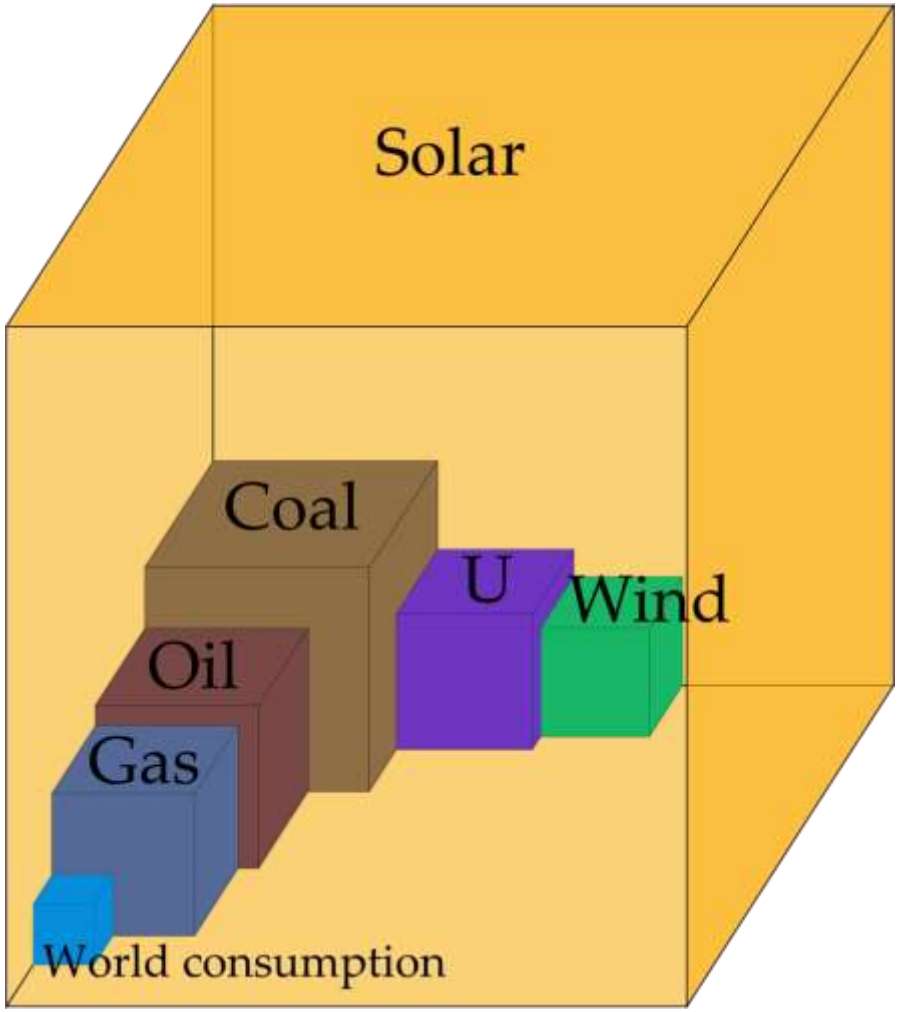
When you get what you want, but not what you need.

Appliance

Useful energy commodities which are actually purchased and used by end users

1.3 Key values : Energy in the world ?

Primary energy raw commodities directly captured from natural resources



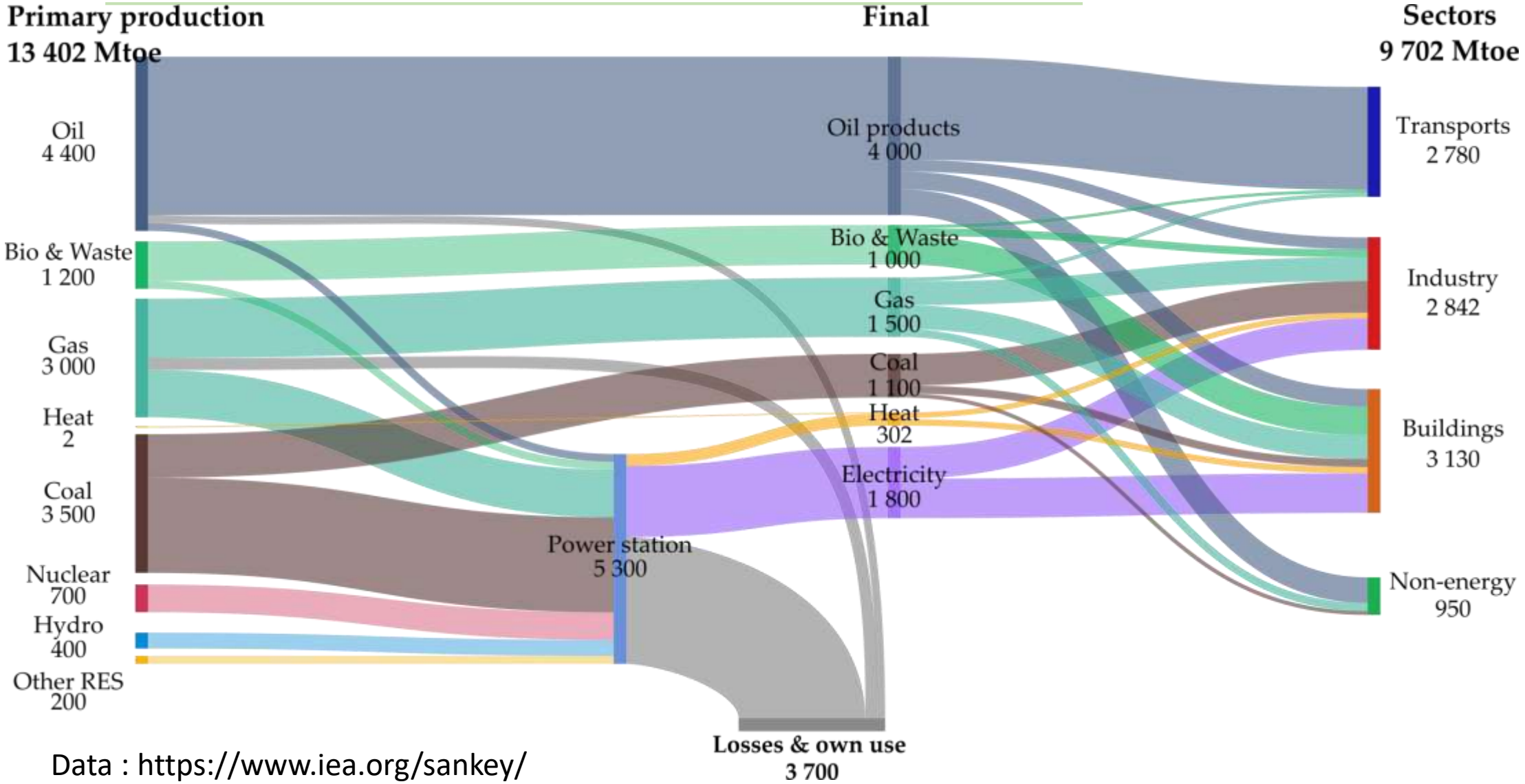
« Fundamental look at supply side energy reserves for the planet »
M. Perez & R. Perez, IEA SHCP Newsletter (2015)

Solar on land over 1 year = 10 000 yearly world consumption

Oil reserve ~ gas reserve ~ 15 yearly world consumption

Coal reserve ~ 60 yearly world consumption

1.3 Key values



Elec. share

19%

TPES / yr

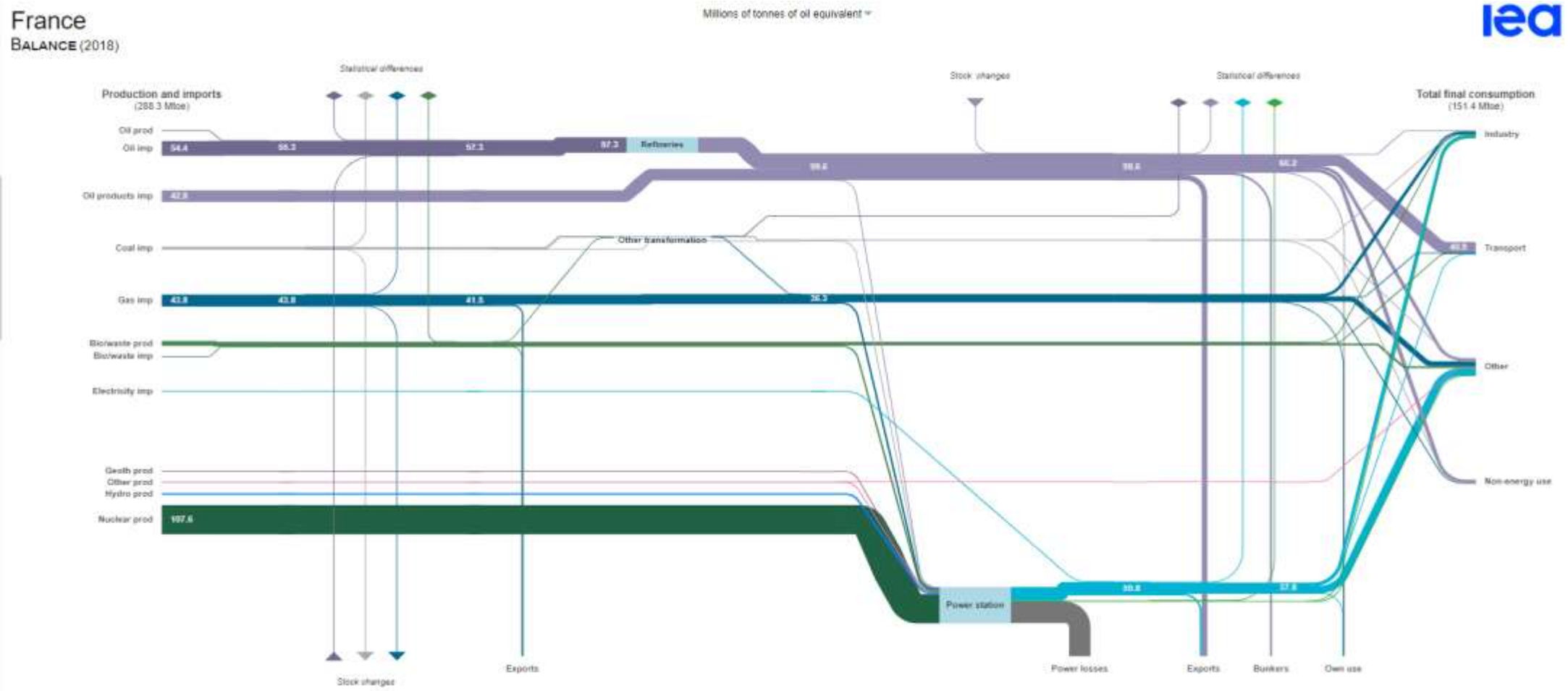
5 10^{20} J
150 000 TWh
18 TW.yr

E / cap / yr

2 toe
75 GJ
20 MWh
3 kW.yr
75 Roberts

Data : https://www.iea.org/sankey/

1.3 Key values



Elec. share

25%

TPES / yr

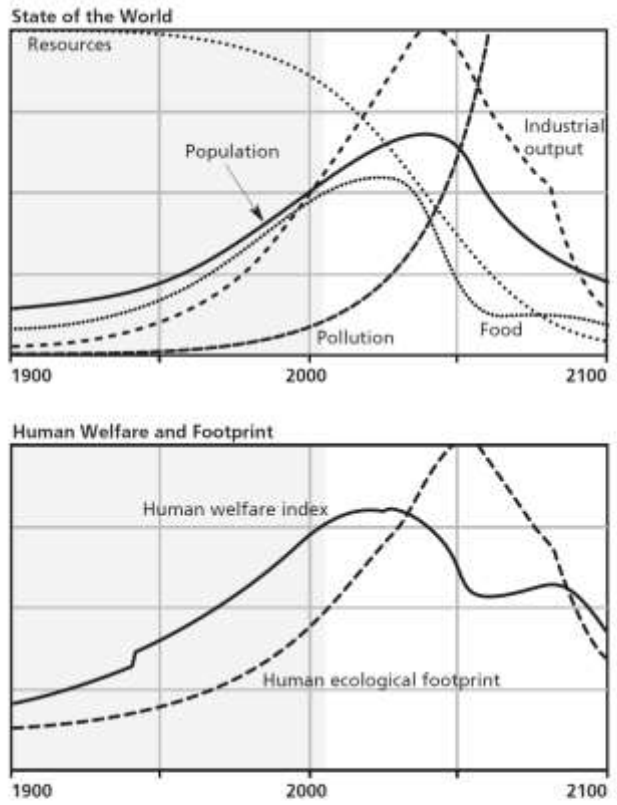
1 10^{19} J
3 300 TWh
400 GW.yr

E / cap / yr

4 toe
200 GJ
50 MWh
6 kW.yr
150 Roberts

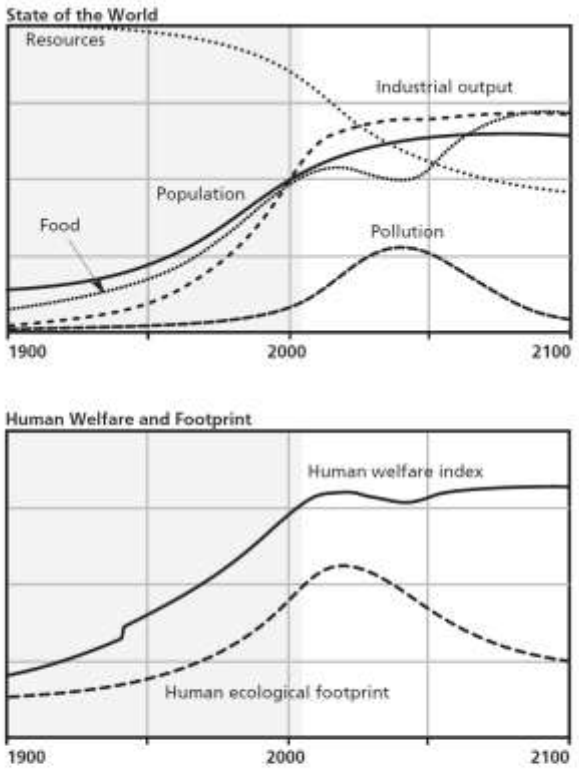
Data : https://www.iea.org/sankey/

1.4 Sustainability / scenarios ?



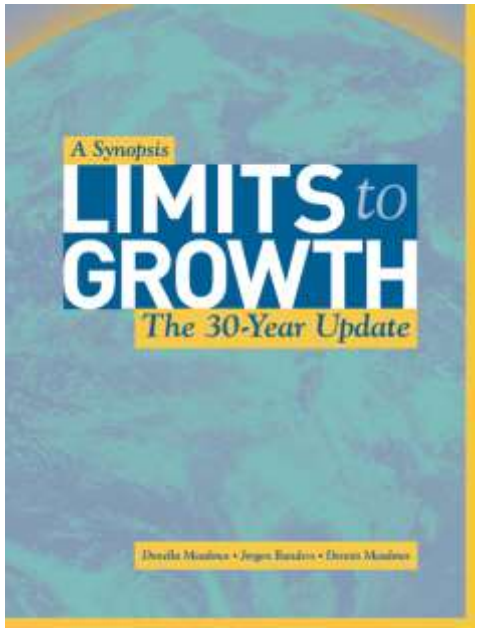
Scenario 2: More Abundant Nonrenewable Resources

This table postulates that advances in resource extraction technologies are capable of postponing the onset of increasing extraction costs. Industry can grow 20 years longer. Population peaks at 8 billion in 2040, at much higher consumption levels. But pollution levels soar (outside the graph!), depressing land yields and requiring huge investments in agricultural recovery. The population finally declines because of food shortages and negative health effects from pollution.



Scenario 9: World Seeks Stable Population and Stable Industrial Output per Person, and Adds Pollution, Resource, and Agricultural technologies from 2002

In this scenario population and industrial output are limited, and in addition technologies are added to abate pollution, conserve resources, increase land yield, and protect agricultural land. The resulting society is sustainable: Nearly 8 billion people live with high human welfare and a continuously declining ecological footprint.

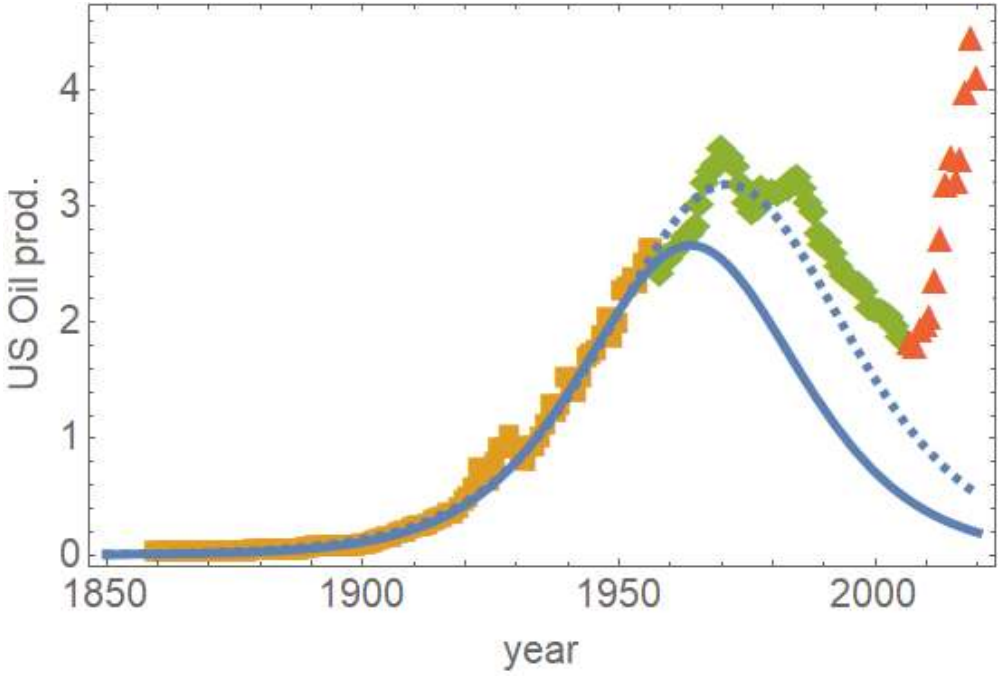


1972 : The club of Rome

1.4 Sustainability / scenarios ?

- What kind of model?
  - Prediction: try to guess an already determined future
  - Prospective: future remains to be built

$$\frac{dQ}{dt} = \frac{1}{K\tau} \times Q(t) \times (K - Q(t))$$



- What are the underlying assumptions?
  - Physics or description?
  - Built-in dynamics? Static paramters?

- What is the question, what is the context?
  - What is the model meant to say?

Courtesy from Daniel Suchet

1.4 Sustainability / scenarios ?

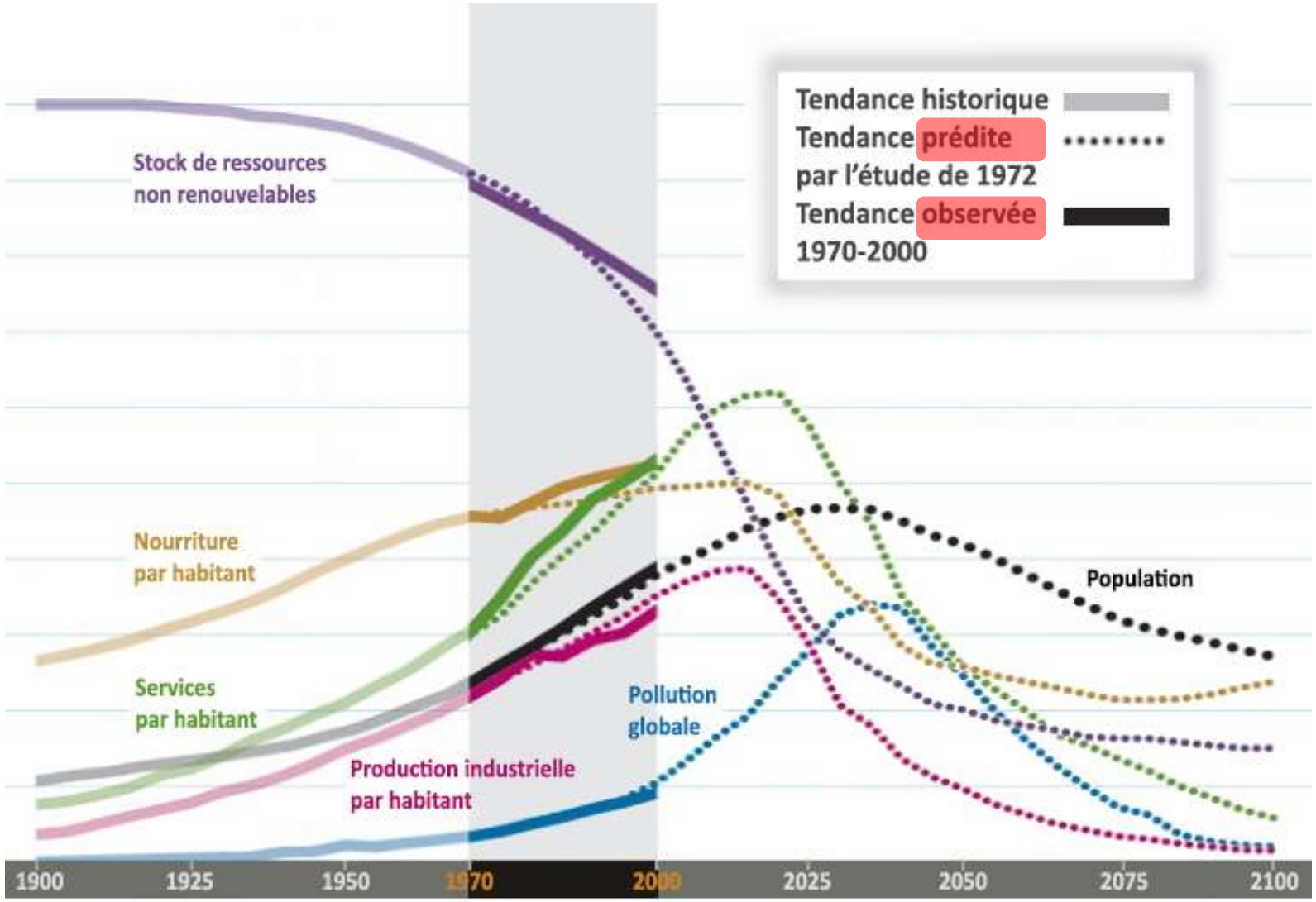


Figure by Smithsonian, after G. Turner (2008)

10 different scenarios

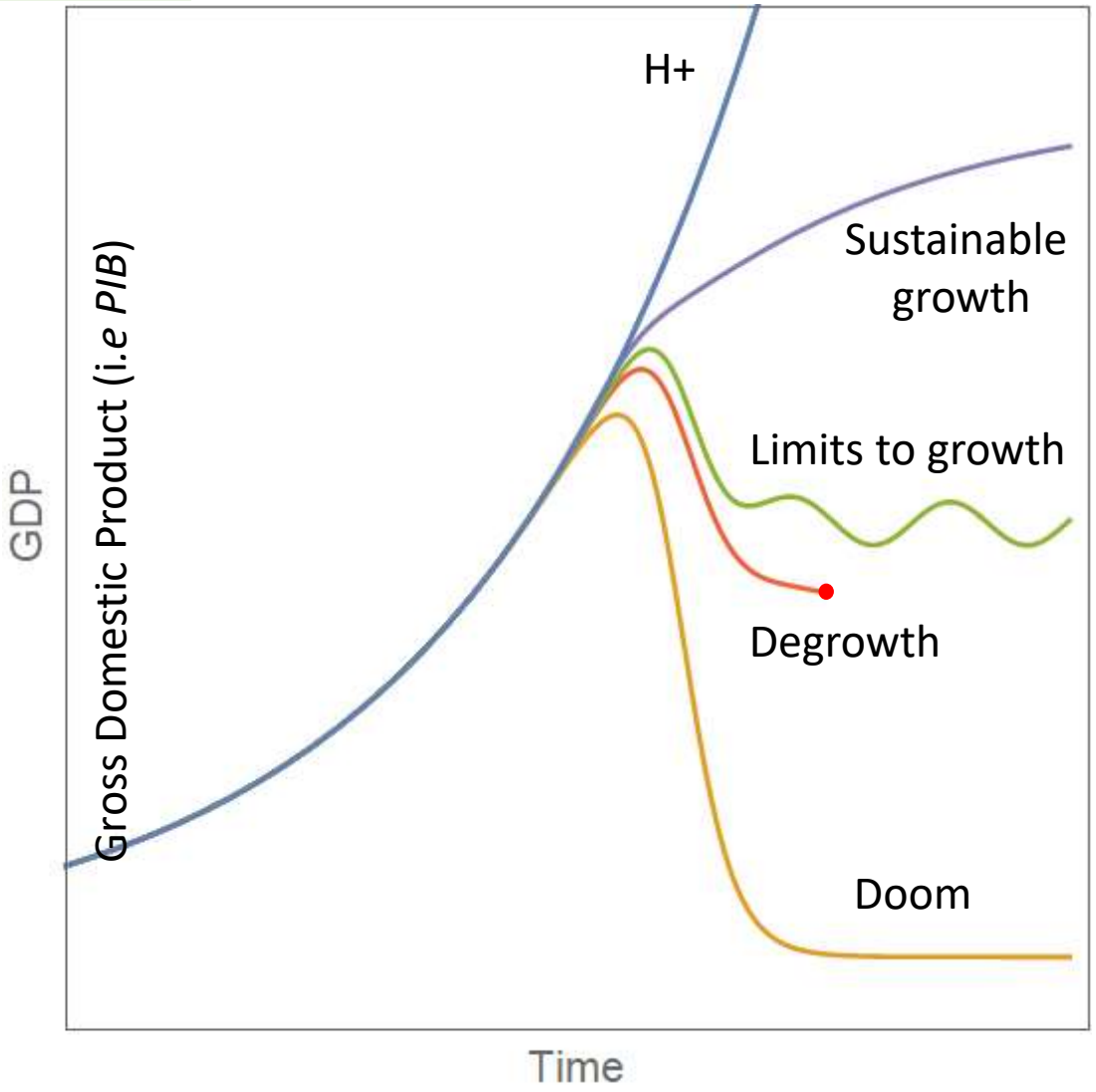
Recover basic assumptions : existence of several limits

Highlights :

- Growth is limited
- Oscillation or collapse
- Delay & erosion

1.4 Sunstainability / scenarios ?

- Transhumanist
  Limits will be overcome, collapse impossible
- Sustainable growth / LtG
  Limits alter growth, but growth remains the target
- Doom
  Collapse unavoidable
- Degrowth
  Reject the relevance of indicators

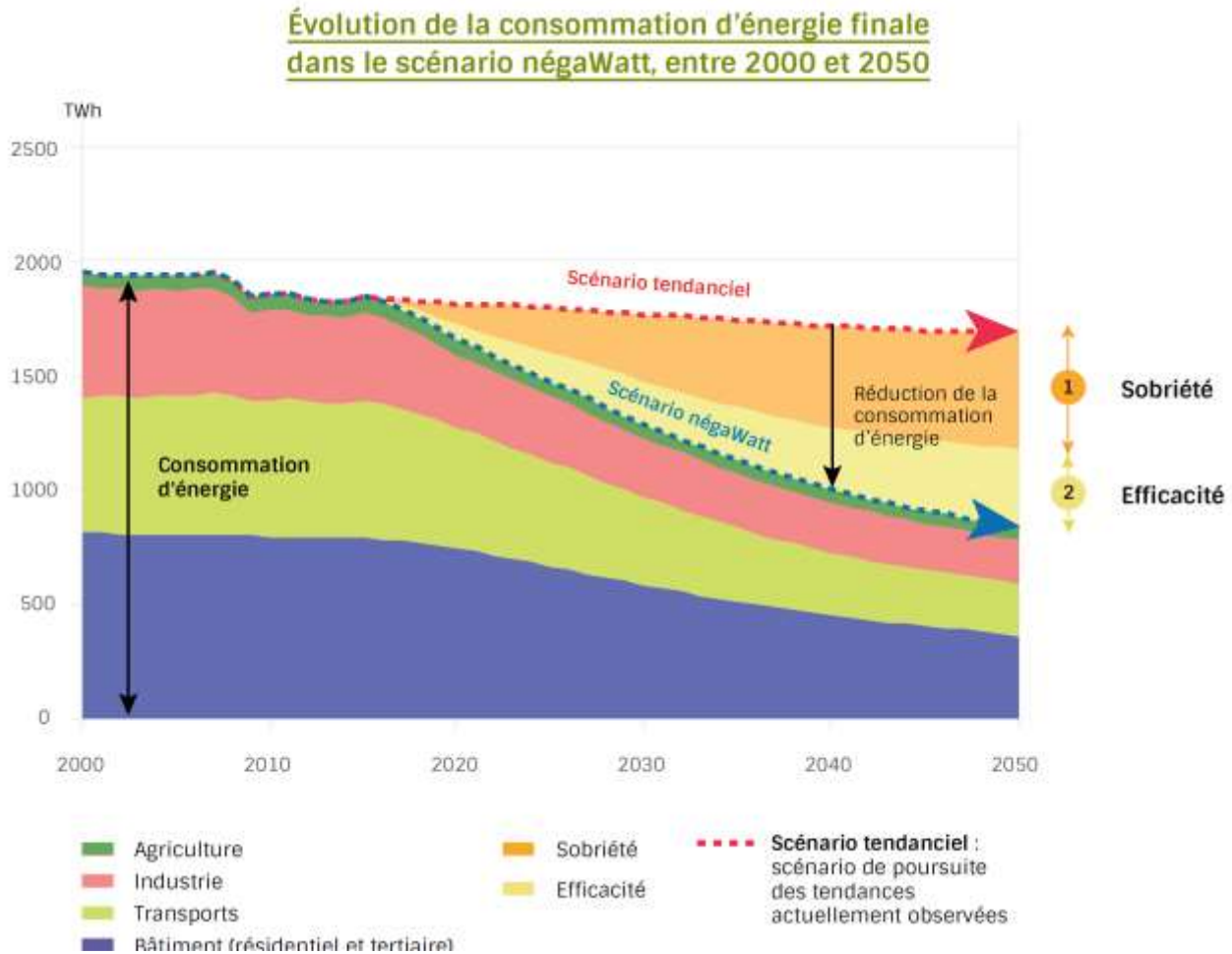


Consider not only 1 scenario,
but the underlying model

2. Energy production

2. Energy production and use

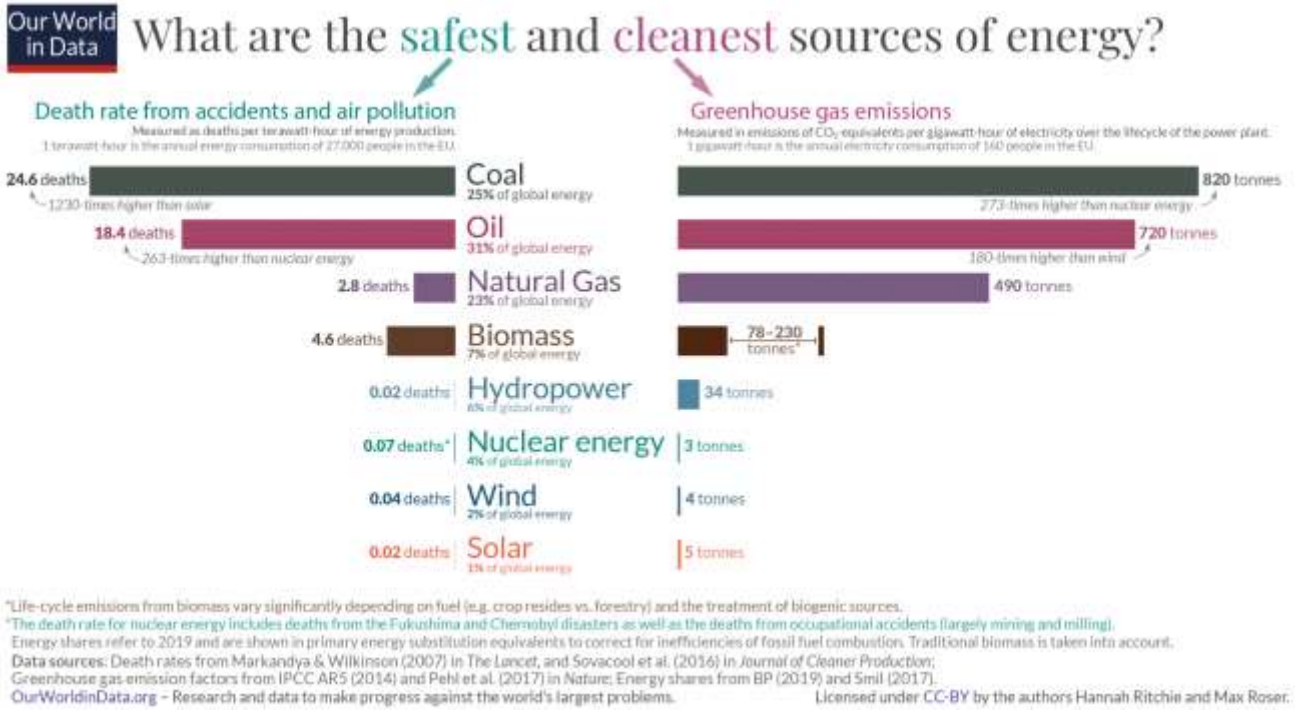
- The cleanest energy is the one we do not use



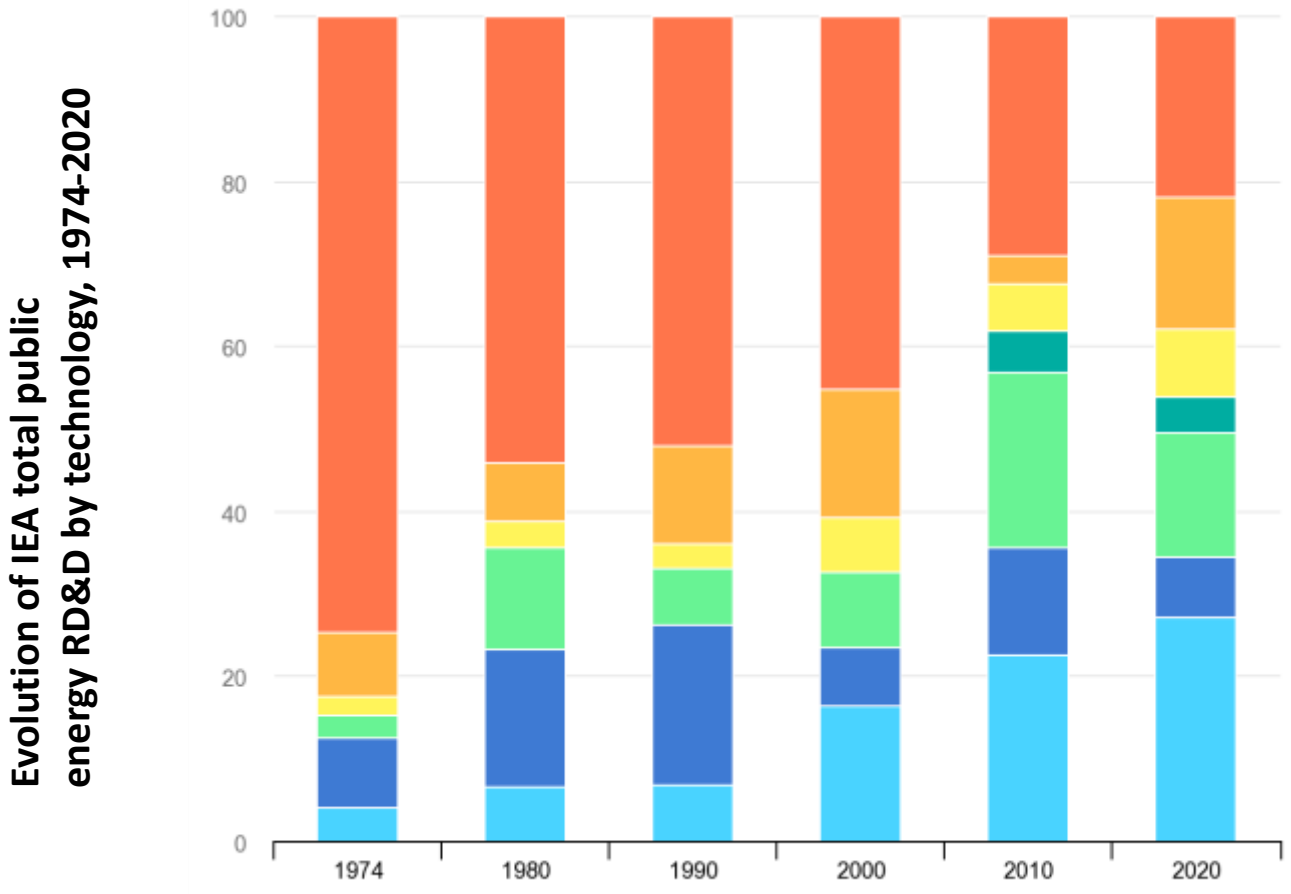
2. Energy production and use

- The cleanest energy is the one we do not use
- Improve efficiencies is key
- Policies are required
- Keep in mind

Safest and low social impact

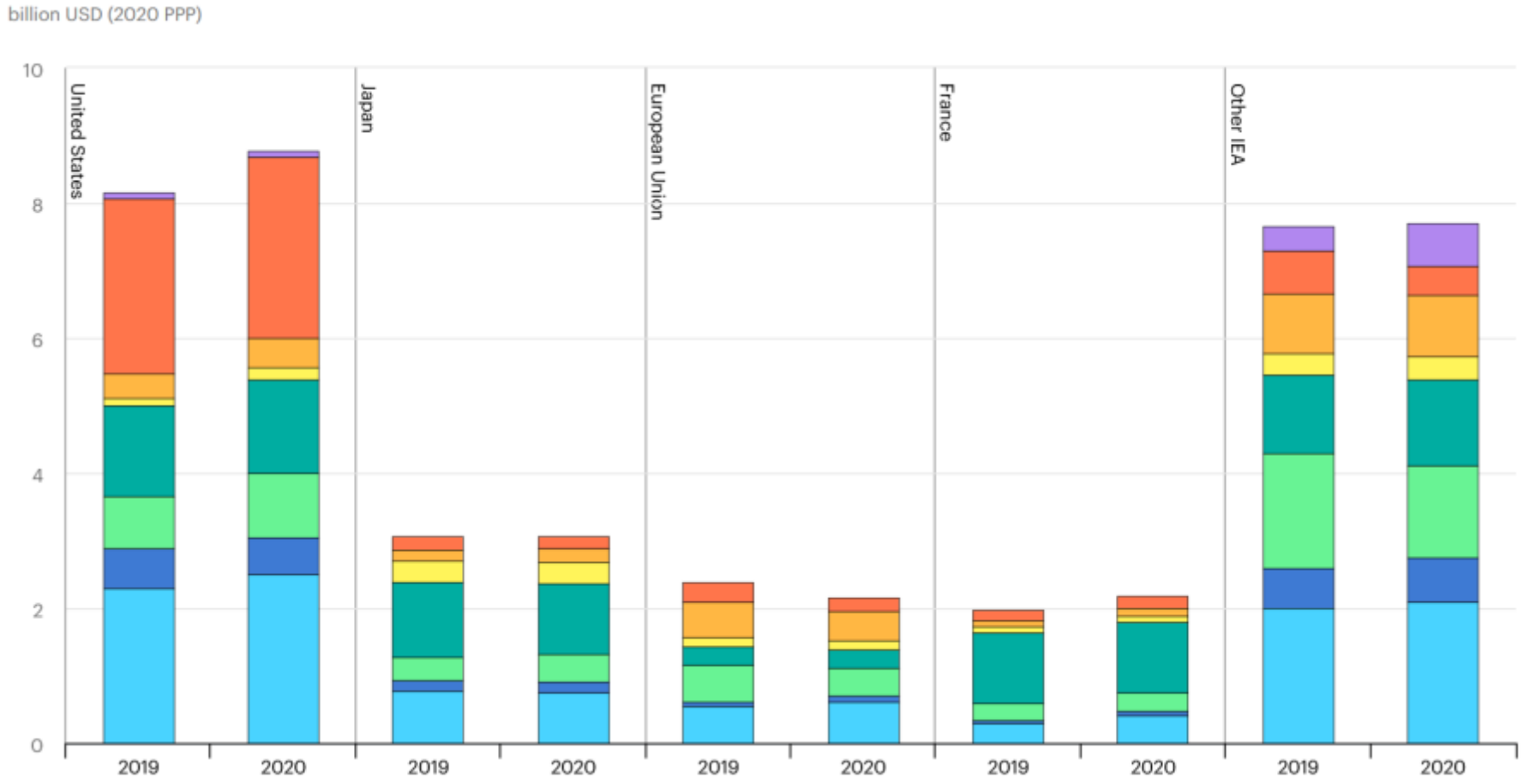


2. Energy production and use – R&D



Energy efficiency · Fossil fuels · Renewable energy · Hydrogen and fuel cells · Other power and storage · Cross-cutting · Nuclear

2. Energy production and use – R&D



IEA. All Rights Reserved

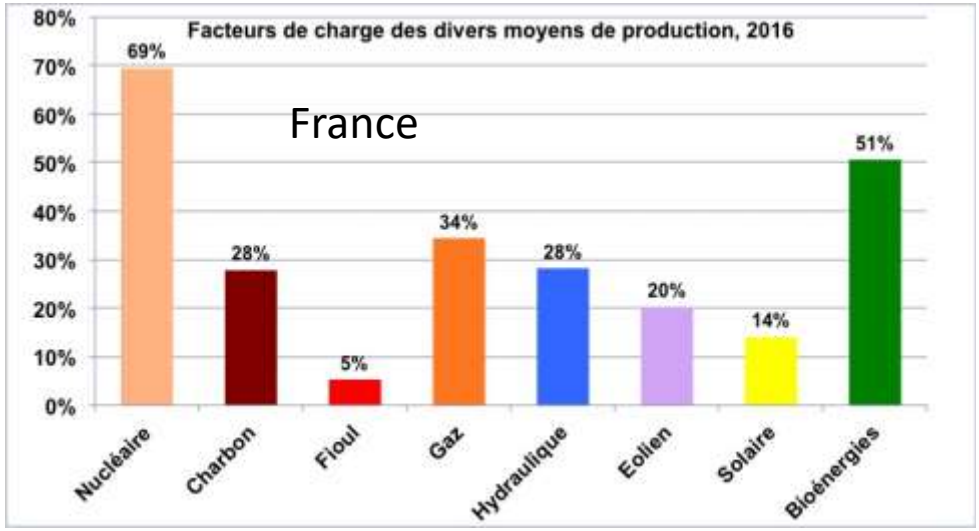
Energy efficiency · Fossil fuels · Renewable energy sources · Nuclear · Hydrogen and fuel cells · Other power and storage technologies · Other cross-cutting technologies/research · Unallocated

Energy production – Capacity factor

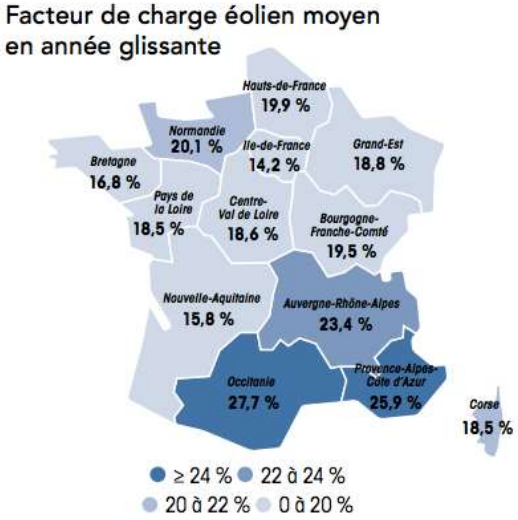
$$Capacity\ Factor = \frac{Actual\ Energy\ Production\ (MWh)}{Nameplate\ capacity\ (MW)\ x\ Time\ (h)}$$

Installed capacity vs. Generation

Very important to predict production

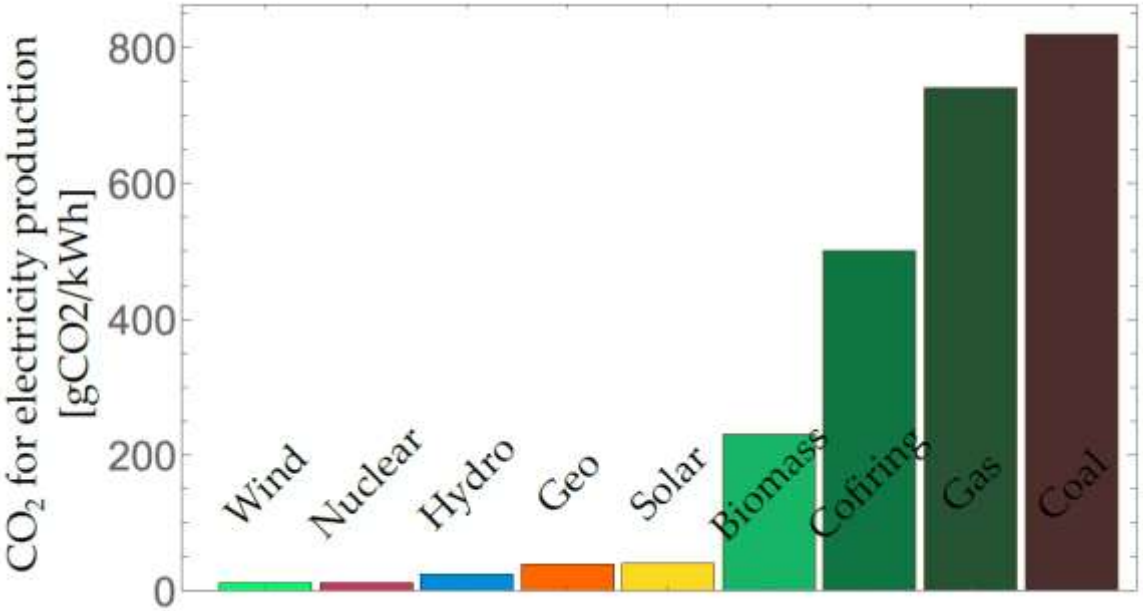


From JM Jancovici



From RTE

Energy production – gCO2/kWh



© Daniel Suchet from 2006 IPCC Guidelines for National Greenhouse Gas Inventories

WORLD NUCLEAR ASSOCIATION

gCO_2/kWh	Japan	Sweden	Finland
coal	975	980	894
gas thermal	608	1170 (peak-load, reserve)	-
gas combined cycle	519	450	472
solar photovoltaic	53	50	95
wind	29	5.5	14
nuclear	22	6	10 - 26
hydro	11	3	-

Electricity technology	Energy intensity (kWh_{th}/kWh_{el})	Greenhouse gas intensity ($g\ CO_2\text{-}e/kWh_{el}$)
Light water reactors	0.18 (0.16 – 0.40)	60 (10 – 130)
Heavy water reactors	0.20 (0.18 – 0.35)	65 (10 – 120)
Black coal (new subcritical)	2.85 (2.70 – 3.17)	941 (843 – 1171)
Black coal (supercritical)	2.62 (2.48 – 2.84)	863 (774 – 1046)
Brown coal (new subcritical)	3.46 (3.31 – 4.06)	1175 (1011 – 1506)
Natural gas (open cycle)	3.05 (2.81 – 3.46)	751 (627 – 891)
Natural gas (combined cycle)	2.35 (2.20 – 2.57)	577 (491 – 655)
Wind turbines	0.066 (0.041 – 0.12)	21 (13 – 40)
Photovoltaics	0.33 (0.16 – 0.67)	106 (53 – 217)
Hydroelectricity (run-of-river)	0.046 (0.020 – 0.137)	15 (6.5 – 44)

Emissions intensity of a range of generating technologies. Figures in brackets indicate range. Taken from Lenzen, M (2008), linked from the image.

Energy production – EROI and EPBT

Energy Return On Investment (EROI)

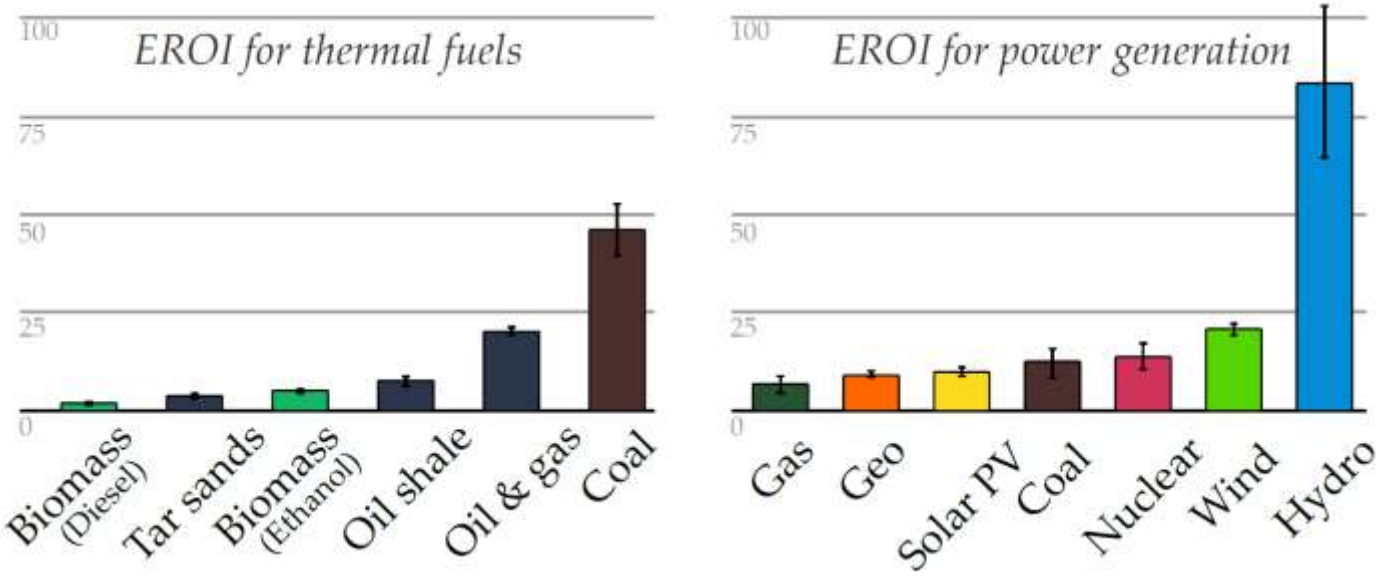
$$EROI = \frac{Generated\ energy}{Invested\ energy}$$

The higher the better

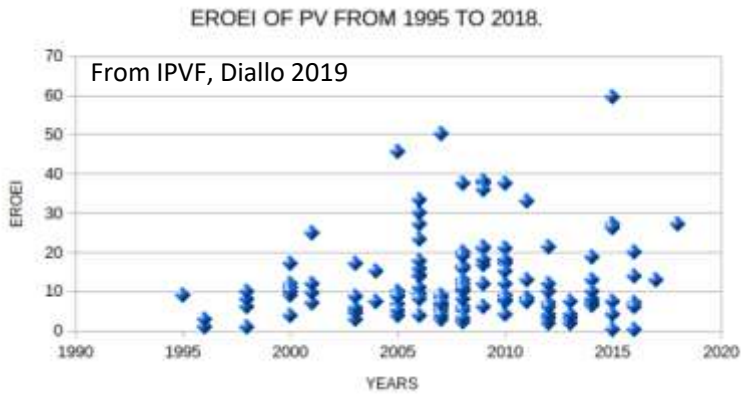
Energy Pay Back Time (EBPT)

$$EPBT = 1/(EROI \text{ x lifetime})$$

In years

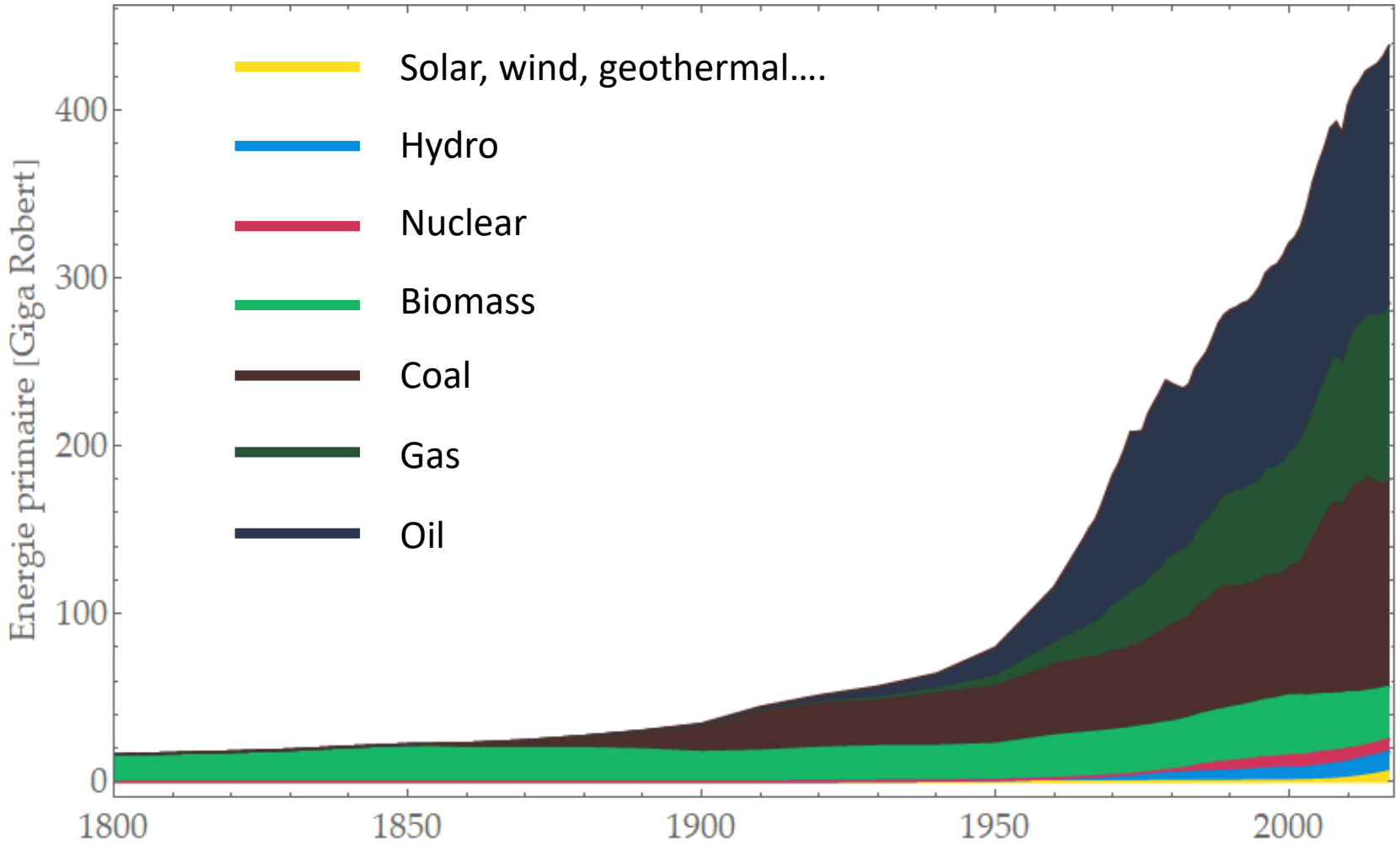


Charles A.S. Hall, et al. Energy Policy, 64:141–152 (2014)



Careful on the updates values !
Some progress are made + uncertainties

2.1 Fossil fuels



These!
About 80%

2.1 Fossil fuels - production

Future development ?

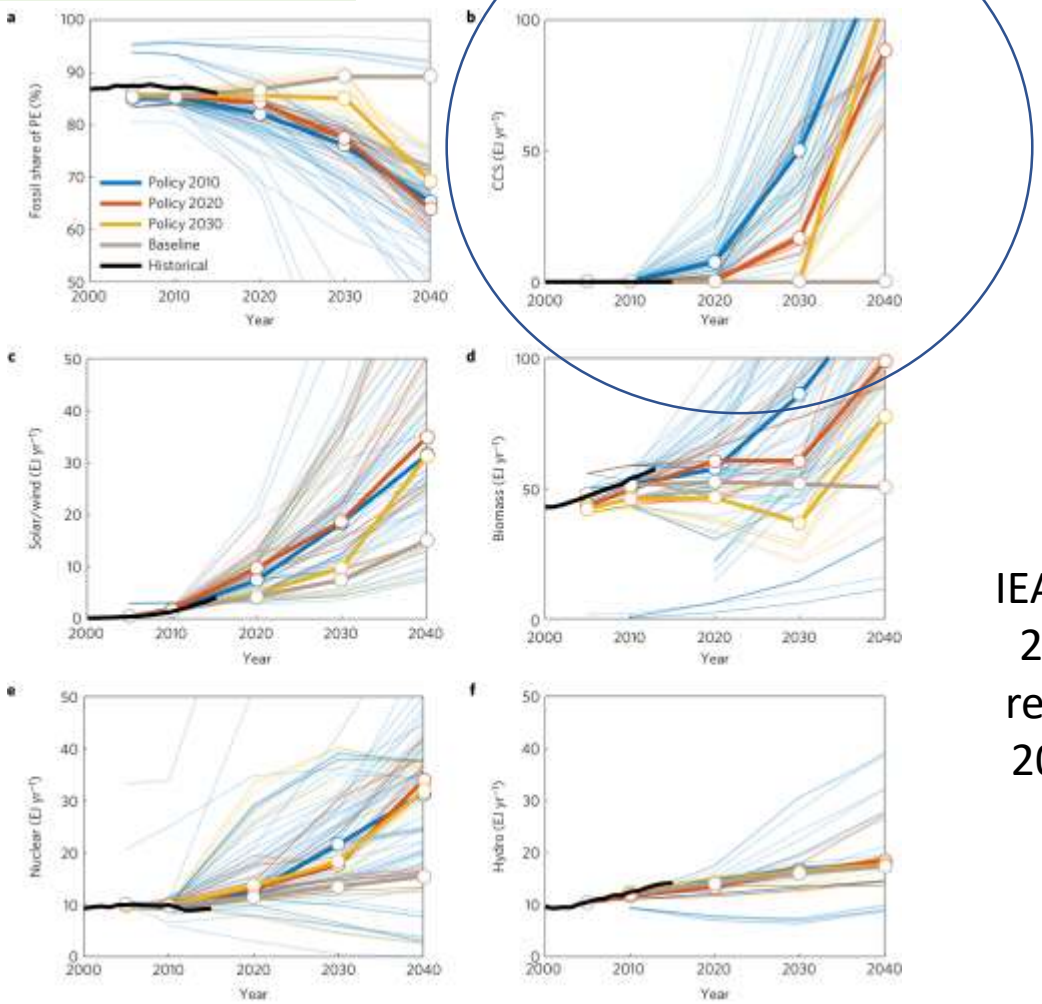
Just no way

(meanwhile… we have to deal with CO2)

Energy production – CO2 emission

Co2 capture and storage (CCS) is key in plenty of scenarios (116)

Global pipeline of commercial CCUS facilities operating and in development, 2010-2021



IEA estimate : 20% of CO_2 reduction by 2050 due to CCS

Red Alert !

Today CCS is about 20-40 $MtCO_2$/year
And world emission is 1000 times bigger !
(Total CCS today is less than the biggest coal power station)

Potential is about : 10 000 Gt (source INERIS,IPCC)
Also very expensive : 100 - 150€/tCO2

Peters, G. P. et al. (2017) Key indicators to track current progress and future ambition of the Paris Agreement, Nature Climate Change, doi:10.1038/nclimate3202

Energy production – CO2 emission - CCS

https://www.iea.org/articles/etp-clean-energy-technology-guide

Notion of TRL (Technology readiness level)

Readiness level ?	Sector	Technology
6	CO2 infrastructure > **Direct air capture**	Solid DAC (S-DAC)
6	CO2 infrastructure > **Direct air capture**	Liquid DAC (L-DAC)

Readiness levels

1	Initial idea Basic principles have been defined
2	Application formulated Concept and application of solution have been formulated
3	Concept needs validation Solution needs to be prototyped and applied
4	Early prototype Prototype proven in test conditions
5	Large prototype Components proven in conditions to be deployed
6	Full prototype at scale Prototype proven at scale in conditions to be deployed
7	Pre-commercial demonstration Prototype working in expected conditions
8	First of a kind commercial Commercial demonstration, full-scale deployment in final conditions
∧ Technology readiness	
∨ Market readiness	
9	Commercial operation in relevant environment Solution is commercially available, needs evolutionary improvement to stay competitive
10	Integration needed at scale Solution is commercial and competitive but needs further integration efforts
11	Proof of stability reached Predictable growth

Solid direct air capture (S-DAC) is a technology aiming at capturing CO2 fro use it as a feedstock or store it underground. This technology relies on amine solid support

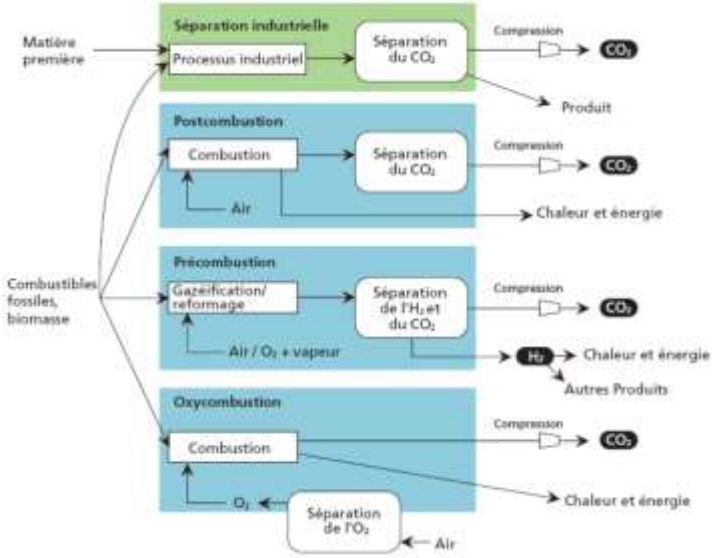
Liquid direct air capture (L-DAC) is a technology aiming at capturing CO2 fro use it as a feedstock or store it underground. This technology relies on wat strong affinity for CO2 (e.g. sodium hydroxide, calcium hydroxide and potassiu

Energy production – CO2 emission - CCS

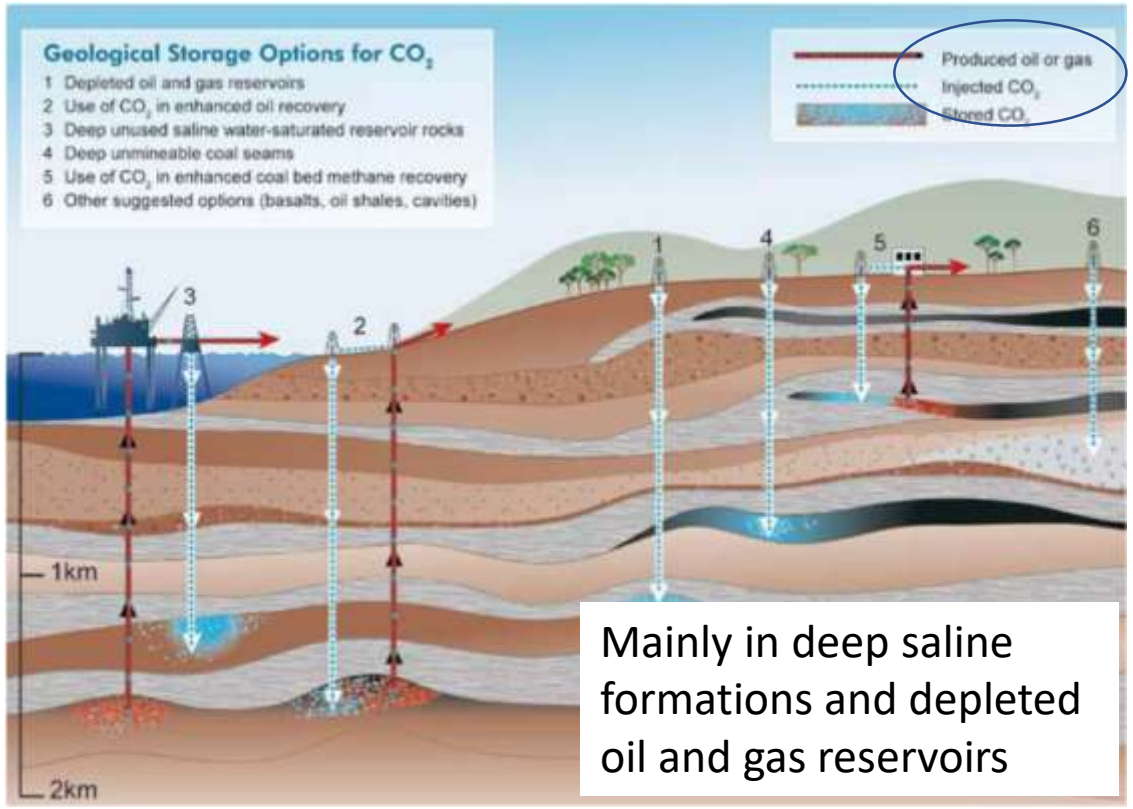
Readiness level ?	Sector	Technology	Step in value chain	Importance for net-zero emissions
9	CO2 infrastructure > **CO2 storage**	Saline formation	Saline formation	Very high
7	CO2 infrastructure > **CO2 storage**	Depleted oil and gas reservoir	Depleted oil and gas reservoir	High
7-8	CO2 infrastructure > **CO2 storage**	Advanced monitoring technologies	Advanced monitoring technologies	High
11	CO2 infrastructure > **CO2 storage**	CO2-enhanced oil recovery	CO2-enhanced oil recovery	Moderate
4	CO2 infrastructure > **CO2 storage**	Mineral storage	Mineral storage	Moderate

Energy production – CO2 emission CCS

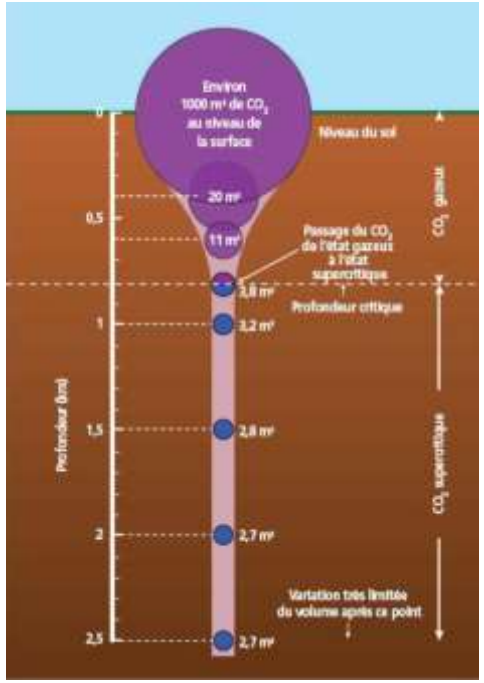
Capture
(essentially to reduce industrial CO_2 production)



Storage
(Careful : possible in specific location)



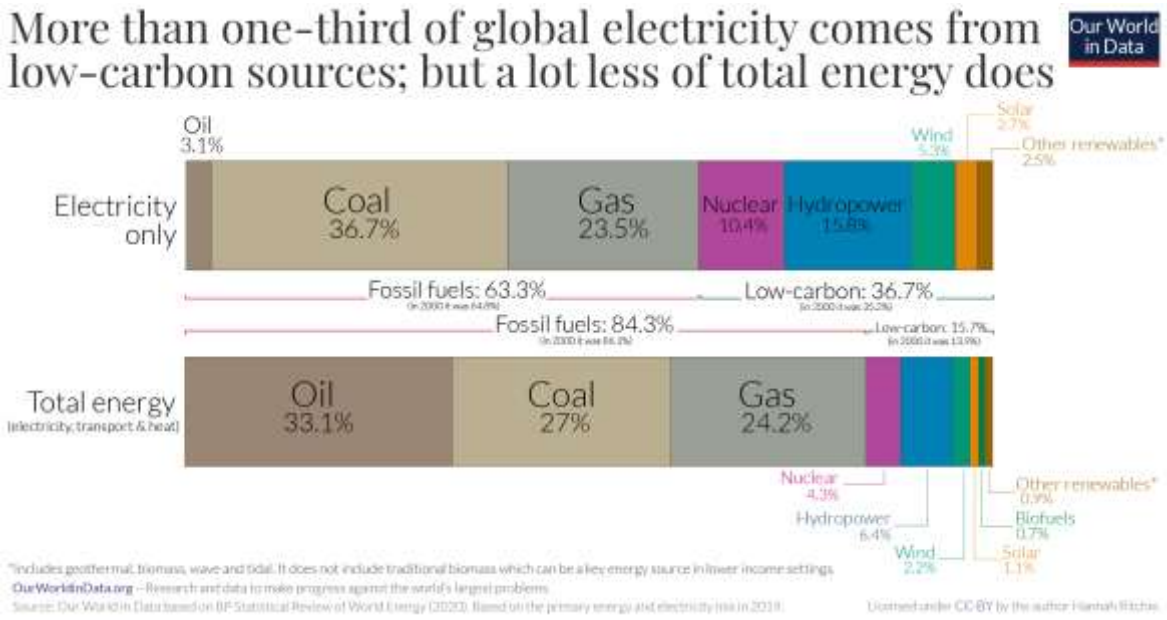
Mainly in deep saline formations and depleted oil and gas reservoirs

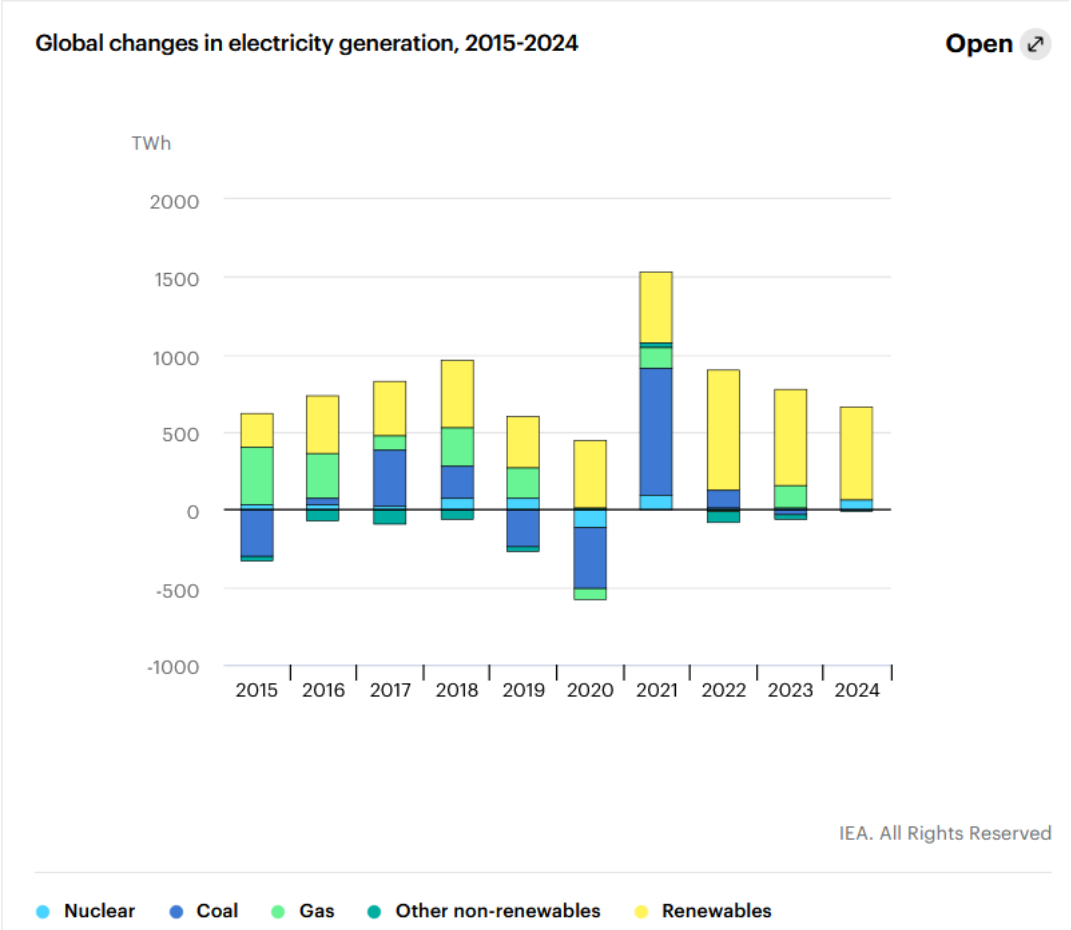


Ex of technical details : INERIS DRS-08–95145-11842B

2.2 Electricity

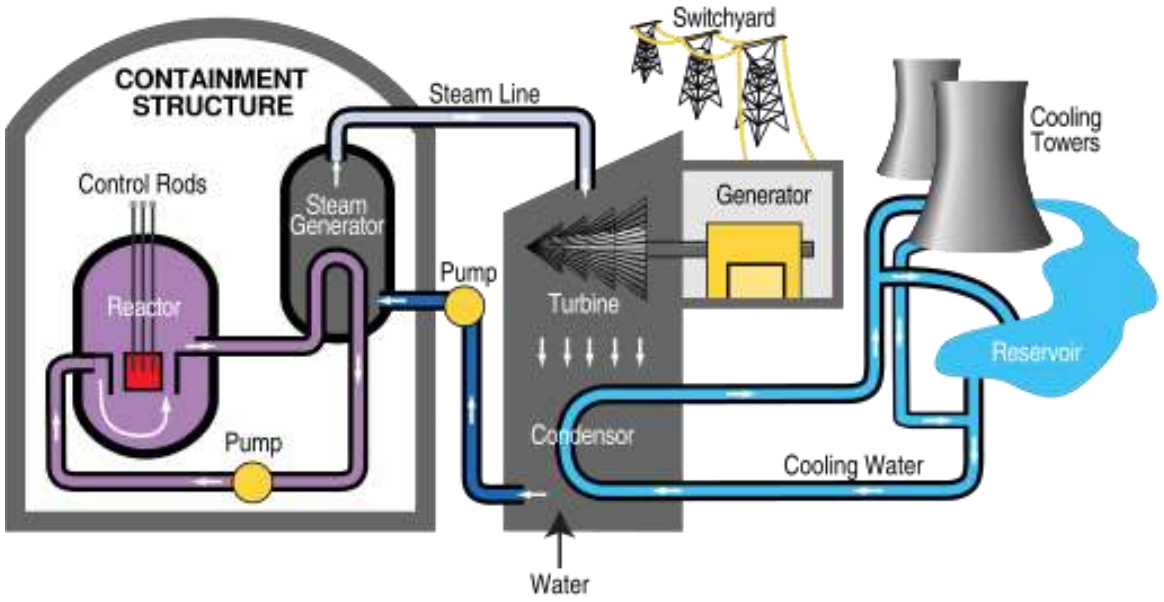
The *cleanest* energy but yet not clean and HAS TO BE cleaner

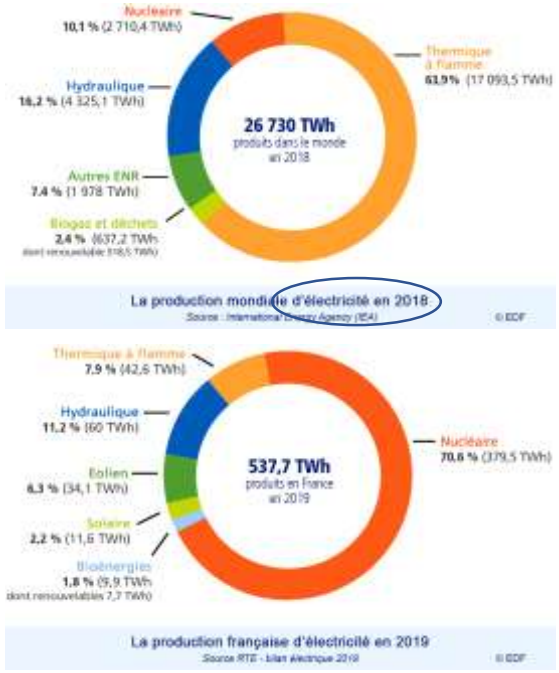




https://ourworldindata.org/electricity-mix

2.2 Electricity – nuclear – fusion ?





- ❑ Type of coolant:
  - Water cooled reactors (93% of current reactors)
  - Molten salt reactors
  - Liquid metal cooled reactors
  - Gas cooled reactors
  - Organic nuclear reactors
- ❑ •Shape...

- ❑ Phase of fuel:
  - Solid fuelled (most common)
  - Fluid fuelled (Aqueous homogeneous reactor, Molten salt reactor)
  - Gas fuelled (proposed)

Different fission reactors

Puissance	Nombre de réacteurs
1 450 MW	4
1 300 MW	20
900 MW	32

Nombre de réacteurs nucléaires en France par puissance

Source : EDF 2020

NB : Efficiency about 33%

© EDF

2.2 Electricity – nuclear

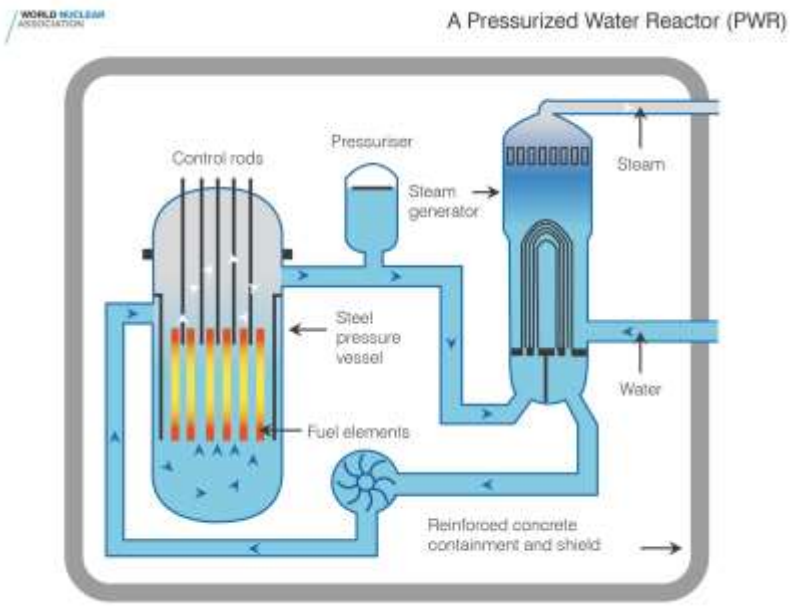
Readiness level ?	Sector	Technology	Step in value chain	Importance for net-zero emissions
10-11	Energy transformation > **Power**	Generation > **Nuclear** > Large-scale light-water reactor	Generation	High
8-9	Energy transformation > **Power**	Generation > **Nuclear** > Sodium-cooled fast reactor	Generation	Moderate
7-8	Energy transformation > **Power**	Generation > **Nuclear** > High-temperature reactor and very high temperature reactor	Generation	Moderate
6-9	Energy transformation > **Power**	Generation > **Nuclear** > Light water reactor-based small modular reactor	Generation	Moderate
1-3	Energy transformation > **Power**	Generation > **Nuclear** > Fusion	Generation	Moderate

NB : I let you read literature on

- Uranium extraction,
- risks (accident, radiation),
- variety of radioactive waste (minor actinides)

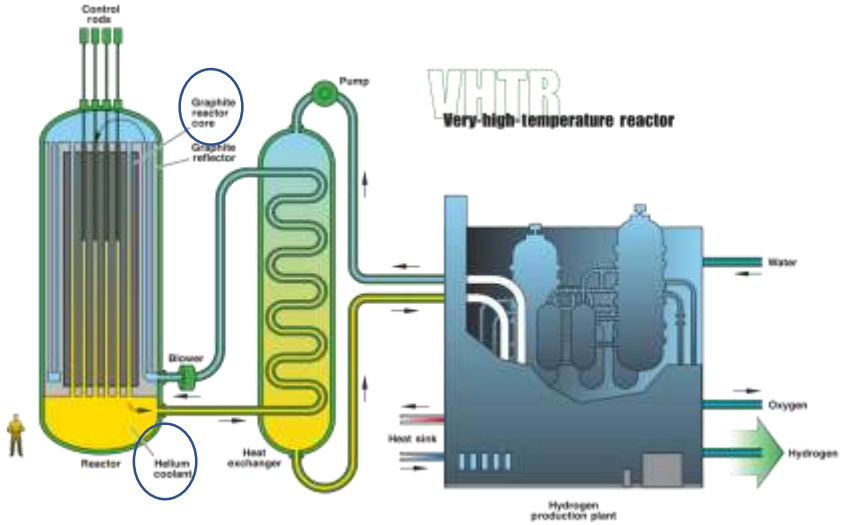
2.2 Electricity – nuclear

GEN III

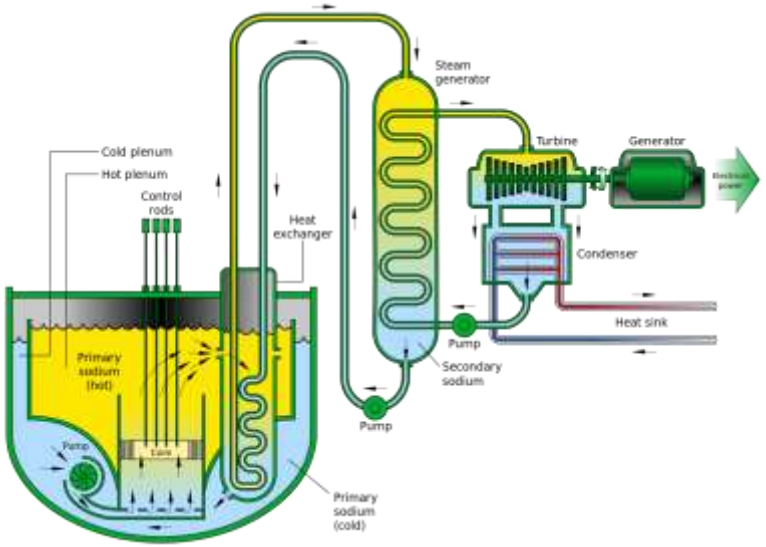


EPR (Gen3III+): MOX (UO_2 + Pu) is used ?

GEN IV



GEN IV

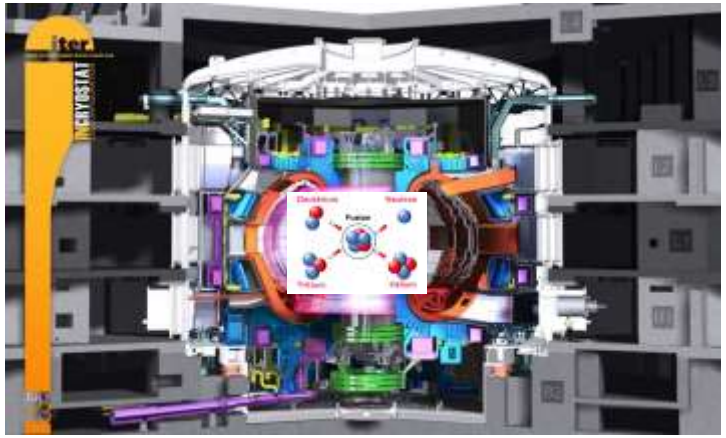


Much better waste production and use
More efficient
But cost, delay and material science issues ?

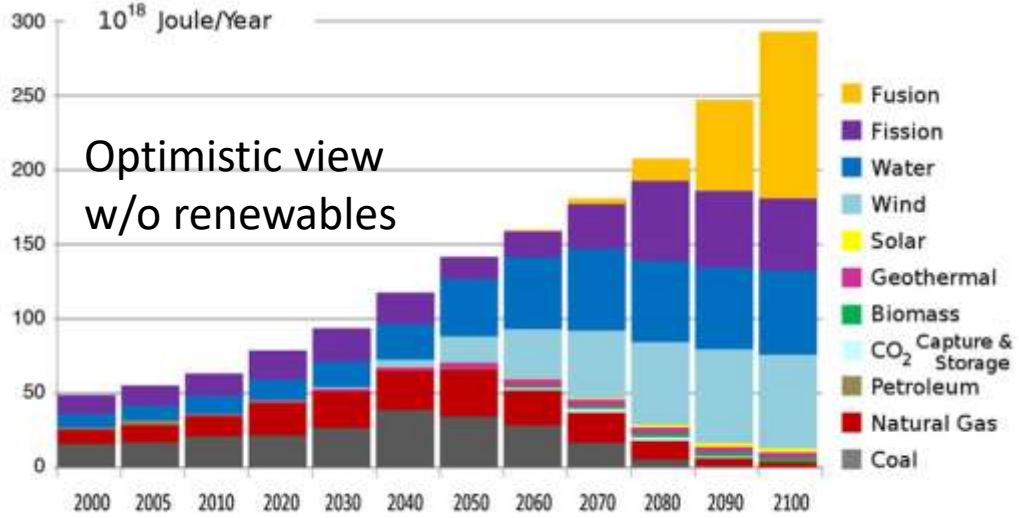
See for instance : French ASTRID project

2.2 Electricity – nuclear – fusion ?

Careful, too late to play a role on climate change



Tokamak of ITER project
(prototype full start by 2026)

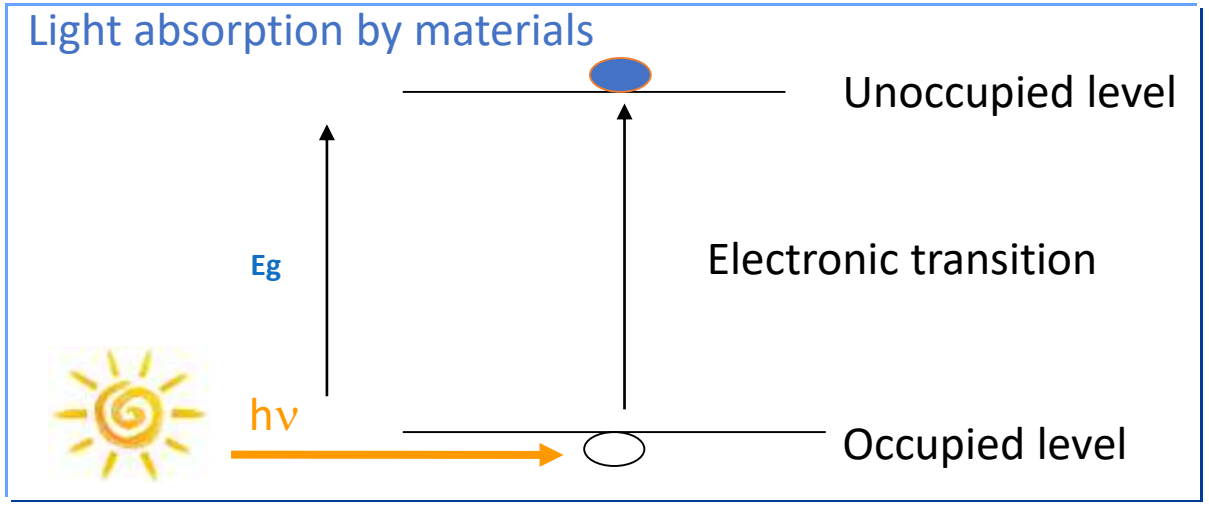


- ✓ fuel = light nuclei (deuterium, tritium, lithium)
  almost unlimited resources (D, Li) or regenerable (T, ^{3}He)
- ✓ no production of **long-lived** radioactive waste
- ✓ no chain reaction ⇒ **no risk of runaway**
- ✓ no generation of fissile products possible
  ⇒ **limited risk of nuclear weapons proliferation**
- ✓ **very low quantity** of radioactive products in the reactor

- ✗ **large installations** ⇒ centralized production
  not suitable for distributed production (emerging countries)
- ✗ **short-lived activation**
- ✗ advanced technologies (superconductivity, materials)
  - ✗ very high temperatures
  - ✗ high neutron flux
- ✗ **unstable** process, **difficult to sustain**
- ✗ risk of **contamination by tritium**

2.2 Electricity - photovoltaics

- The only direct energy conversion : light to electricity
- Photovoltaic effect : appearance of a voltage in semiconducting material where sufficient energetic photons are absorbed
- Not linked to pn junction…



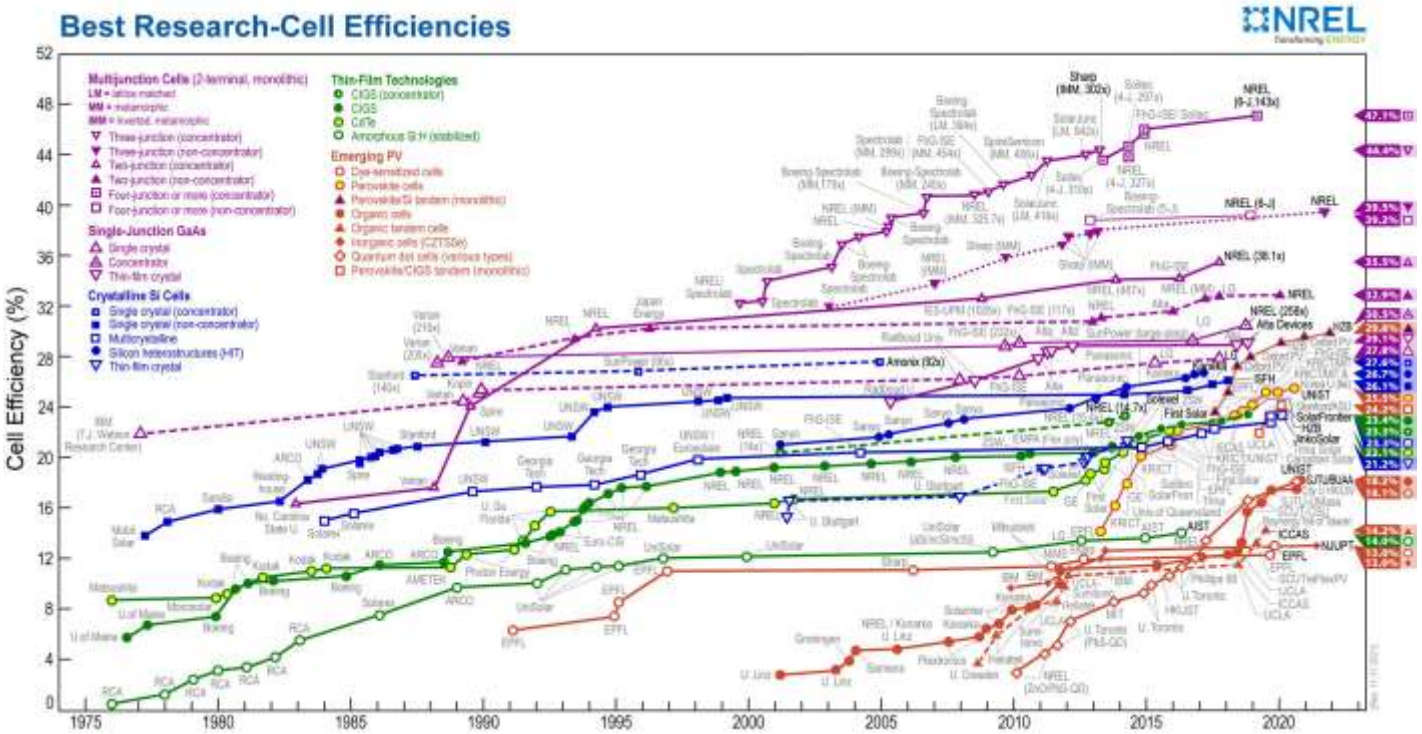
Generation	Separation	Collection
of carriers due to light absorption	of carriers	of carriers at terminals
Voltage (PV effect)	Current	

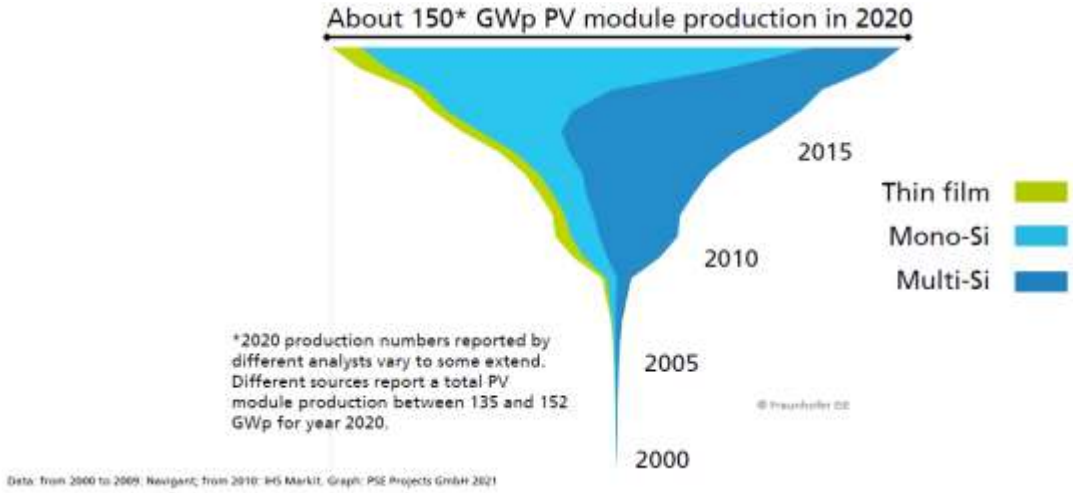
2.2 Electricity - photovoltaics

Readiness level ?	Sector	Technology	Step in value chain	↓ Importance for net-zero emissions
9-10	Energy transformation > **Power**	Generation > Solar > **Photovoltaic** > Crystalline silicon	Generation	High
8	Energy transformation > **Power**	Generation > Solar > **Photovoltaic** > Thin-film PV	Generation	Moderate
9-10	Energy transformation > **Power**	Generation > Solar > **Photovoltaic** > Concentrated PV	Generation	Moderate
9	Energy transformation > **Power**	Generation > Solar > **Photovoltaic** > Multi-junction cell	Generation	Moderate
6	Energy transformation > **Power**	Generation > Solar > **Photovoltaic** > Organic thin-film solar cell	Generation	Moderate
4	Energy transformation > **Power**	Generation > Solar > **Photovoltaic** > Perovskite solar cell	Generation	Moderate
8	Energy transformation > **Power**	Generation > Solar > **Photovoltaic** > Floating solar PV	Generation	Moderate

2.2 Electricity - photovoltaics

Many technologies : silicon by far the most important
but thin films persistent for niche markets

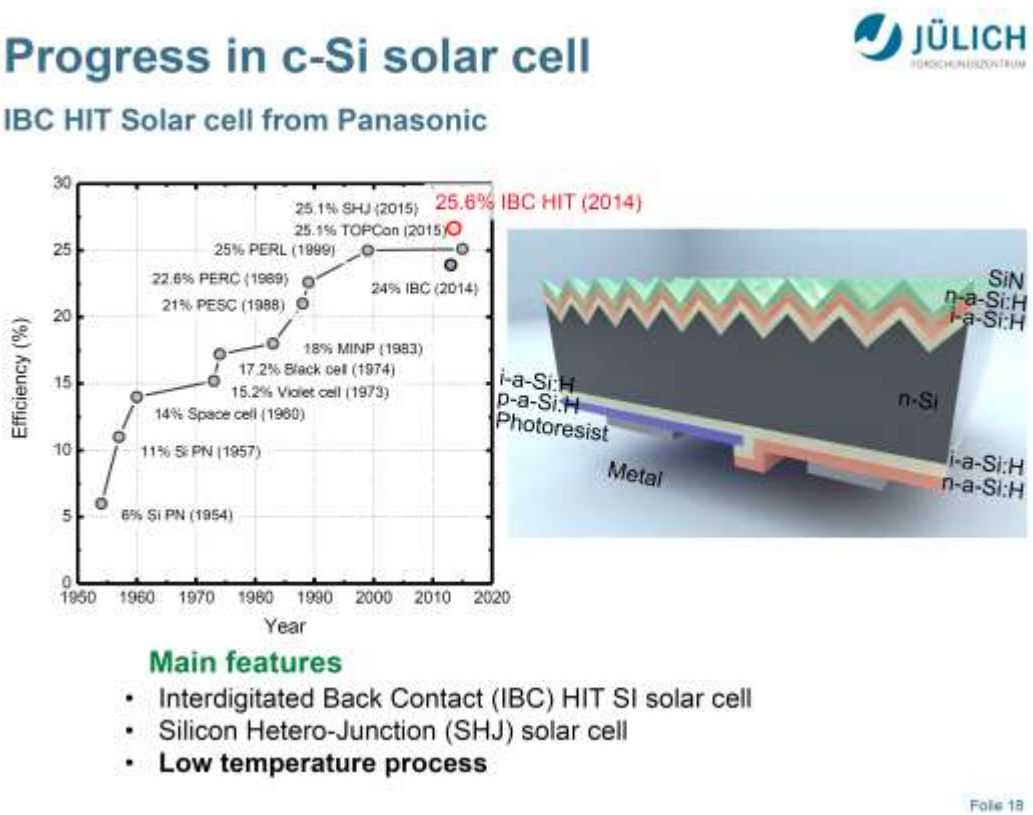


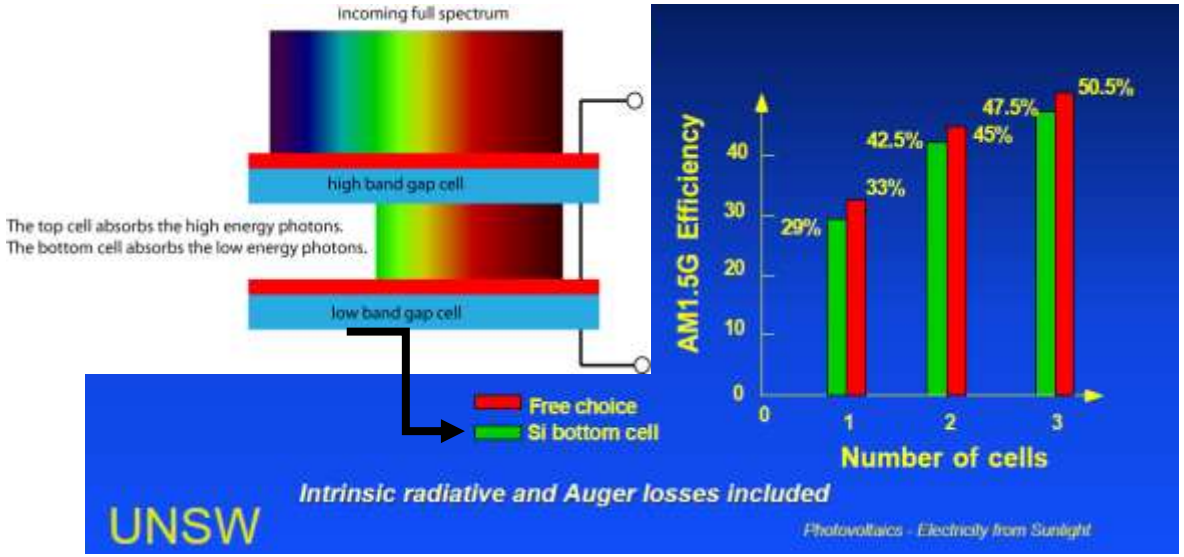


Single junction : limit at about 30% efficiency, 300W panels
Sun is about 100W/m²

Exponential growth dominated by Silicon

2.2 Electricity - photovoltaics



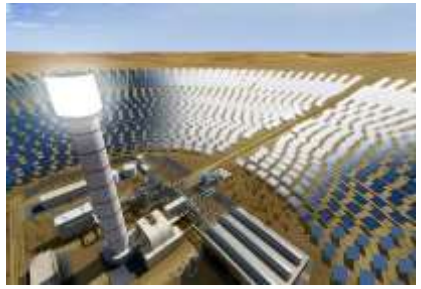


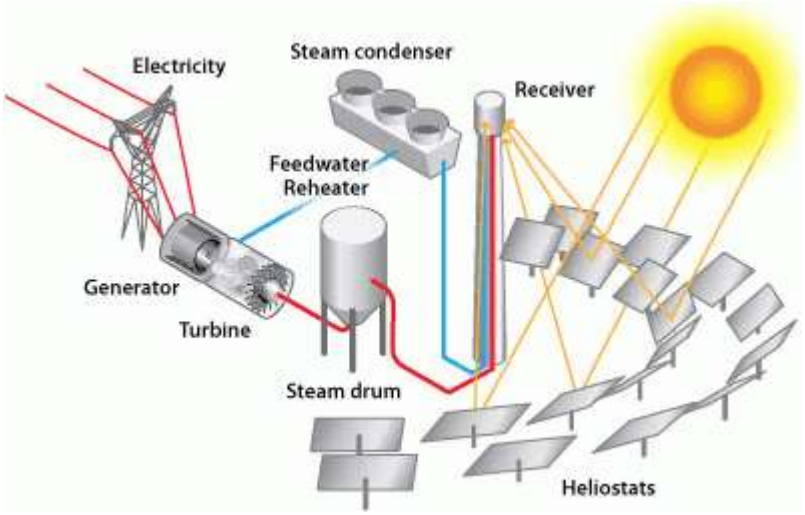
Silicon has a slow improvement but it is cheap
Some Thins films have fast developement

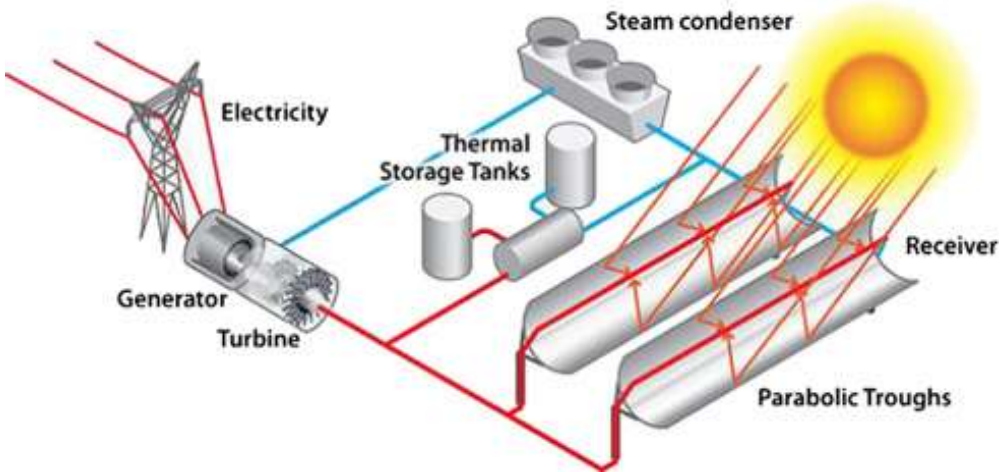
Multi junction comes from spatial application
Might be a way to increase efficiency above 30%

2.2 Electricity – Solar thermal electricity

Readiness level ?	Sector	Technology	Step in value chain	↓ Importance for net-zero emissions
9	Energy transformation > **Power**	Generation > Solar > **Solar thermal electricity** > Solar tower	Generation	High
9	Energy transformation > **Power**	Generation > Solar > **Solar thermal electricity** > Parabolic trough	Generation	High
7	Energy transformation > **Power**	Generation > Solar > **Solar thermal electricity** > Linear Fresnel reflector	Generation	Moderate





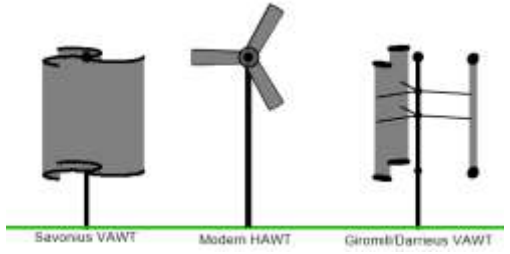


Possible heat storage for hours

2018 : 5 GW

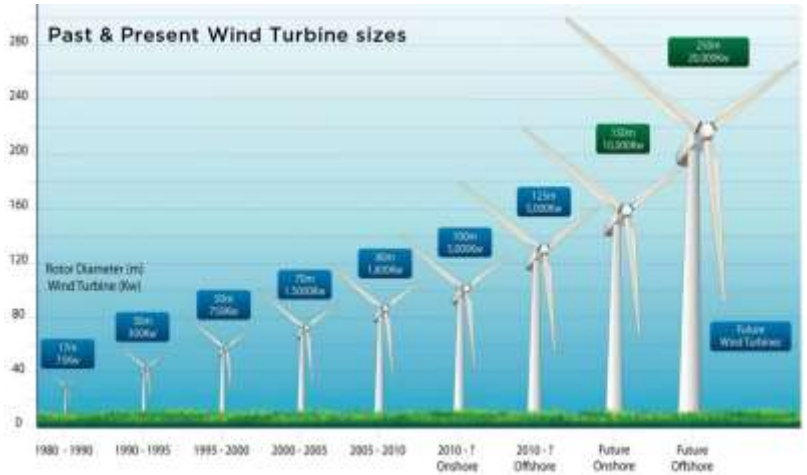
2.2 Electricity – wind turbine

Readiness level ?	Sector	Technology	Step in value chain	↓ Importance for net-zero emissions
9-10	Energy transformation > **Power**	Generation > **Wind** > Onshore	Generation	High
9	Energy transformation > **Power**	Generation > **Wind** > Offshore > Seabed fixed offshore wind turbine	Generation	High
8	Energy transformation > **Power**	Generation > **Wind** > Offshore > Floating offshore wind turbine	Generation	High
3-5	Energy transformation > **Power**	Generation > **Wind** > Airbone wind energy system	Generation	Moderate
5	Energy transformation > **Power**	Generation > **Wind** > Offshore > Floating hybrid energy platform	Generation	Moderate

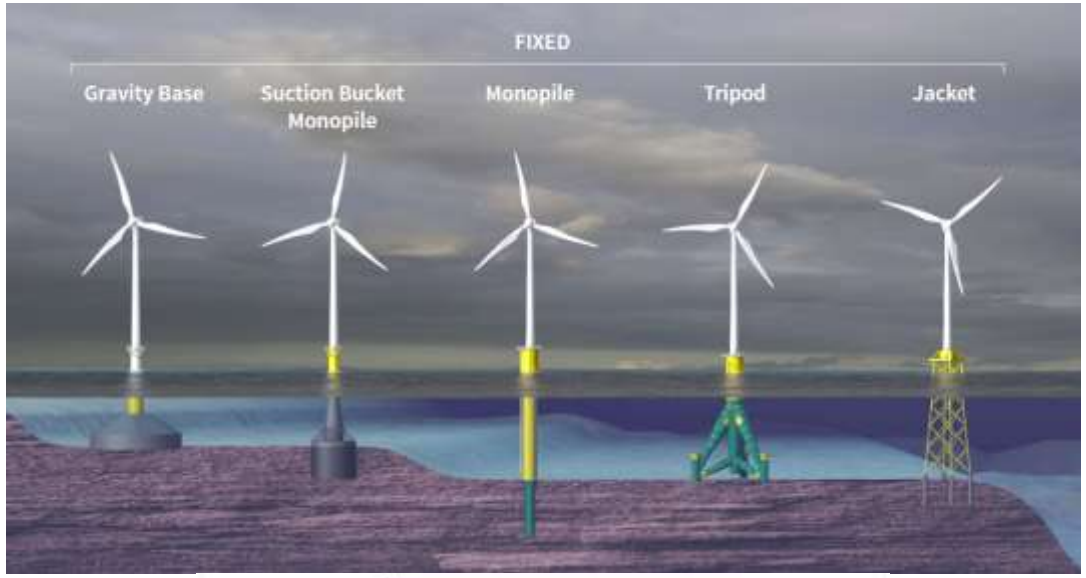


Efficiency : The Bett Limit is 59.3%,
typical output power range kW to 10 MW

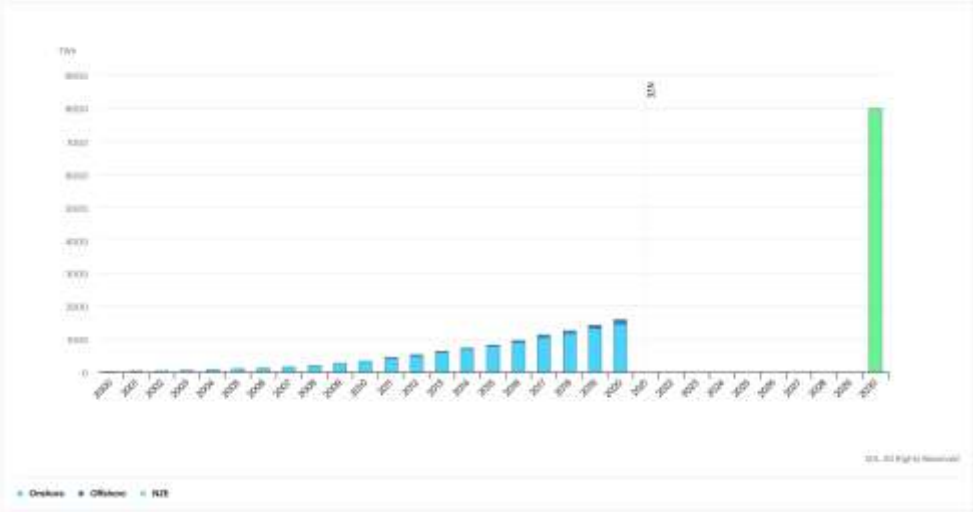
Wind turbine exists in many forms (wind speed)



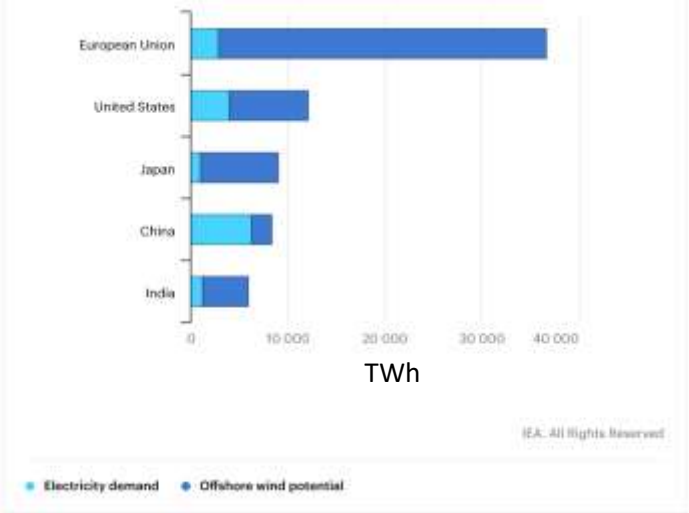
2.2 Electricity – wind turbine

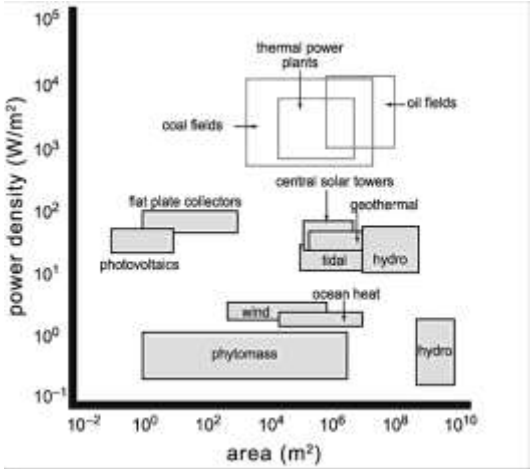


Wind power generation in the Net Zero Scenario, 2000-2030



Offshore wind technical potential and electricity demand, 2018





- Very fast growth
- Important in all scenarios
- Require space
- Off shore is key (cost reduction needed)

2.2 Electricity – biomass and biofuels

Readiness level ?	Sector	Technology	Step in value chain	Importance for net-zero emissions
3	Energy transformation > **Power**	Generation > **Biomass** > CCUS > Pre-combustion/physical absorption	Generation	High
8	Energy transformation > **Power**	Generation > **Biomass** > CCUS > Post-combustion/chemical absorption	Generation	High

Same as natural gas and coal

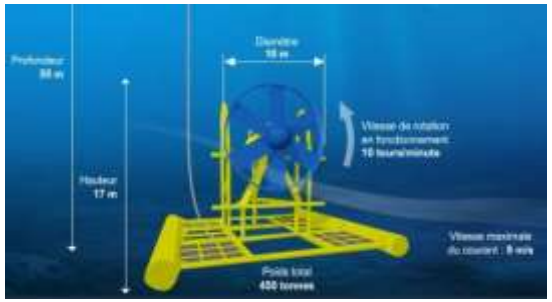
Readiness level ?	Sector	Technology	Step in value chain	Importance for net-zero emissions
6	Energy transformation > **Biofuels**	Production > Biodiesel and biokerosene > Gasification and Fischer-Tropsch > without CCUS	Production	Very high
4	Energy transformation > **Biofuels**	Production > Biodiesel and biokerosene > Gasification and Fischer-Tropsch > with CCUS	Production	Very high
5	Energy transformation > **Biofuels**	Production > Biodiesel and biokerosene > Gasification and hydrogen enhacement and Fischer-Tropsch	Production	High
6	Energy transformation > **Biofuels**	Production > Biodiesel and biokerosene > Alcohol-to-Jet	Production	High
7	Energy transformation > **Biofuels**	Production > Biodiesel and biokerosene > Synthetic Iso-Paraffins	Production	High
7	Energy transformation > **Biofuels**	Production > Biorefining	Production	High
4-5	Energy transformation > **Biofuels**	Production > Double-cropping (sequential cropping)	Production	High

+ 22 moderate impact solutions

(See ex on transport)

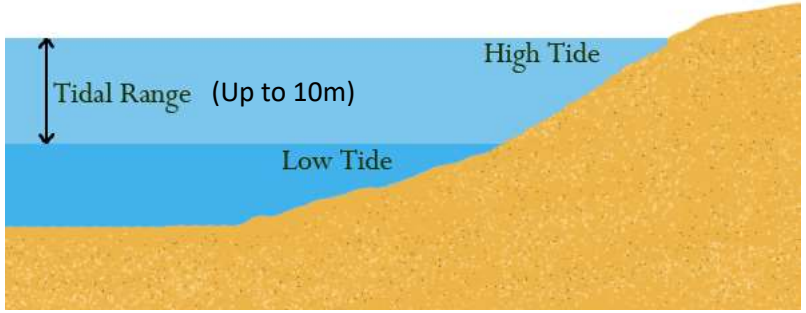
2.2 Electricity - tides

Readiness level ?	Sector	Technology	Step in value chain	Importance for net-zero emissions
5	Energy transformation > **Power**	Generation > **Tidal** > Tidal stream/Ocean current	Generation	High
8-9	Energy transformation > **Power**	Generation > **Tidal** > Tidal range	Generation	High



- Predictable
- Various shapes as wind turbines
- TRL5: play a role in 10 years
- Water Higher density x800 than wind, but less intense
- (2MW : 80m wind turbine vs 20m for **tidal turbine**)

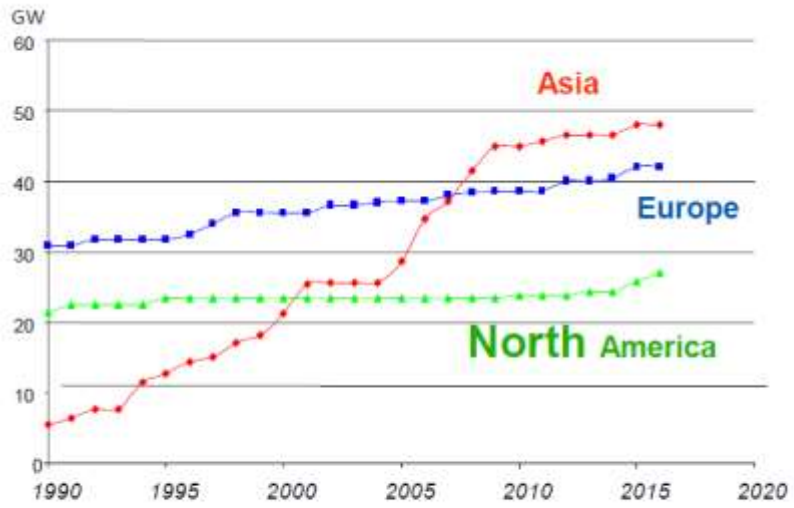
Ex : Since 2010, more than 26.8 MW of tidal power have been deployed in Europe. 11.9 MW are currently in operation and 14.9 MW have been decommissioned
(source : IEA)



Ex : The La Rance **tidal range** (240MW) plant in France generates 500GWh annually for the European electricity grid

2.2 Electricity - hydroelectricity

- The most important renewable energy
- PSP : Key element to store electricity (vs. intermittency from other renewables)

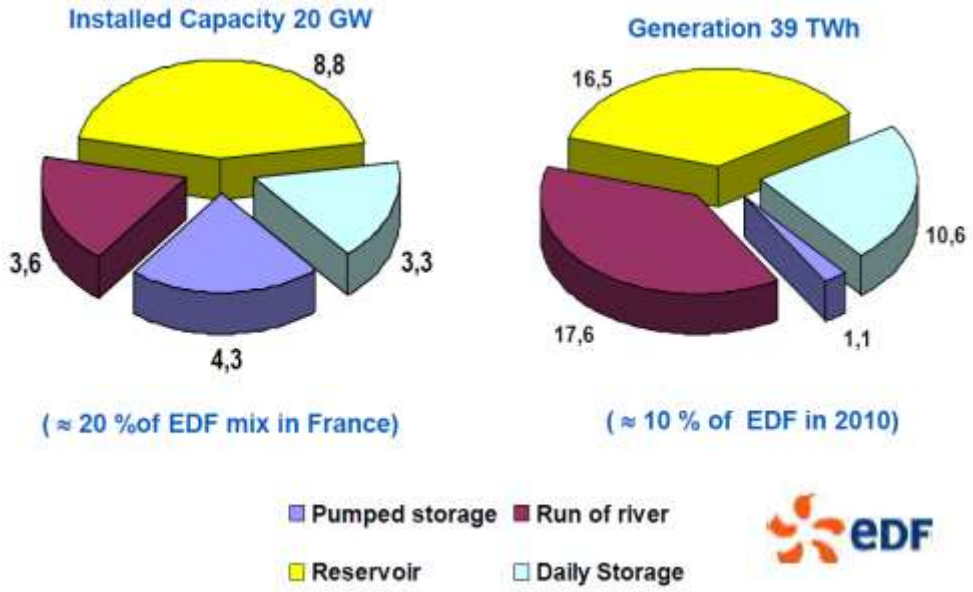


Source : EDF R&D

Total storage capacity in the world (end 2010)

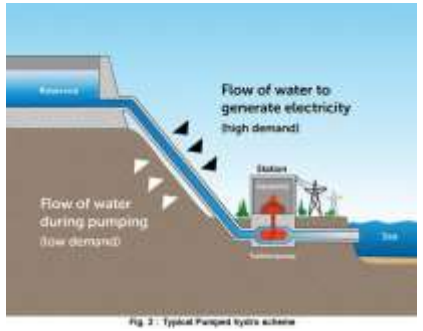
Pumped Storage	: **140** GW
CAES & Gas Turbine	: 0,5 GW
Batteries	: < 0,3 GW

Source : Fraunhofer Institute, EPRI, EDF R&D



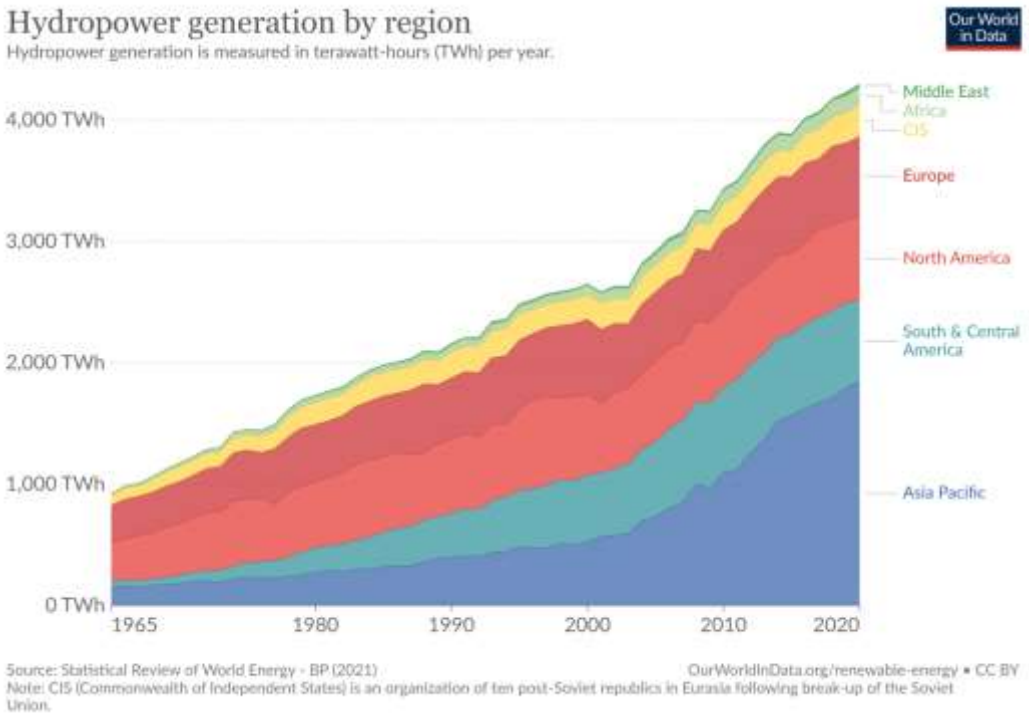
Pump storage power station (PSP)

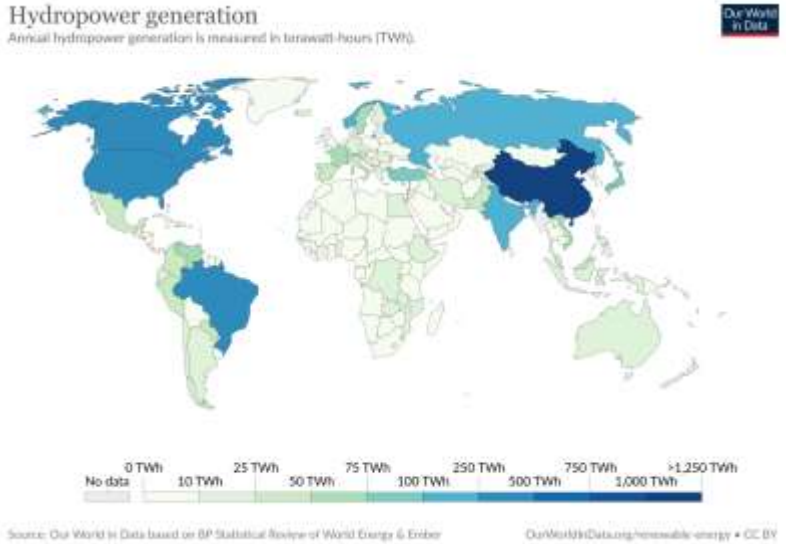
Excellent efficiency (70-90%)

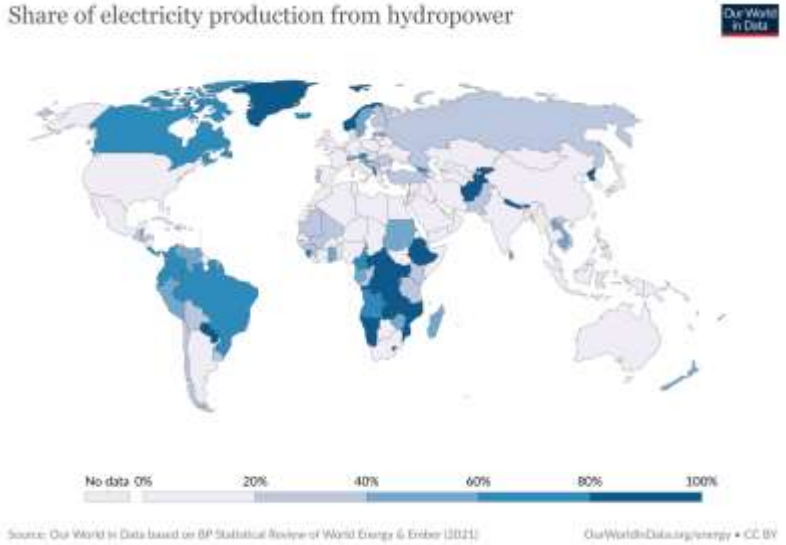


2.2 Electricity - hydroelectricity

- Limited growth due to space except in Asia
- Only a few countries have >50% of their electricity from hydro.

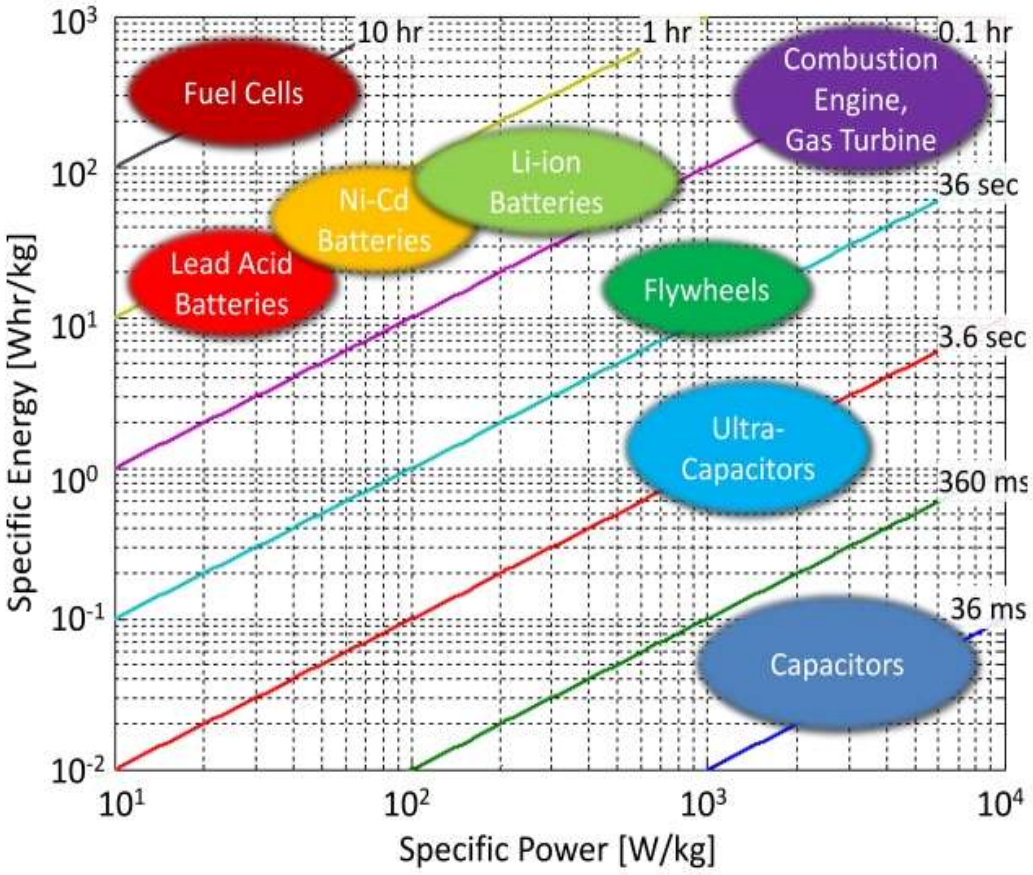


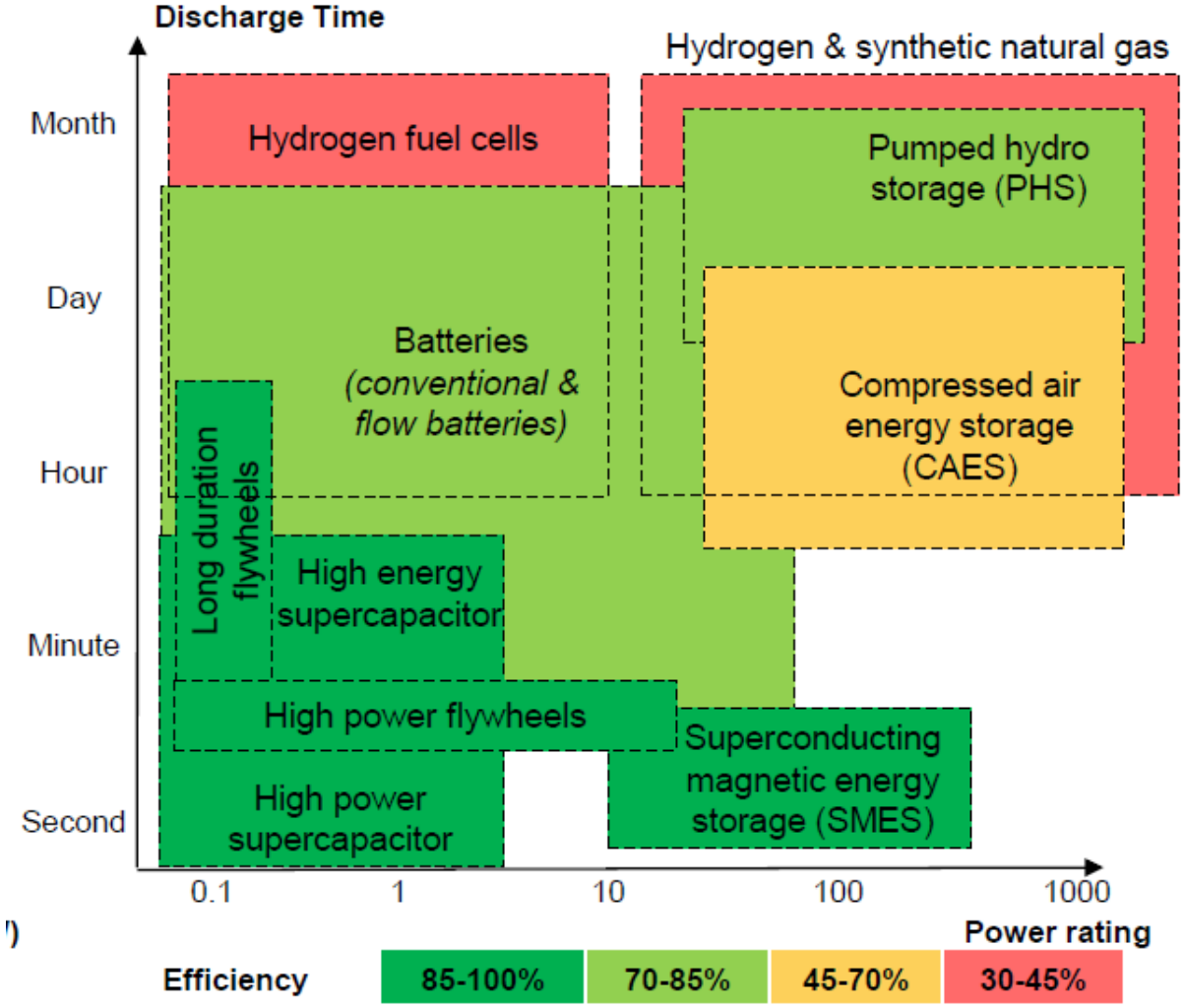




2.2 Electricity - storage

Ragone chart:





2013 SBC Energy Institute

2.2 Electricity - storage

Readiness level ?	Sector	Technology	Step in value chain	Importance for net-zero emissions
9	Energy transformation > **Power**	**Storage** > Battery storage > Lithium-ion (grid-scale or behind-the-meter)	Storage	Very high
8	Energy transformation > **Power**	**Storage** > Battery storage > Redox flow	Storage	High
11	Energy transformation > **Power**	**Storage** > Mechanical storage > Pumped storage	Storage	High
9	Energy transformation > **Power**	**Storage** > Mechanical storage > Flywheel	Storage	Moderate
8	Energy transformation > **Power**	**Storage** > Mechanical storage > Compressed air energy storage	Storage	Moderate
9	Energy transformation > **Power**	**Storage** > Mechanical storage > Liquid air energy storage	Storage	Moderate

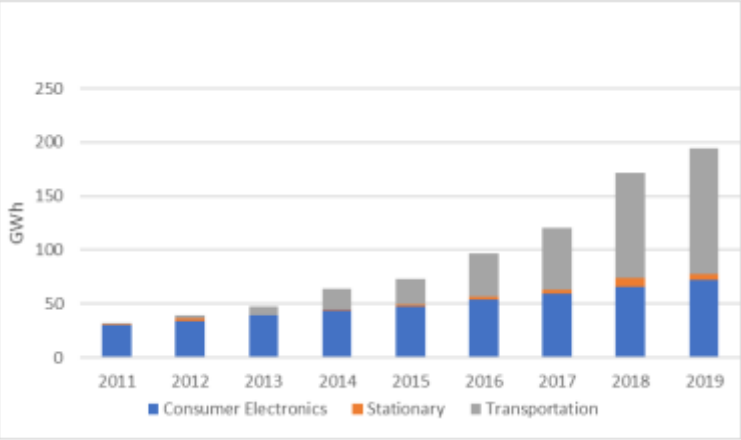
2.2 Electricity – storage- battery

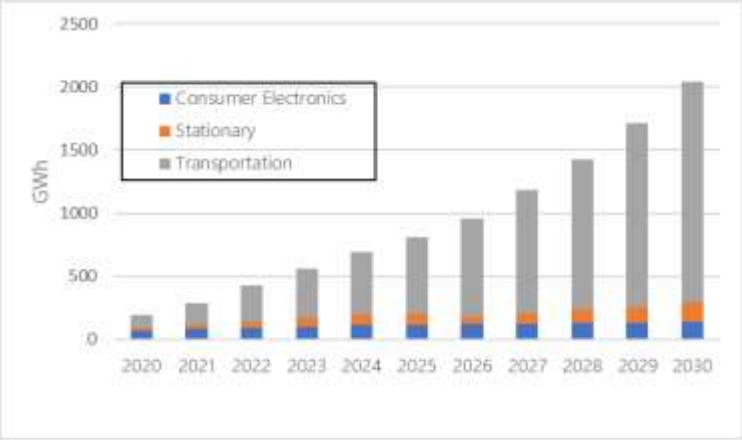
John B. Goodenough, M. Stanley Whittingham, Akira Yoshino
"for the development of lithium-ion batteries"

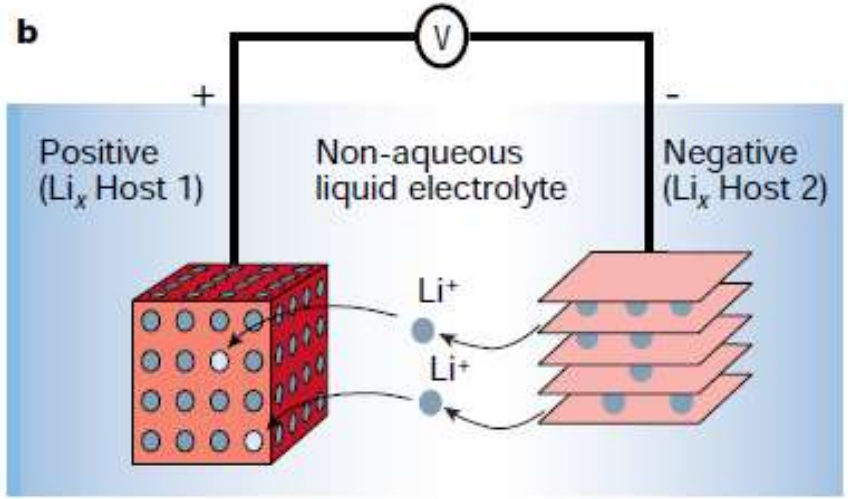
Li-ions

- Originally Li-metal (issue with short circuit)
- Then Li-Polymer vs. Liquid electrolyte
- Li-air in future ?

Development of Electrode is ongoing

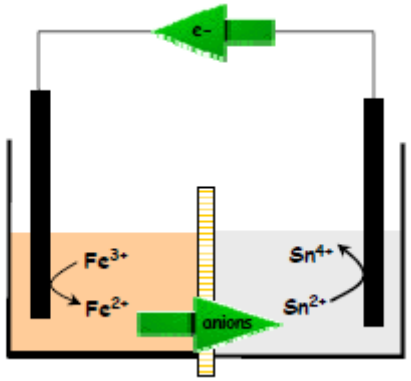




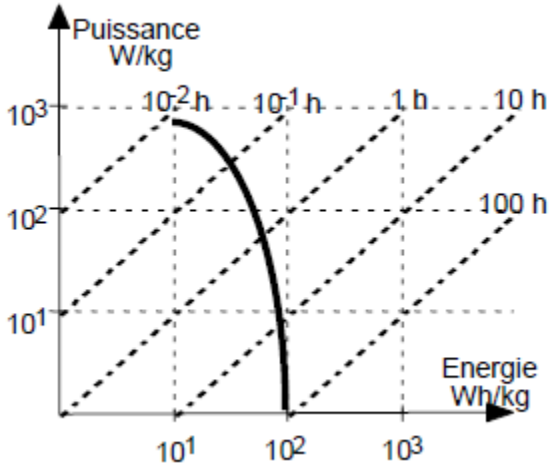


From U.S. Department of Energy

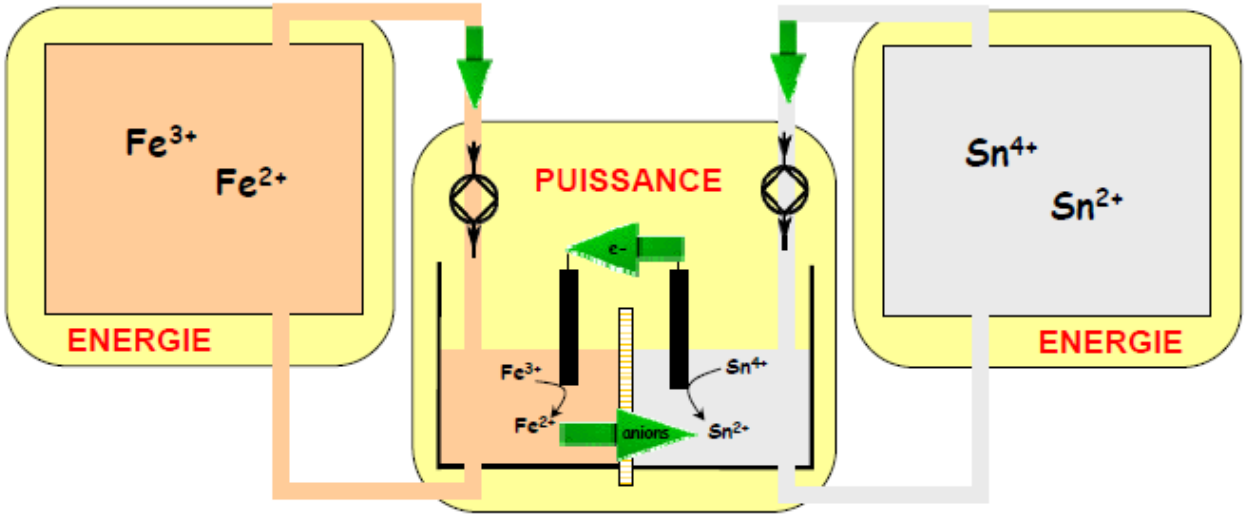
2.2 Electricity – storage- battery



Classical Battery
Power and energy are coupled



Redox-flow



Powers : Sizing
Energy : Electrolyte quantity

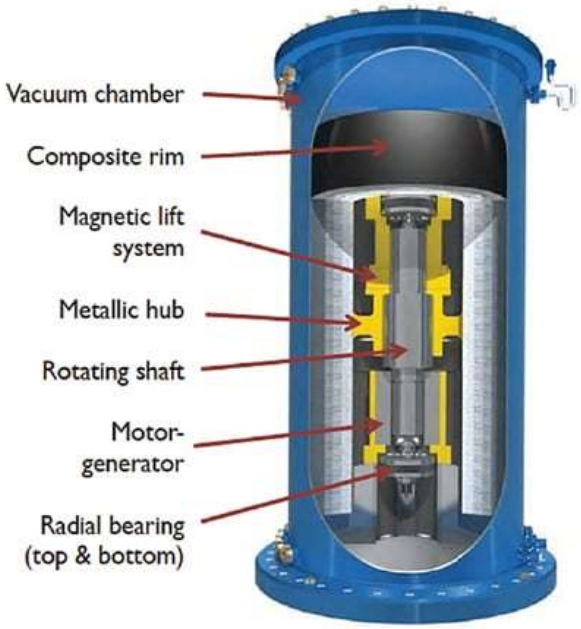
+ Long lifetime

2.2 Electricity – storage - Flywheel

Storing energy as rotation speed

$$E_C = \frac{1}{2} J \omega^2 \qquad J_{\text{cylinder}} = \frac{1}{2} m r^2$$

High power, limited energy
Mechanical constraints (stress on material, bearings…)



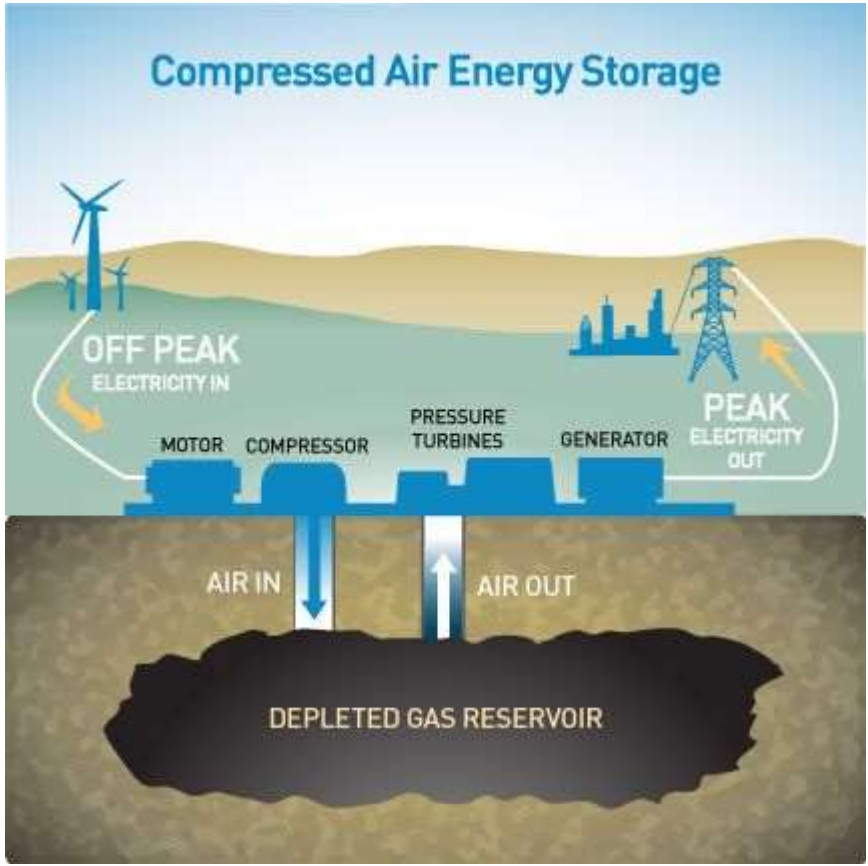
Beacon power system

Hazle Township, Pennsylvania
200 flywheels, 20 MW for frequency regulation

2.2 Electricity – storage - Compressed air

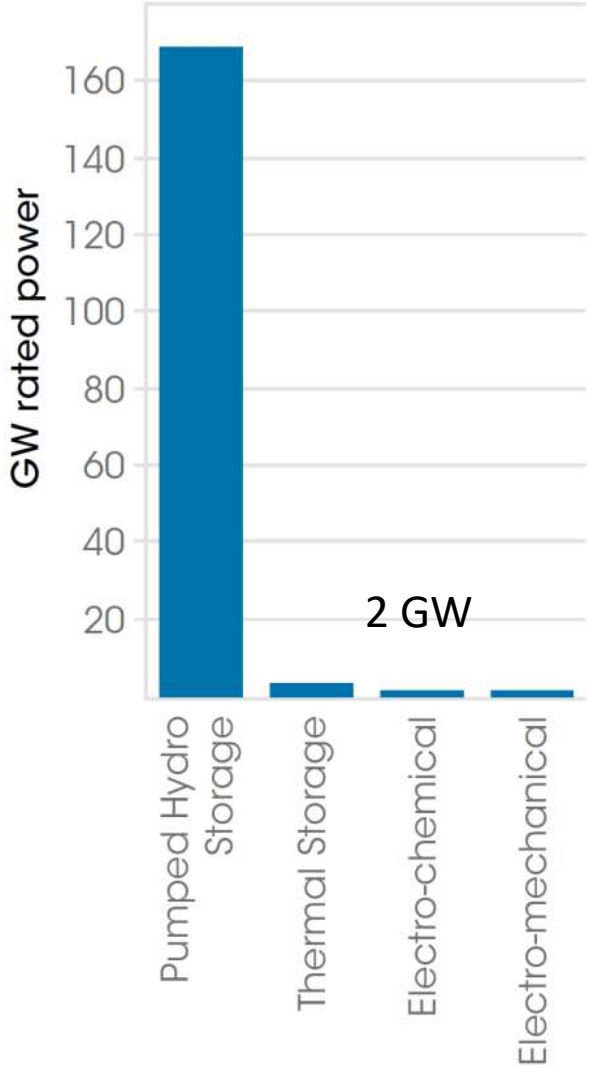
CAES – can be adiabatic

Couple with thermal storage

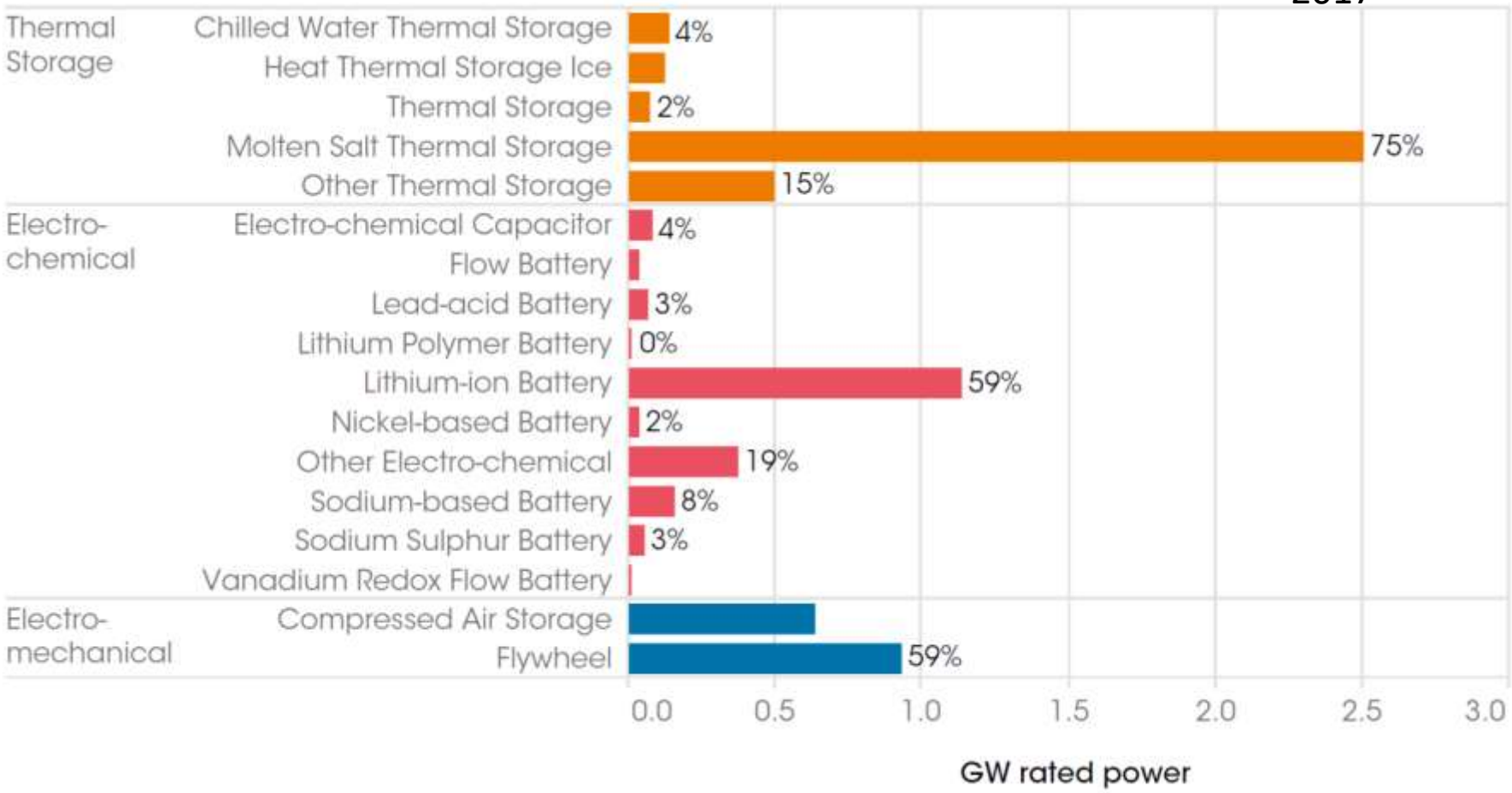


	Huntdorf, Germany	McIntosh, USA
Pressure	45 to 70 bar	45 to 76 bar
Volume	310 000 m^3	560 000 m^3
Power	290 MW	110 MW
Energy	1160 MWh (=4h)	2640 MWh (=24h)

2.2 Electricity – storage - updated values



2017

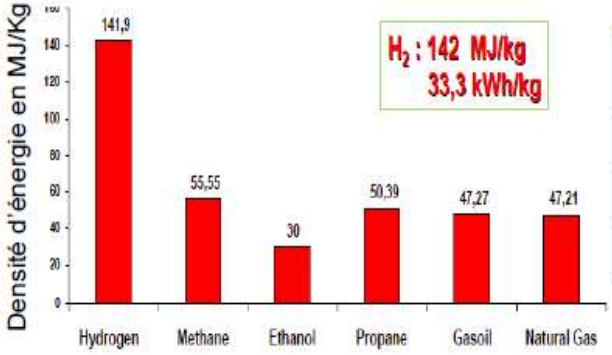


2.3 Hydrogen

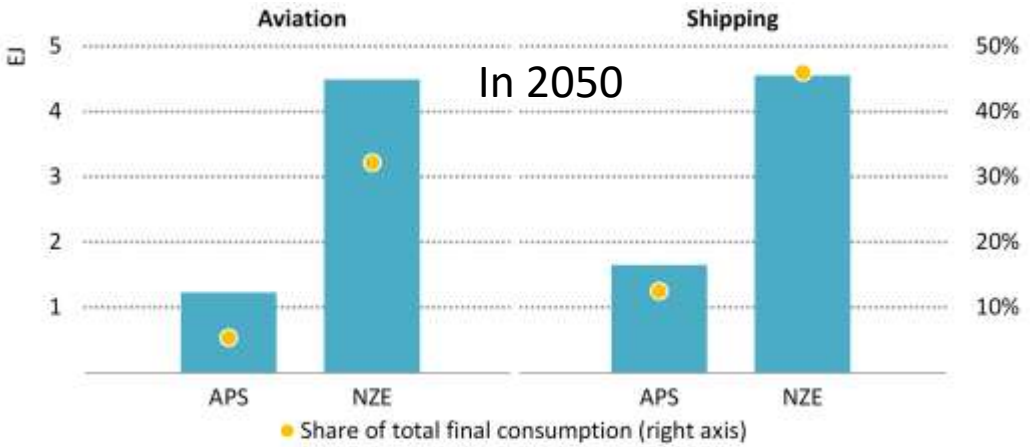
- H_2 is not an Energy ! It is an energy vector (as electricity)

- High mass density, low volume density
- No easy way to produce it in a clean way

- Power-to-power : H2 to electricity (fuel cell)
- Power-to-Gas : about 20%max of H2 in in gas network



Combustible	Densité d'énergie massique (MJ/kg)	Densité d'énergie volumique (MJ/l)
Hydrogène	142	8 (à 70 MPa)
Gaz naturel	54	10 (à 20MPa)
Essence	42	28



International Energy Agency | World Energy Outlook 2021

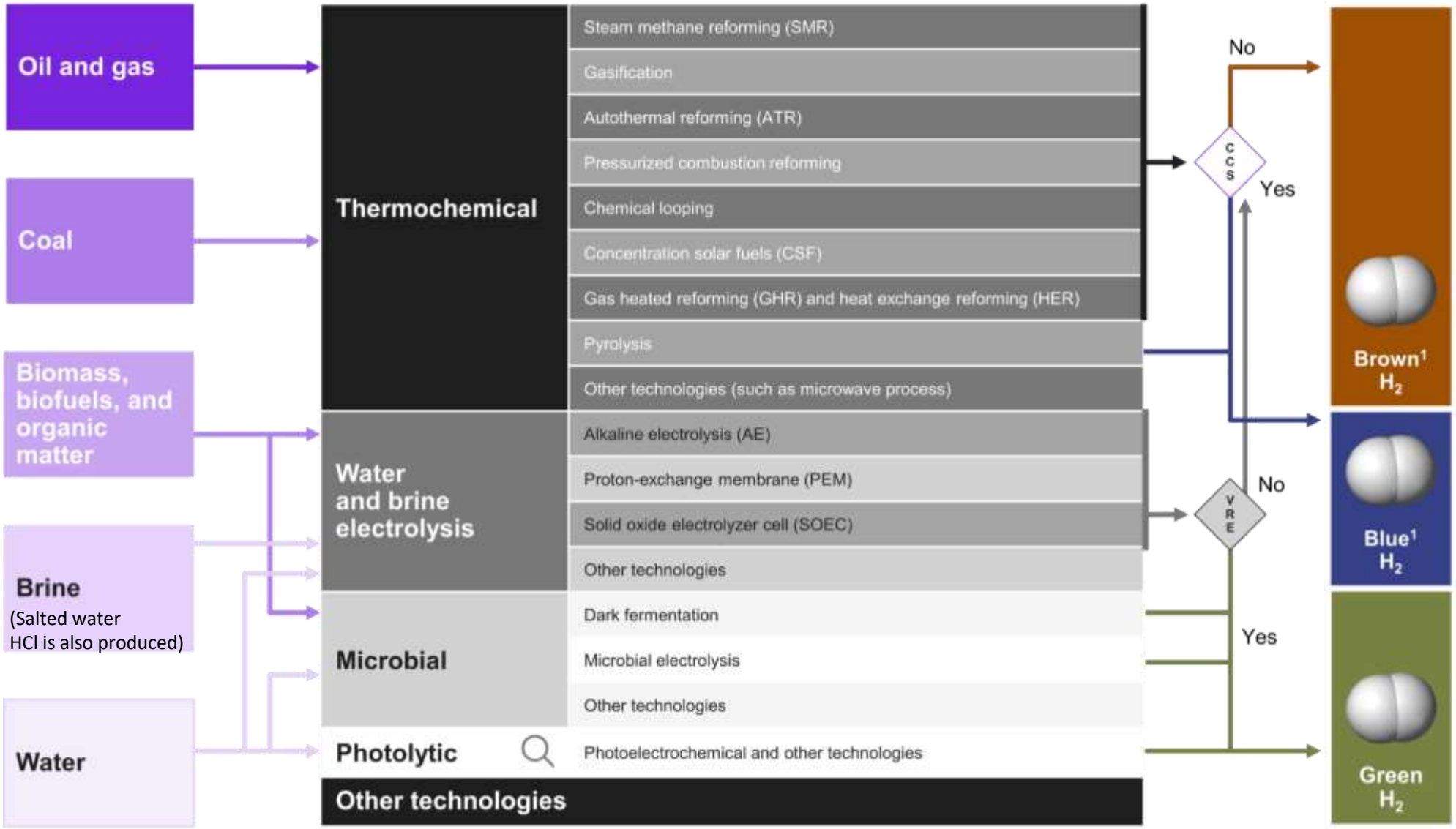
There is limited hydrogen-based fuel use before 2030, but it has a large role in the APS and NZE after 2030. Hydrogen-based fuels provide 45% of fuel use in shipping in the NZE in 2050

2.3 Hydrogen

Readiness level ?	Sector	Technology	Step in value chain	Importance for net-zero emissions
9	Energy transformation > **Hydrogen**	Production > Electrolysis > Alkaline	Production	Very high
9	Energy transformation > **Hydrogen**	Production > Electrolysis > Polymer electrolyte membrane	Production	Very high
8-9	Energy transformation > **Hydrogen**	Production > Methane reforming with CCUS > Steam reforming	Production	High
8-9	Energy transformation > **Hydrogen**	Production > Methane reforming with CCUS > Autothermal reforming	Production	High
7	Energy transformation > **Hydrogen**	Production > Methane reforming with CCUS > Autothermal reforming with gas heated reformed	Production	High
9-10	Energy transformation > **Hydrogen**	Storage > Salt cavern storage	Storage	High
2-4	Energy transformation > **Hydrogen**	Storage > Depleted oil & gas fields, aquifers	Storage	High
11	Energy transformation > **Hydrogen**	Storage > Storage tank	Storage	High

+ 12 Moderate

2.3 Hydrogen - Production



Kerney energy transition institute

LA FILIÈRE HYDROGÈNE

Énergies fossiles

Énergie nucléaire

Énergies renouvelables

- Gaz
- Charbon
- Pétrole

- Hydraulique
- Éolienne
- Solaire
- Géothermique

Biomasse

Production biologique par :

- Microalgues, organismes photosynthétiques, bactéries non photosynthétiques
- Chimie bio-inspirée mimant le fonctionnement des hydrogénases naturelles

- Vapoformage
- Oxydation partielle
- Reformage autothermique

- Électrolyse

Transformation thermochimique et gazéification de la biomasse

Distribution, use…

2.3 Hydrogen -production

Electrolysis

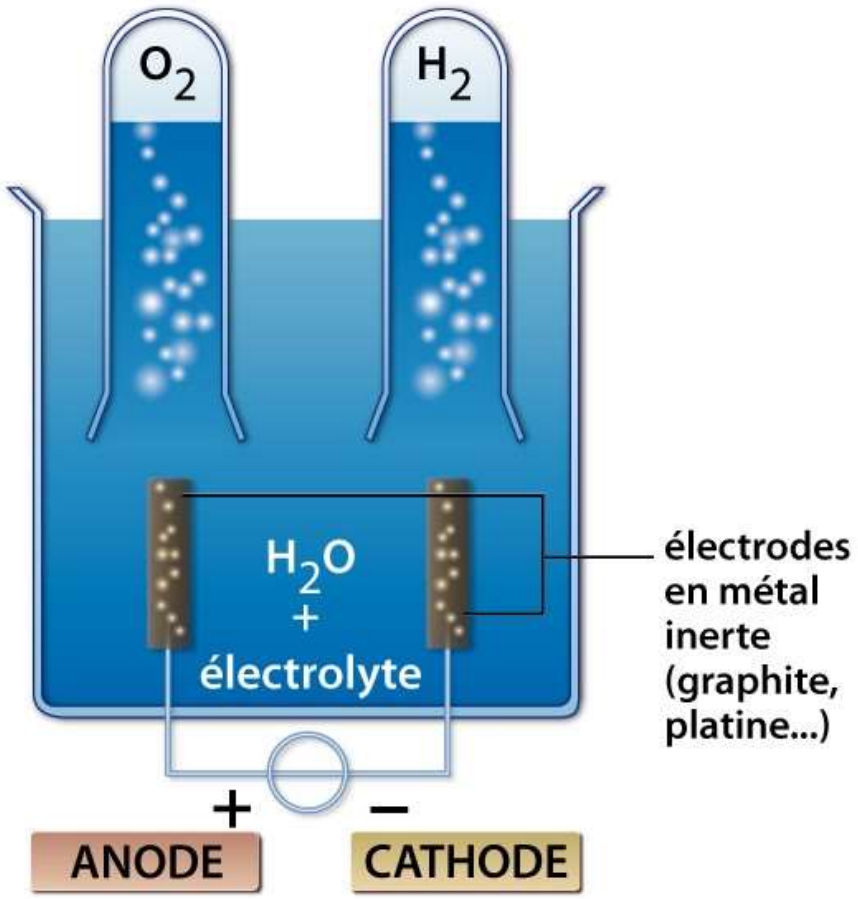
$$H_2O \rightarrow H_2 + \frac{1}{2} O_2$$

$$\Delta G^0 = - RT \ln K = - nfE^0$$

$$\Delta G^0 = 237 \text{ kJ/mol}$$

$$\Rightarrow E^0 = 1.23 \text{ V at } 298 \text{ K}$$

- Required voltage > 2V
  (1.23 V + pertes ohmiques)
- High efficiency (>70-80%)



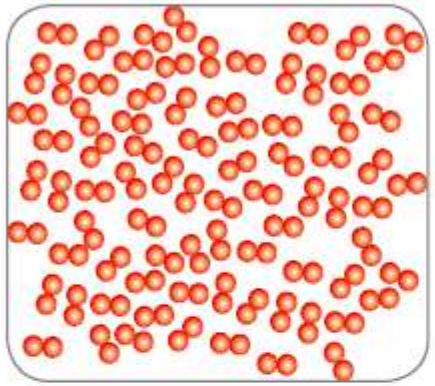
Ref Larousse

2.3 Hydrogen - storage

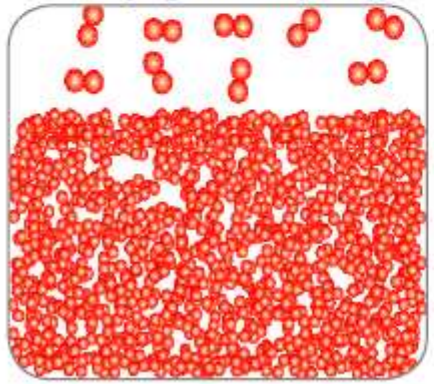
Hydrogen can be stored in different forms

In tanks...

Compressed Gas



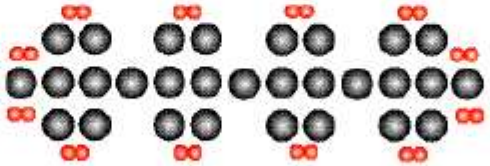
Cryogenic Liquid



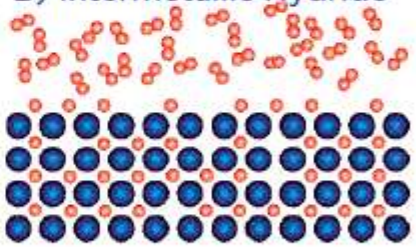
And in materials...

Hydrogen can be stored on the surfaces of solids (by adsorption) or within solids (by absorption). In adsorption (A), hydrogen attaches to the surface of a material either as hydrogen molecules (H_2) or hydrogen atoms (H). In absorption (B), hydrogen molecules dissociate into hydrogen atoms that are incorporated into the solid lattice framework – this method may make it possible to store larger quantities of hydrogen in smaller volumes at low pressure and at temperatures close to room temperature. Finally, hydrogen can be strongly bound within molecular structures, as chemical compounds containing hydrogen atoms (C, D). Density increases from A to D.

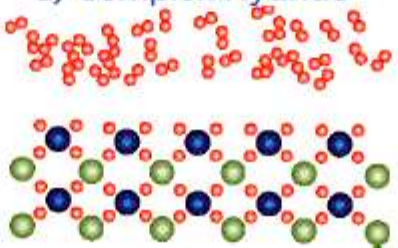
A) Surface Adsorption



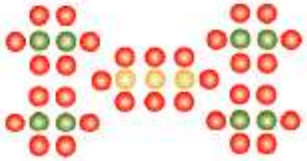
B) Intermetallic Hydride



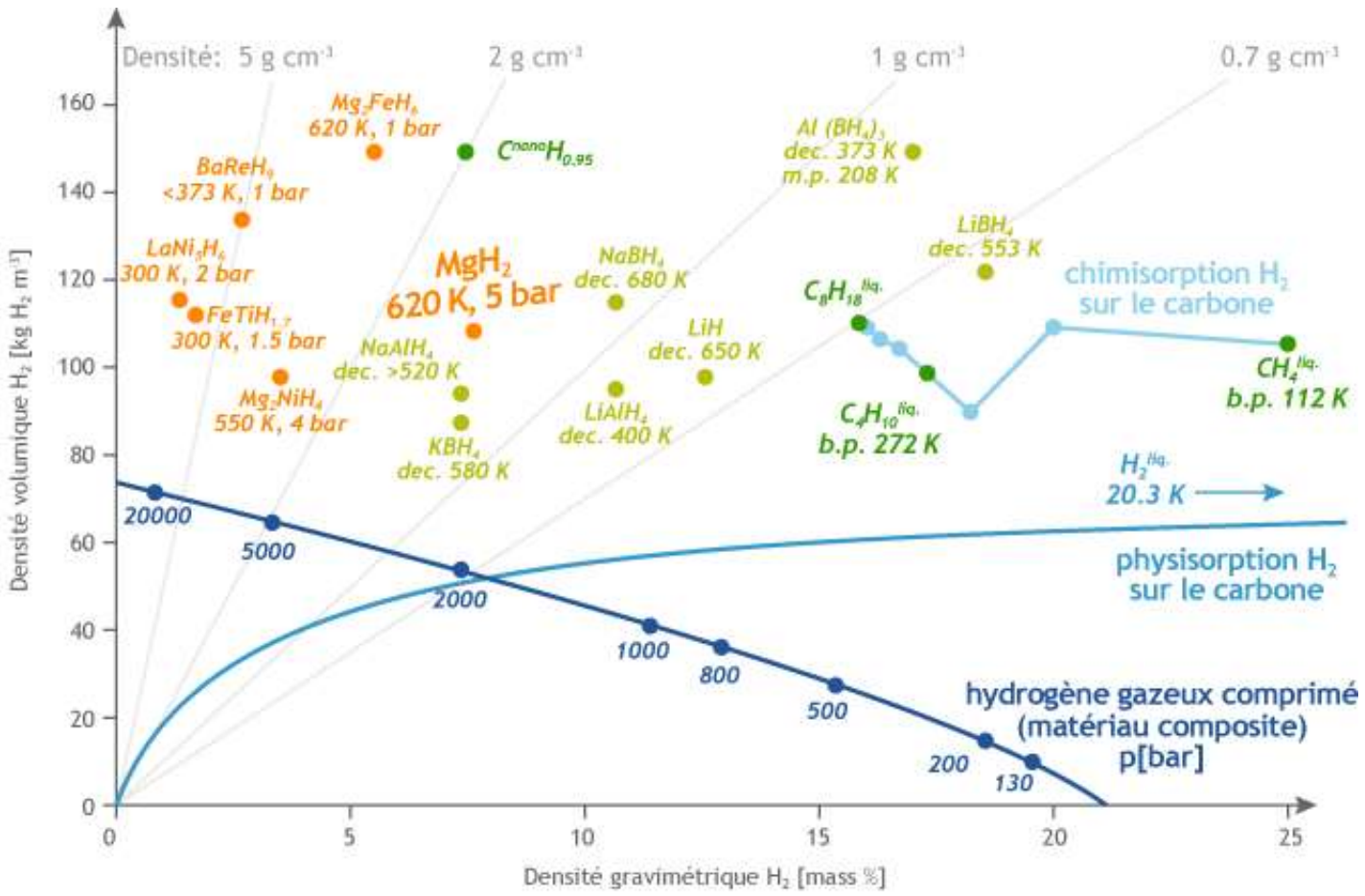
C) Complex Hydride

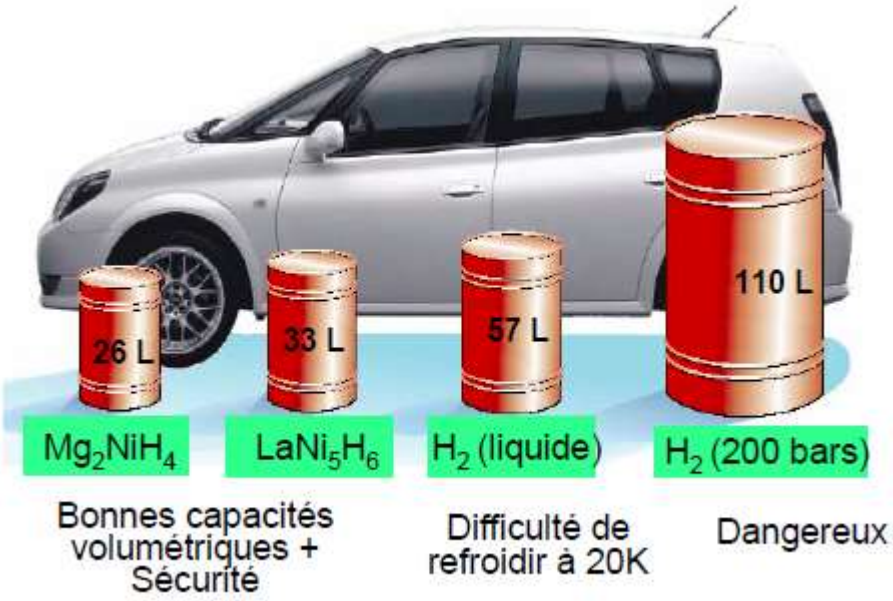


D) Chemical Hydride



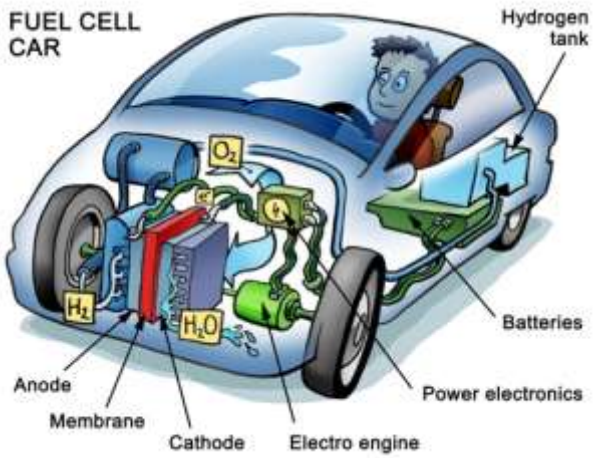
2.3 Hydrogen - storage

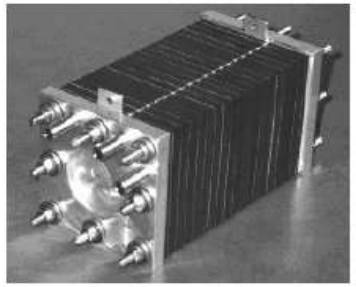




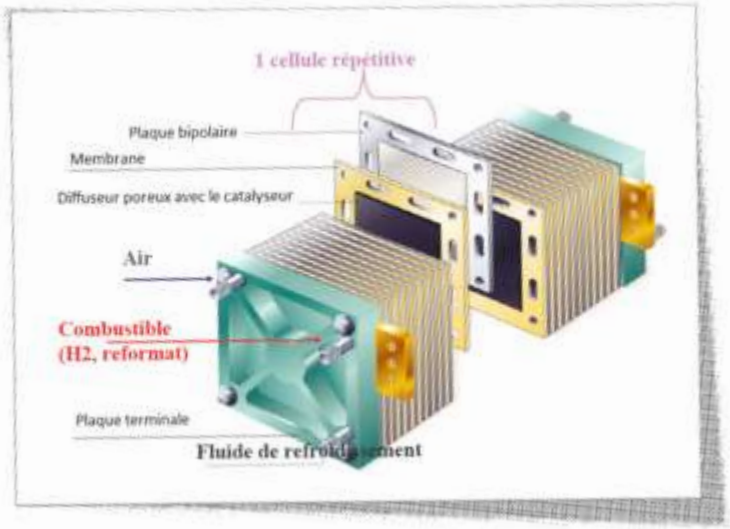
2.3 Hydrogen - use

Fuel cells





PEMFC

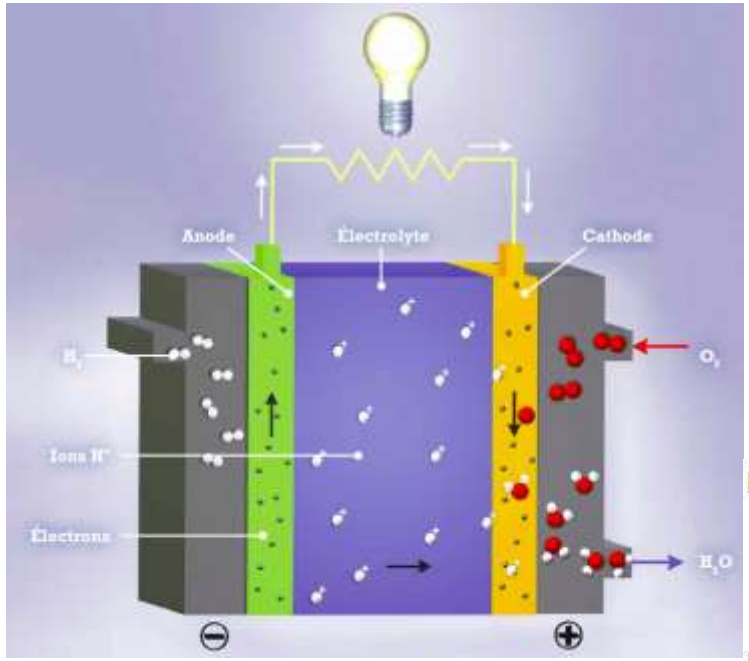


2.3 Hydrogen - use

Fuel cells

$H_2 + ½\ O_2 \longrightarrow H_2O$ + electricity + heat

H_2 storage



O_2 (or air) storage

pour un électrolyte acide :

$$H_2 \rightarrow 2H^+ + 2e^-$$

pour un électrolyte alcalin :

$$H_2 + 2OH^- \rightarrow 2H_2O + 2e^-$$

pour un électrolyte acide :

$$\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O$$

pour un électrolyte alcalin :

$$\frac{1}{2}O_2 + H_2O + 2e^- \rightarrow 2OH^-$$

$\Delta G^0 = -237 kJ/mol H_2$ (état standard)

$$E^0_{eq} = -\frac{\Delta G^0}{nF} = \frac{237 \times 10^3}{2 \times 96500} = 1,229 \approx 1,23\ V$$

2.3 Hydrogen - use

Types de piles à combustibles	Sigle	Electrolyte	°C. de fonct.	Espèce mobile	Applications	Remarques
Pile à membrane échangeuse de protons	PEFC ou PEMC	Membrane polymère solide	80°C	H+	Transport Stationnaire Portable	Cinétique rapide Haut rendement mW à 100KW Nbreuses applications
Pile alcaline	AFC	Hydroxyde de potassium	60-200°C	OH-	Transport	Missions spatiales Haut rendement si haute température
Pile à acide phosphorique	PAFC	Acide phosphorique	200°C	H+	Stationnaire	Techno mature Acide donc corrosion Haute puissance MW Application principale : cogénération
Piles à carbonates fondus	MCFC	Carbonates de métaux alcalins	600-700°C	CO_3^{2-}	Stationnaire	Peu d'applications Haute température
Piles à oxydes solides	SOFC IT-SOFC	Céramique	800-1000°C 550°C	O^{2-}	Stationnaire Transport	Plus long développement 2 versions en T°
Piles à alimentation directe en méthanol	DMFC	Membrane polymère	80°C	H+	Portable Stationnaire Transport	PEFC avec méthnaol au lieu de H Techno « récente »
Pile réversible	RFC	Membrane polymère	80°C	H+	Transport Stationnaire	Electrolyseur + PAC Couplage solaire
Piles zinc-air	ZAFC	Liquide alcalin	ambiant	OH-	Portable Transport	Lien avec batterie Deux roues PowerZinc®

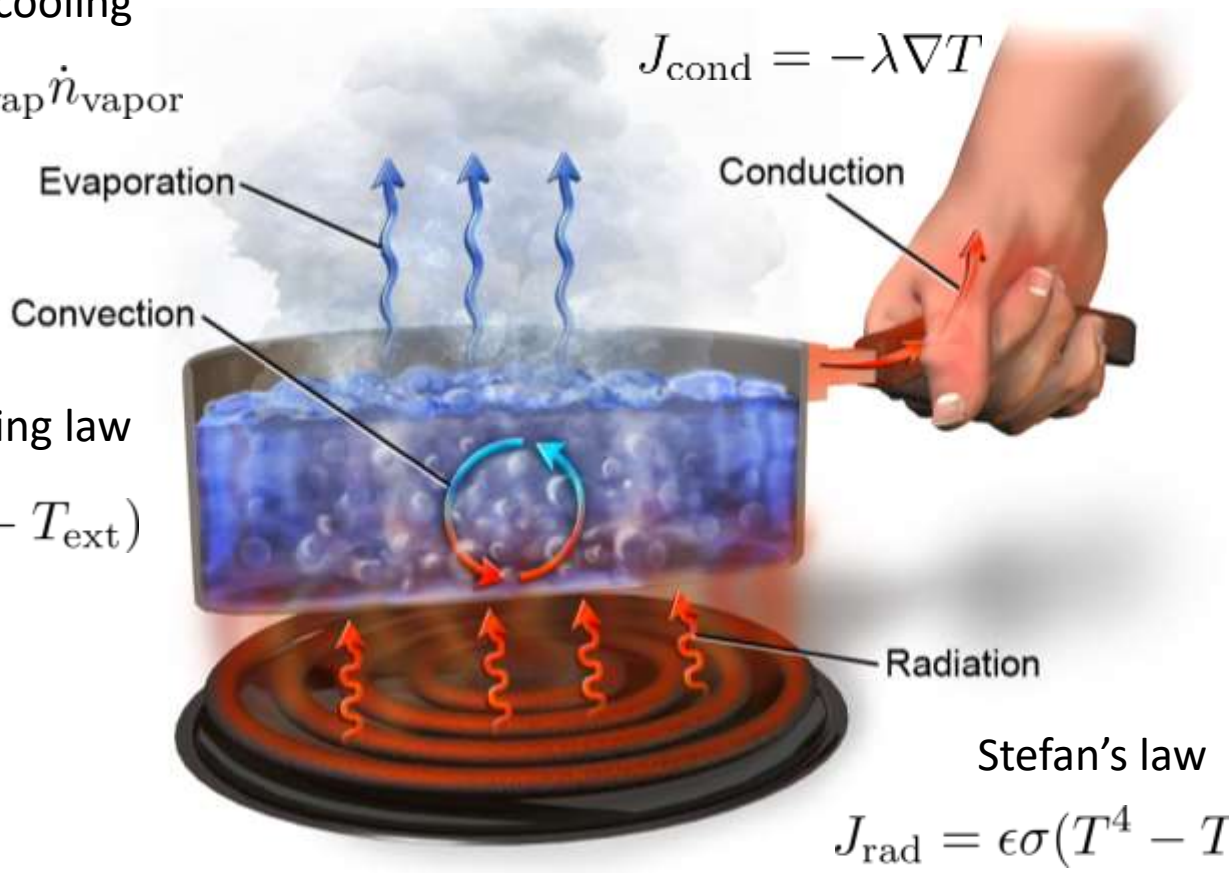
2.4 Heat

Evaporative cooling

$$J_{\text{latent}} = L_{\text{evap}} \dot{n}_{\text{vapor}}$$

Fourier's law

$$J_{\text{cond}} = -\lambda \nabla T$$



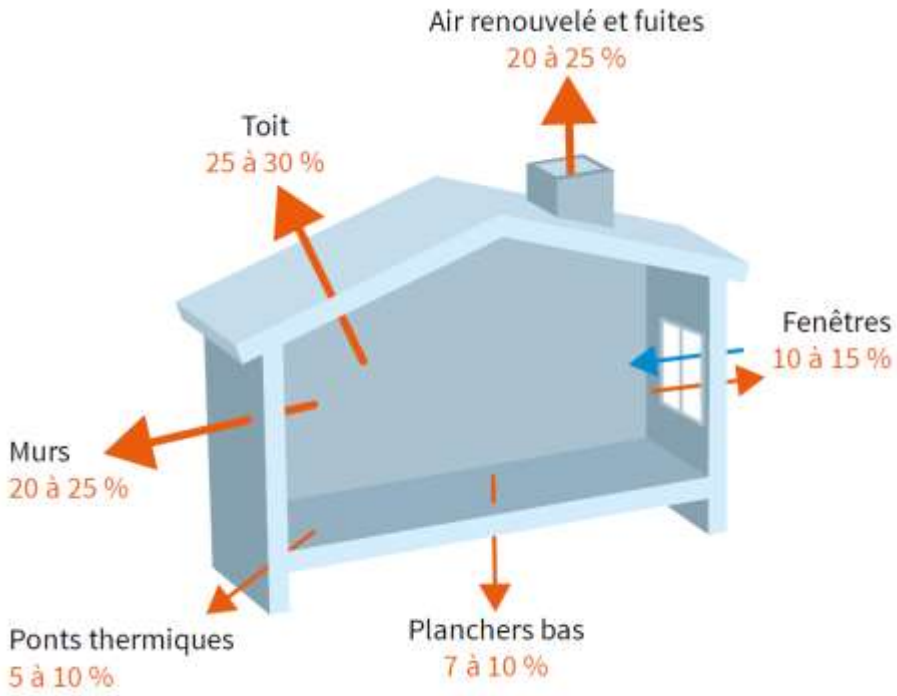
Newton's cooling law

$$J_{\text{conv}} = h(T - T_{\text{ext}})$$

Stefan's law

$$J_{\text{rad}} = \epsilon \sigma (T^4 - T_{\text{ext}}^4)$$

Source: thermtest



Courtesy from Daniel Suchet

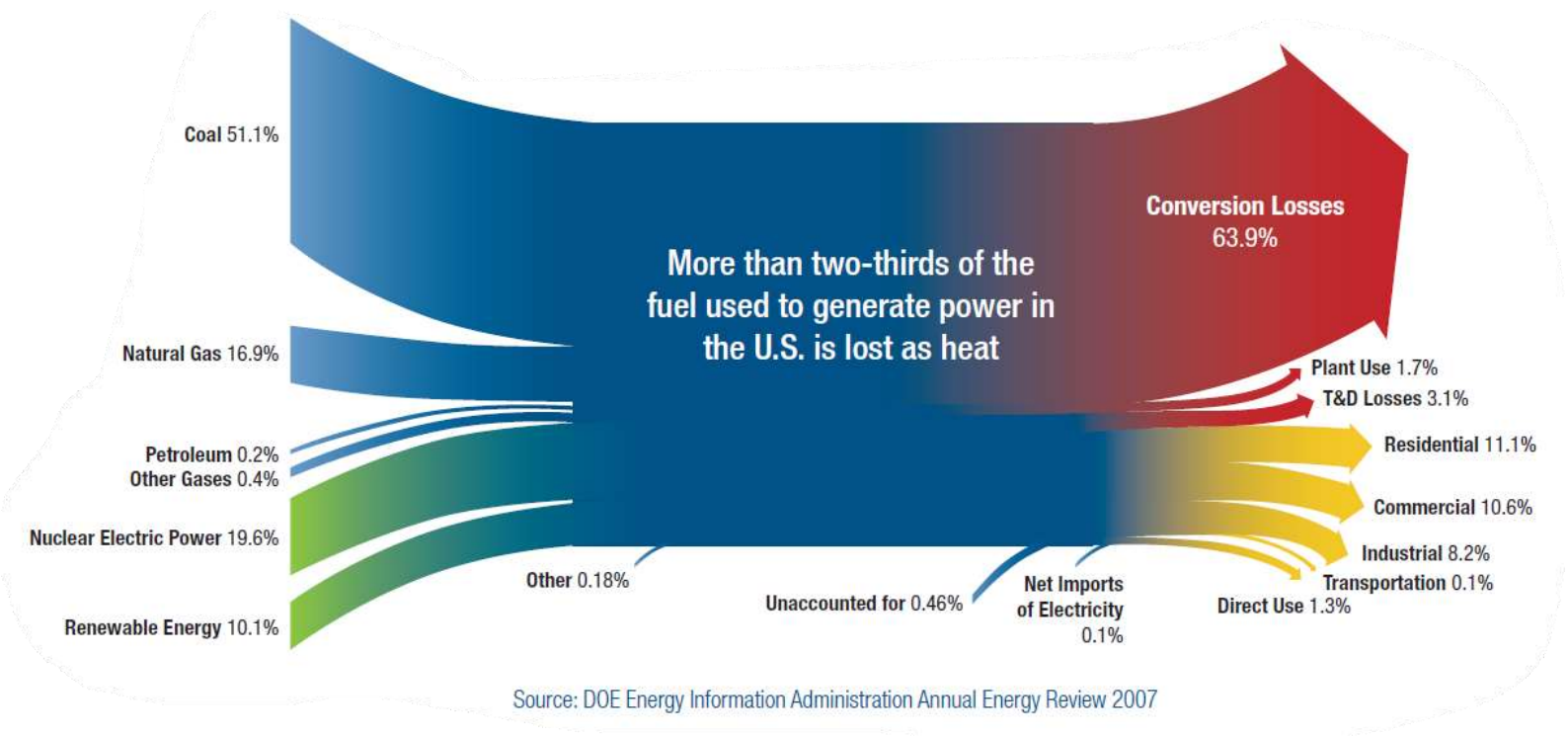
2.4 Heat

Readiness level ?	Sector	Technology	Step in value chain	Importance for net-zero emissions
9	Energy transformation > **Heat**	Generation > Large-scale heat pump	Generation	Very high
8-9	Energy transformation > **Heat**	Storage > Sensible heat storage	Storage	High
5-7	Energy transformation > **Heat**	Storage > Latent heat storage > High-temperature	Storage	High
10	Energy transformation > **Heat**	Generation > Solar thermal district heating	Generation	Moderate
9	Energy transformation > **Heat**	Storage > Latent heat storage > Ice storage >	Storage	Moderate
3-4	Energy transformation > **Heat**	Storage > Thermochemical heat storage > Chemical reaction	Storage	Moderate
5-7	Energy transformation > **Heat**	Storage > Thermochemical heat storage > Sorption process	Storage	Moderate

2.4 Heat

Combined heat and power generation

Try not to waste so much heat !



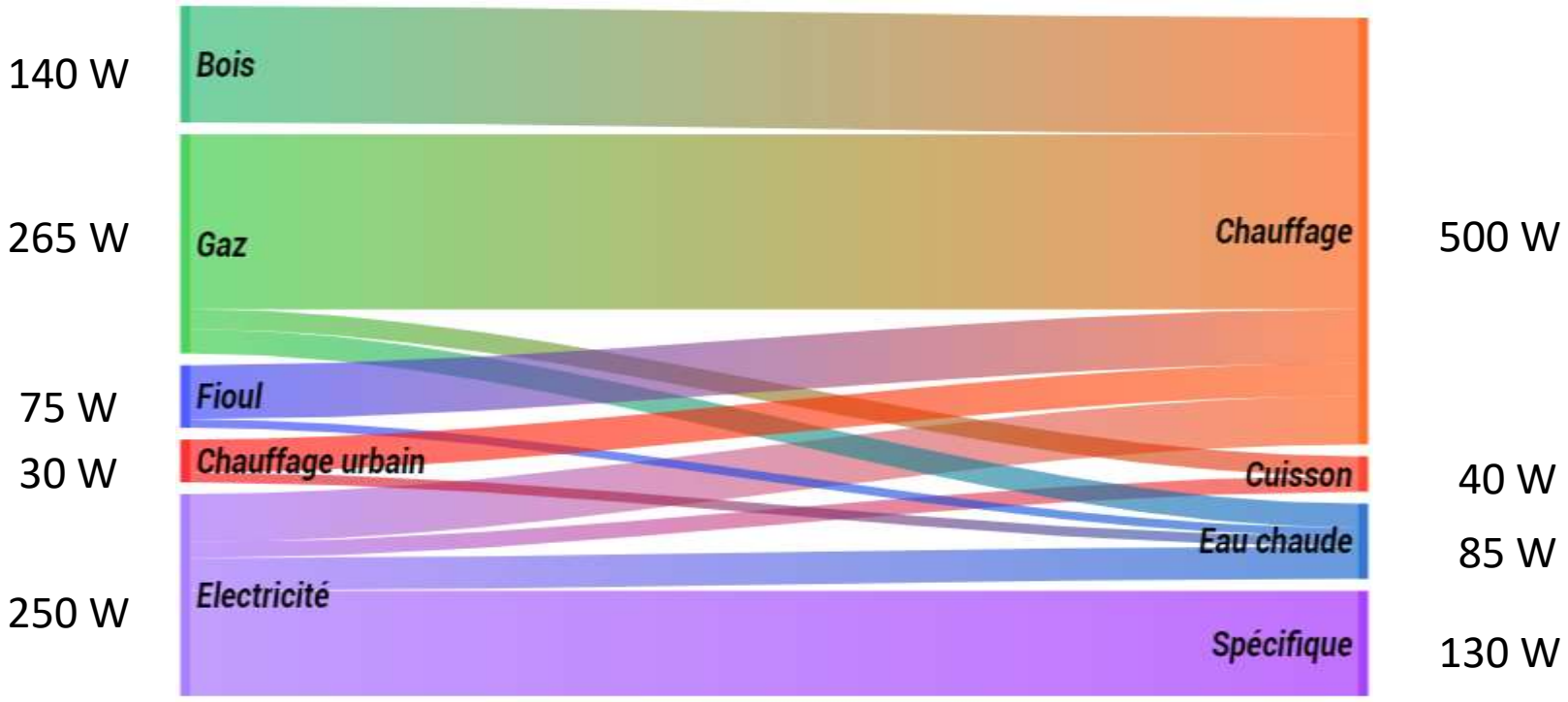
Two options

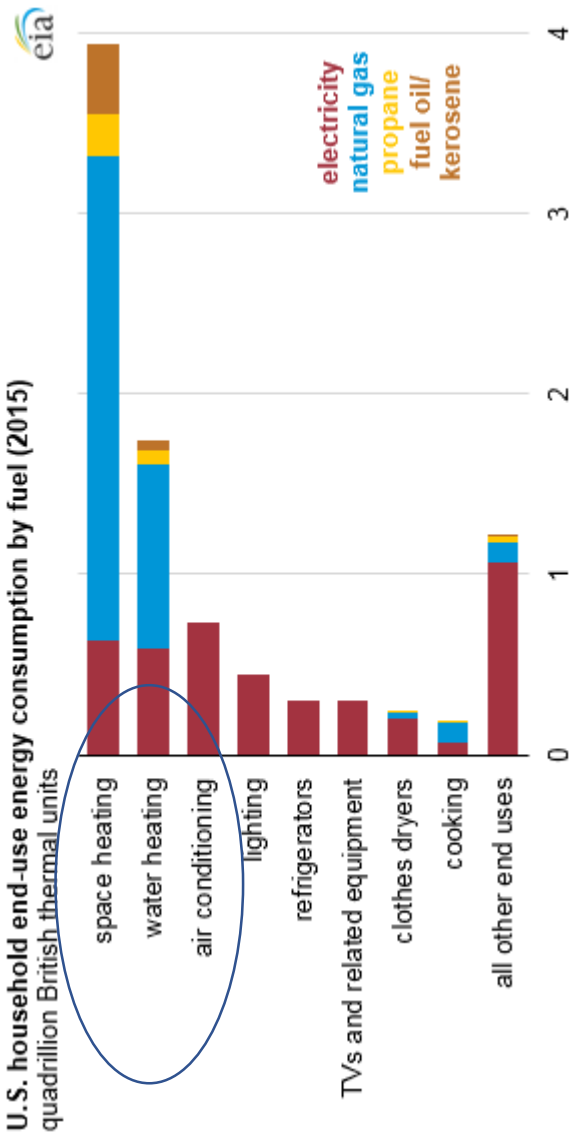
Topping cycle system
Collect heat normally wasted over electricity production

Bottoming cycle system
Turn wasted heat from industrial processes into electricity

2.4 Heat - production

Average residential consumption per capita in France (data : CEREN (2019))





2.4 Heat - production

From IEA : is cooling the future of heating ?

https://www.iea.org/commentaries/is-cooling-the-future-of-heating

- Estimated increase in surface : a 20% growth in heated floor area in 10 years and more than x2 by 2070 for air conditioners (+10 air conditioners / world or +7 billion!)

- Increasingly efficient heating technologies (sales of air-to-air heat pumps +10% per year since 2010, heat pump water heaters x2 and sales of solar thermal water x1.5)

- CO2 emissions from the supply of heat to buildings only decrease by a little over 20% by 2050 and by about 40% by 2070, compared to today. In contrast, they fall by more than 95% in the sustainable development scenario by 2070.

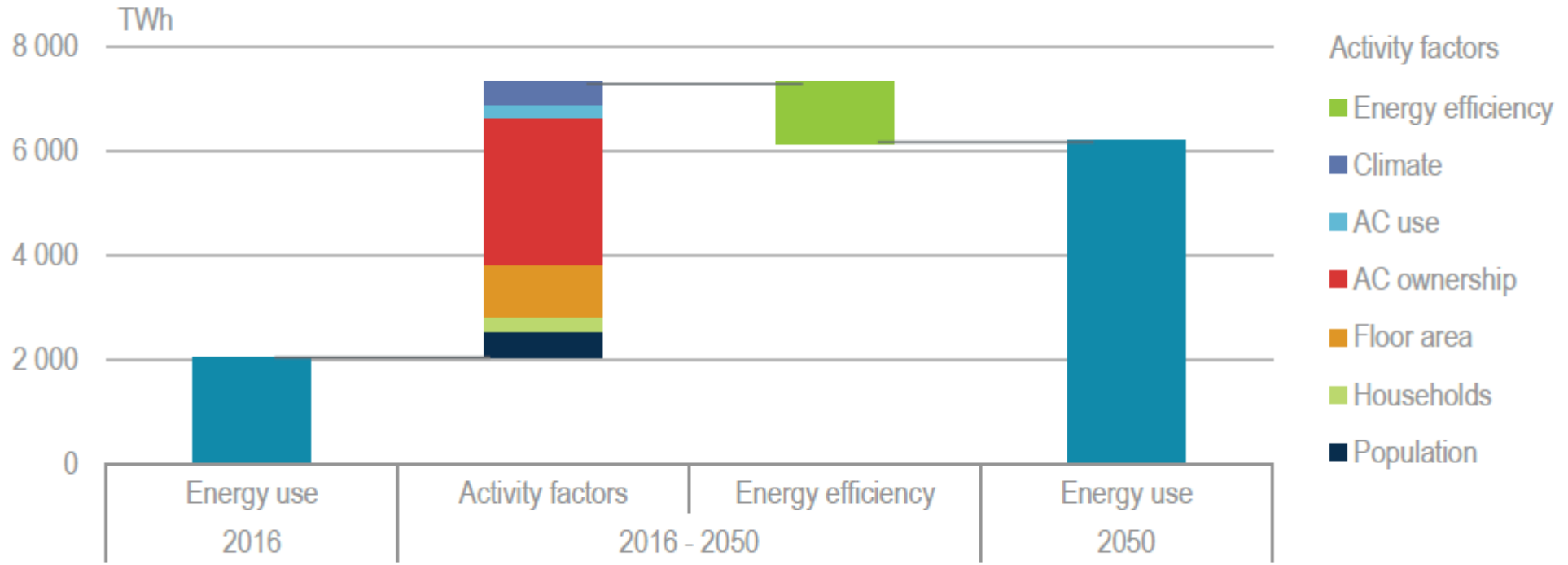
- Based on stated policy intentions, cooling demand + 3% per year over the next three decades, (x8 heating demand over the past 30 years).

- https://www.iea.org/reports/heat-pumps : the average performance of air conditioners is expected to increase by more than 50% by 2030 and nearly double by 2070. Without such efficiency improvements, under the stated policies, electricity demand for cooling could nearly triple by 2070.

2.4 Heat - production

AC Cooling

Figure 3.7 • The role of drivers of energy demand for space cooling in the Baseline Scenario

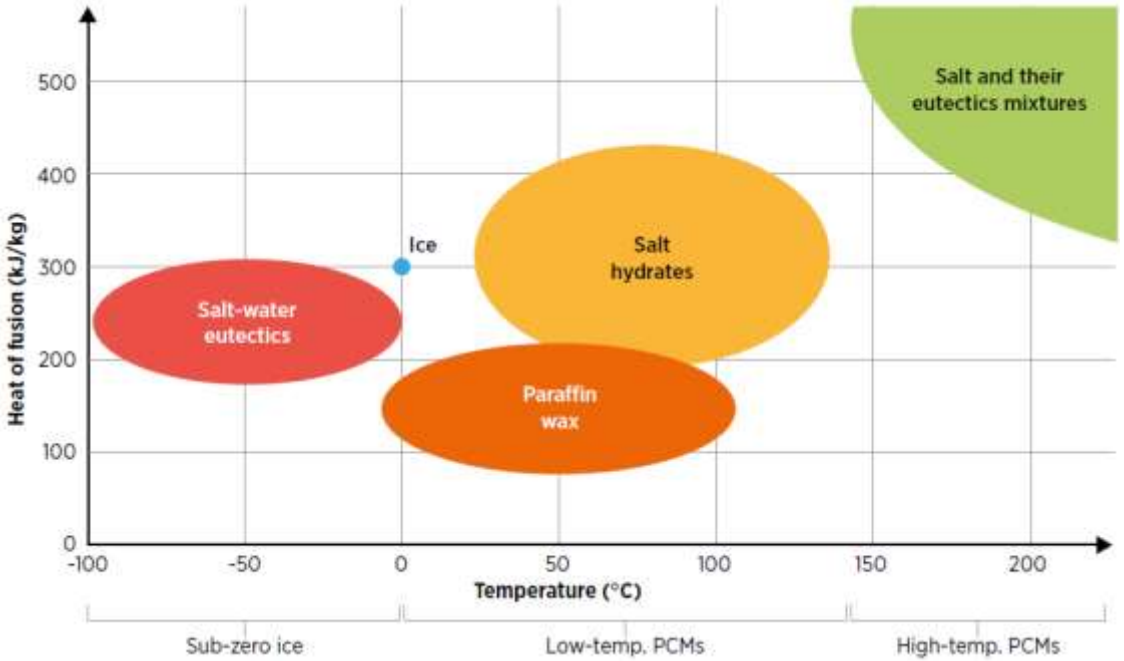


Key message • Booming sales of ACs more than outweigh the impact of continuing gains in energy efficiency.

Jevon's paradox !

2.4 Heat - storage

Sensible heat *(change T)*	Water tank Molten salts Solid state (bricks…) Underground (Borehole, aquifer…)
Latent heat *(change phase)*	Phase change at constant temperature Much larger density *Melt 1kg of ice == 1kg of water 0°C → 80°C*
Thermo chemical *(reaction)*	Chemical looping ($CaCO_3 \leftrightarrow CaO + CO_2$) Sorption based (salt hydratation)
Mechanical TES *(reaction)*	Compressed / liquified air



2.4 Heat - storage

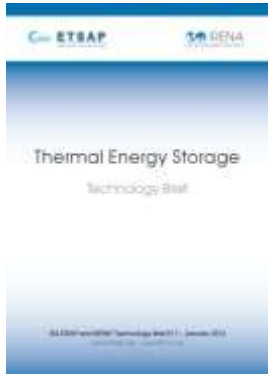


Table 6: Energy capacities, power, efficiency and storage time of thermal energy storage technologies

TES technology	Capacity kWh/t	Power kW	Efficiency (%)	Storage time	Cost (USD/kWh)
Hot water tank	20-80	1-10 000	50-90	day-year	0.1-0.13
Chilled water tank	10-20	1-2 000	70-90	hour-week	0.1-0.13
Aquifer	5-10	500-10 000	50-90	day-year	Varies
Borehole	5-30	100-5 000	50-90	day-year	Varies
PCM-general	50-150	1-1 000	75-90	hour-week	13-65
Ice storage tank	100	100-1 000	80-90	hour-week	6-20
Thermal-chemical	120-150	10-1 000	75-100	hour-day	10-52

2.5 Efficient energy use

Improve efficiencies is key (ex source IEA)

No single solution is perfect.

→ Don't claim your solution is perfect (it's not)

→ Don't reject a solution because it has drawbacks (business as usual wins)

Be Careful :

- TRL too low : balance has to be found between risks (going from R&D and industry) and urgency ("keep in mind the climate inertia" i.e. slow response about 15 years)

Notion of TRL (Technology readiness level)

2.5 Efficient energy use

Improve efficiencies is key (ex source IEA)

No single solution is perfect.

→ Don't claim your solution is perfect (it's not)

→ Don't reject a solution because it has drawbacks (business as usual wins)

Be Careful :

- TRL too low : balance has to be found between risks (going from R&D and industry) and urgency ("keep in mind the climate inertia" i.e. slow response about 15 years)
- **Rebound effect**

Jevon's paradox (rebound effect)

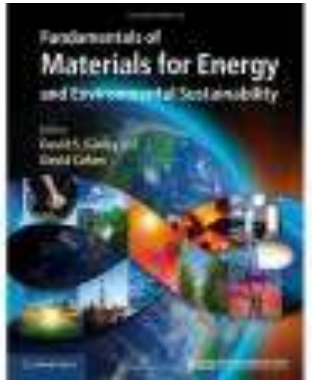
It is wholly a confusion of ideas to suppose that the economical use of fuel is equivalent to a diminished consumption. The very contrary is the truth.

2.5 Efficient energy use - ex: lightening

Readiness level ?	Sector	Technology	Step in value chain	Importance for net-zero emissions
11	Buildings > **Lighting**	Lamps and luminaires > Conventional LED	Lamps and luminaires	High
9	Buildings > **Lighting**	Lamps and luminaires > Organic LED	Lamps and luminaires	High
9	Buildings > **Lighting**	Lamps and luminaires > Polymer LED	Lamps and luminaires	High
7	Buildings > **Lighting**	Direct current lighting	Direct current lighting	Moderate
9	Buildings > **Lighting**	Advanced lighting control system	Advanced lighting control system	Moderate

https://www.iea.org/articles/etp-clean-energy-technology-guide

2.5 Efficient energy use - ex: lightening



Ex of white LED

Table 35.1. Efficiencies and efficacies of various forms of commercially available lighting as of 2009

Type of light source	Efficiency (%)	Efficacy (lm W^{-1})
Incandescent light bulb	5	16
Long fluorescent tube	25	80
Compact fluorescent lamp (CFL)	20	60
Sodium lamp (high-pressure)	45	130
High-power white LEDs (350 mA drive current at 25 °C)	30	132 (cool white) 83 (warm white)
Low-power white LEDs (20 mA drive current at 25 °C)	55	170
High-power white LEDs (5-year target)	55	188 (cool white) 138 (warm white)

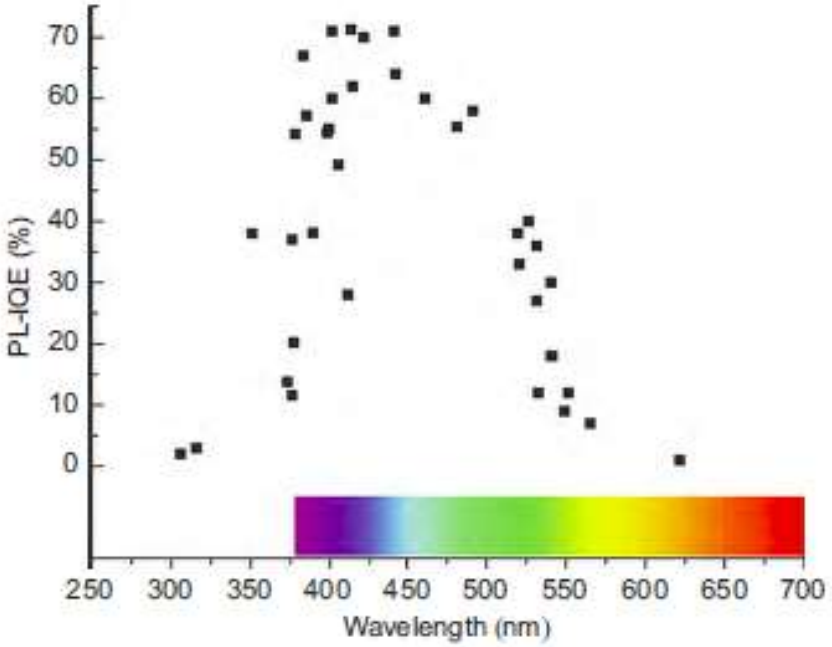
Table 35.5. A comparison of energy cost and CO_2 emissions for various types of lamp including the LED luminaires used in the example

	65-W Incandescent lamp (reference)	14-W Compact fluorescent lamp	35-W Halogen downlighters	8-W LED luminaires used in this case
Number of lamps	9	9	9	9
Power used per lamp (W)	65	14	35	8
Total power of all lamps (W)	585	126	315	72
Energy cost over 50,000 h ($)	5,850	1,260	3,150	720
Relative energy savings over 50,000 h of operation ($)	–	4,590	2,700	5,130
Annual energy cost ($)	85.4	18.4	46.0	10.5
Carbon dioxide emitted over 50,000 h of operation (kg)	11,700	2,520	6,330	1,440
Relative amount of carbon dioxide saved over 50,000 h of operation (kg)	–	9,180	5,400	10,260

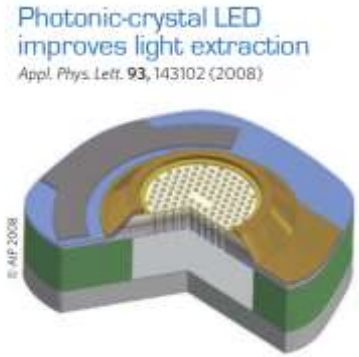
Values based on energy costs in the UK of $0.2 per kW·h and production of 0.4 kg of carbon dioxide per kW·h. A modest domestic usage of kitchen lighting of 2 h per day was used to calculate the annual energy cost. In addition, over the 50,000 h of operation of the LED luminaires, the consumer would most likely buy, change, and dispose of a staggering 450 incandescent light bulbs or 72 low-energy light bulbs!

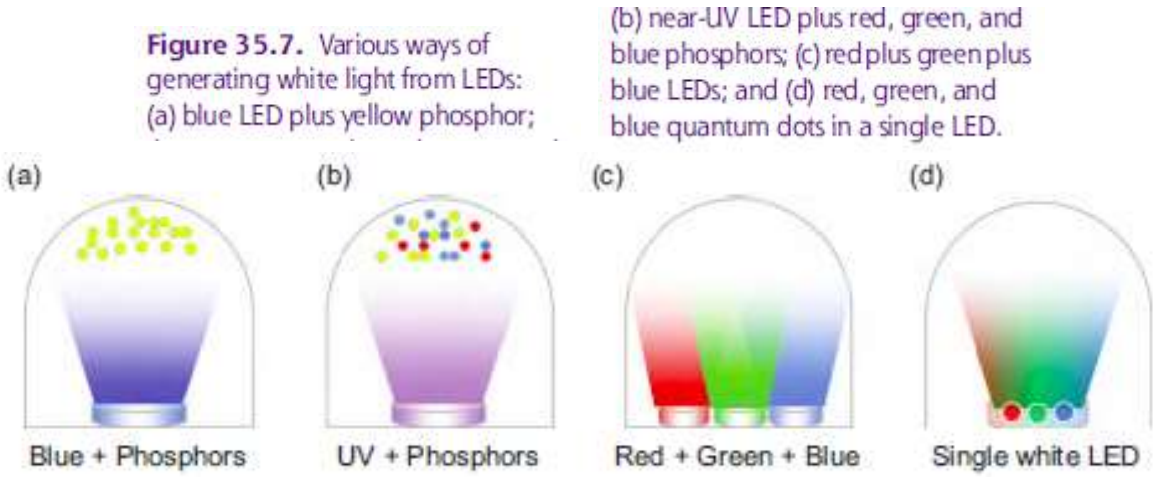
2.5 Efficient energy use - ex: lightening

Efficient for all wavelengths ?
Green gap



Different ways to improve light exctraction

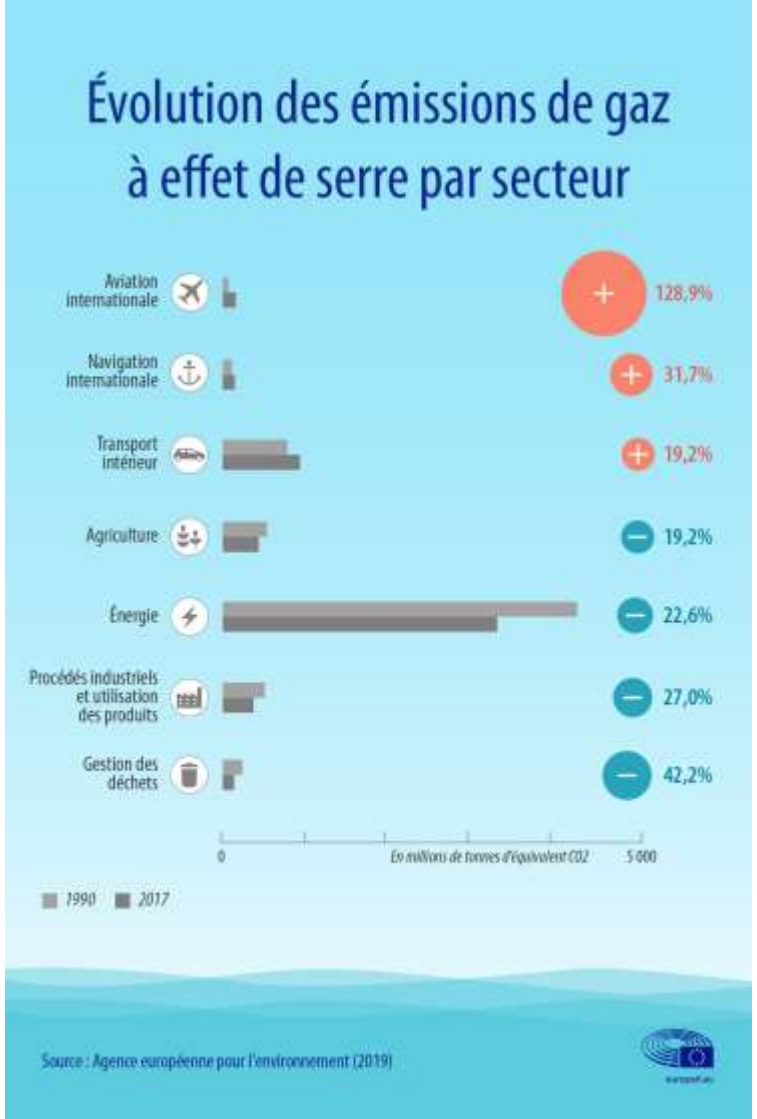




Issues :

Cold thermalization "green gap" R&D

2.5 Efficient energy use - transport



2.5 Efficient energy use - transport

Better Thermal cars : lighter, slower, shorter distances

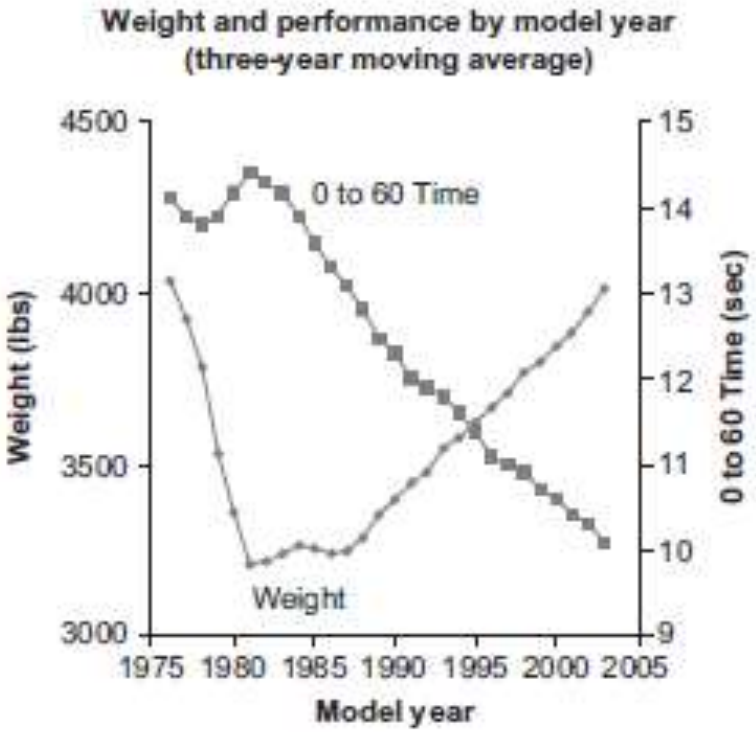


Table I: Lightweighting Potentials and Relative Component Costs for Various Automotive Lightweighting Materials Options.

Lightweighting Material	Material Replaced	Mass Reduction (%)	Relative Cost (per Part)[a]
High-strength steel	Mild steel	10	1
Aluminum	Steel, cast iron	40–60	1.3–2
Magnesium	Steel, cast iron	60–75	1.5–2.5
Magnesium	Aluminum	25–35	1–1.5
Glass FRP composites	Steel	25–35	1–1.5
Graphite FRP composites	Steel	50–60	2–10+
Aluminum matrix composites	Steel, cast iron	50–65	1.5–3+
Titanium	Alloy steel	40–55	1.5–10+
Stainless steel	Carbon steel	20–45	1.2–1.7

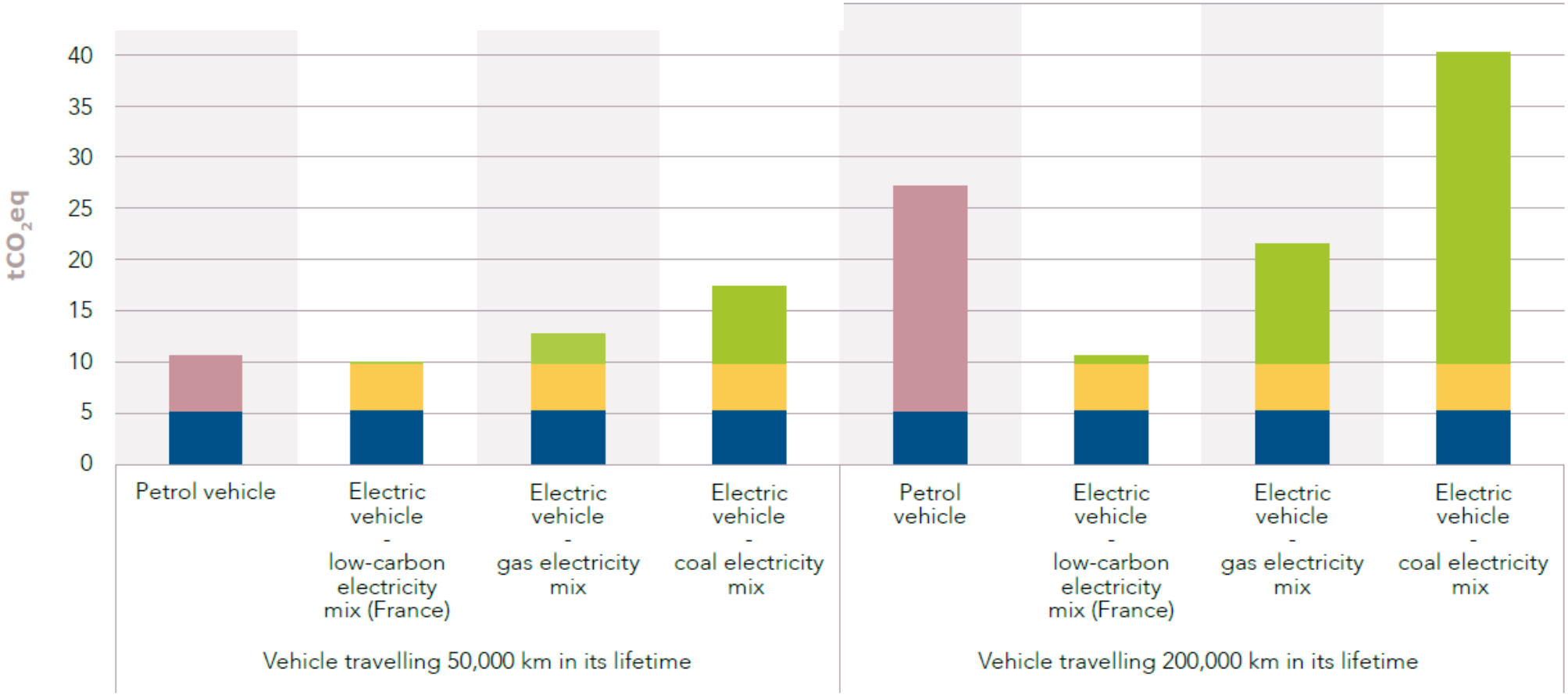
Table 31.3 A comparison of the Carnot efficiency and the Carnot efficiency with irreversible heat-transfer processes as it relates to the potential ideal efficiency of a heat engine

$$n = 1 - \frac{\sqrt{T_{cold}}}{T_{hot}}$$

	Flame temperature (K)	Carnot efficiency (%)	Carnot efficiency with irreversibility (%)
Ethanol	2193	83.0	58.8
Diesel	2327	84.0	60.0
Gasoline	2302	83.8	59.7
Methanol	2143	82.6	58.3
Natural gas	2063	81.9	57.5
Propane	2263	83.5	59.4

2.5 Efficient energy use - transport

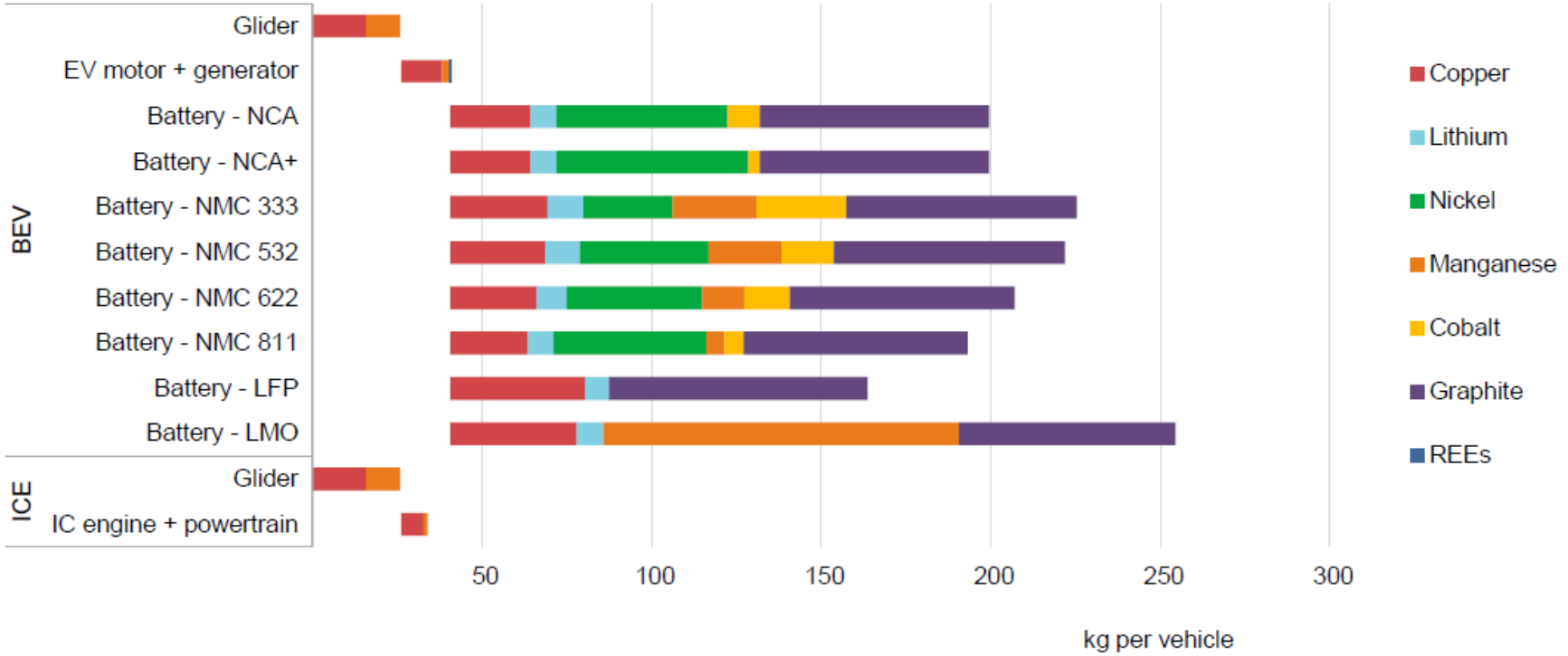
7.3 The carbon benefit of e-mobility is still significant when the whole life cycle of the vehicle is included, even with batteries that are made in China…



2.5 Efficient energy use - transport

EVs use around six times more minerals than conventional vehicles

Typical use of minerals in an internal combustion engine vehicle and a battery electric vehicle



IEA. All rights reserved.

Notes: For this figure, the EV motor is a permanent-magnet synchronous motor (neodymium iron boron [NdFeB]); the battery is 75 kilowatt hours (kWh) with graphite anodes.

Sources: Argonne National Laboratory (2020b, 2020a); Ballinger et al. (2019); Fishman et al. (2018b); Nordelöf et al. (2019); Watari et al. (2019).

Remember that no solution is perfect !

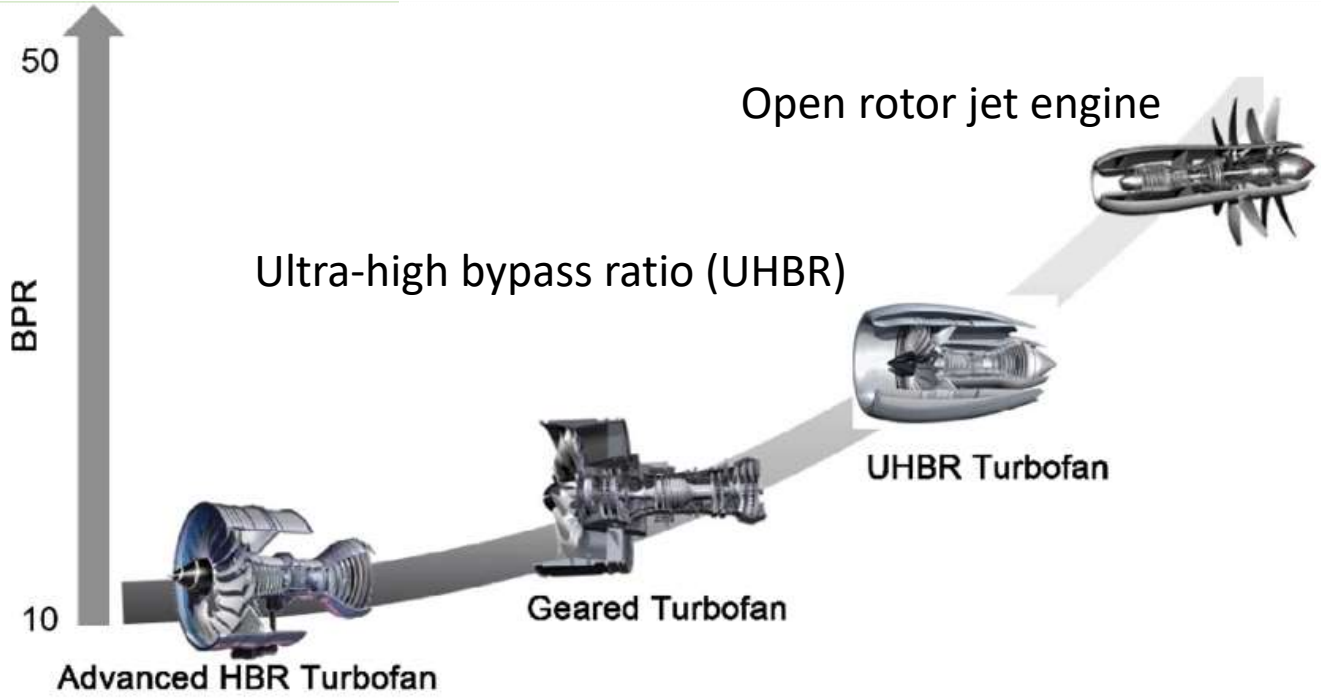
2.5 Efficient energy use - transport

No zero CO_2 emission in use

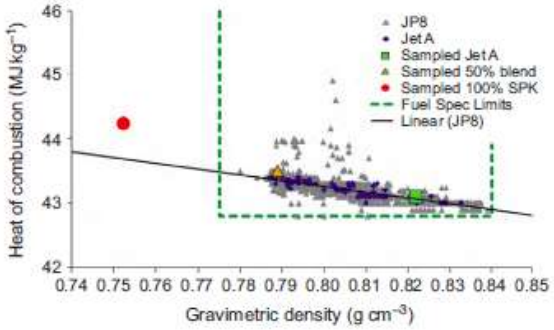
Improvements :
- Light weight materials
- Biofuels
- Engines

Readiness level ?	Sector	Technology	Step in value chain	Importance for net-zero emissions
4	Transport > **Aviation**	Vehicle-aircraft-vessel and components > Open Rotor	Vehicle-aircraft-vessel and components	High
6-9	Transport > **Aviation**	Vehicle-aircraft-vessel and components > Geared Turbo Fan- Ultra-High Bypass Ratio engine	Vehicle-aircraft-vessel and components	High

- Hydrogen is thought (but hazardous ?)
- No electric flight



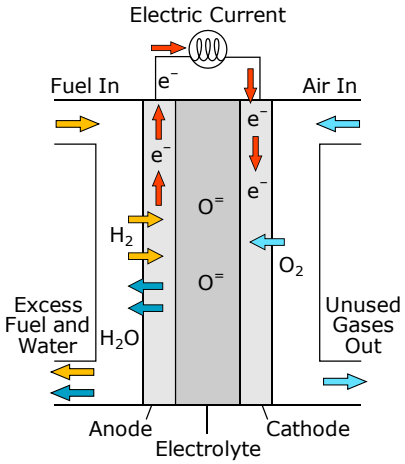
SPK (Synthetic Paraffinic Kerosene)



2.5 Efficient energy use - transport

Readiness level ?	Sector	Technology	Step in value chain	Importance for net-zero emissions
7	Transport > **Shipping**	Vehicle-aircraft-vessel and components > Hydrogen fuel cell electric vehicle > Solid Oxide	Vehicle-aircraft-vessel and components	Very high
4-5	Transport > **Shipping**	Vehicle-aircraft-vessel and components > Ammonia-fuelled engine	Vehicle-aircraft-vessel and components	Very high
9	Transport > **Shipping**	Charging and refuelling > Bunkering > Ammonia	Charging and refuelling	Very high

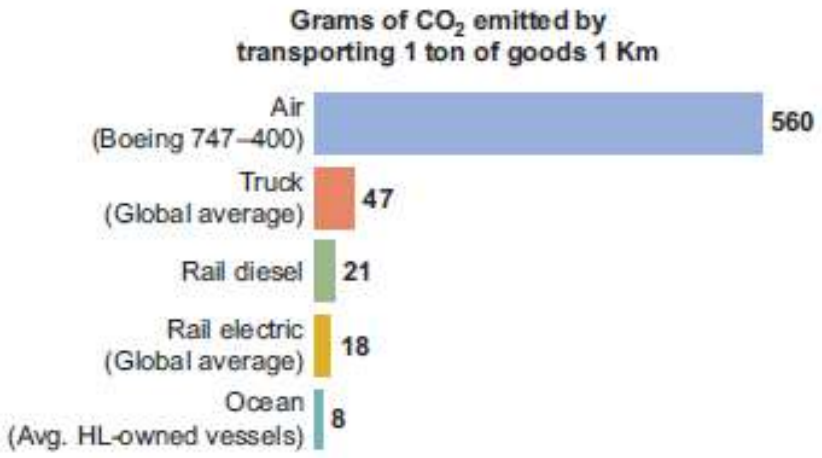
solid oxide fuel cell (or SOFC)



Liquid ammonia has 1.5 times higher energy density than liquid hydrogen+ room temperature storage

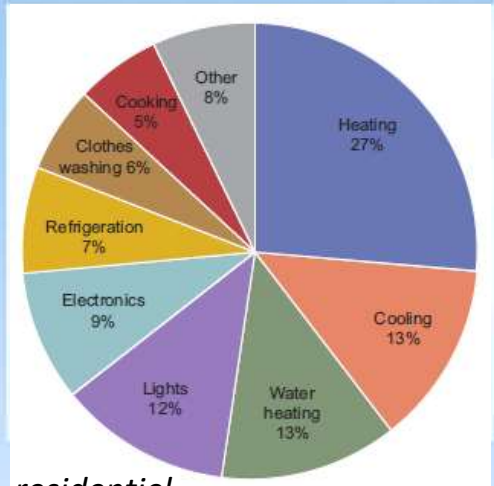
2.5 Efficient energy use - transport

8-9	Transport > **Shipping**	Vehicle-aircraft-vessel and components > Battery electric vehicle	Vehicle-aircraft-vessel and components	High
4-5	Transport > **Shipping**	Vehicle-aircraft-vessel and components > Hydrogen-fuelled engine	Vehicle-aircraft-vessel and components	High
7	Transport > **Shipping**	Vehicle-aircraft-vessel and components > Hydrogen fuel cell electric vehicle > Proton Exchange Membrane	Vehicle-aircraft-vessel and components	High
7	Transport > **Shipping**	Vehicle-aircraft-vessel and components > Hydrogen fuel cell electric vehicle > Molten Carbonate	Vehicle-aircraft-vessel and components	High
4-5	Transport > **Shipping**	Vehicle-aircraft-vessel and components > Ammonia Solid Oxide fuel cell electric vehicle	Vehicle-aircraft-vessel and components	High
8-9	Transport > **Shipping**	Vehicle-aircraft-vessel and components > Rotor Sail-Sail	Vehicle-aircraft-vessel and components	High
9	Transport > **Shipping**	Operations > Cold Ironing	Operations	High
3	Transport > **Shipping**	Charging and refuelling > Bunkering > Hydrogen	Charging and refuelling	High



2.5 Efficient energy use - insulation

Emissivity control



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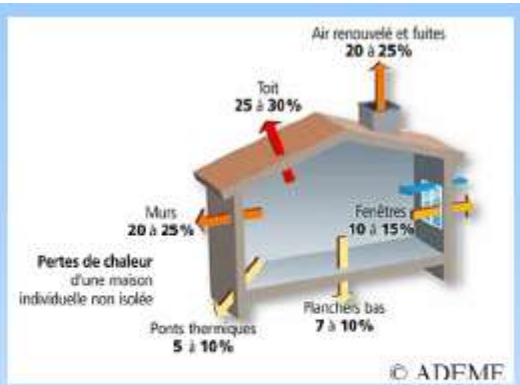


Insulation

Thermal solar

Bioclimatic

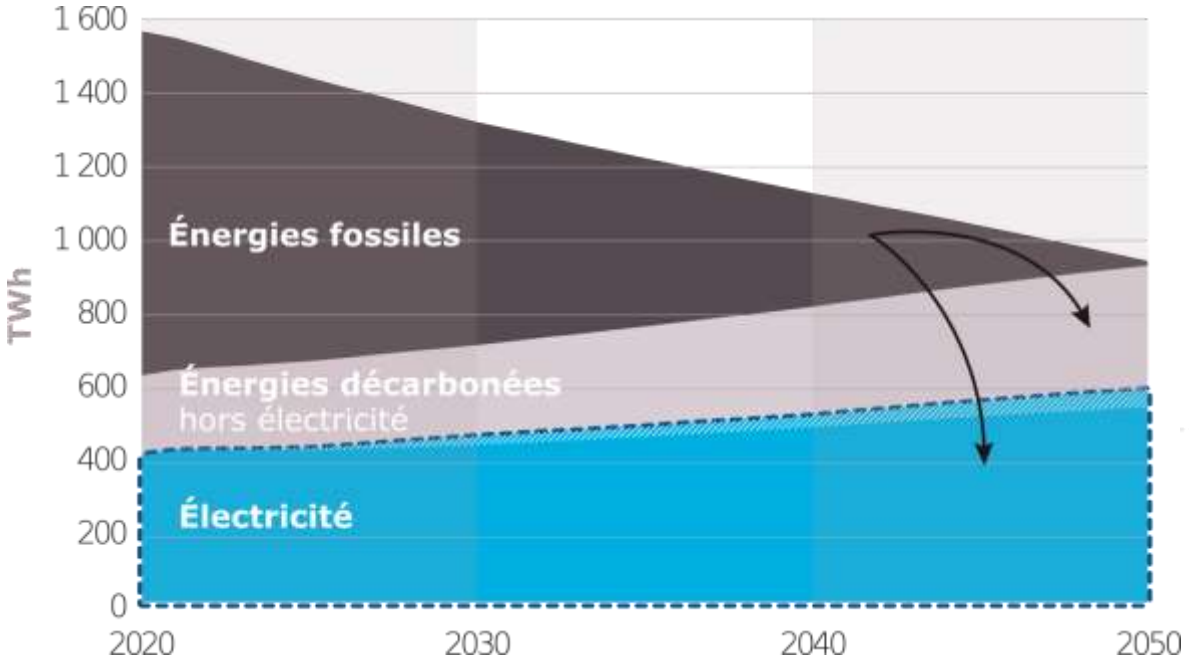
Geothermal

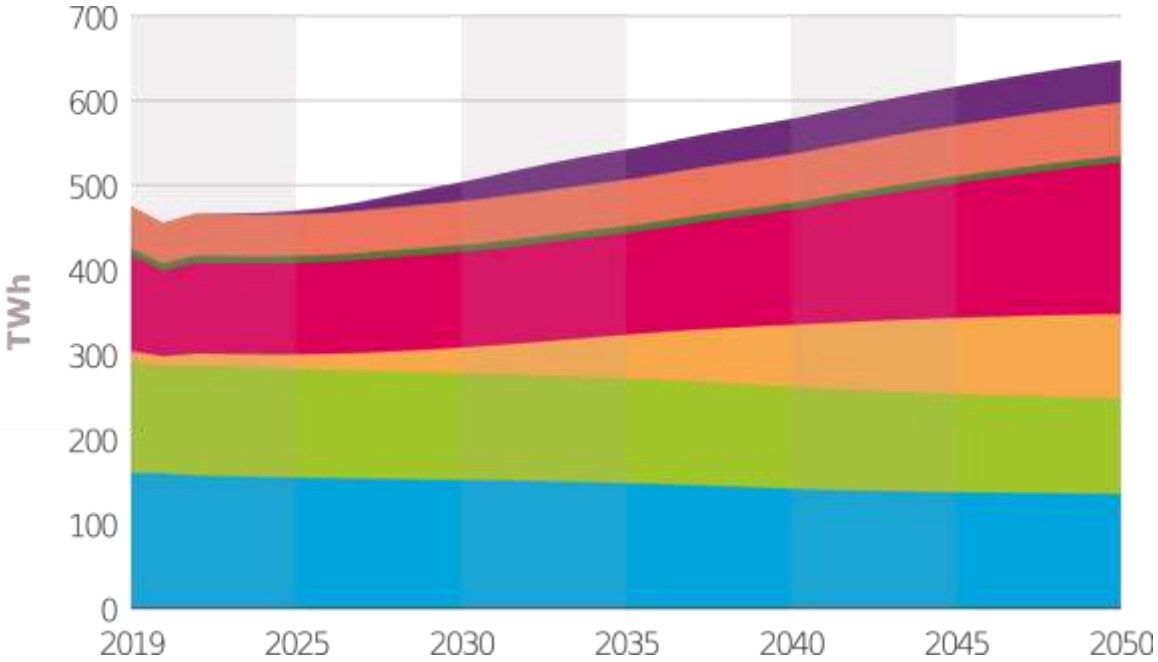
2.5 Efficient energy use - insulation

Readiness level ?	Sector	Technology	Step in value chain	Importance for net-zero emissions
6	Buildings > **Buildings construction and renovation**	Thermal performance > Building envelope > Wall, roof & façade > Building integrated solar thermal collector (BIST)	**Thermal performance**	Very high
9	Buildings > **Buildings construction and renovation**	Thermal performance > Building envelope > Wall, roof & façade > Air sealing	**Thermal performance**	Very high
8	Buildings > **Buildings construction and renovation**	Thermal performance > Building envelope > Fenestration > Highly Insulating Window	**Thermal performance**	Very high
8	Buildings > **Buildings construction and renovation**	Thermal performance > Building envelope > Fenestration > Insulation Glass Coating	**Thermal performance**	Very high
11	Buildings > **Buildings construction and renovation**	Thermal performance > Ventilation > Dual flow ventilation	**Thermal performance**	Very high
11	Buildings > **Buildings construction and renovation**	Thermal performance > Ventilation > Natural ventilation	**Thermal performance**	Very high
11	Buildings > **Buildings construction and renovation**	Thermal performance > Building orientation	**Thermal performance**	Very high
9	Buildings > **Buildings construction and renovation**	Thermal performance > Building envelope > Wall, roof & façade > Structural Insulated Panel	**Thermal performance**	High

+13 Moderate

2.5 Efficient energy use – smarter grid

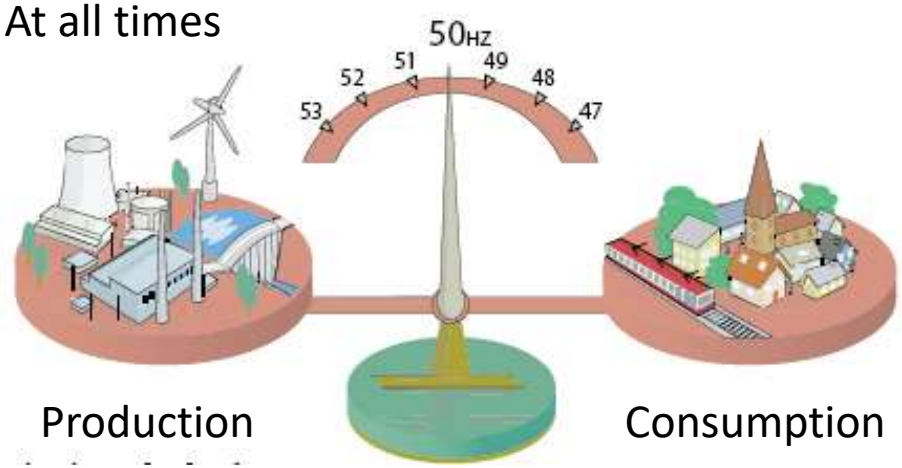


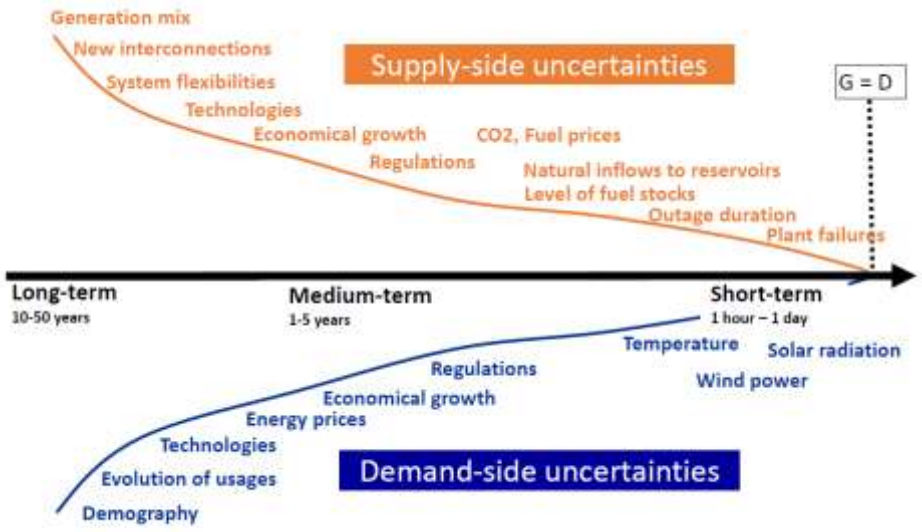


"The study concludes, without any ambiguity, that a sustained development of electric renewable energies in France is essential to meet its climate commitments."

2.5 Efficient energy use – smarter grid

At all times



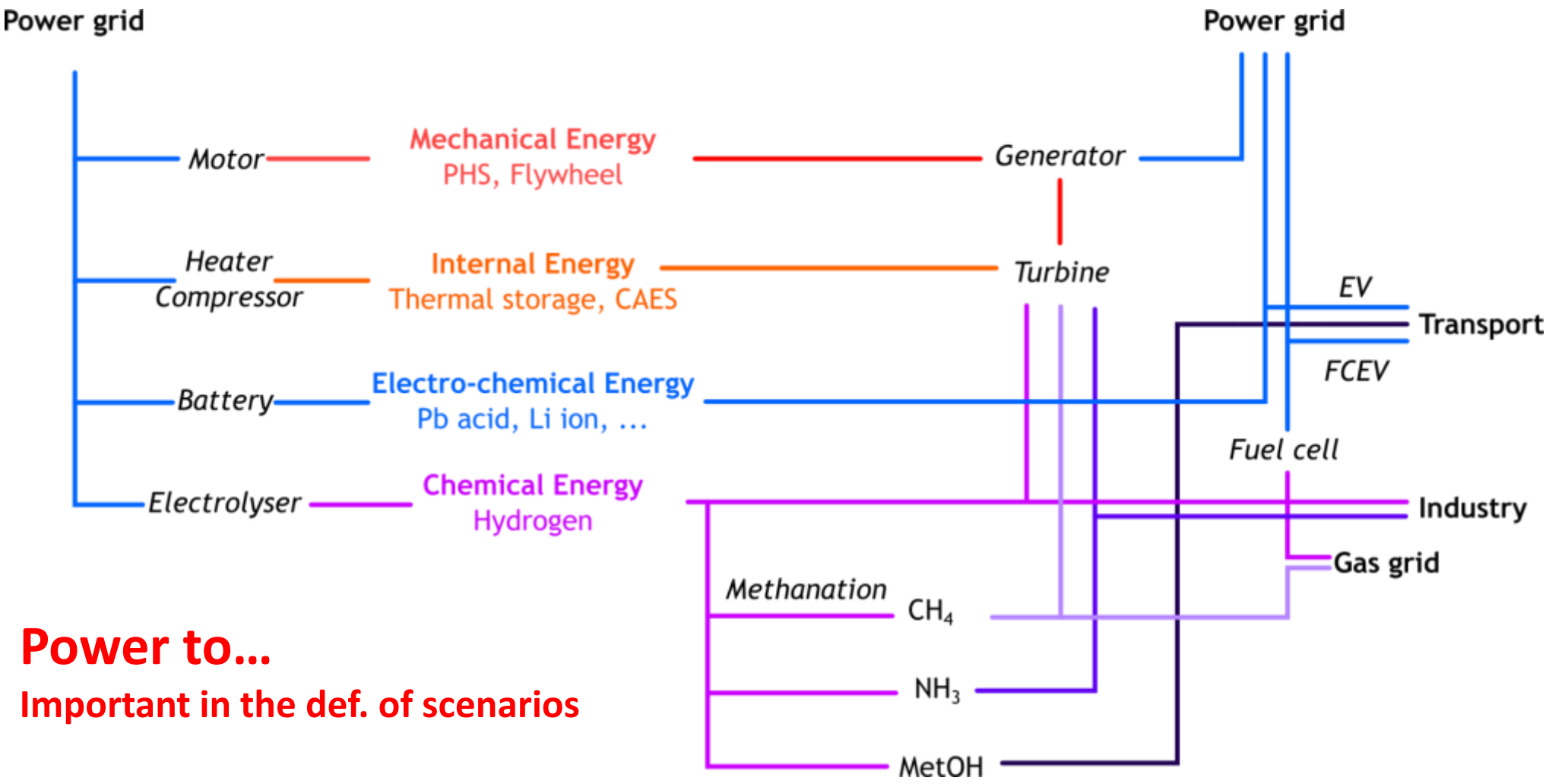


Better grid is key regarding the electricity growth :

- Inertia (depends on production systems)
- Asynchronicity
- Intermittency (sec, min)
- Variability (days, months)
- Predictibility

- Storages + H2 (power to gas)? + electric vehicle ?

2.5 Efficient energy use – smarter grid



Power to power
Power to gas
Power to mobility
Power to methane
Power to…

Power to…

Important in the def. of scenarios

2.5 Efficient energy use – connected or not to be

Evolution will depend on :

- Sobriety
- Cloud development
- Better use (equipment vs. request, videos…)
- Use of devices – which one?
- Development of devices – efficiency, numbers, use..
- Recycling
- …

Équipement	Consommation d'énergie
Smartphone	**de 2 à 7** kWh / an
Tablette	**de 5 à 15** kWh / an
Écran	**de 20 à 100** kWh / an
Ordinateur portable	**de 30 à 100** kWh / an
Ordinateur fixe	**de 120 à 250** kWh / an
Box (Internet +TV)	**de 150 à 300** kWh / an

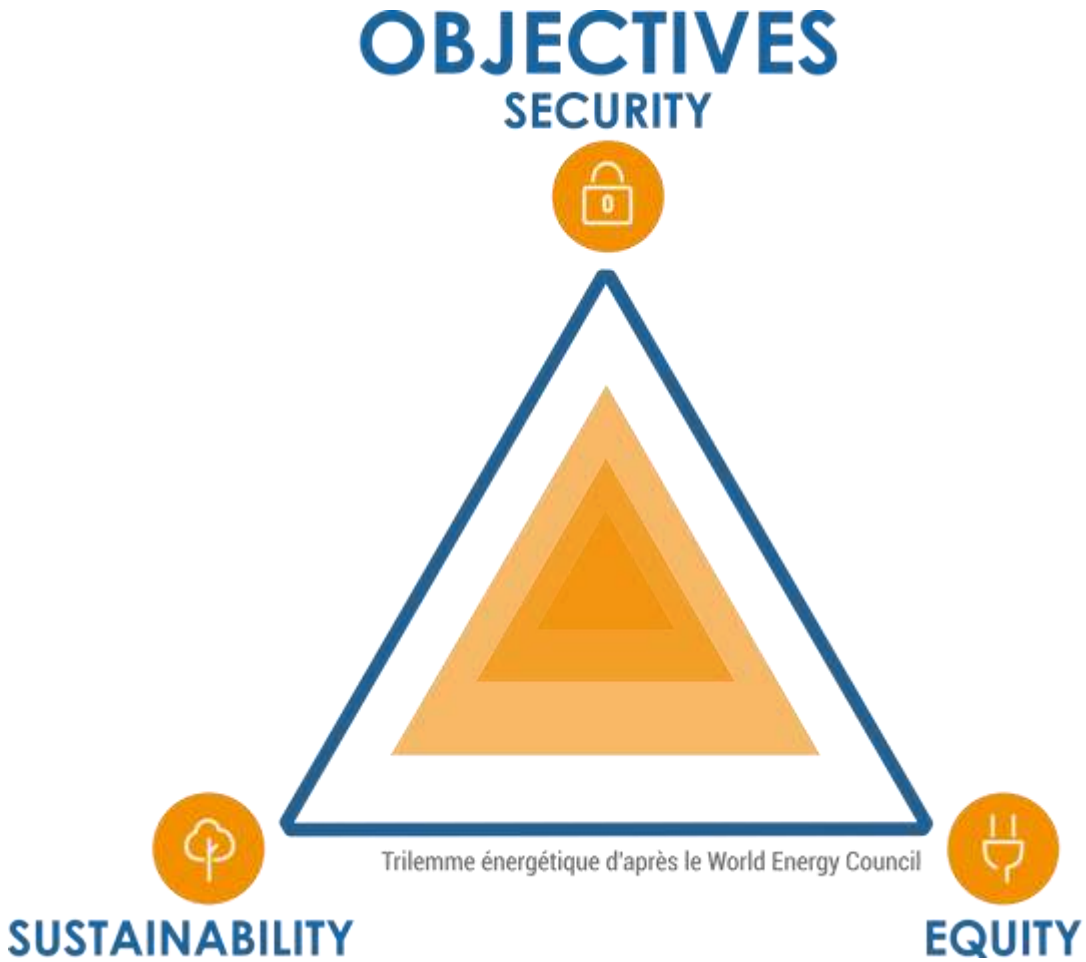
Sources : ADEME et GreenIt

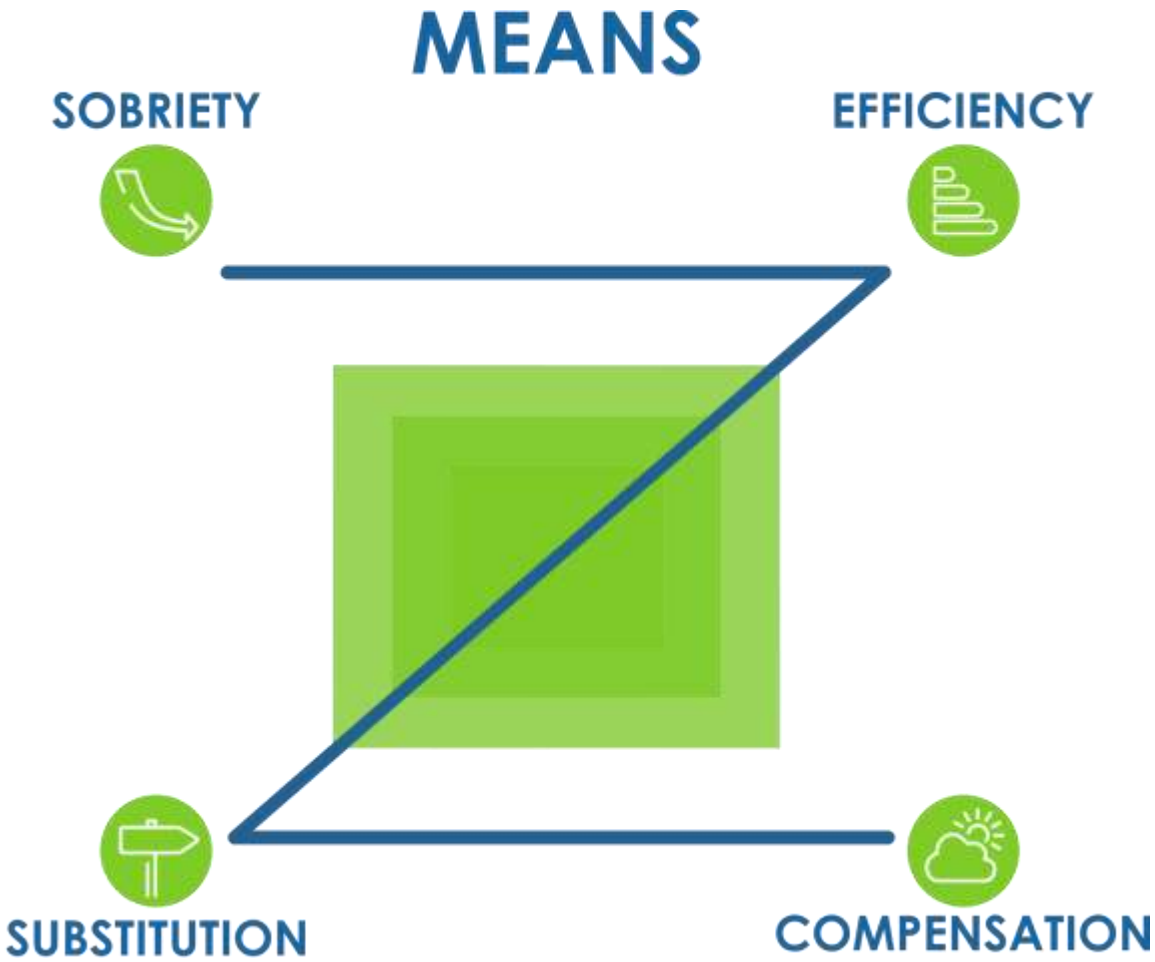
3. Global considerations

Transition mindmap

What do we want to do?

How do we want to do?





Courtesy from Daniel Suchet

Energy sustainability

How long can the environment continue with our current system?

Use renewable resources at a slower rate than renewal
Built alternatives when using non renewable ressources
Produce wastes at a slower rate than removal

Ressources

Pollution

Climate

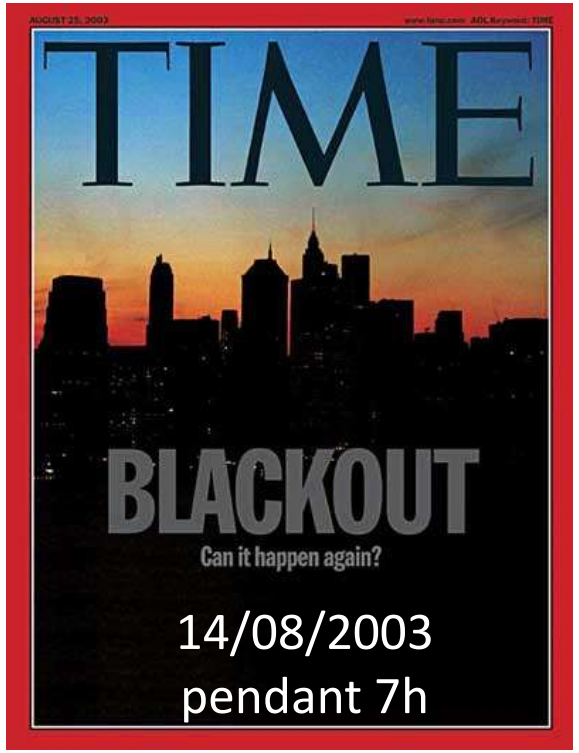
Energy security

How steady is energy supply? At what costs?

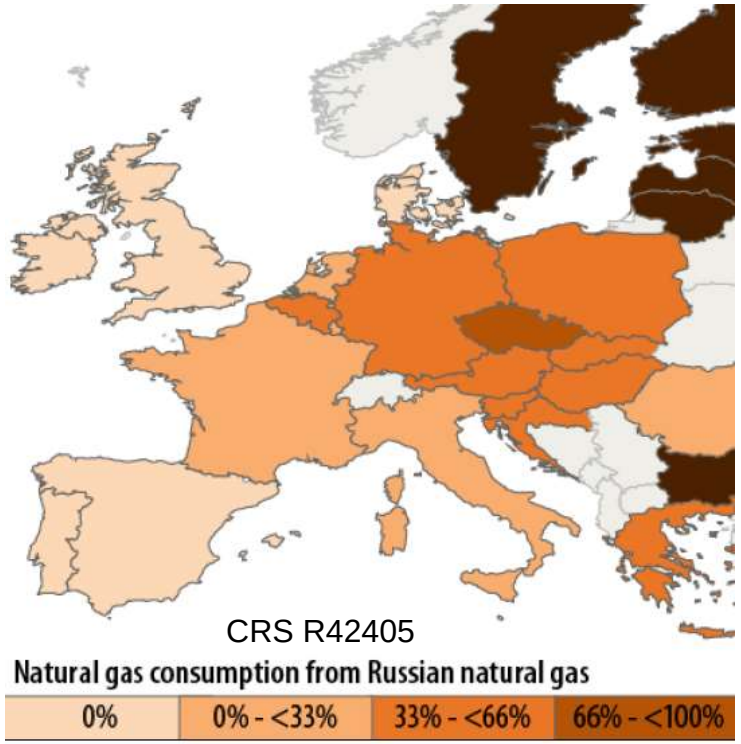
Accidents

Courtesy from Daniel Suchet

Stability



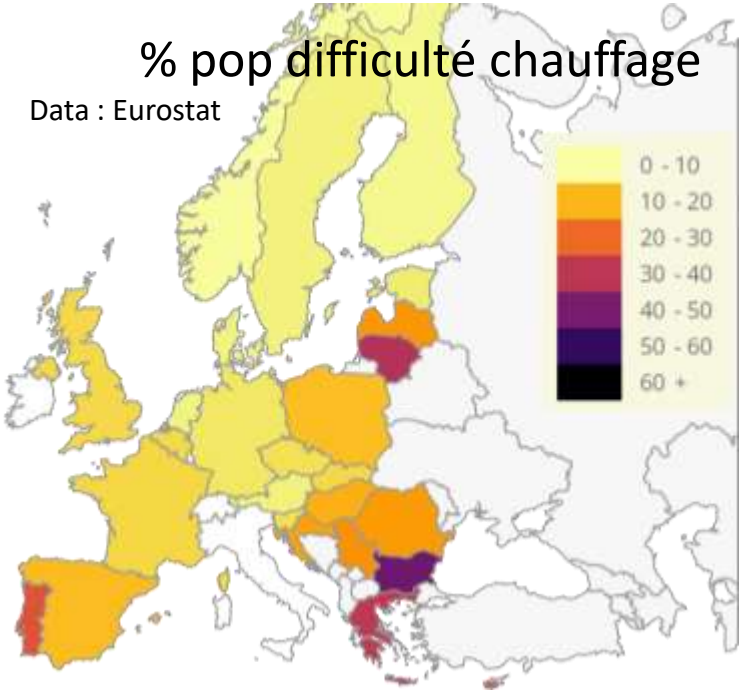
Dépendances



Energy equity

How affordable is energy?

Fuel poverty

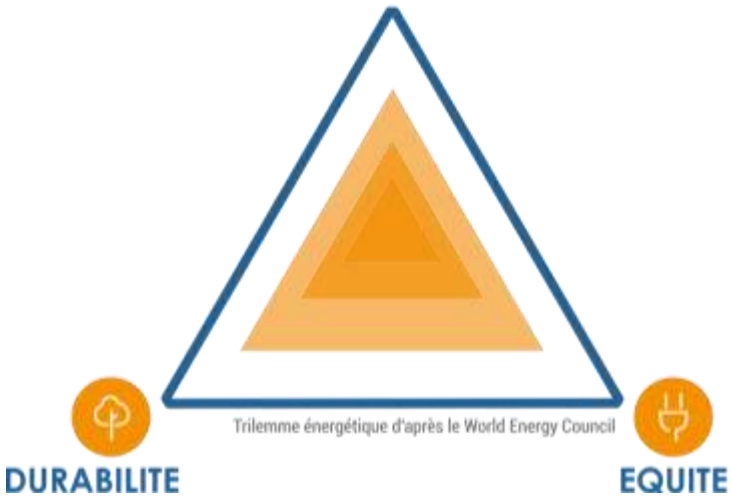


Domestic inegalities

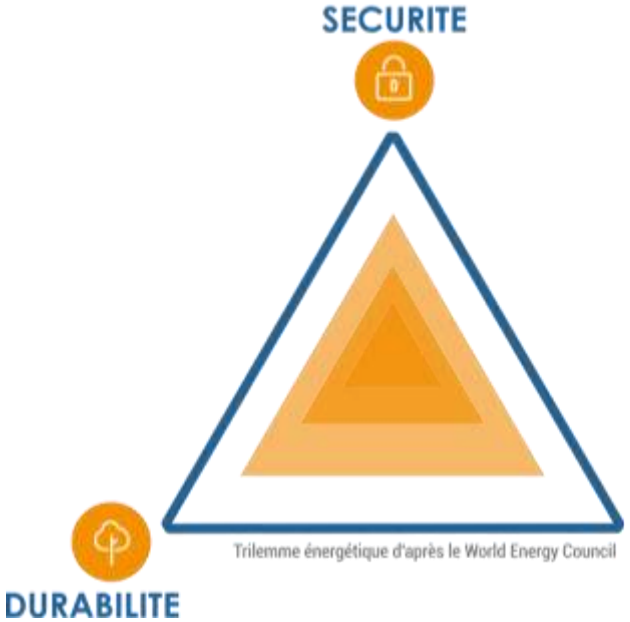
International inegalities

Courtesy from Daniel Suchet

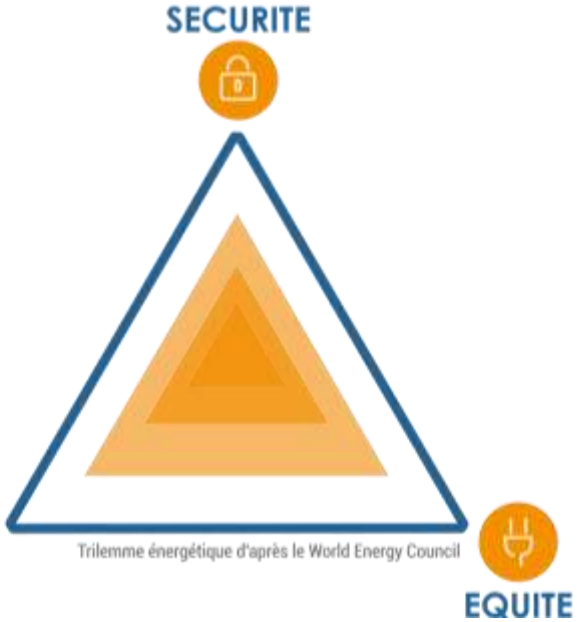
Three complementary targets



Cheap, sustainable, unsecured
→ unstable



Stable, sustainable, unaffordable
→ inacceptable

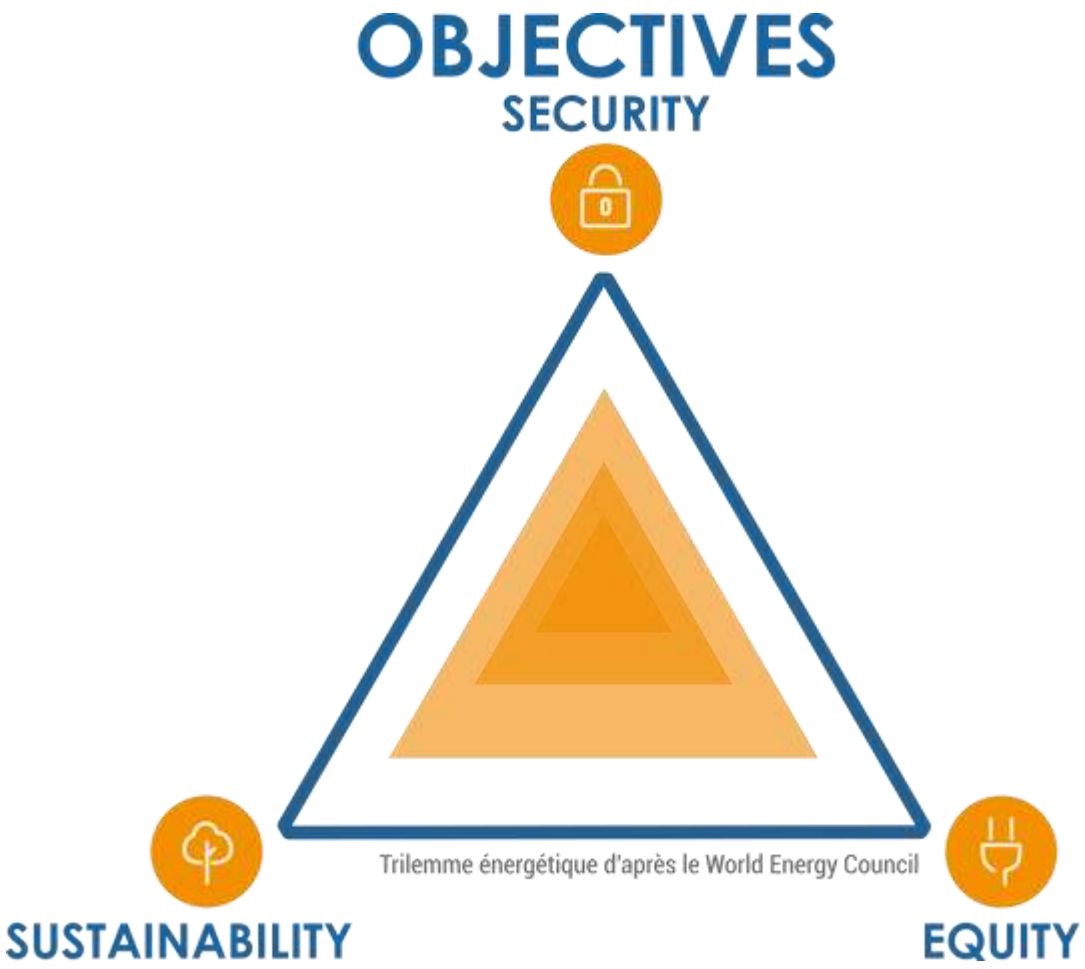


Cheap, stable, unsustainable
→ unbearable

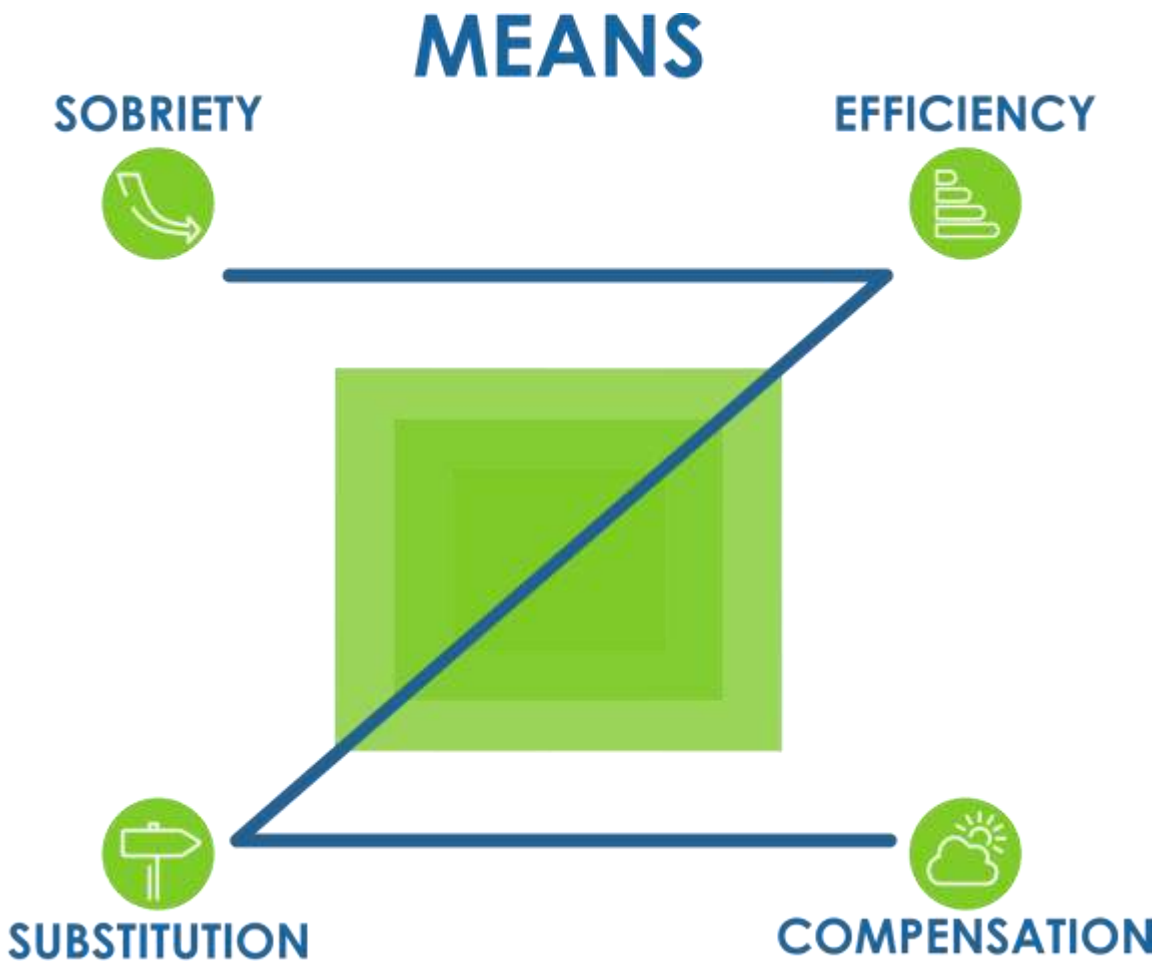
Courtesy from Daniel Suchet

Transition mindmap

What do we want to do?



How do we want to do?



Courtesy from Daniel Suchet

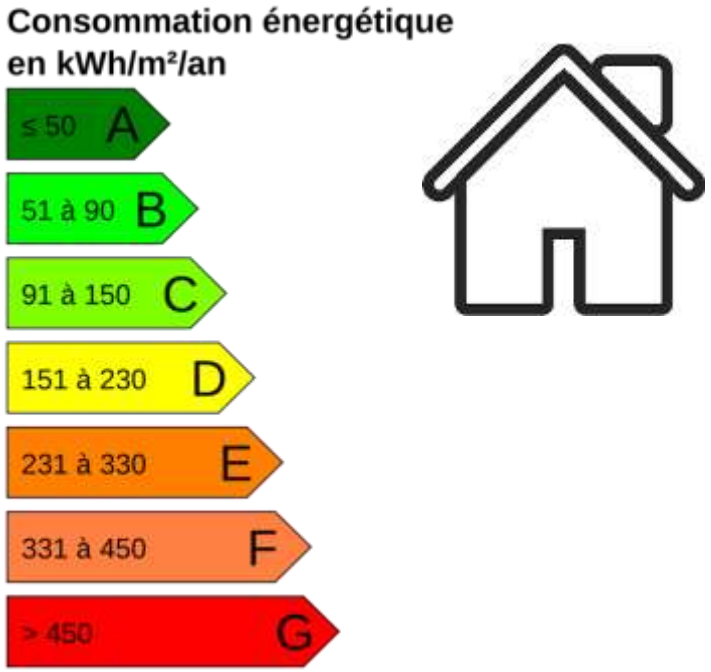
Sobriety

Reduce expected services

Courtesy from Daniel Suchet

Efficiency

Achieve the same service, with less energy consumption



Courtesy from Daniel Suchet

Substitution

Consume the same amount of energy, from another source

Compensation

Use the same source, balance the downfalls

Courtesy from Daniel Suchet

Question toolbox

OBJECTIFS

Which priority?

Means adequate to tackle objectives ?

Indirect effects?

MOYENS

Technical feasability?

Context?

Jevon's paradox (rebound effect)

It is wholly a confusion of ideas to suppose that the economical use of fuel is equivalent to a diminished consumption. The very contrary is the truth.

No single solution is perfect.

→ Don't claim your solution is perfect (it's not)

→ Don't reject a solution because it has drawbacks (business as usual wins)

Courtesy from Daniel Suchet

Kaya's equation

"IPAT" analysis

Impact = Population × Affluence × Technology

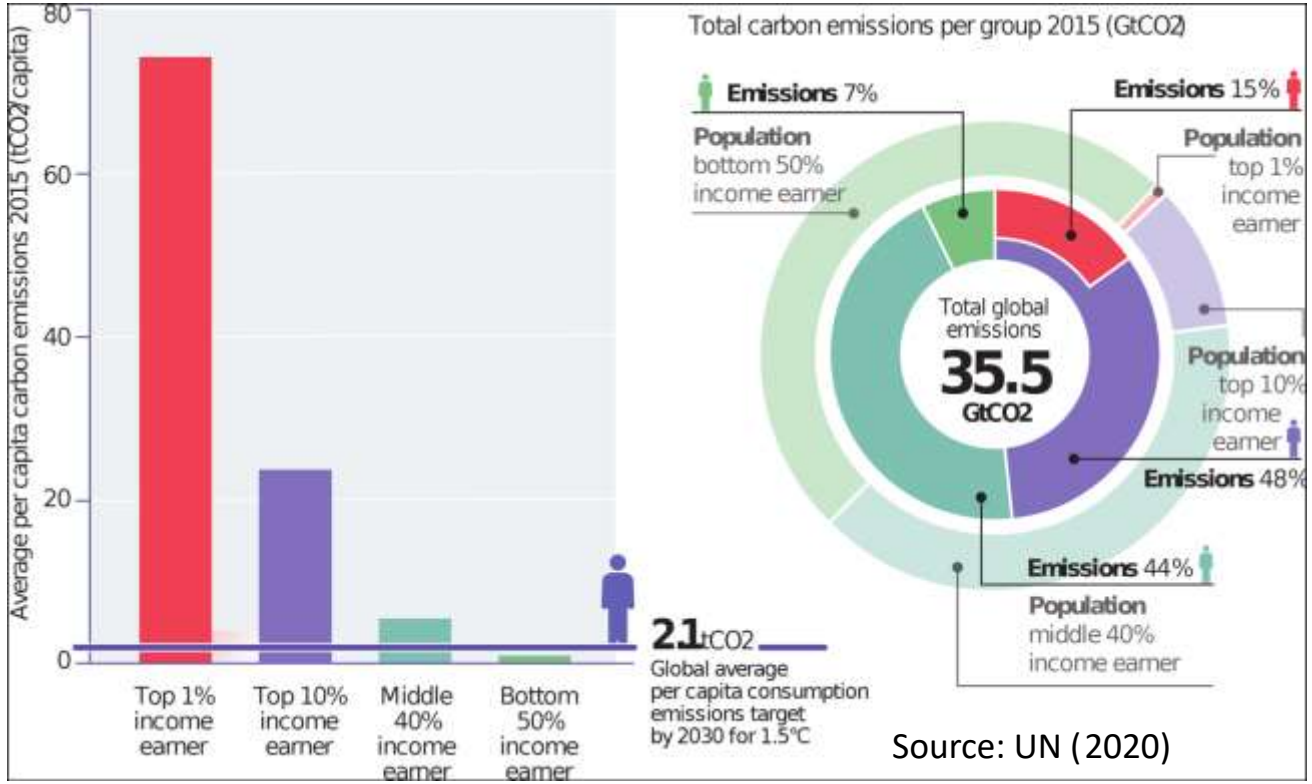
Ehrlich and Holdren (1971)

Yoichi Kaya (1997)

$$CO_2 = \frac{CO_2}{Energy} \times \frac{Energy}{GDP} \times \frac{GDP}{Capita} \times Capita$$

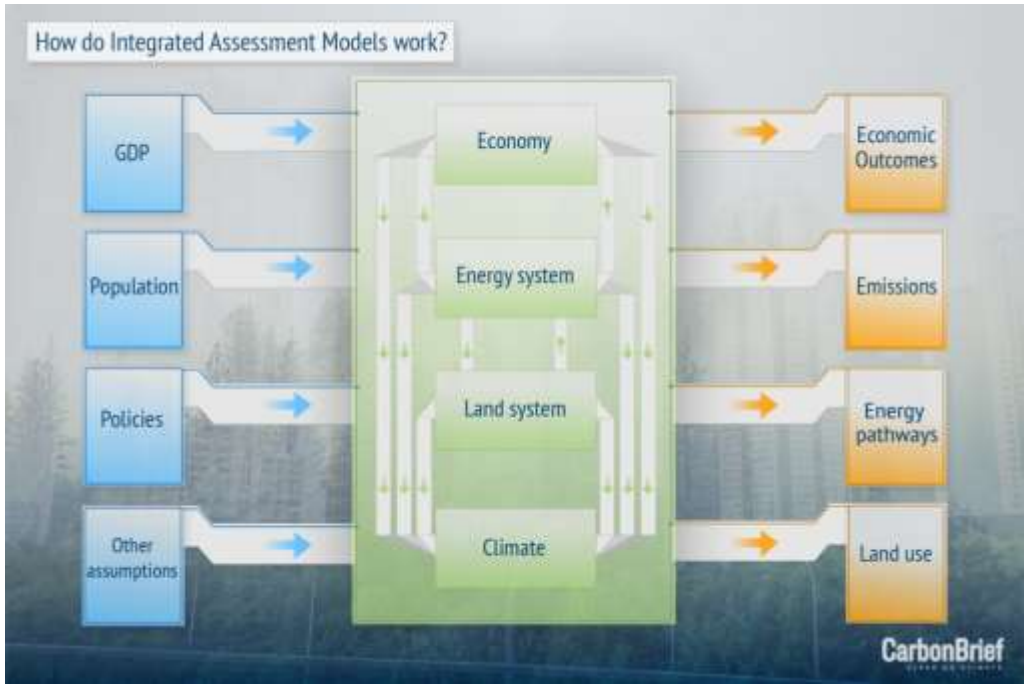
Carbon intensity *Energy intensity* *Economic welfare*

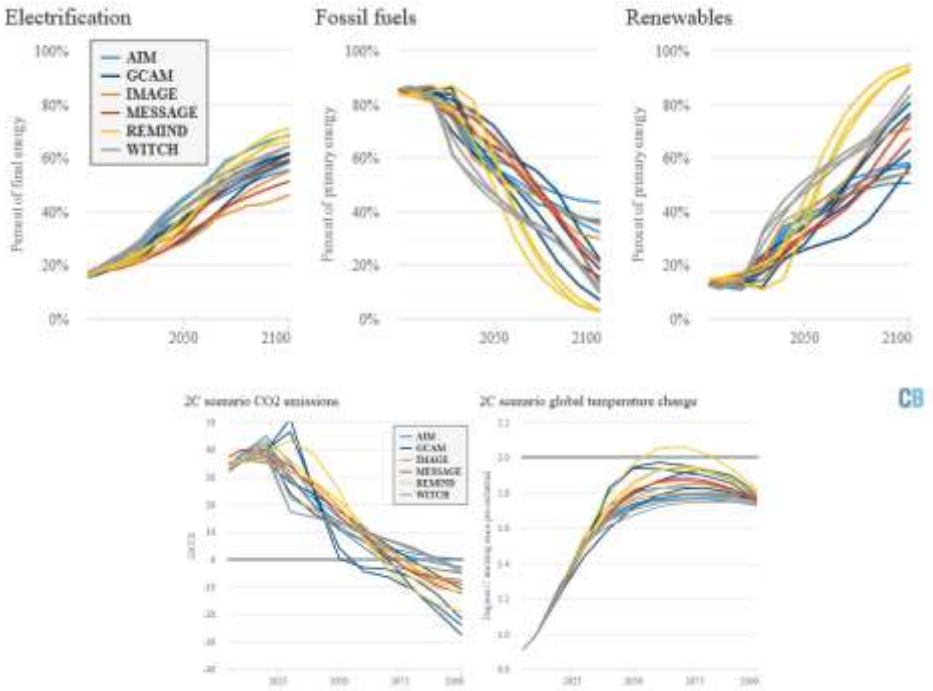
Be careful with
over-interpretation !



Source: UN (2020)

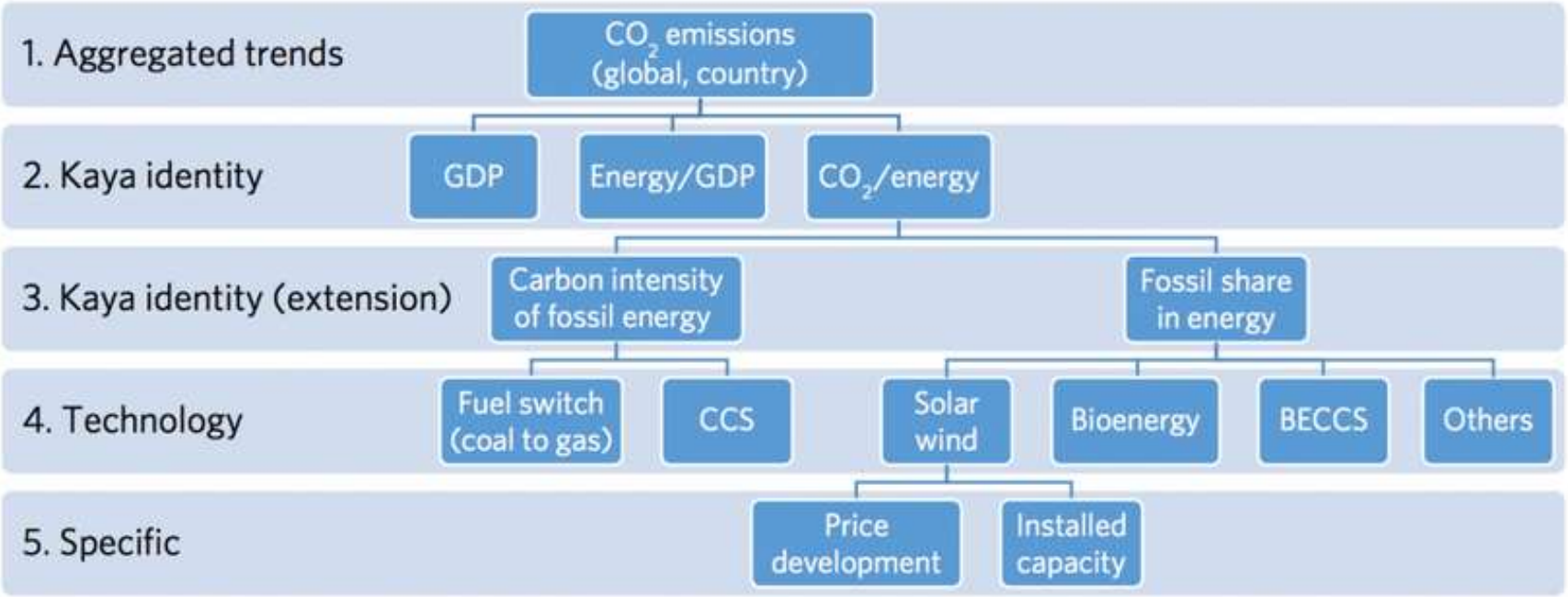
3.1 Scenarios





https://www.carbonbrief.org/qa-how-integrated-assessment-models-are-used-to-study-climate-change

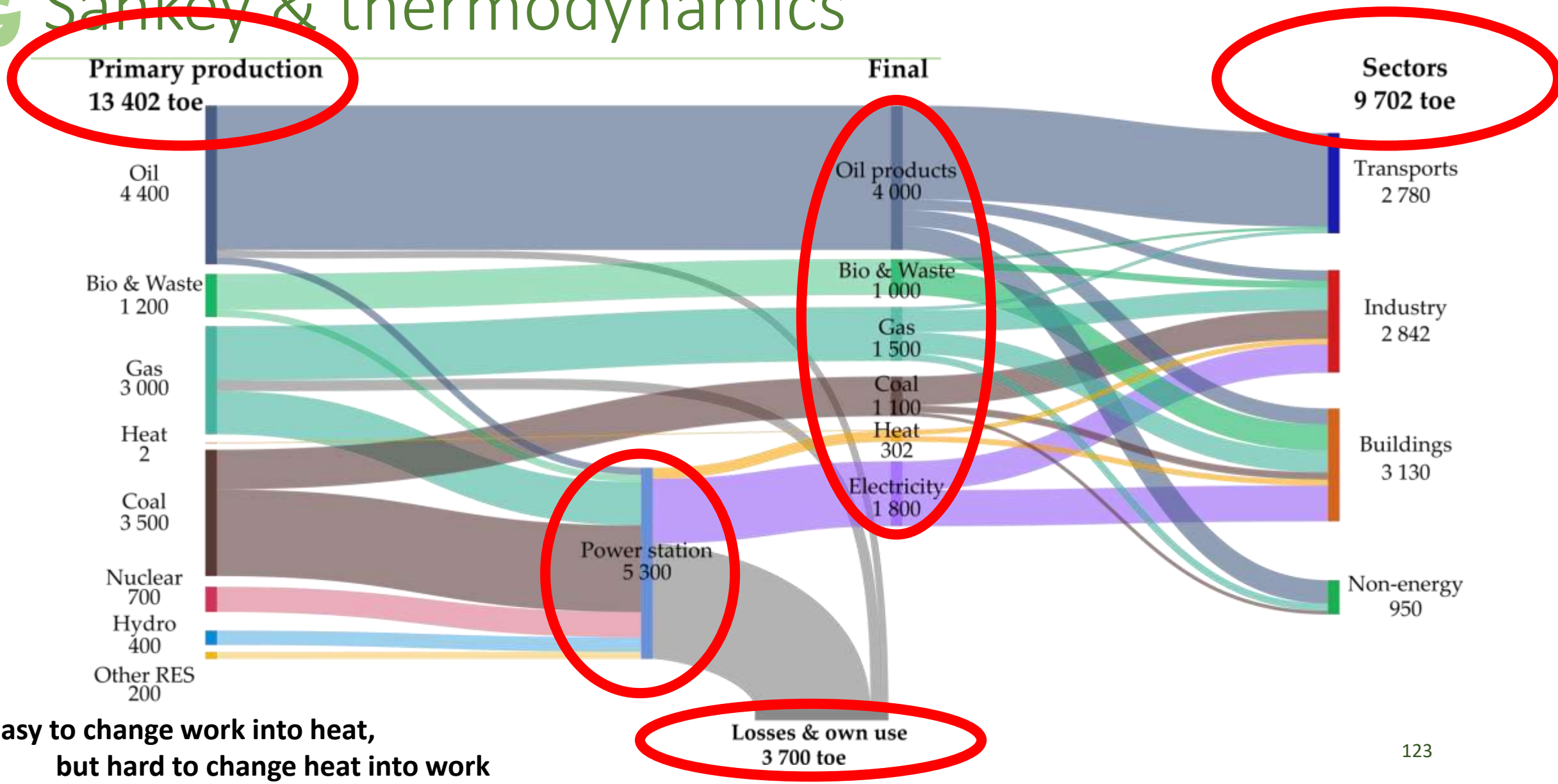
3.1 Scenarios



A hierarchy of potential indicators for tracking progress towards the Paris Agreement. The upper layers are closer to policy and the emissions pledges themselves, while the lower layers represent the inputs needed to meet the pledges. Source: Peters et al. (2017).

Peters, G. P. et al. (2017) Key indicators to track current progress and future ambition of the Paris Agreement, Nature Climate Change, doi:10.1038/nclimate3202

Sankey & thermodynamics



It is easy to change work into heat,
but hard to change heat into work

3.1 Scenarios from RTE

Increase of the electricity production (absolute and relative)
Decrease of total energy production

Figure 3 Évolution de la consommation totale d'électricité et de la consommation d'énergie finale pour les autres énergies en France

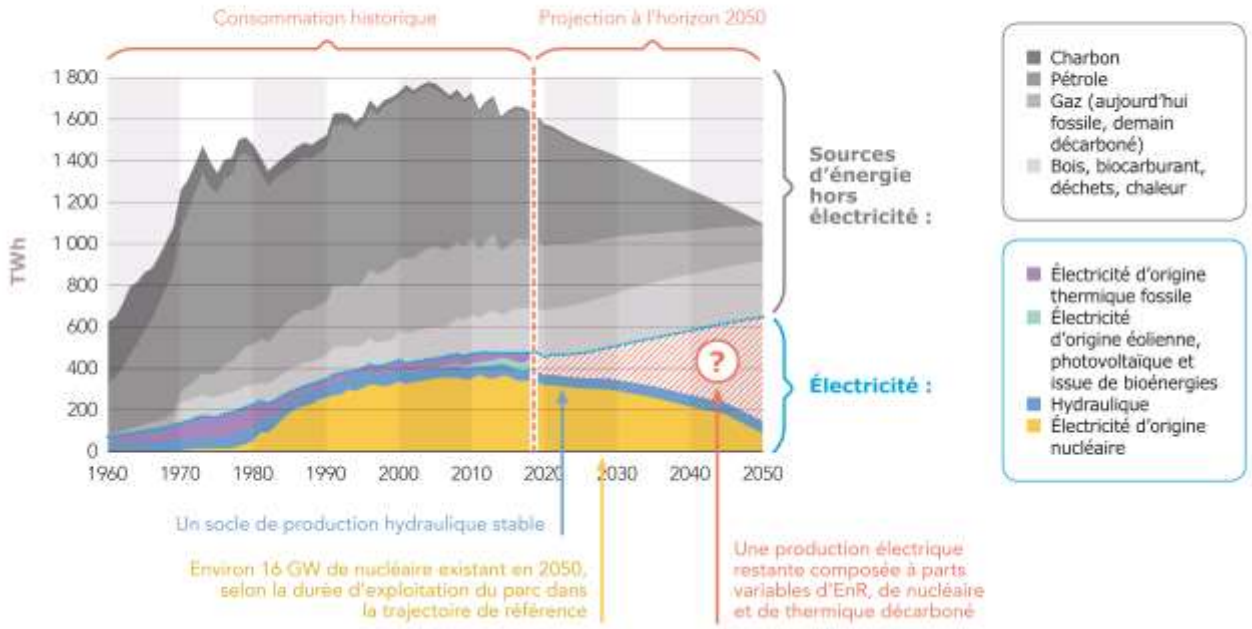
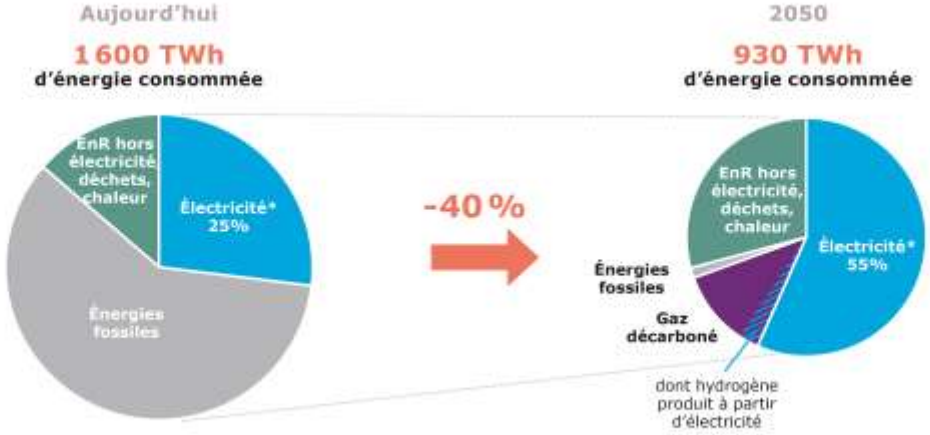
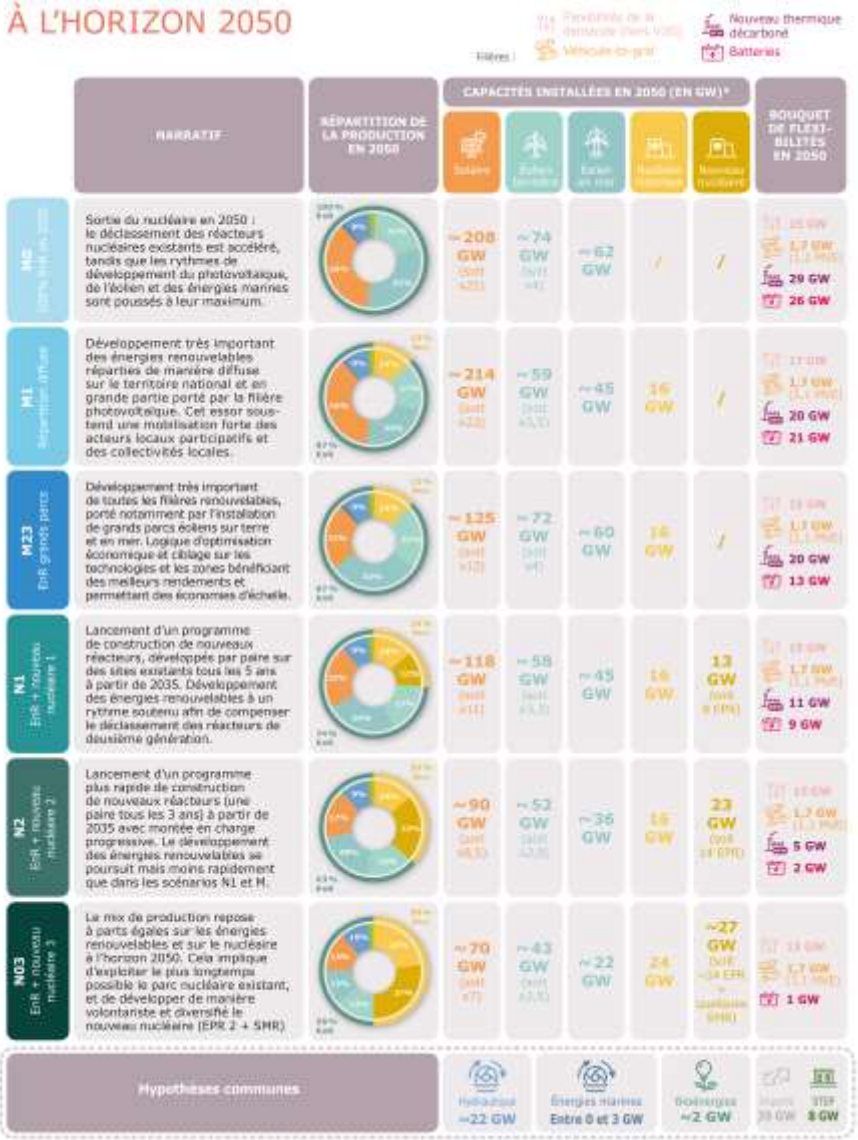


Figure 2 Consommation d'énergie finale en France et dans la SNBC



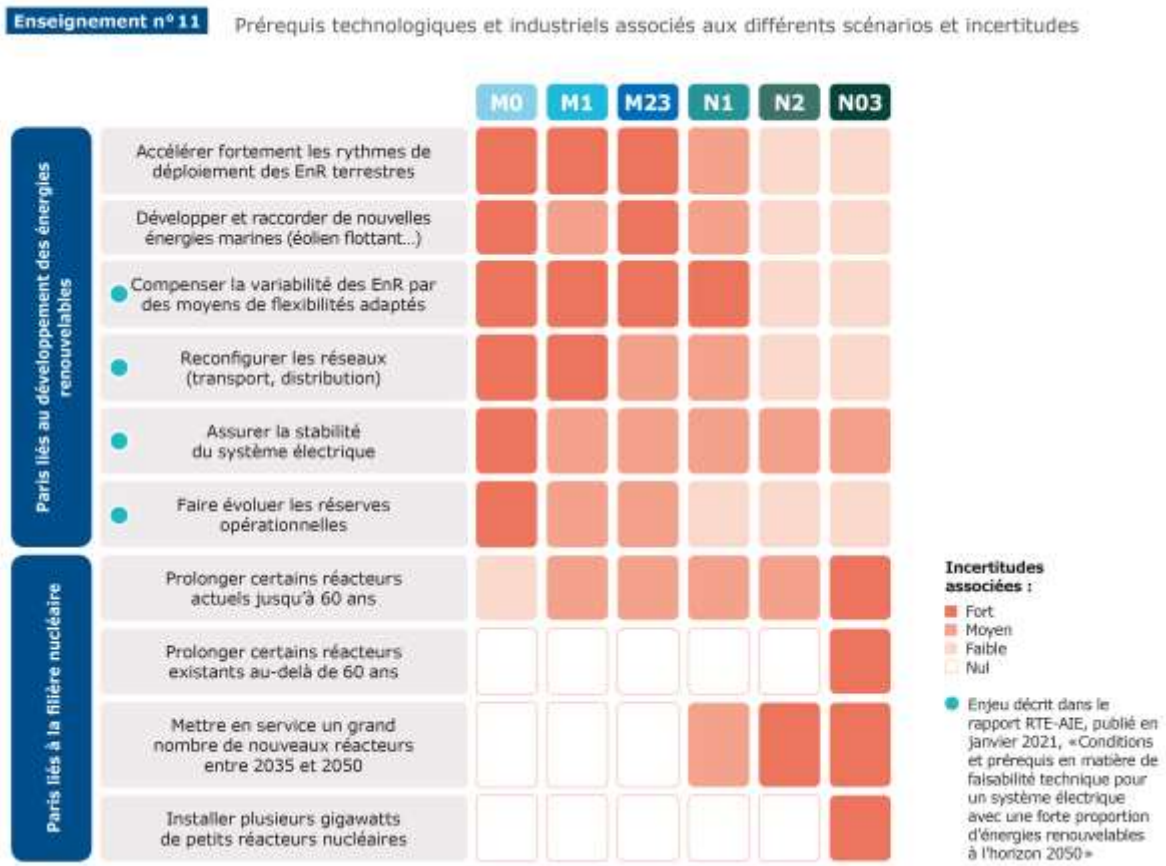
* Consommation finale d'électricité (hors pertes, hors consommation issue du secteur de l'énergie et hors consommation pour la production d'hydrogène)
Consommation intérieure d'électricité dans la trajectoire de référence de RTE = 645 TWh

3.1 Scenarios from RTE



- In each scenario, growth of renewable
- Different ratio old nuclear/new nuclear

3.1 Scenarios from RTE



- Different risks
  Open question on sustaining actual nuclear power plant

- The economical might play a role, not huge difference though, careful on extreme scenarios

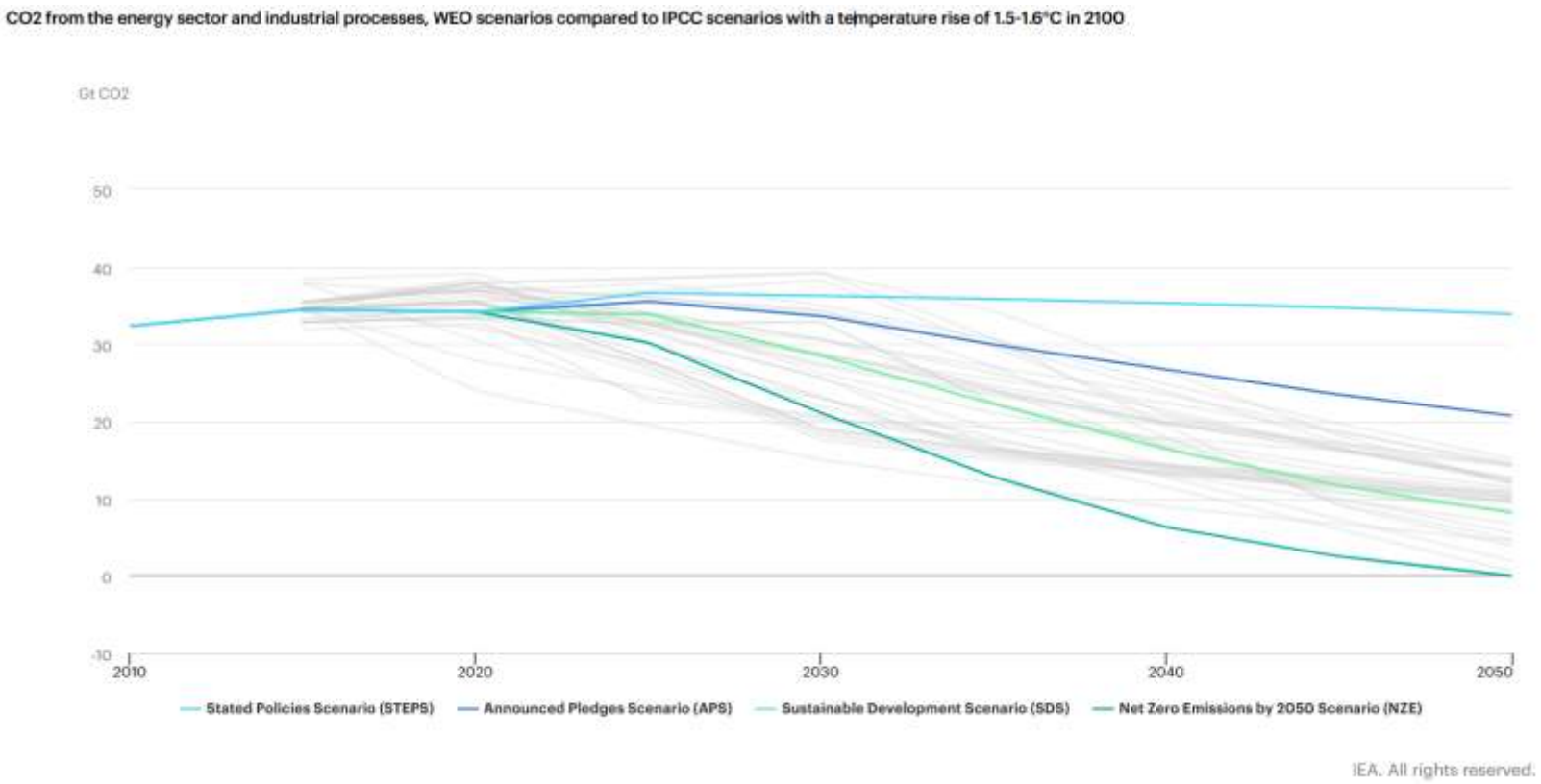
- Technological uncertainties in extreme scenarios

3.1 Scenarios from IEA

	Net Zero Emissions by 2050 Scenario	Announced Policies Scenario	Stated Policies Scenario	Sustainable Development Scenario
Definitions	A scenario which sets out a narrow but achievable pathway for the global energy sector to achieve net zero CO_2 emissions by 2050. It doesn't rely on emissions reductions from outside the energy sector to achieve its goals.	A scenario which assumes that all climate commitments made by governments around the world, including Nationally Determined Contributions (NDCs) and longer-term net zero targets, will be met in full and on time.	A scenario which reflects current policy settings based on a sector-by-sector assessment of the specific policies that are in place, as well as those that have been announced by governments around the world.	An integrated scenario specifying a pathway aiming at: ensuring universal access to affordable, reliable, sustainable and modern energy services by 2030 (SDG 7); substantially reducing air pollution (SDG 3.9); and taking effective action to combat climate change (SDG 13).
Objectives	To show what is needed across the main sectors by various actors, and by when, for the world to achieve net zero energy related and industrial process CO_2 emissions by 2050 while meeting other energy-related sustainable development goals.	To show how close do current pledges get the world towards the target of limiting global warming to 1.5 °C, it highlights the "ambition gap" that needs to be closed to achieve the goals agreed at Paris in 2015.	To provide a benchmark to assess the potential achievements (and limitations) of recent developments in energy and climate policy.	To demonstrate a plausible path to concurrently achieve universal energy access, set a path towards meeting the objectives of the Paris Agreement on climate change and significantly reduce air pollution.

3.1 Scenarios from IEA

https://www.iea.org/reports/world-energy-model

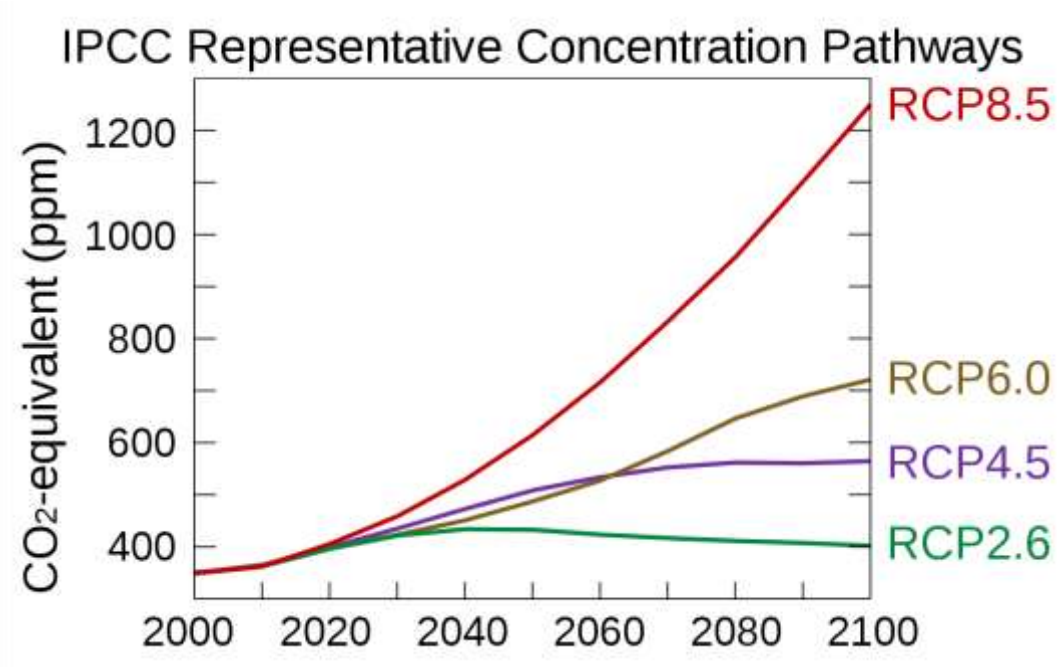


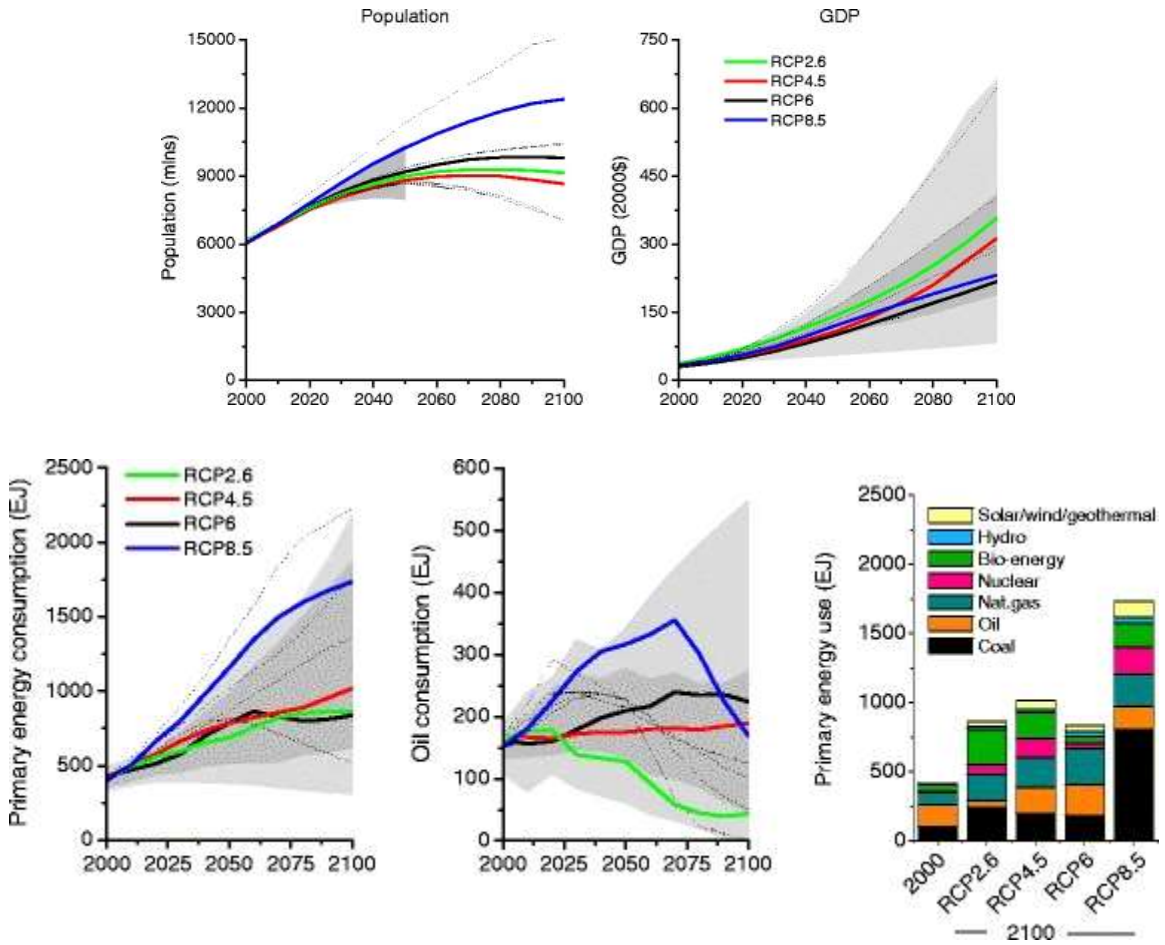
NZE and SDS assumptions :
Corss-cutting policies
Power sector policies
+
Building,
Transport
Building
Electricity and Heat
Others

Also compare with IPCC scenarios

3.1 Scenarios from IPCC

RCP x : Radiative forcing (+y W/m²) predicited in 2100





The representative concentration pathways: an overview. *Climatic Change* **109,** 5 (2011). https://doi.org/10.1007/s10584-011-0148-z

This is *an* end, what’s yours ?

BackSlides

2.3 Hydrogen -production

Vaporéformage

1) Formation du «gaz de synthèse» ($CO + H_2$)

Besoin de chaleur

$$CH_4 + H_2O \rightarrow CO + 3\ H_2 \quad (\Delta H = 206\ kJ/mol)$$

Procédé endothermique: 900°C/25 bars avec un catalyseur (souvent Ni)

2) Réaction du gaz à l'eau (T de 200 à 400°C)

Exothermique
Source de chaleur

$$CO + H_2O \rightarrow CO_2 + H_2 \quad (\Delta H = -41\ kJ/mol)$$

Résidu de CO (0,3-0,8%)?

- Oxydation partielle: $CO + ½\ O_2 \longrightarrow CO_2$
- Méthanisation : $CO + 3\ H_2 \longrightarrow CH4 + H_2O$
- Séparation par membrane

2.3 Hydrogen -production

Vaporéformage

1) Formation du «gaz de synthèse» ($CO + H_2$)

Besoin de chaleur

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Exothermique
Source de chaleur

$$CO + H_2O \rightarrow CO_2 + H_2 \quad (\Delta H = -41\ kJ/mol)$$

Rendement
65-80%

Réaction globale (Bilan)

$$CH_4 + 2\,H_2O \rightarrow CO_2 + 4\,H_2 \quad (\Delta H = 165\ kJ/mol)$$

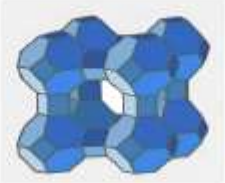
3) Purification de l'hydrogène (séparation H_2/CO_2)

Pressure Swing Adsorption

- Décarbonatation en utilisant une solution concentrée de NaOH → 95-98 %
- **Adsorption** sélective de gaz sur des zéolithes à températures près ambiantes → 99.999 %

Purité de H_2

$M_{x/n}[(AlO_2)_x(SiO_2)_y]\ .\ z\ H_2O$



2.3 Hydrogen -production

Oxydation partielle

1) Formation de « gaz de synthèse »

$$C_nH_m + n/2\ O_2 \rightarrow n\ CO + m/2\ H_2 \qquad \Delta H < 0$$

Procédé exothermique : réaction à 1300°C/50 bars

(CH_4) → 46 % H_2, 46 % CO, 6 % CO_2, 1 % NO_x (+ faible que par vapo-reformage)

(**m** faible on a du **charbon**; **m** élevé on a du pétrole)

2) Réaction du gaz avec l'eau

$$CO + H_2O \rightarrow CO_2 + H_2 \qquad \Delta H = -41 kJ/mol$$

Rendement 50 à 65%

3) Purification de l'hydrogène

par décarbonatation et adsorption par variations de pressions

Production de CO_2 plus élevée que par vaporeformage

- Bien pour charbon, pétrole…
- Rendement 55-65%
- Plus onéreux que réformage
- Forte émission de CO_2

2.3 Hydrogen -production

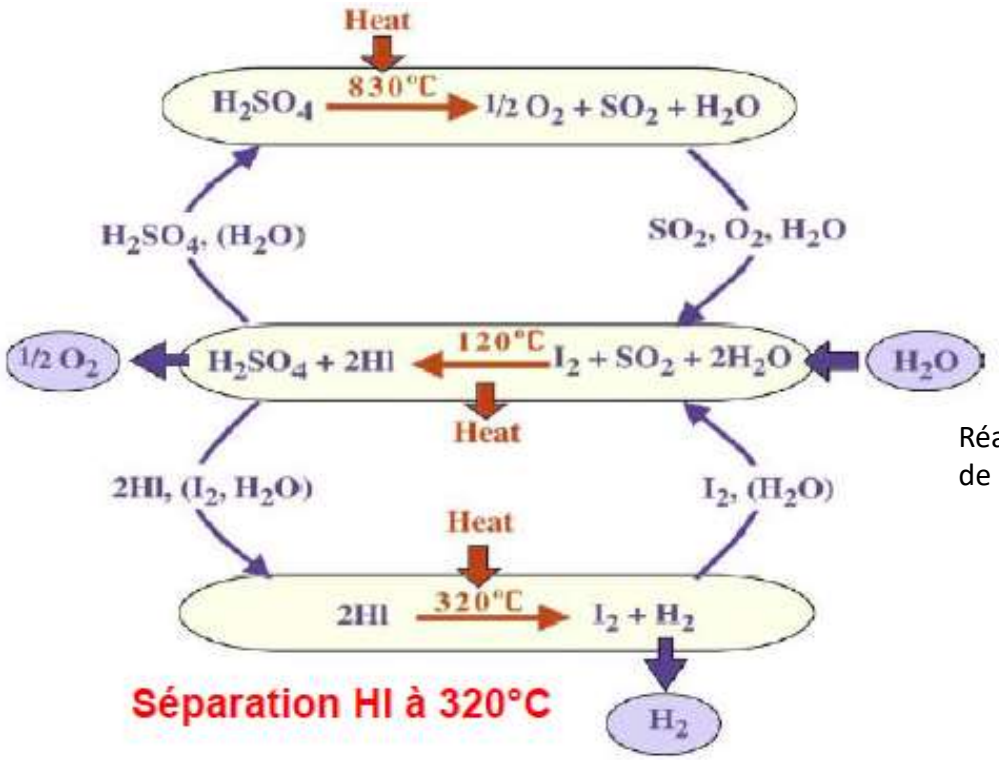
Thermochimie

Hot source
(centrales : nucléaire - solaire)

→ cycle Iode-soufre
(Inventé dans les années 1970
Par General Atomics, USA)

50 % environ d'efficacité

Les premiers réacteurs industriels prévus pour 2040 ??



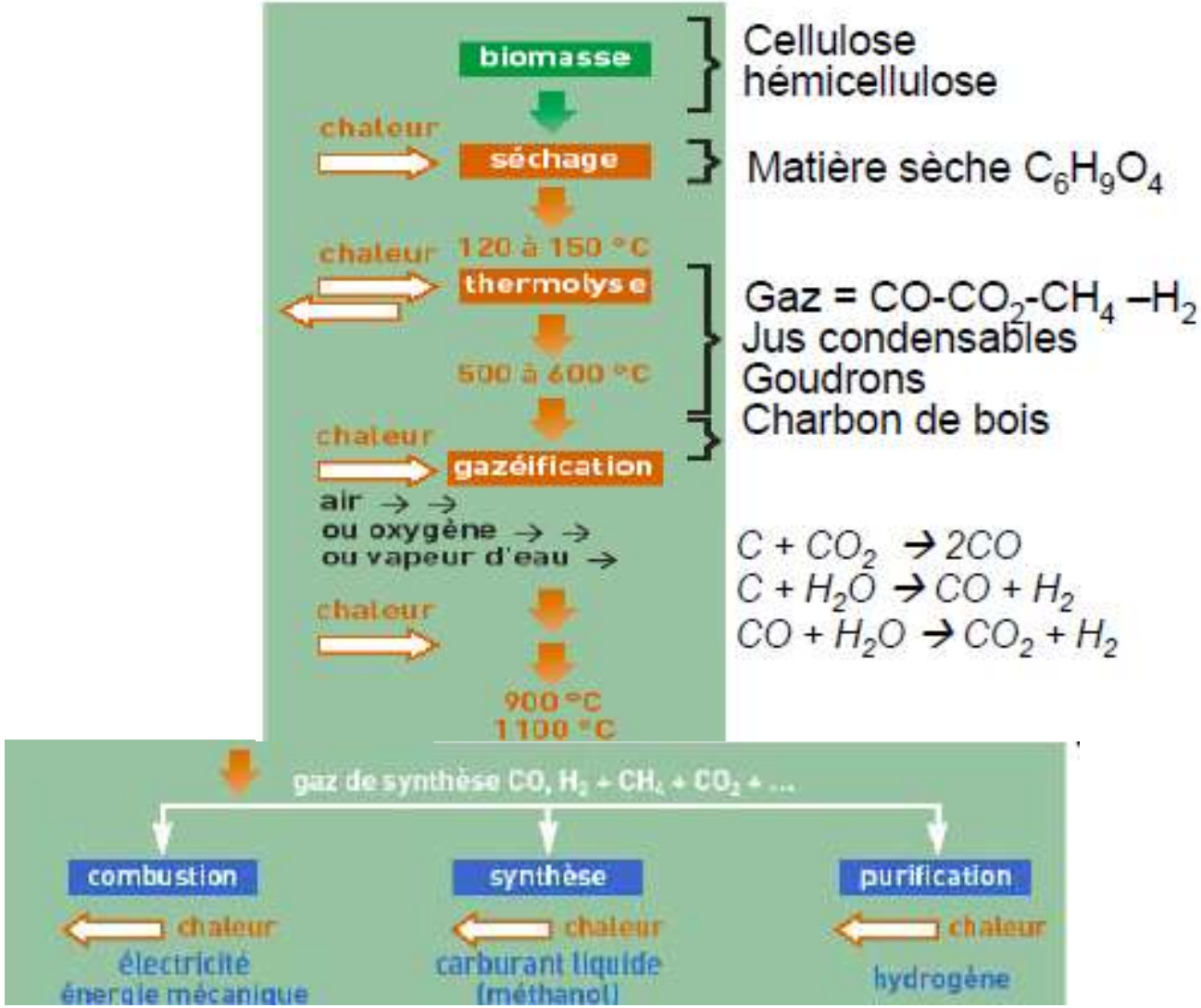
Réaction
de Bunsen

Séparation HI à 320°C

J.M. Tarascon, College de France

2.3 Hydrogen -production

Biomass

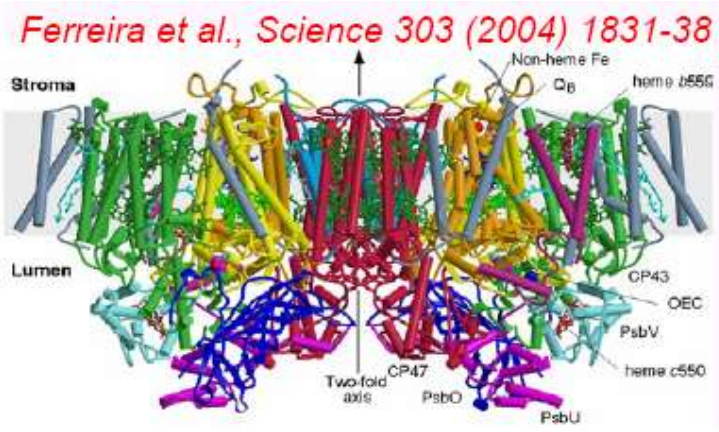


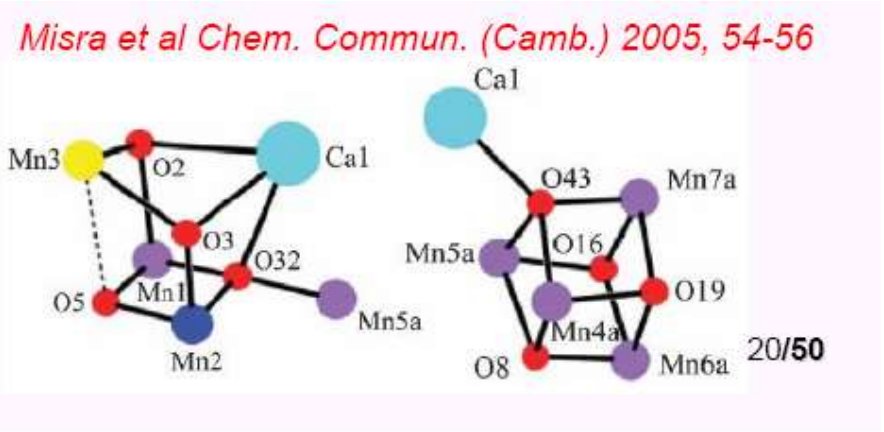
Gazeification (proche Oxydation partielle)
Fermentation aussi possible

- **High temperature**
- **Low efficiency**

2.3 Hydrogen -production

Biomass





- **Direct H2 production from bacteria**

- **Biomass efficiency ~1%**
  - ✓ Annual production ~172 billions of tons (dry), i.e. 15 x fossile fuel consumption
  - ✓ Stored amount is ~1800 billions tons (dry equivalent), ~fossile

- **Photosynthesis (artificial), sugar production**

2.3 Hydrogen -production

Artificial Photosynthesis

microalgues

cyanobactéries

$$2\,H_2O \xrightarrow{\text{Photosynthesis}} O_2\uparrow + 4\,e^- + 4\,H^+ \xrightarrow{\text{Hydrogenase}} 2\,H_2\uparrow$$

Biohydrogène : cyanobactérie, microalgues
hydrogénases, catalyseurs bioinspirés

(Eviter l'utilisation de Pt)

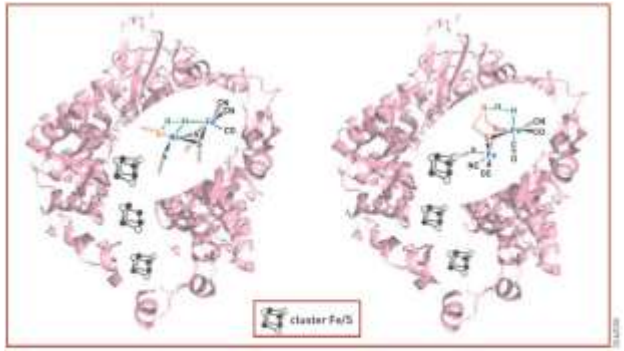


Figure 1.
Représentation schématique de la structure des hydrogénases NiFe (à gauche) et FeFe (à droite) dans l'état intermédiaire-clé de leur cycle catalytique. Les résidus cystéine 1 ——— S1, ligands des centres métalliques, sont symbolisés par leur atome de soufre. Le ligand dithiométhylamine du site actif des hydrogénases FeFe apparaît en rouge. La fonction amine qu'il contient est indiquée en orange, comme le ligand cystéine terminal jouant le même rôle dans le site actif des hydrogénases NiFe. L'interaction entre un ligand hydrure coordiné au site actif et un proton porté par les sites basiques (orange), qui facilite la réduction des protons en hydrogène ou l'oxydation de ce dernier, est schématisée en vert.

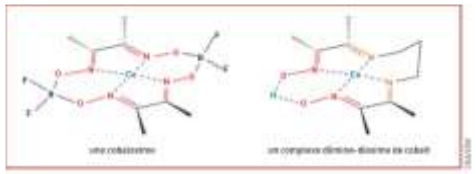


Figure 4.
Structure d'une cobaloxime, catalyseur à base de cobalt de première génération, et d'un complexe dimère-dioxime de cobalt développé plus récemment. Les fonctions oxime sont représentées en rouge et les fonctions imine en orange.

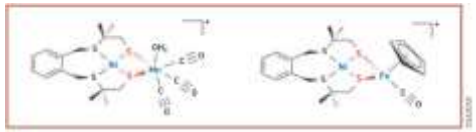


Figure 5.
Structure de composés nickel-manganèse et nickel-fer développés comme modèles structuraux et fonctionnels du site actif des hydrogénases NiFe.

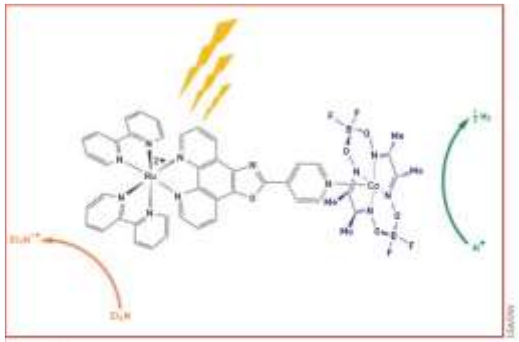


Figure 5.
Structure et fonctionnement d'un système photocatalytique supramoléculaire de production d'hydrogène et renfermant un complexe de ruthénium comme photosensibilisateur et une cobaloxime en tant que catalyseur de production d'hydrogène. La triéthylamine (Et_3N) fournit les électrons nécessaires à la transformation de l'eau en hydrogène au niveau du cobalt.