Lecture 1
Introduction

PHY 555 – Energy & Environment

Erik Johnson, Mathieu de Naurois, Daniel Suchet

PHY555 – Content and program

		Lecture	PC (X)	PC (STEEM)
1	Introduction	23-sept	23-sept	27-sept
2	Sustainability, climate change and resource exhaustion	30-sept	30-sept	4-oct
3	Fossil fuels: oil, gas and coal	07-oct	07-oct	11-oct
4	Heat engines: from cars to power plants	21-oct	21-oct	25-oct
5	Thermal energy	28-oct	28-oct	15-nov
6	Nuclear energy: fission and fusion	18-nov	18-nov	22-nov
7	Wind & hydro: mechanical energies	25-nov	25-nov	28-nov
8	Solar energy: thermal, chemical and electrical	28-nov	28-nov	29-nov
9	Electricity: grid and storage	2-dec	2-dec	6-dec
	Final exam		dec	

PHY555 – Pedagogical targets

Cultural General overview of the energy issue:

What is at stake? Current status? Past evolutions? Future Perspectives?

Engineer Orders of magnitudes, rules of thumb, technical challenges…

Physics Basic science, ultimate limitations… and a lot of thermodynamics !

References :

Textbook (work in progress), chapters uploaded on Moodle
MacKay, D. « Sustainable energy: without the hot air » (2015) (https://www.withouthotair.com/)
Smil. V, « Power density », MIT Press (2016)
Jaffe R. L. & W. Taylor, « The Physics of Energy », Cambridge University Press (2018)
Diu, B., Guthmann, C. et al., « Thermodynamique », Hermann (2007)
Kittel, Thermal Physics, WH Freeman (1980)
Atkins' Physical chemistry, Oxford University Press (2018)

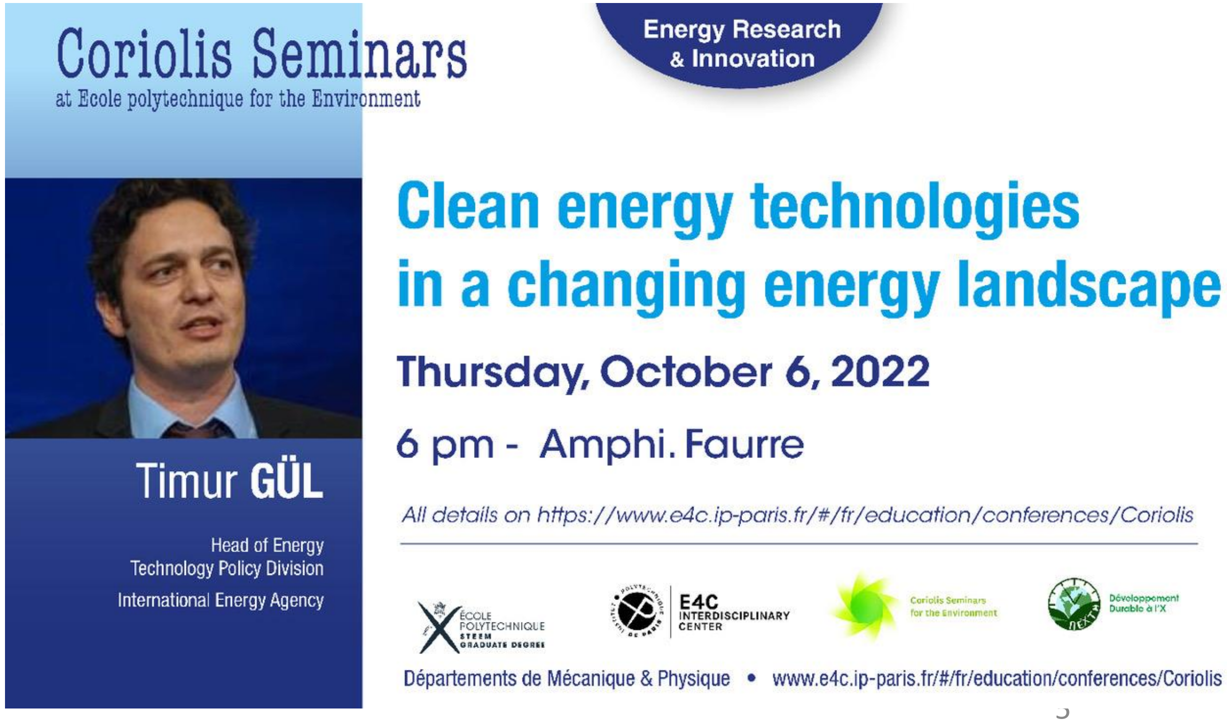
Moodle **Slack: https://phy555.slack.com**

Evaluations

Weekly quiz	Individual work Open Friday 12h, closes next Friday 8h ~ 5 lecture related questions Should not take more than 30’
Homework	Teamwork (3-4 students) 3 weeks to prepare
Final exam	Individual work Documents allowed 3h, in class

An energy ecosystem

IPVF · LPICM · LABORATOIRE PMC · LMD … ENSTA ParisTech université PARIS-SACLAY … INSTITUT POLYTECHNIQUE DE PARIS E4C



Lecture 1 Introduction

I. Energy : what? why?

II. Energy accounting : how much of which energy ?

III. Energy today : balance and diagrams

IV. Energy transition : where to go, how to get there?

V. Thermodynamics reminders

What is energy ?

Let’s ask Google

Energy production

Energy transmission

Energy consumption

Actually

Wind and solar cover < 4% of energy production

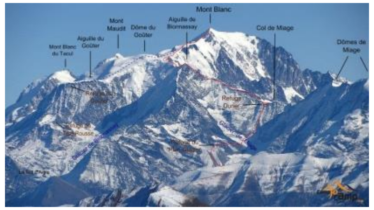
Electricity represents < 20% of energy consumption

Lightning is <2% of energy usage…

What is energy? Bottom-up approach

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

Kinetic

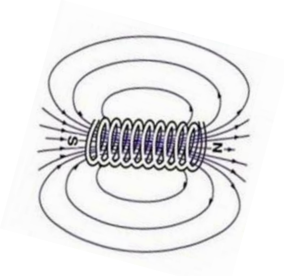


$E = mgz$

Gravity

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

Elastic

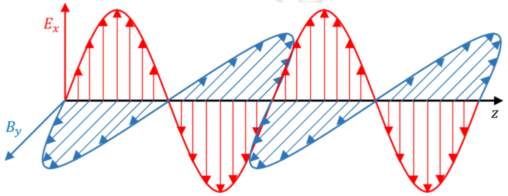


$E = \frac{1}{2}LI^2$

Inductance

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

Capacitance

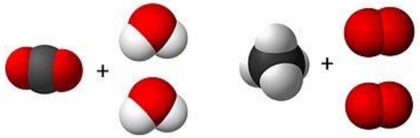


$\int d^3\mathbf{r} \left(\frac{1}{2}\epsilon E + \frac{1}{2\mu_0}B^2 \right)$

Electromag.

$\Delta E = C\Delta T$

Thermal



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

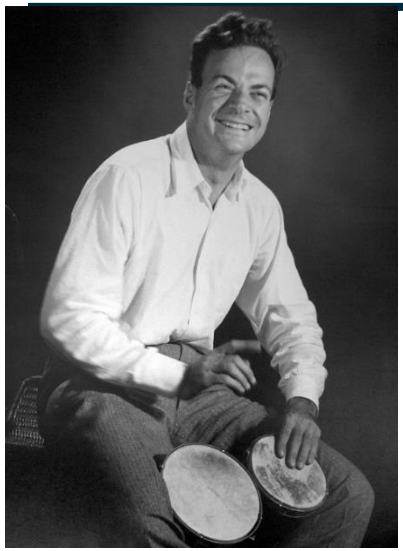
Chemical

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

Phase

Very specific, not very generic…

What is energy? Top-down approach



R. Feynman

E. Noether

"There is a fact, or if you wish a law, governing all natural phenomena that are known to date. There is no exceptions to this law – it is exact so far as is known. The law is called the conservation of energy. It says that **there is a certain quantity, which we call energy, that does not change in the manifold changes which nature undergoes**. That is a most abstract idea, because it is a mathematical principle; it says that there is a numerical quantity, which does not change when something happens. It is not a description of a mechanism, or anything concrete; it is just a strange fact that we can calculate some number and when we finish watching nature go through her tricks and calculate the number again, it is the same."

Feynman, *The Feynman Lectures on Physics* (1961)

Energy conservation derives from time invariance
(Noether theorem, 1918)

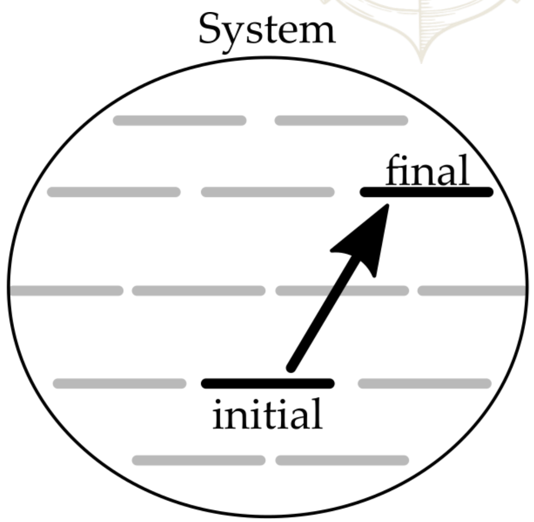
Very powerful, not very useful…

What is energy? Practical approach

When performing any transformation onto a system,

‘‘energy’’ is a necessary (but not sufficient) quantity

which must be brought (or removed) from that system.



To provide this energy, we use an ‘‘energy source’’,

whose spontaneous evolution delivers energy.

Why would the energy source release its energy to the system ?

Among all possible transitions, which transformation actually occurs ?

The environment in which these transformations occur is key.

What is energy? Energy and power

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

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

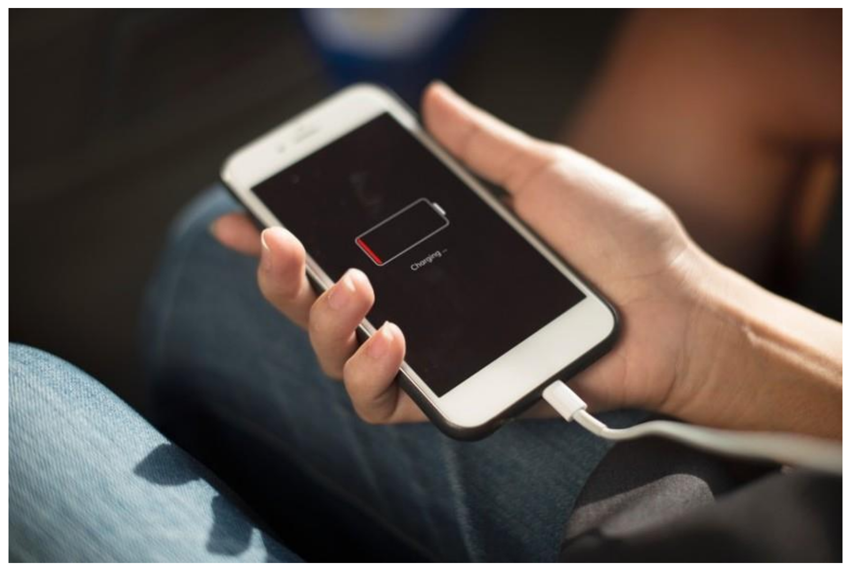
200 W accumulated during 0.5 s = 100 J

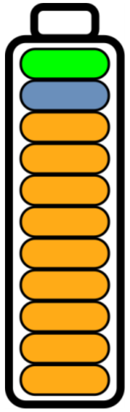
1 W accumulated during 1min 40s = 100 J

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

Tomorrow: power more limiting than energy?

Why energy? All is transformation !





Usage 10%

Transport 10%

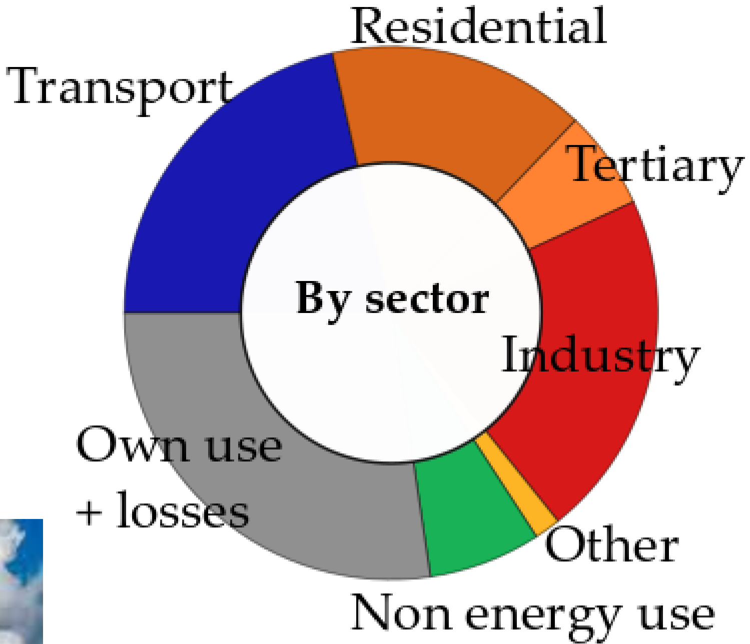
Production 80%

Source : ADEME

+ network, database, ads…

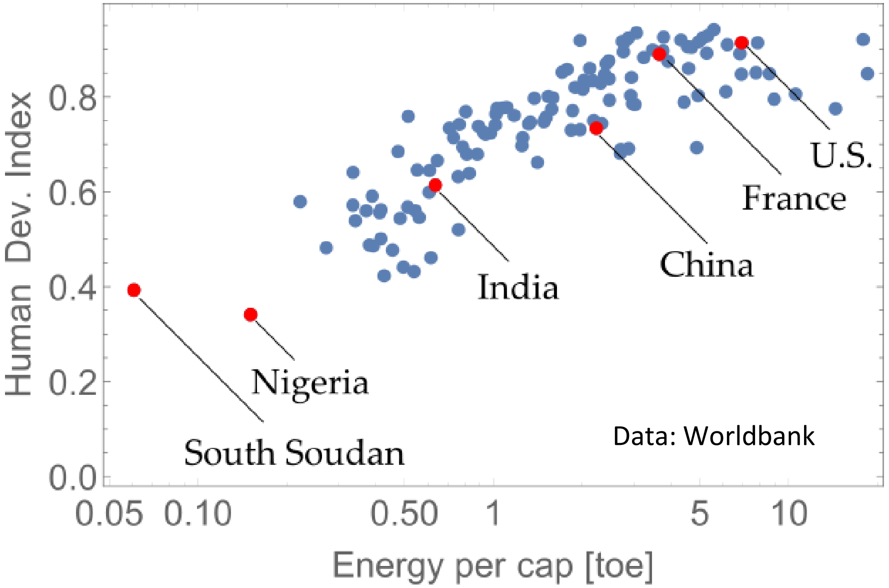
Why energy? A strategic resource

World Total Final Consumption, IEA 2020

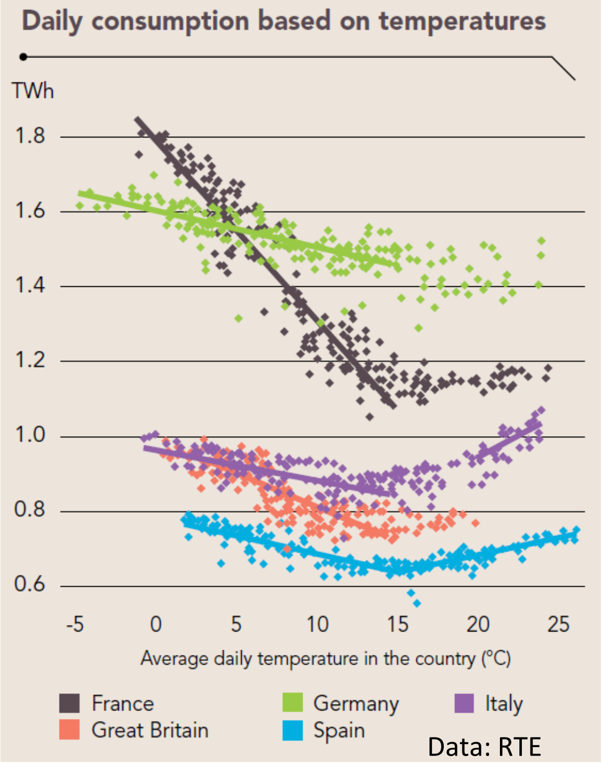


Why energy? A powerful indicator

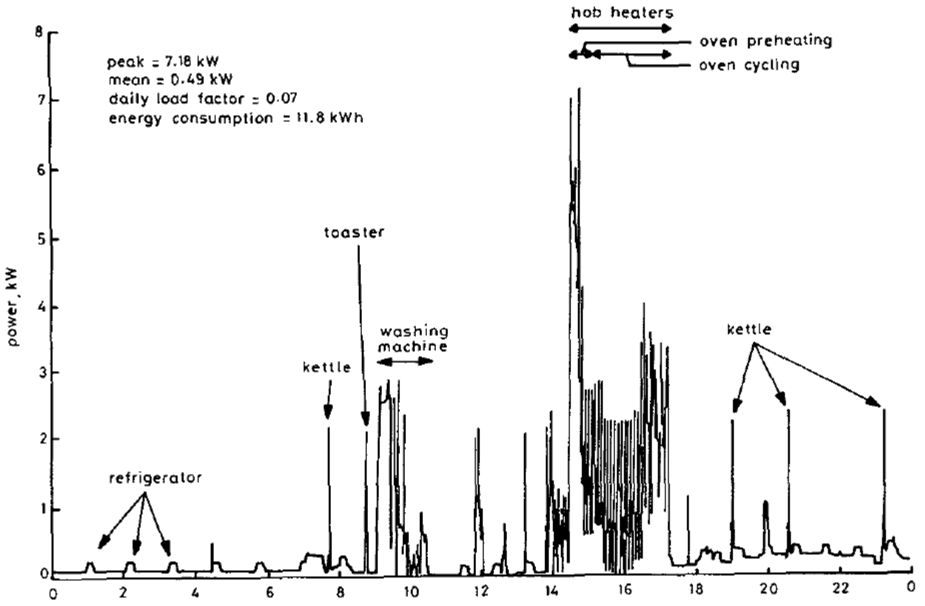
Energy consumption and society



Energy and policies



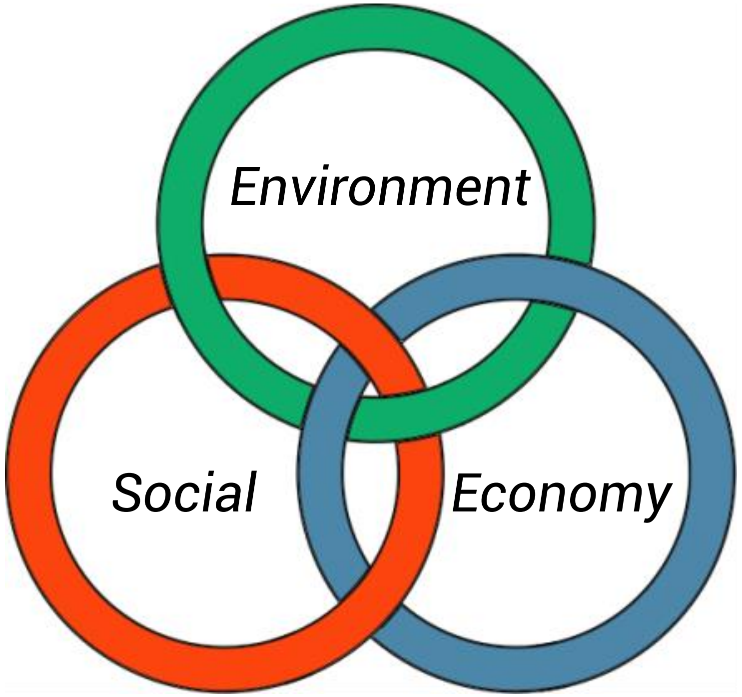
Energy consumption and households

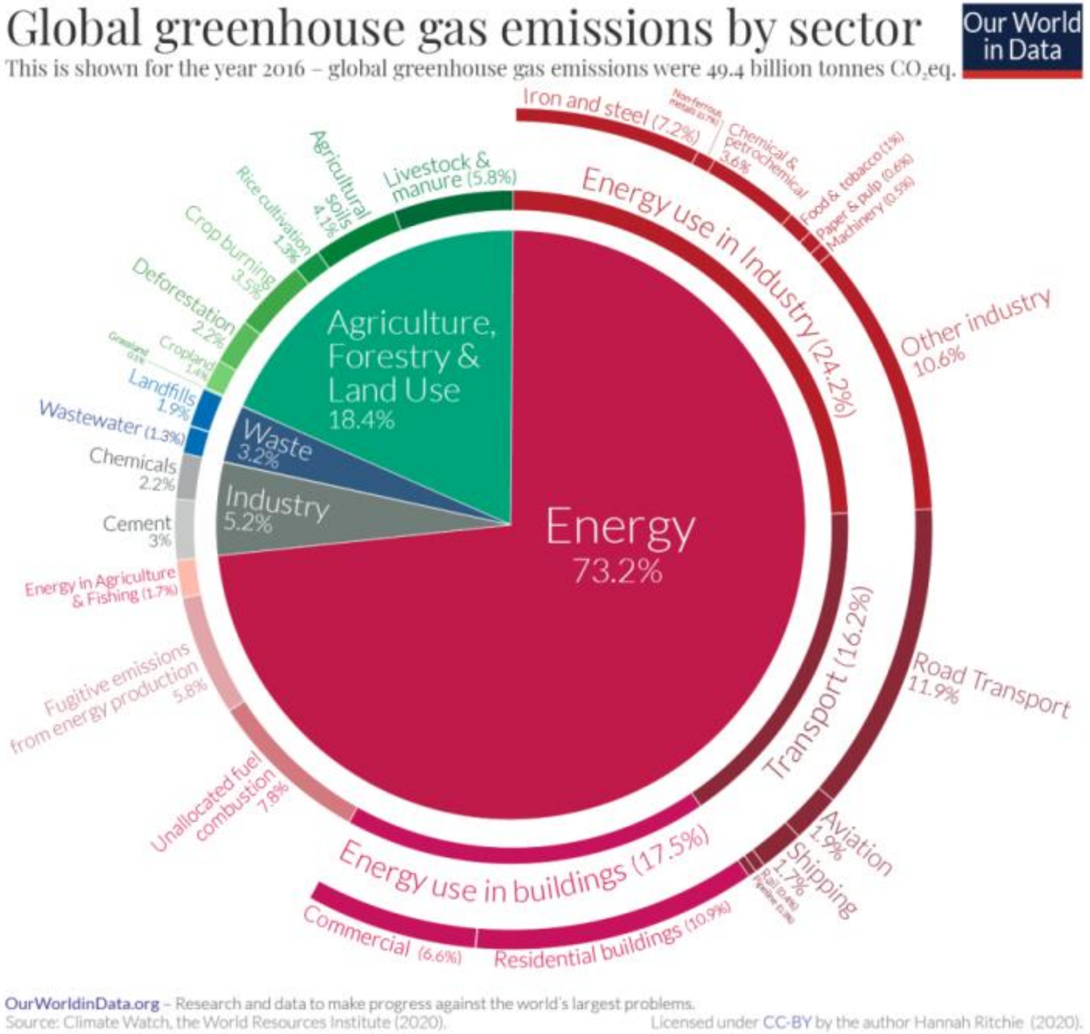


M. Newborough and P. Augood, 10.1049/ip-gtd:19990318

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

Why energy? An impactful consumption





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I. Energy : what? why?

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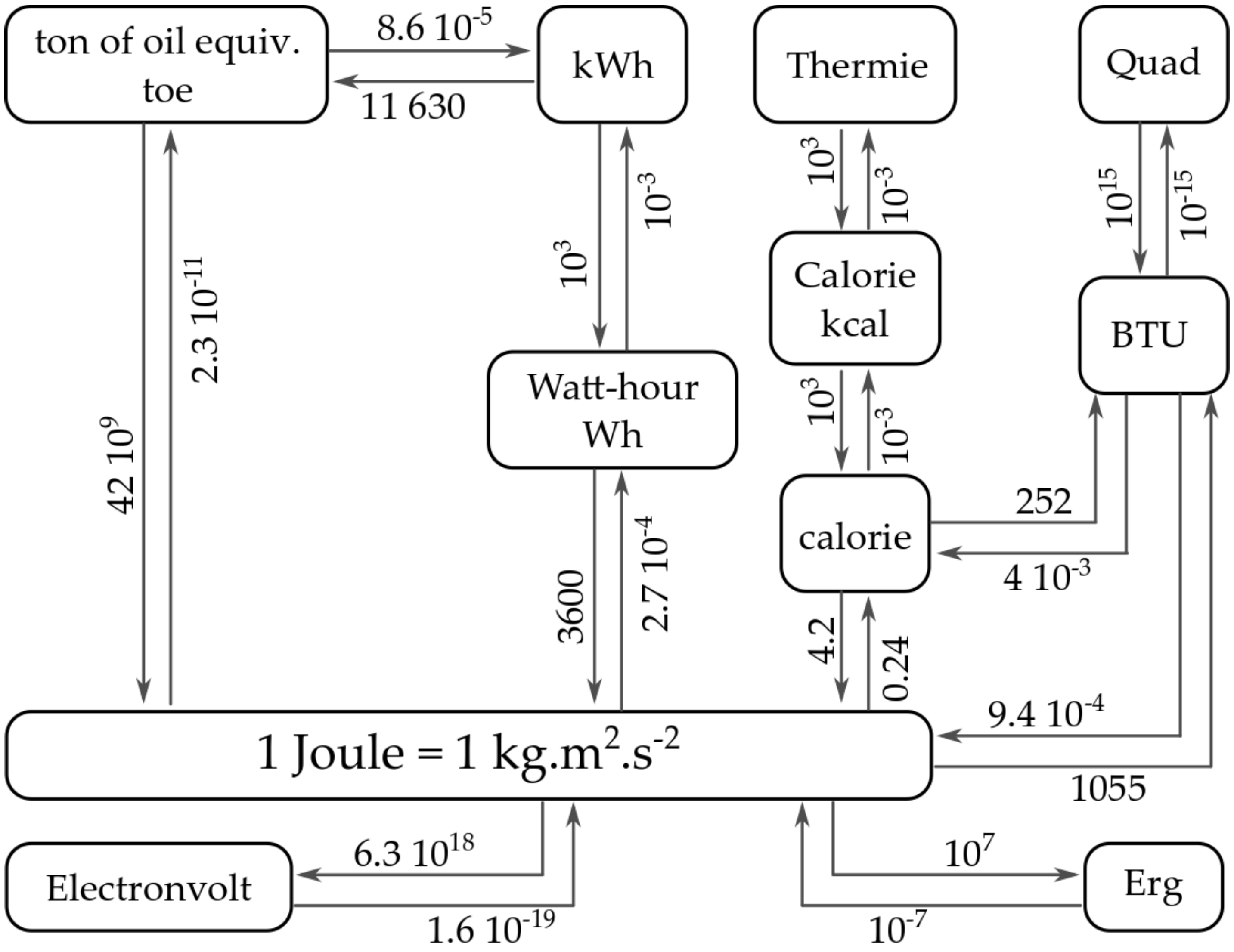
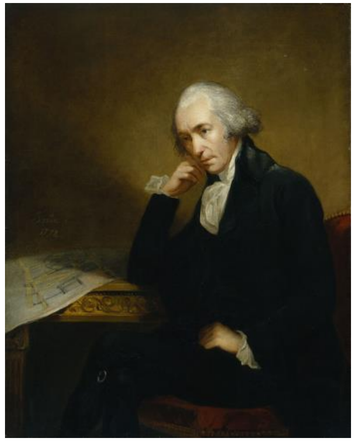
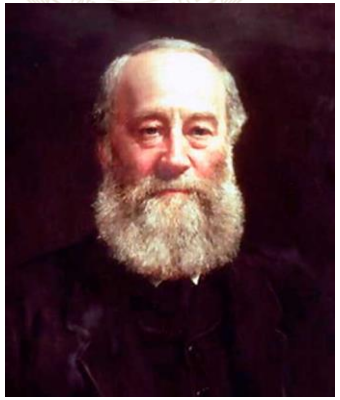
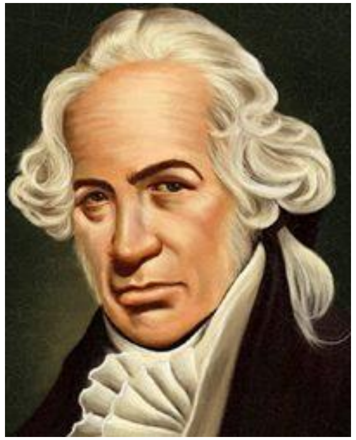
A mess of units









Carl Frederik von Breda.

John Maler Collier

Manchester Science Museum Group Collection

πάντων μέτρον έστὶν ἄνθρωπος

PUISSANCE MAX	700 W
DURATION	1 MIN
BREAK	5 MIN
WORKING HOURS	8/24

EVERYDAY

≡ 40 W

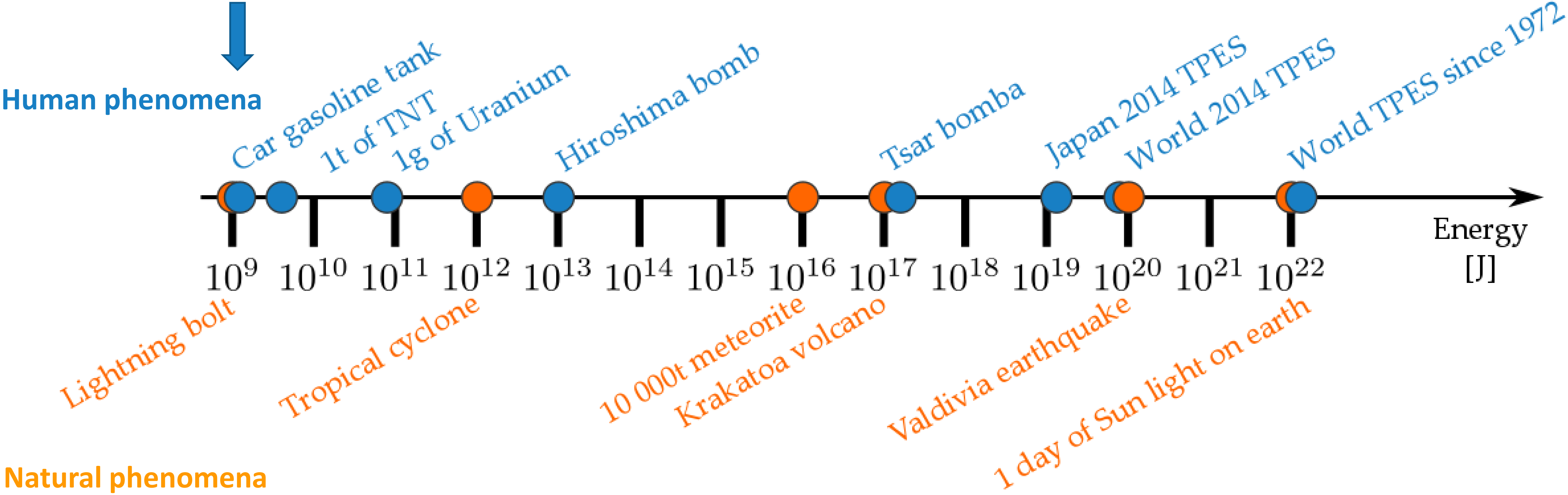
ALL YEAR LONG

≡ 350 KWH ≡ 1 GJ ≡ 0,03 TOE

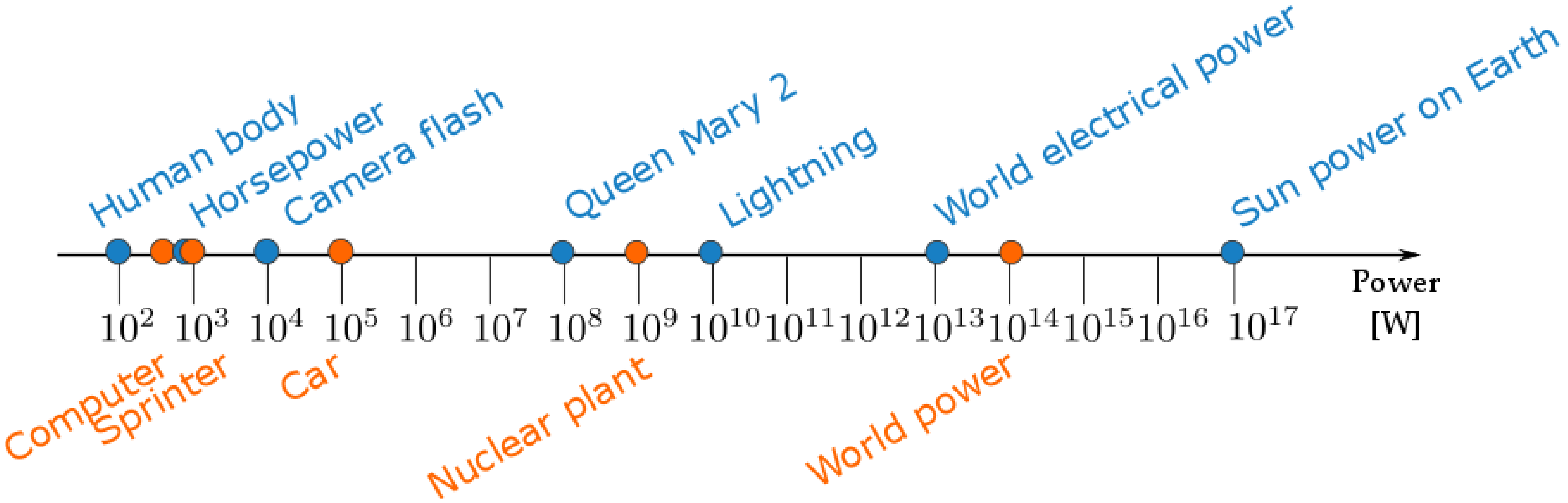
≡ 1 ROBERT

Man versus wild

8h/day, everyday, during 1 year



Power – orders of magnitude

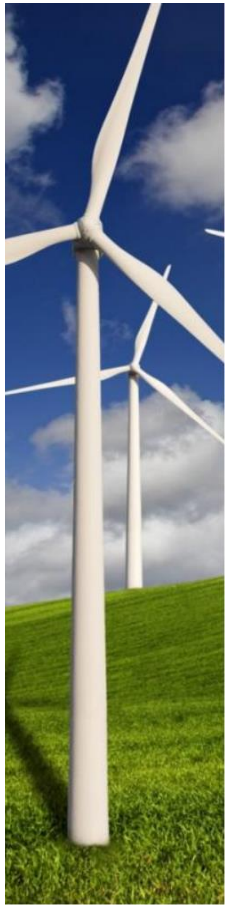


Which energy? Energy accounting

Primary energy raw commodities directly captured from natural resources

Solar

Wind



Hydro

Biomass

Muscle

Oil

Coal

Gas

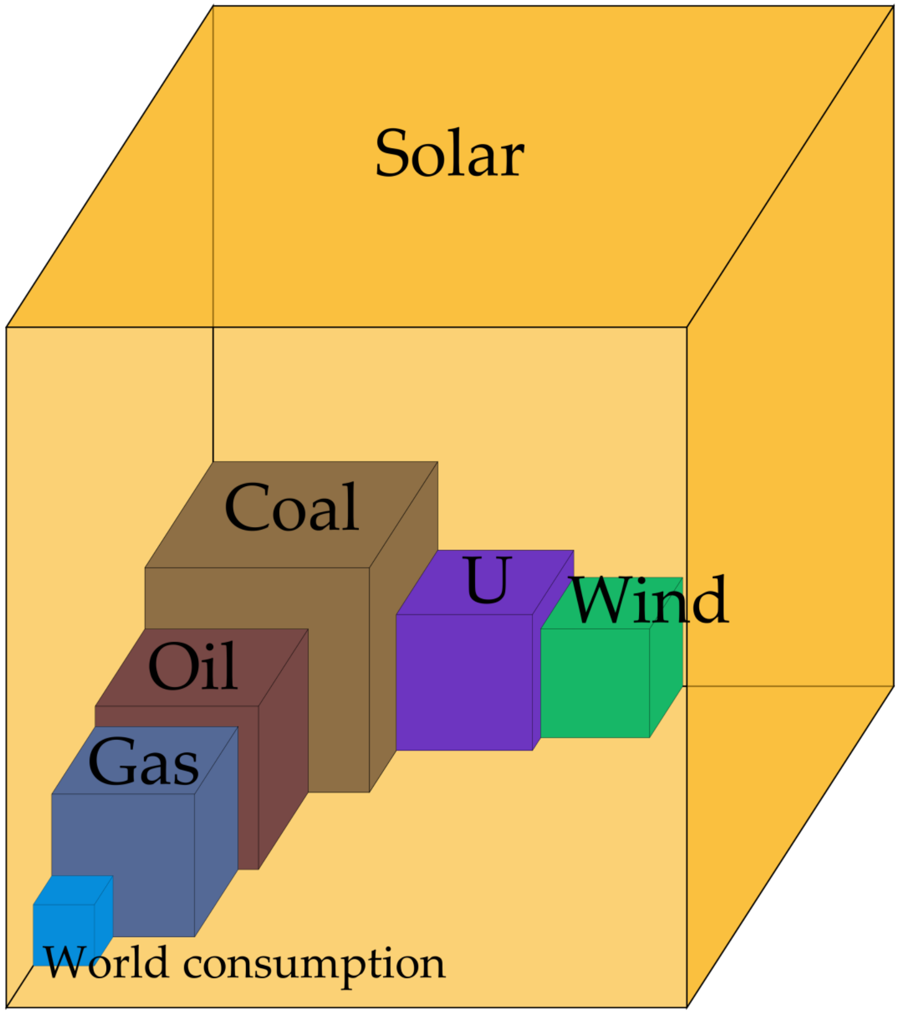
Nuclear

Geothermal

From the Sun

How much energy? Resource side

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

Which energy? Energy accounting

Primary energy raw commodities directly captured from natural resources

Crude oil, coal, NG, 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…

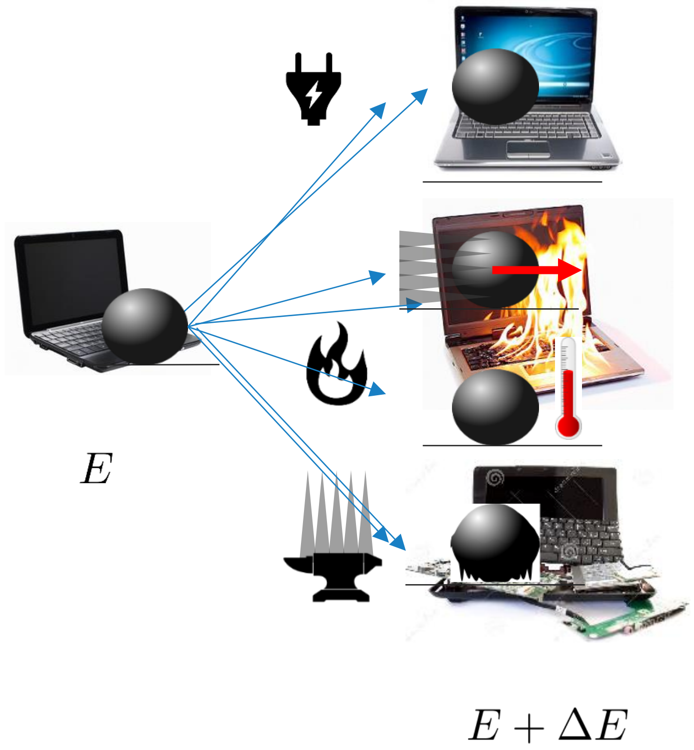
Final energy

commodities which are actually purchased and used by end users

Appliance

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

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



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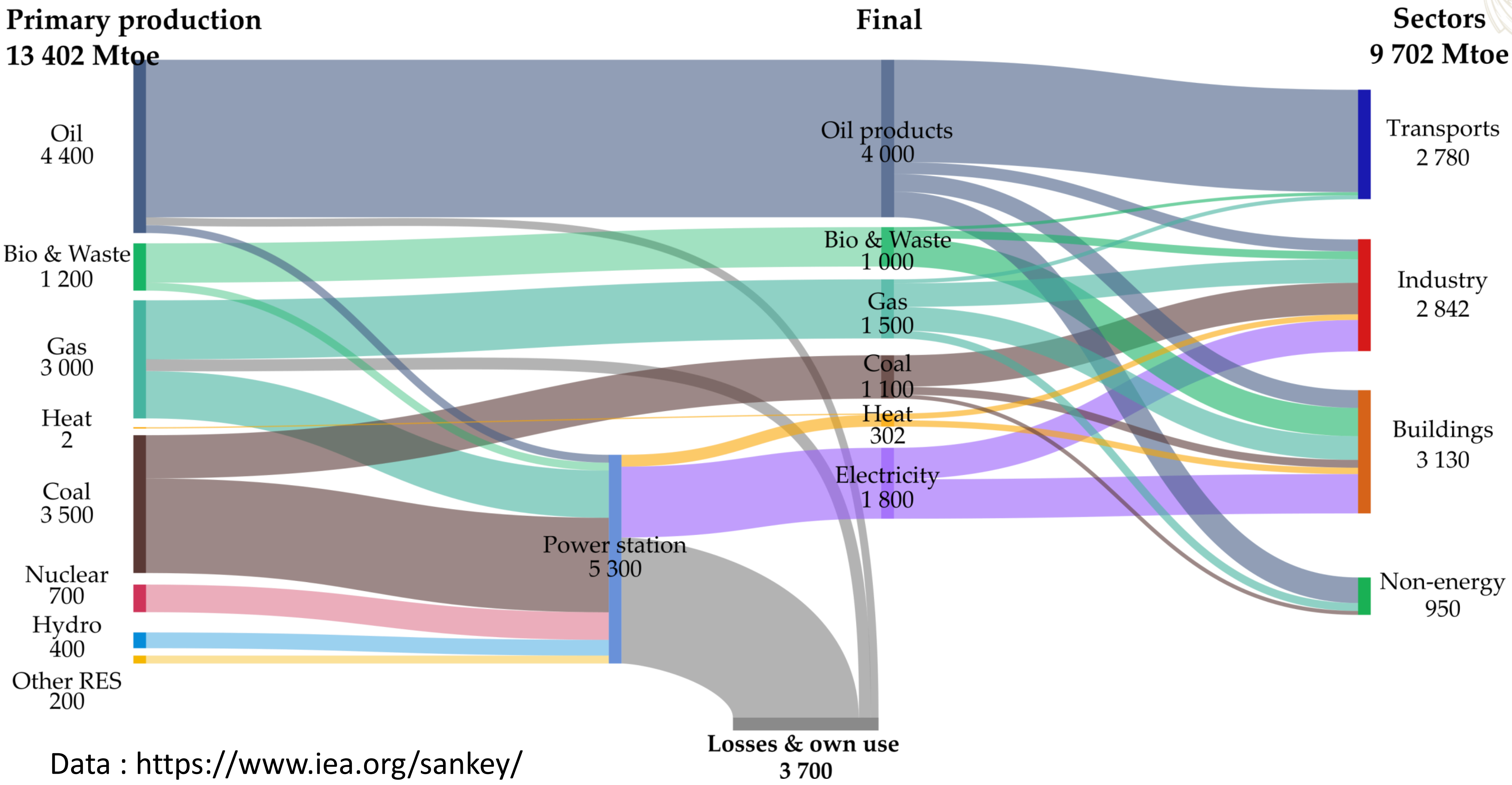
Sankey diagram



Elec. share

19%

TPES / yr

5 10^{20} J

150 000 TWh

18 TW.yr

E / cap / yr

2 toe

75 GJ

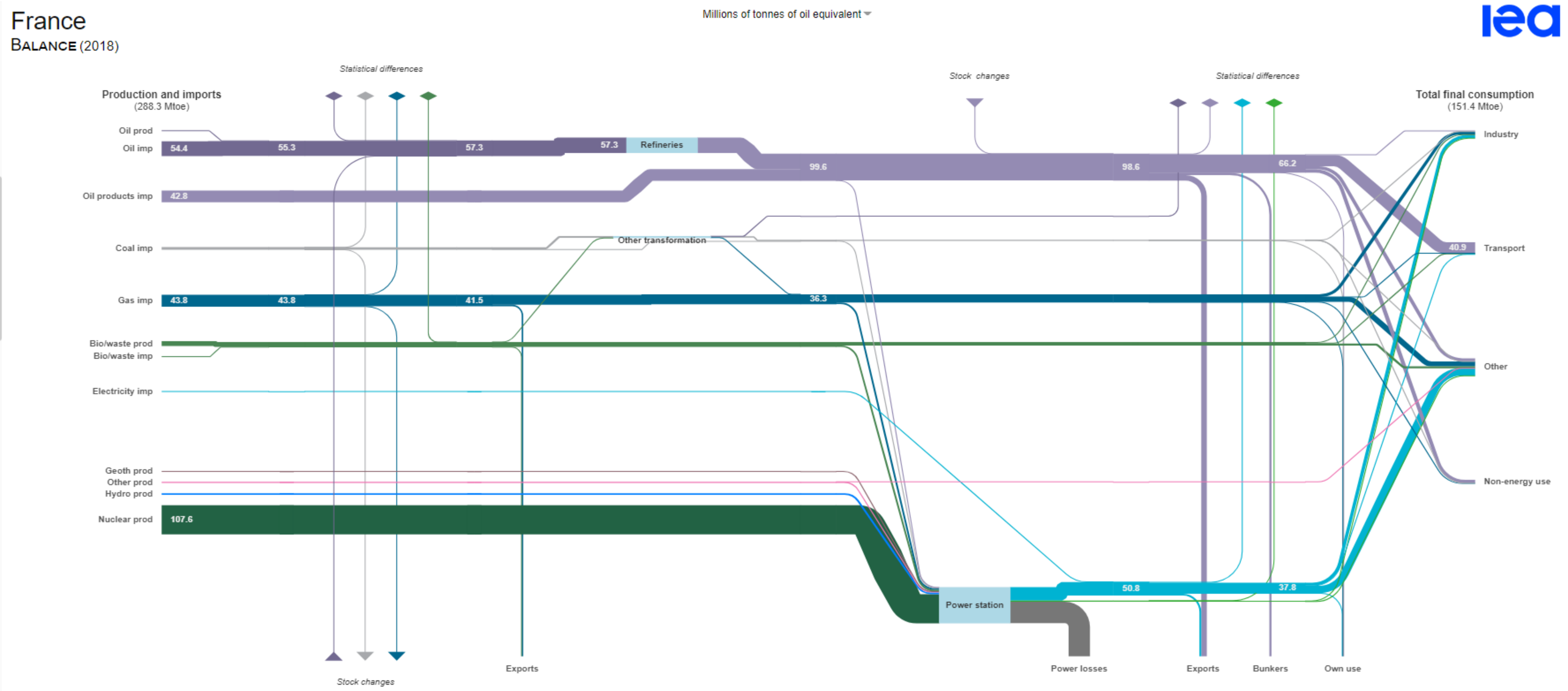
20 MWh

3 kW.yr

75 Roberts

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

Sankey diagram (bis)



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

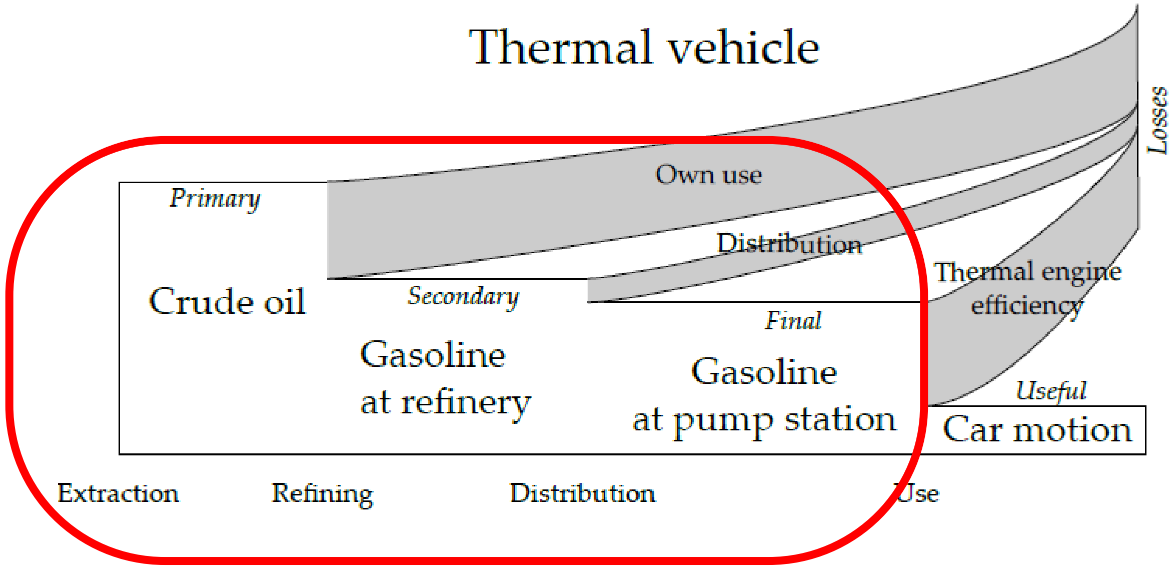
Data : https://www.iea.org/sankey/

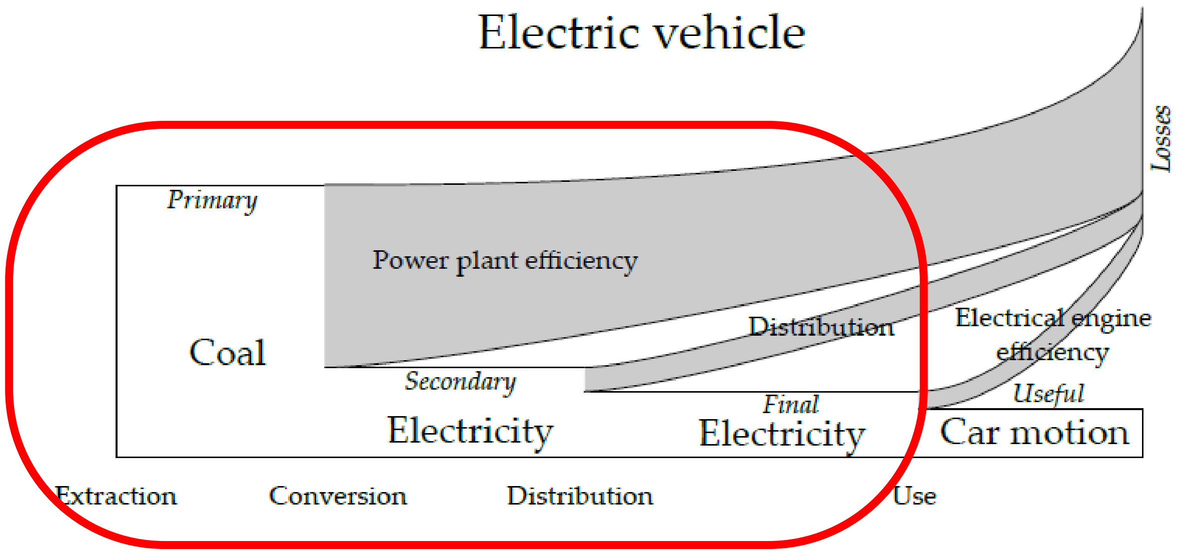
(Caution with energy balance)

Average values

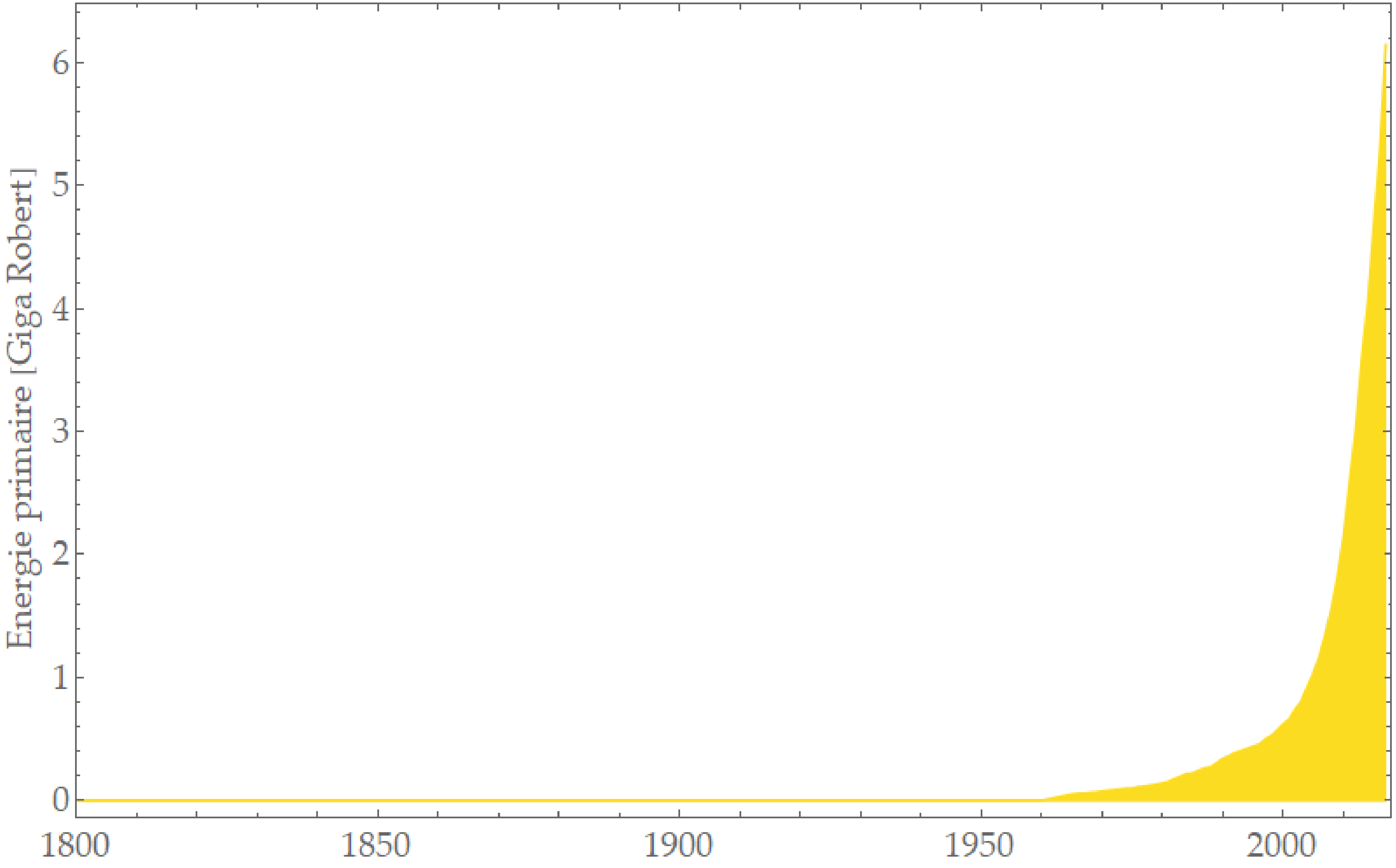
Work and heat are mixed together

Usually stop at final (not useful) energy





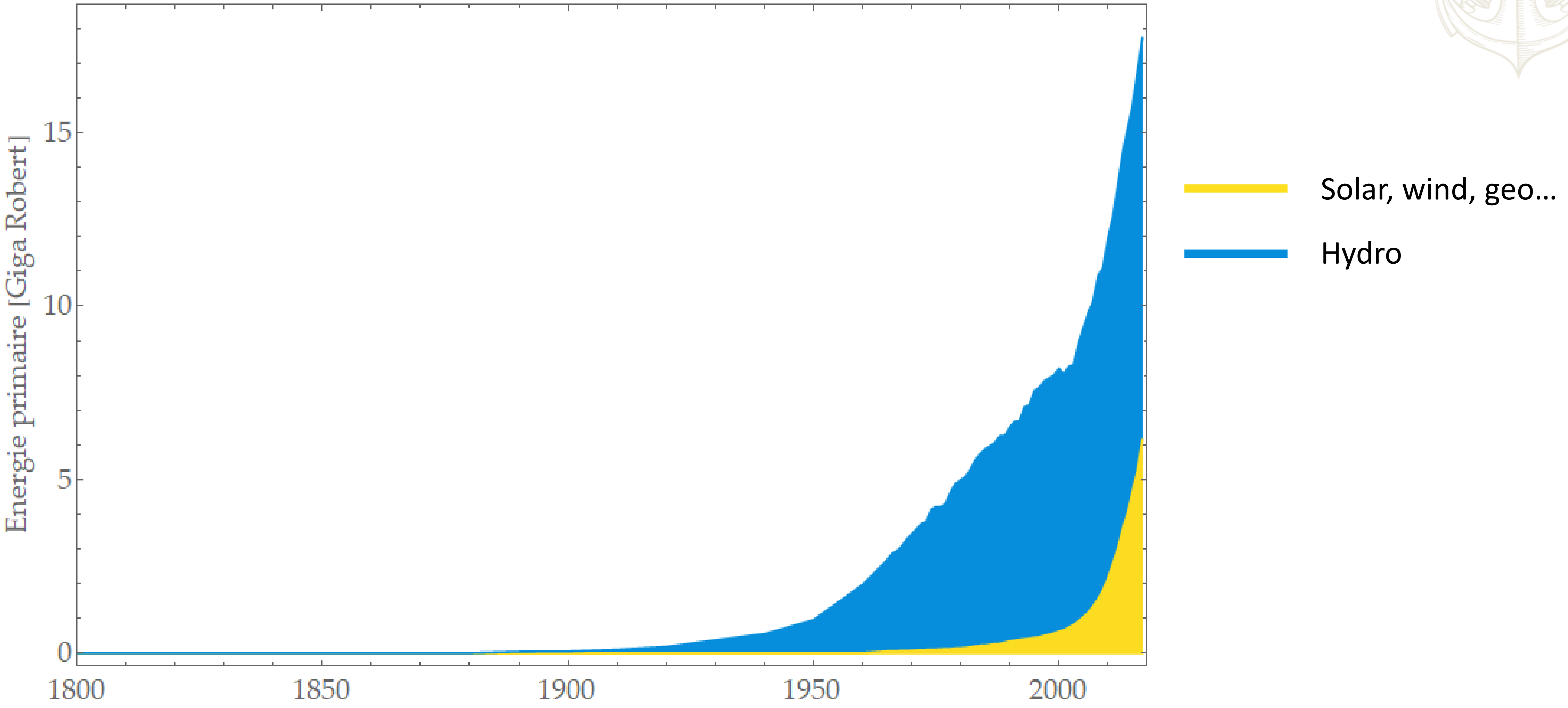
How did we get there?



Solar, wind, geo…

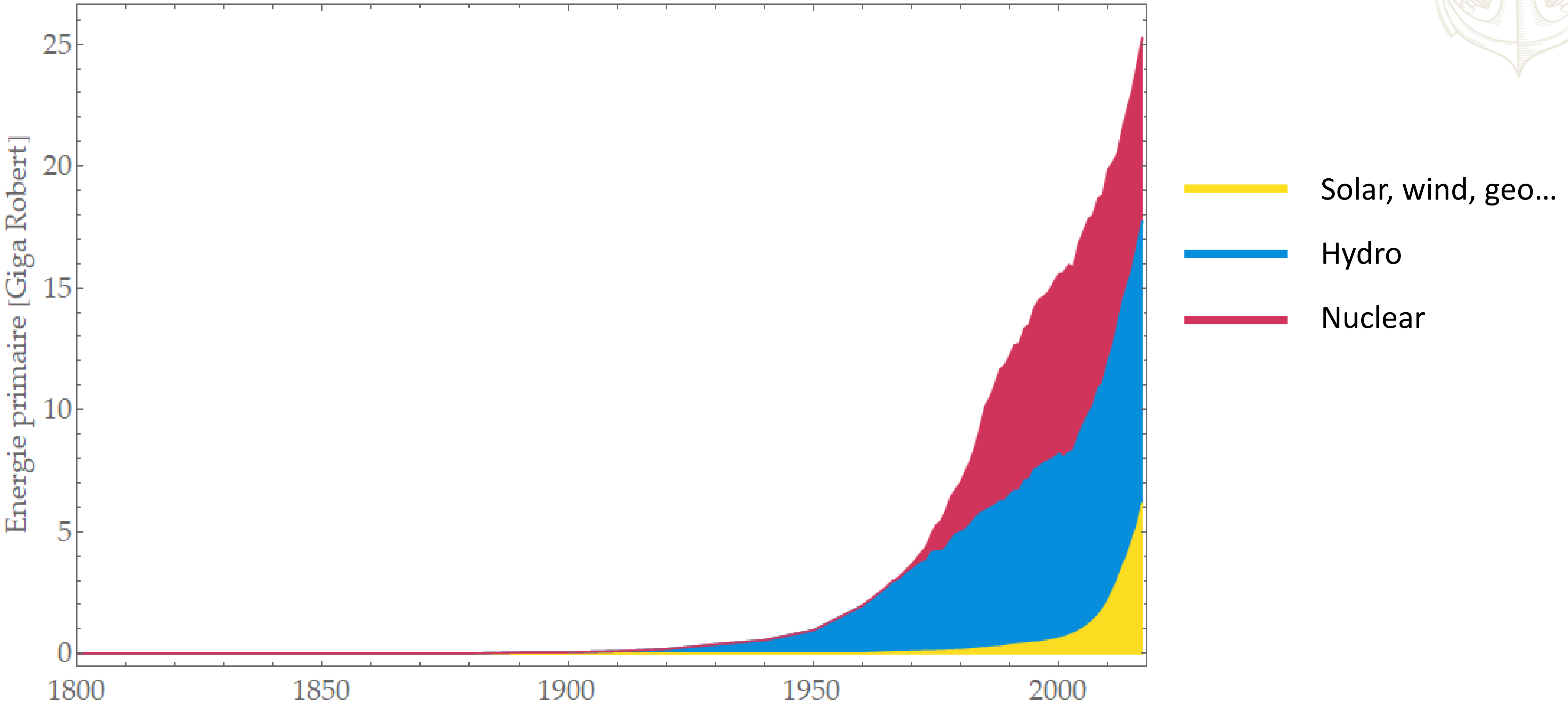
Source International Energy Agency (2014)

How did we get there?



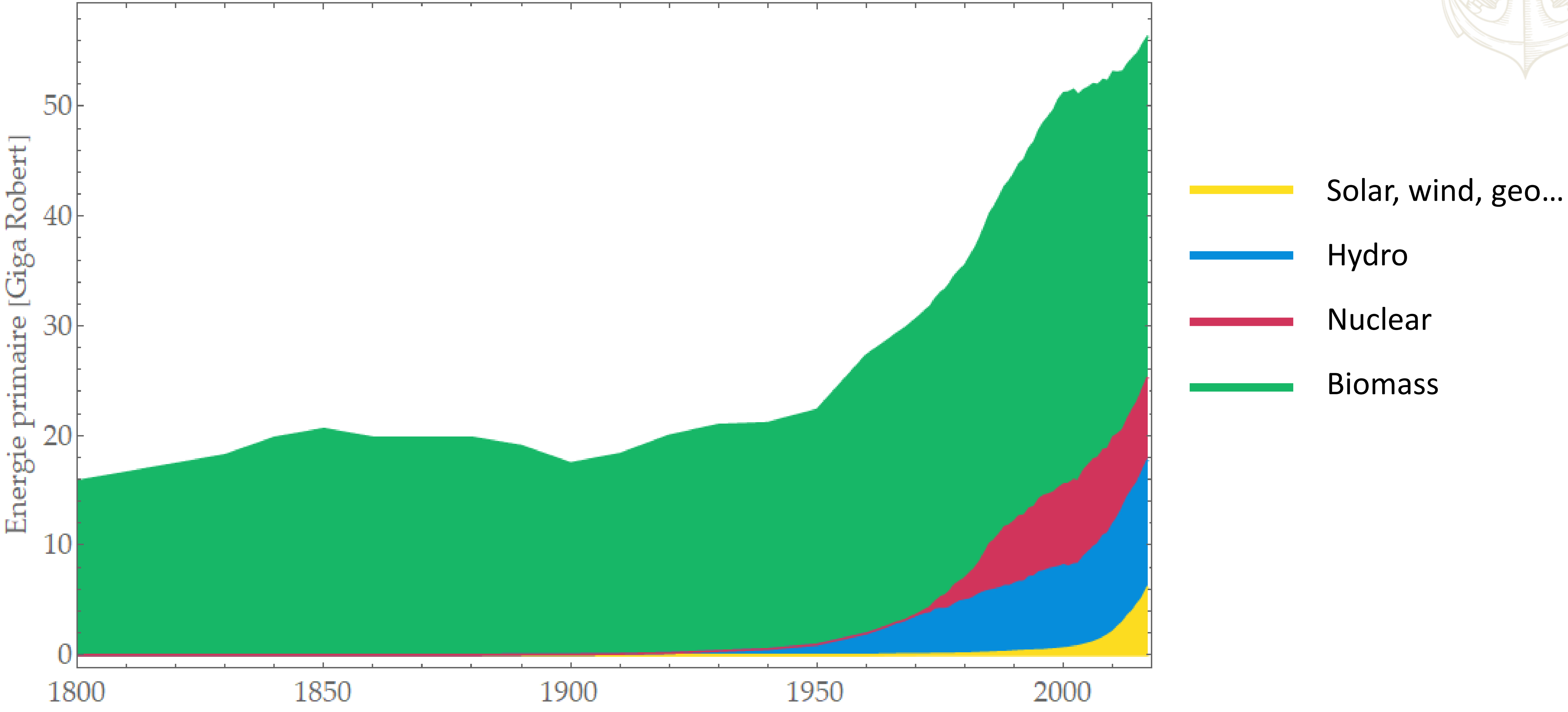
Source International Energy Agency (2014)

How did we get there?



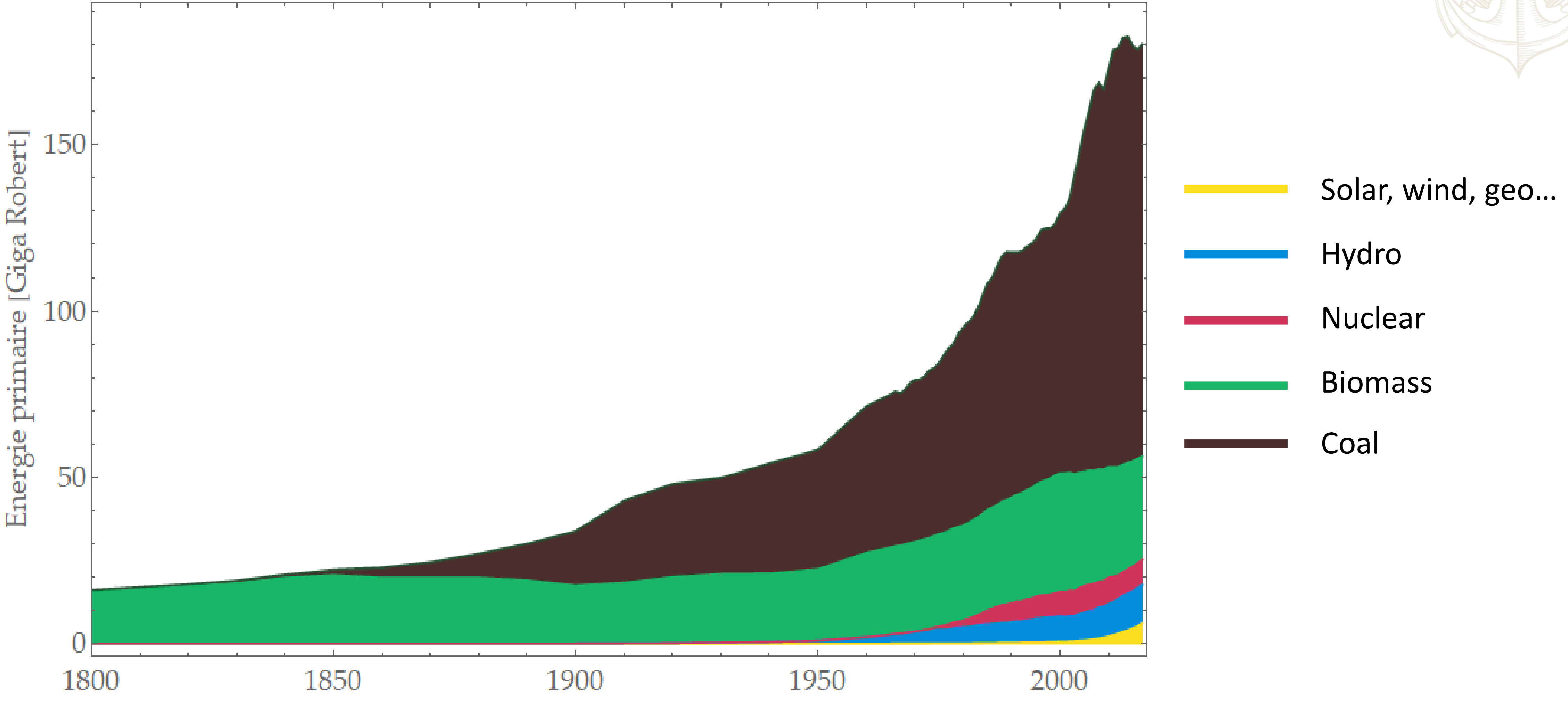
Source International Energy Agency (2014)

How did we get there?



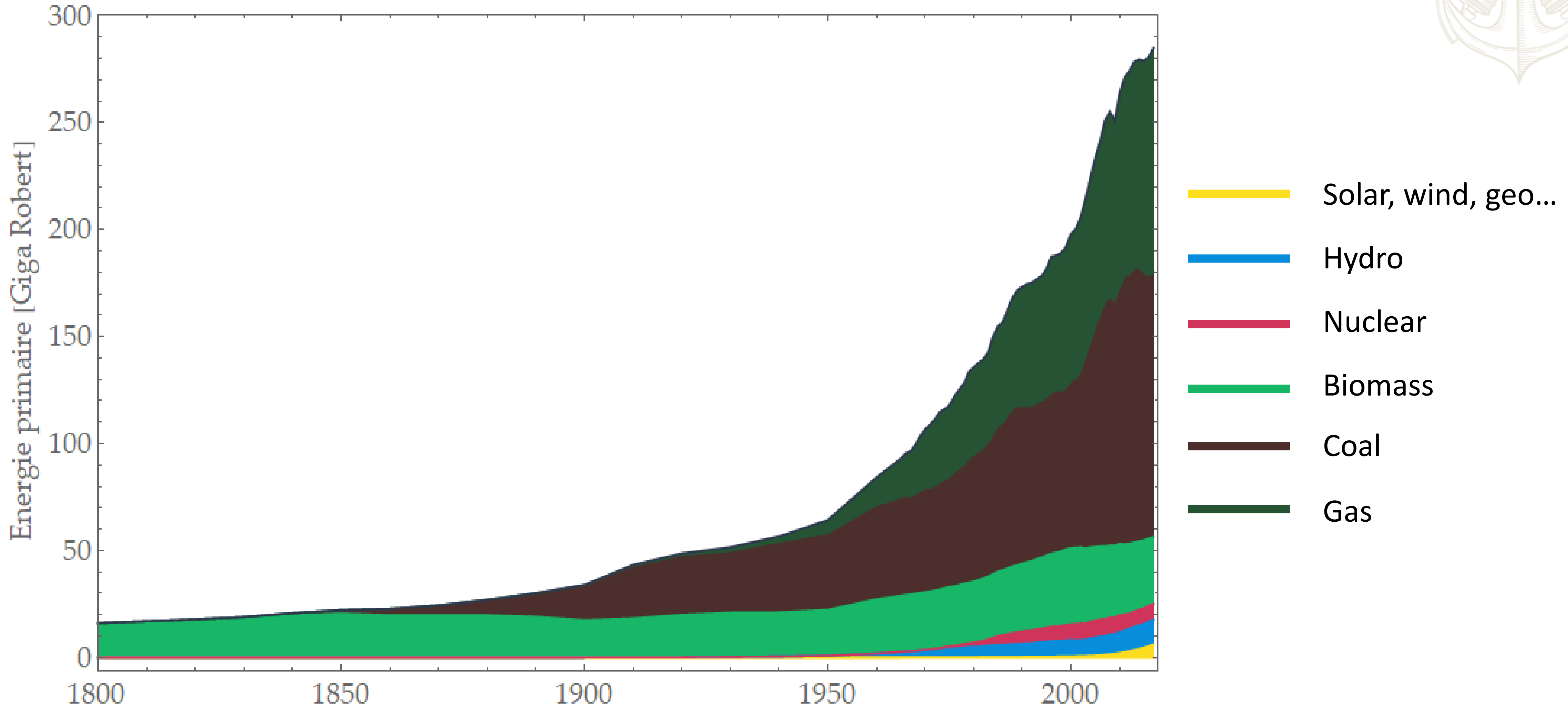
Source International Energy Agency (2014)

How did we get there?



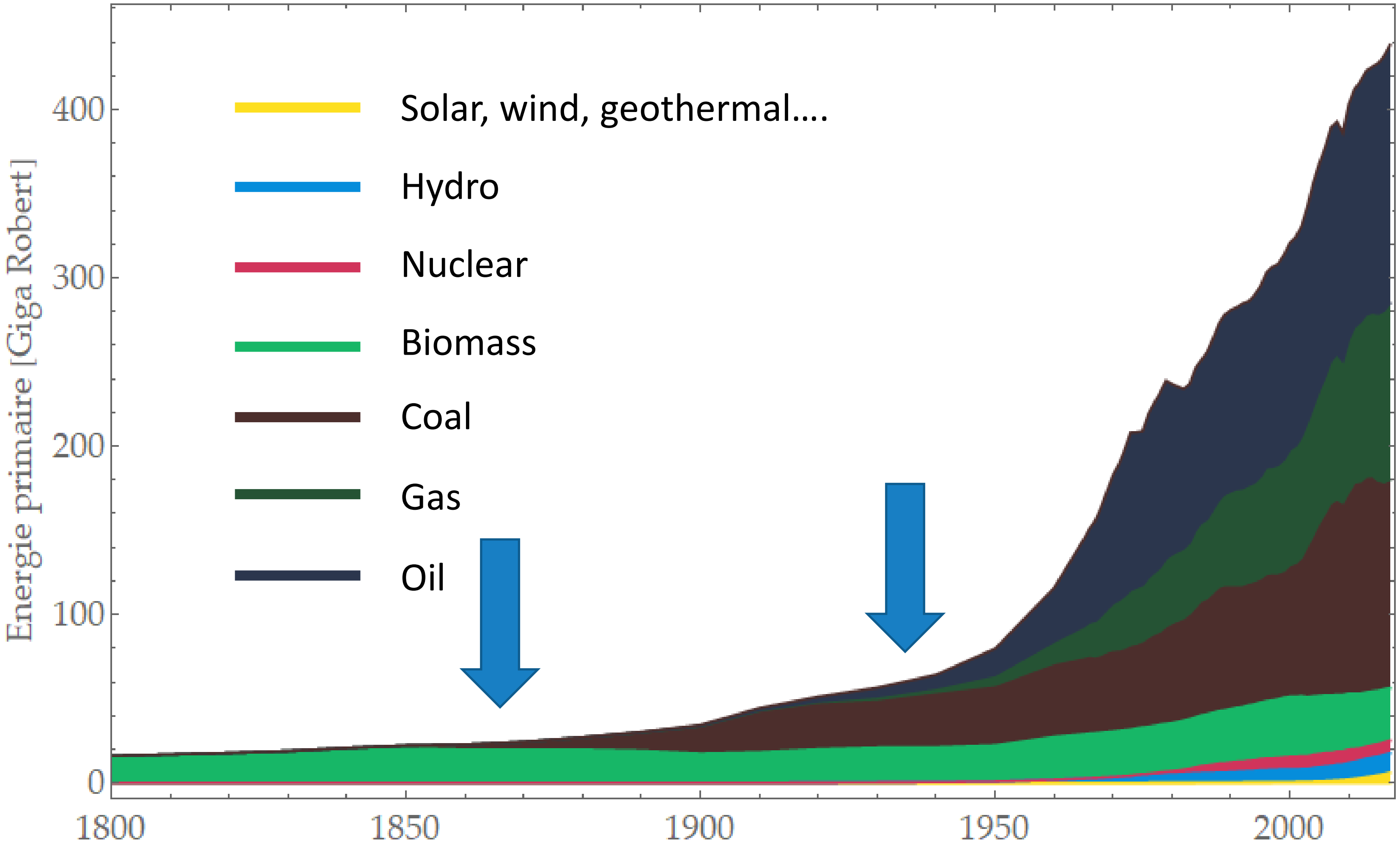
Source International Energy Agency (2014)

How did we get there?



Source International Energy Agency (2014)

How did we get there?



Energy transtions

Pile up, more than replace

Fossil

Carbon based

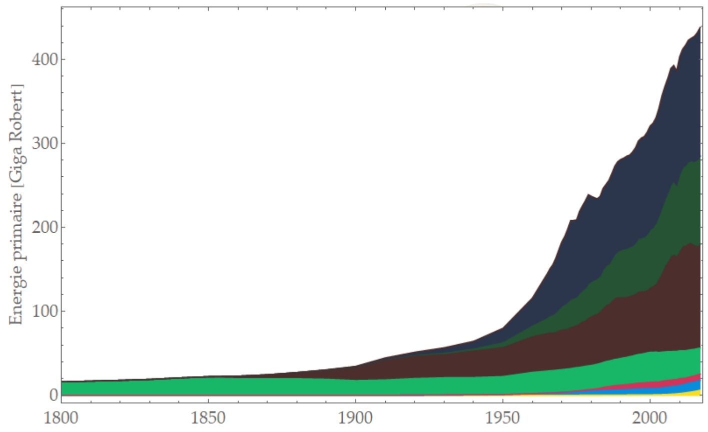
Nuclear

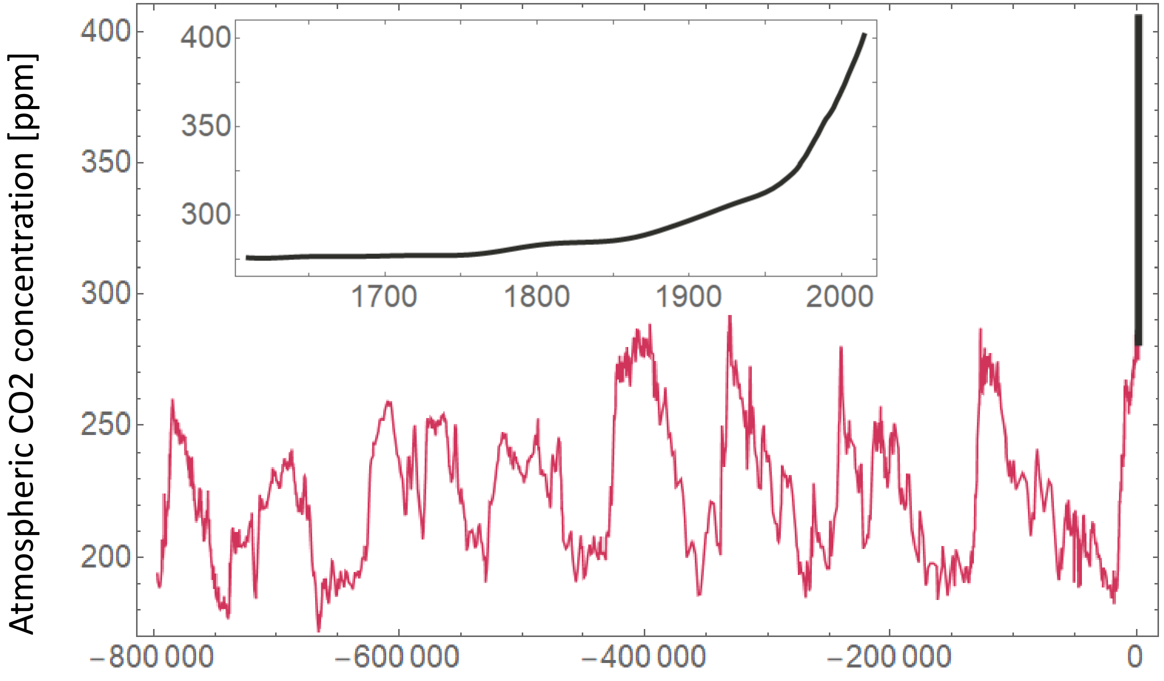
Carbon free

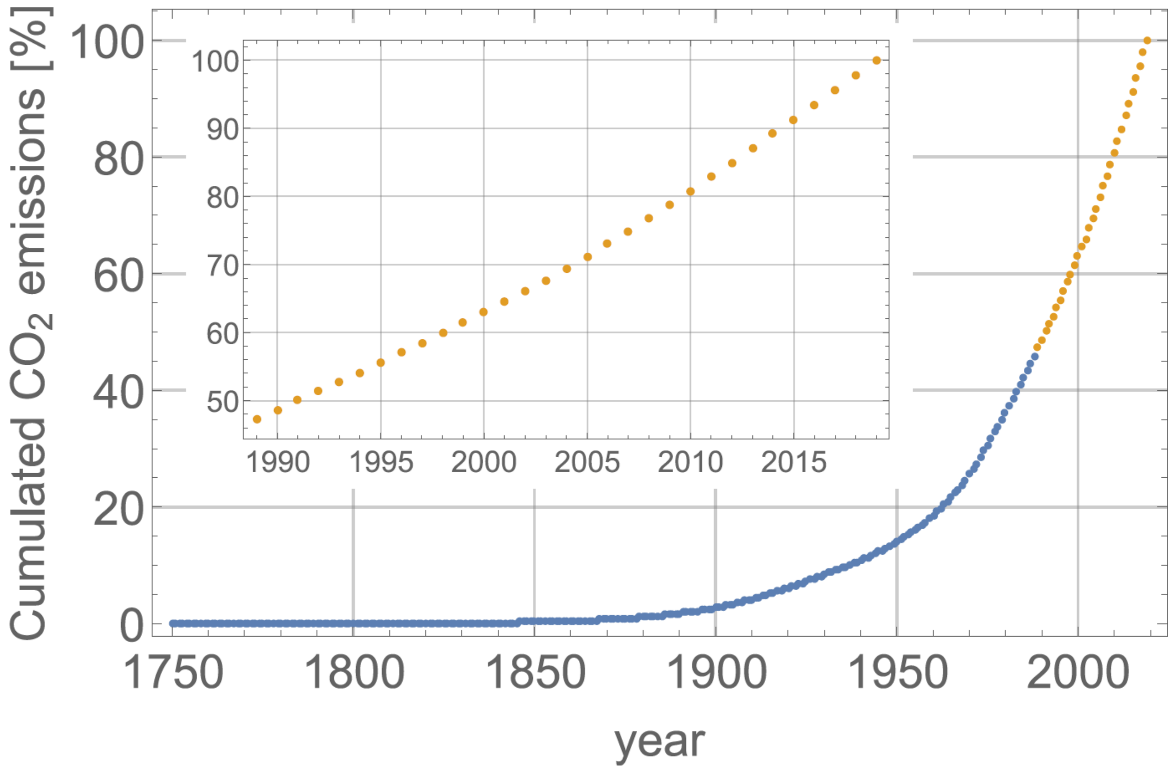
Renewable

Source International Energy Agency (2014)

In previous episodes…

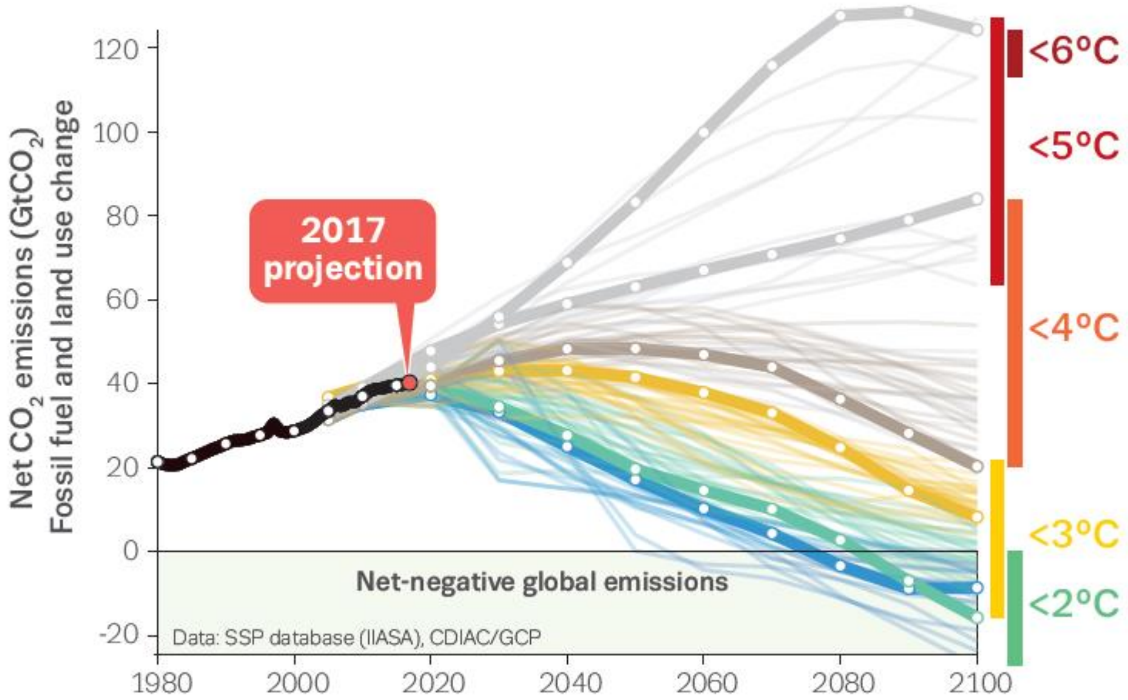






See Lecture / PC 2

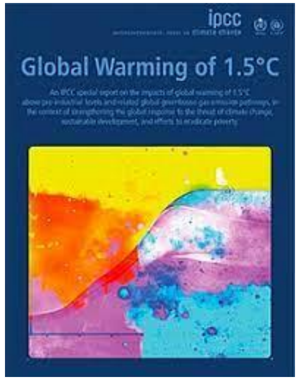
What's next?



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."



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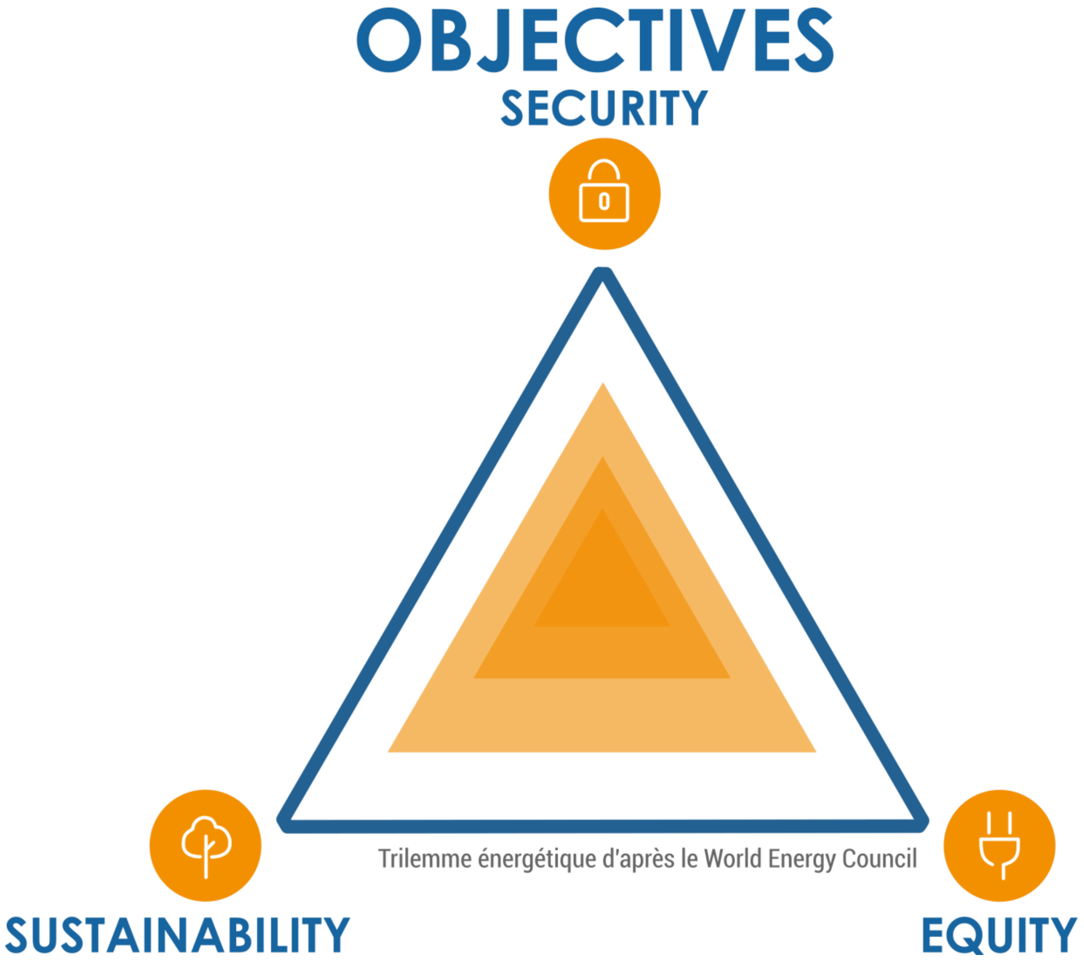
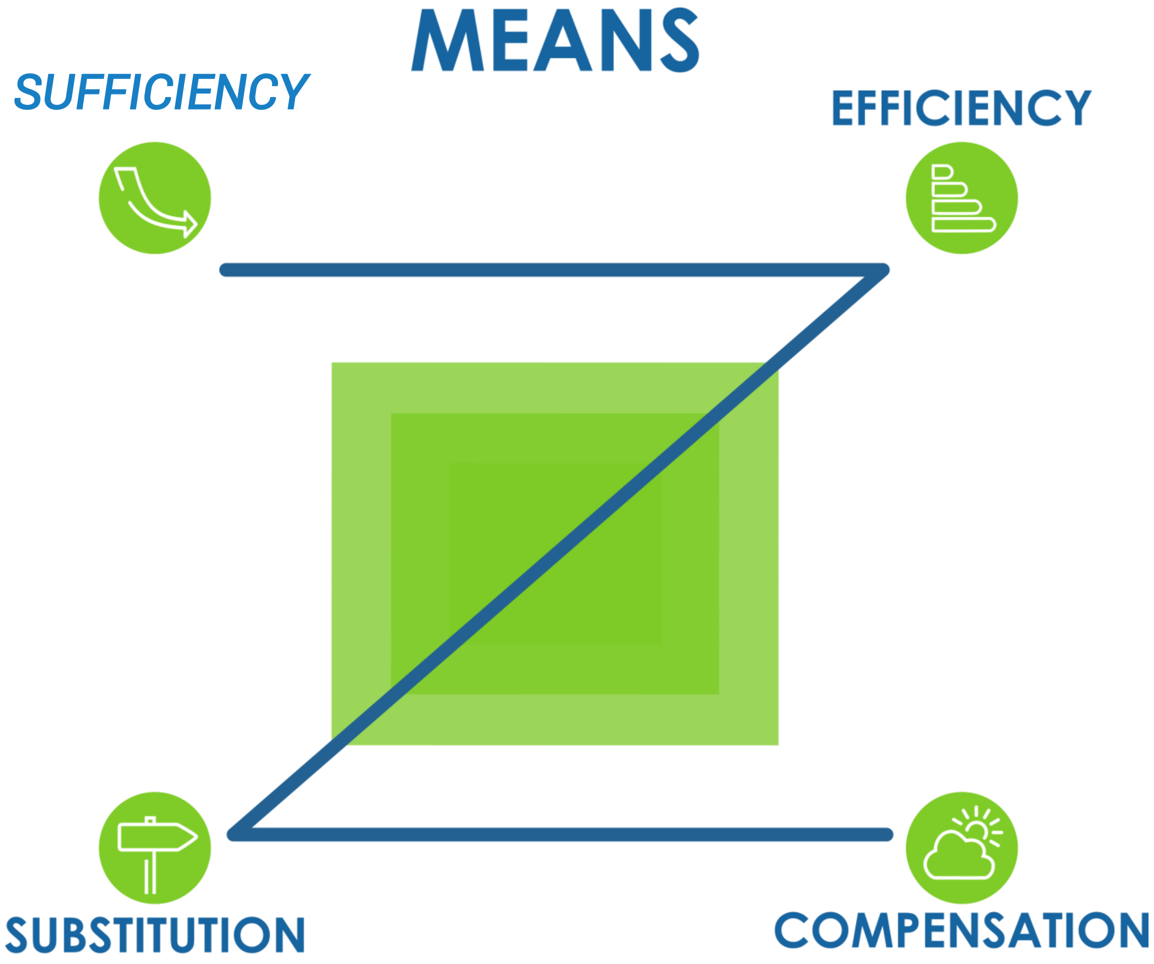
Transition mindmap

What do we want to do?



How do we want to do?



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

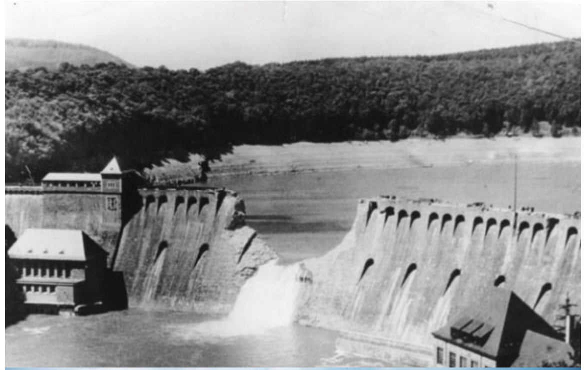
Pollution

Climate

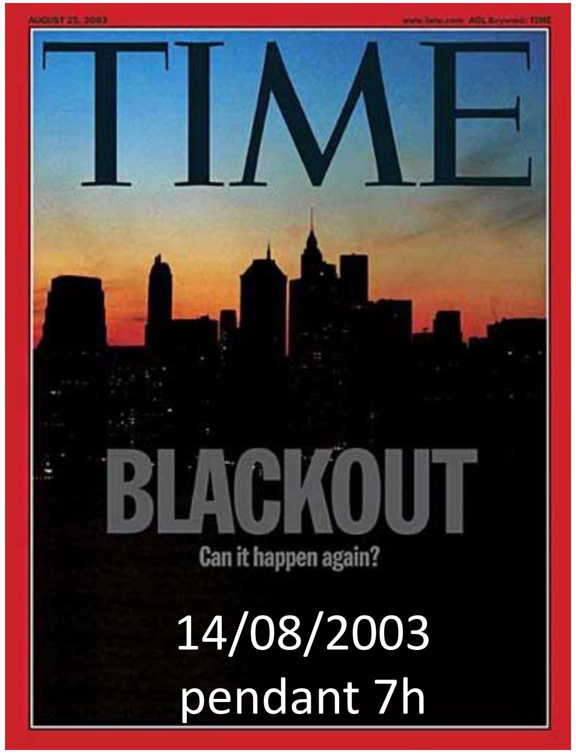
Energy security

How steady is energy supply? At what costs?

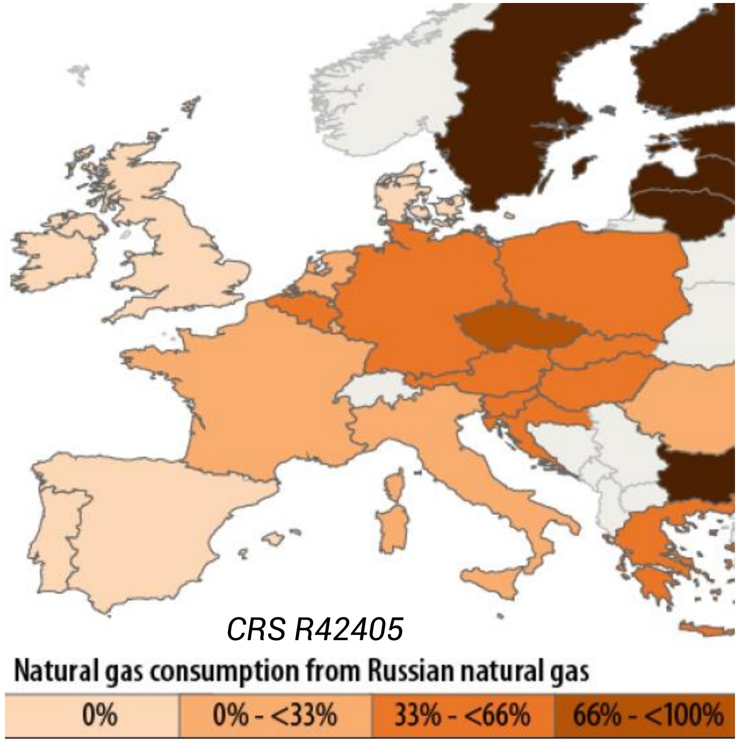
Accidents



Stability



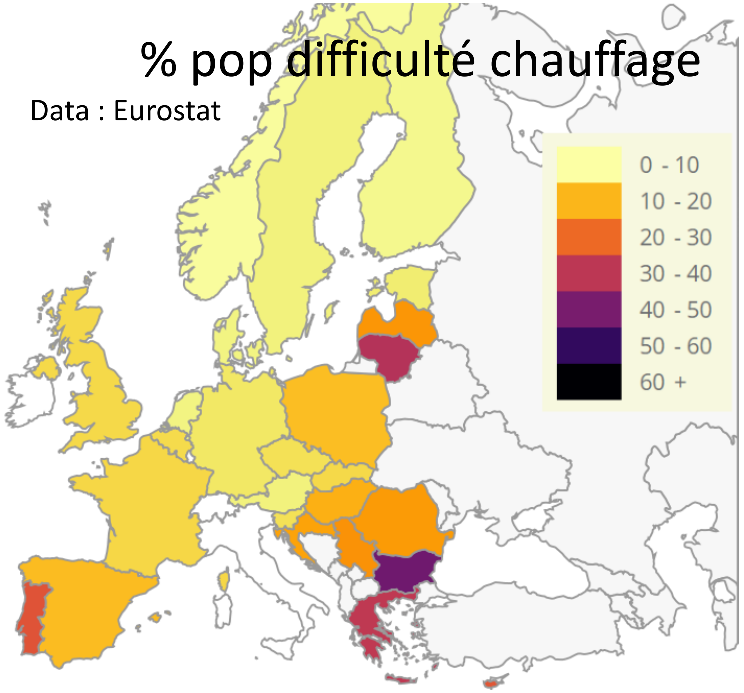
Dépendances



Energy equity

How affordable is energy?

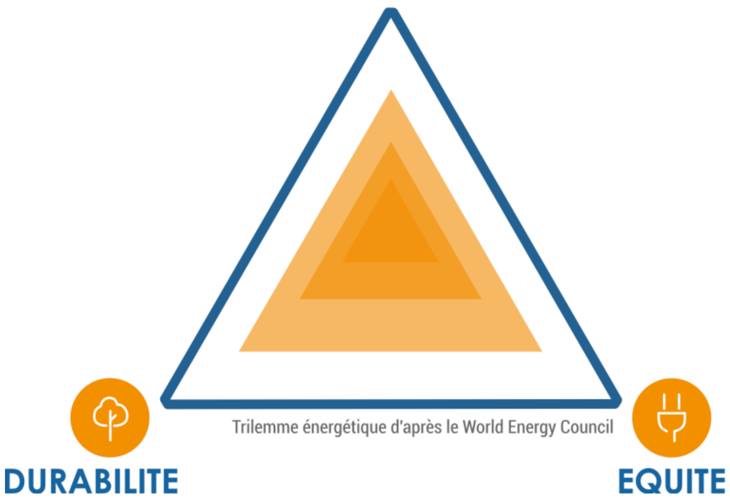
Fuel poverty



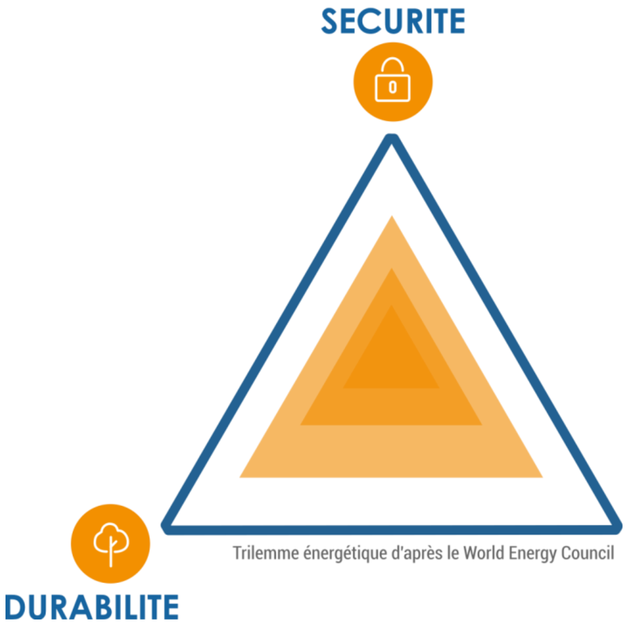
Domestic inegalities

International inegalities

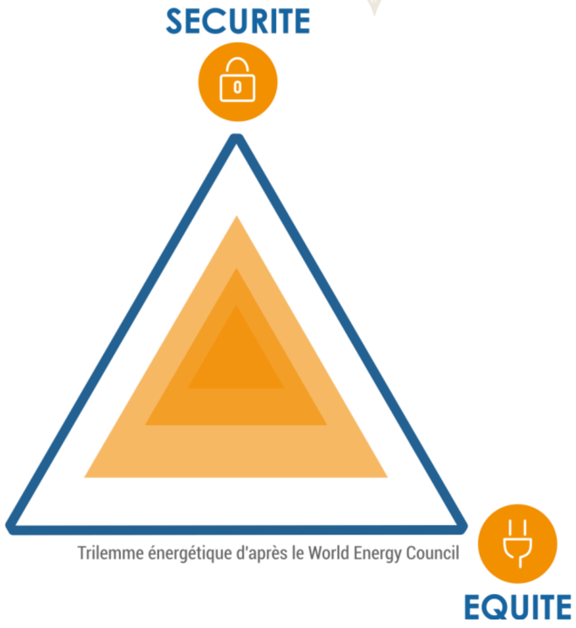
Three complementary targets



Cheap, sustainable, unsecured
→ unstable



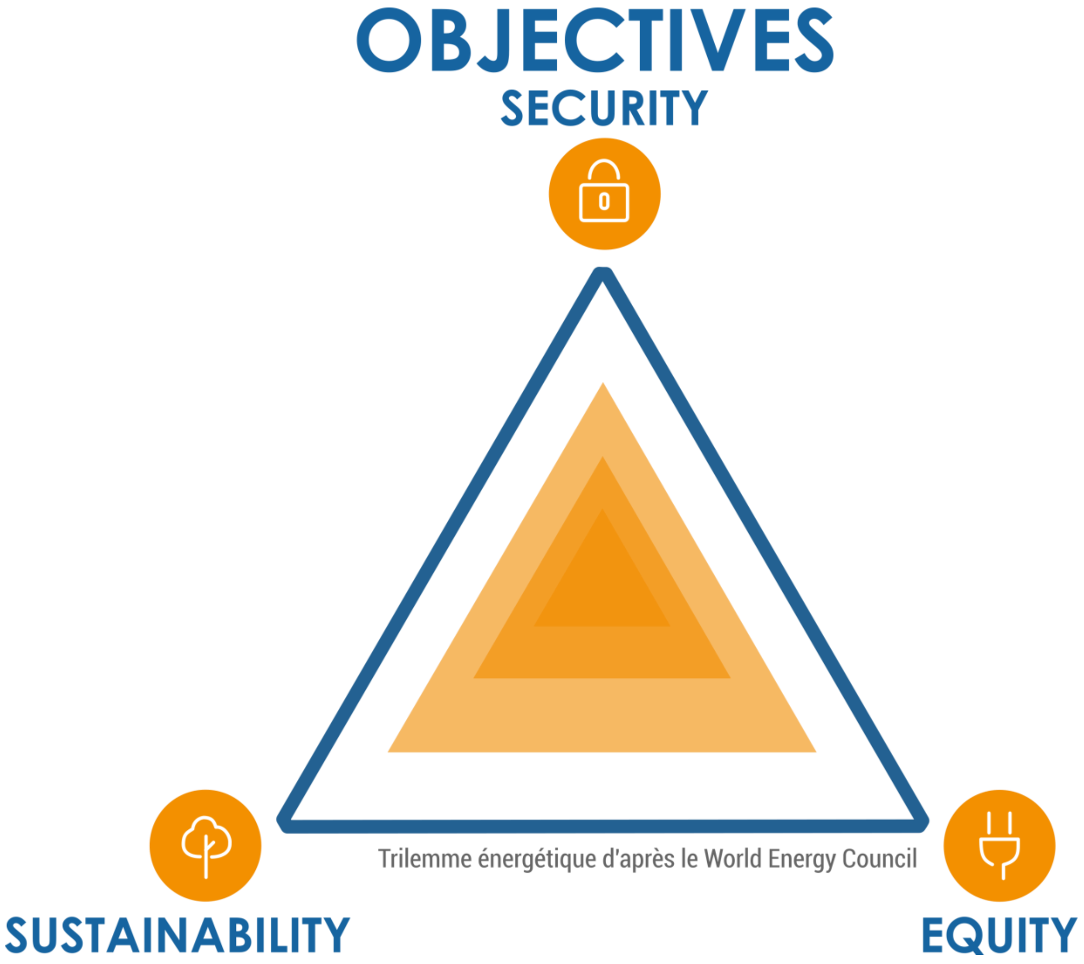
Stable, sustainable, unaffordable
→ inacceptable



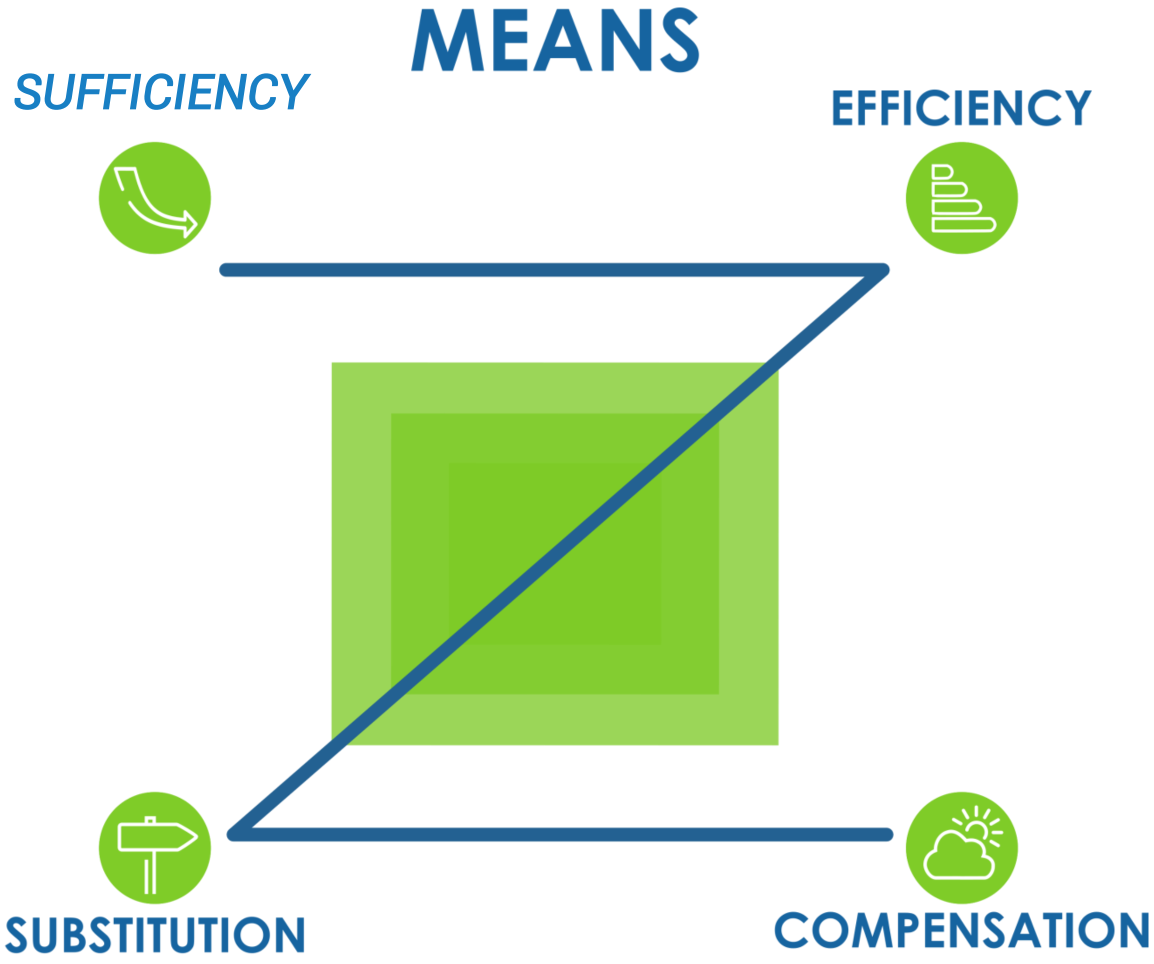
Cheap, stable, unsustainable
→ unbearable

Transition mindmap

What do we want to do?



How do we want to do?

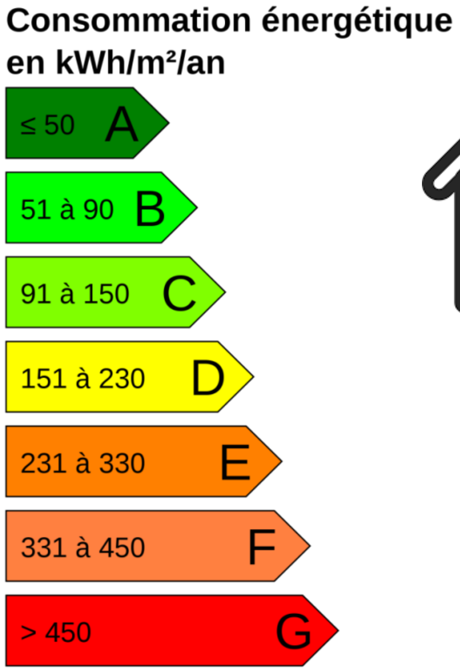


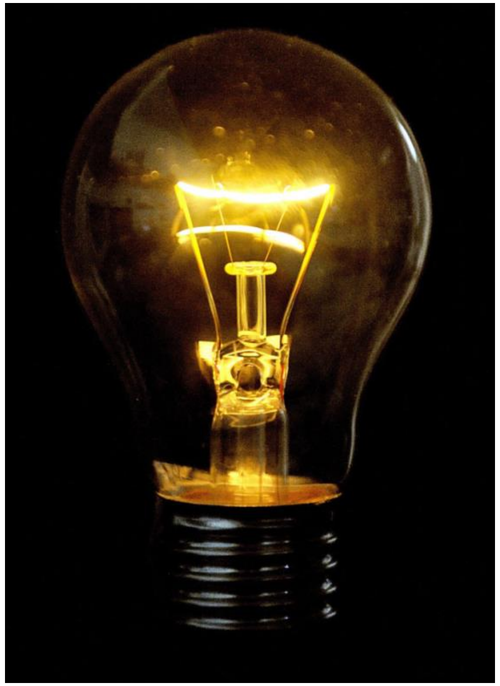
Sufficiency

Reduce expected services

Efficiency

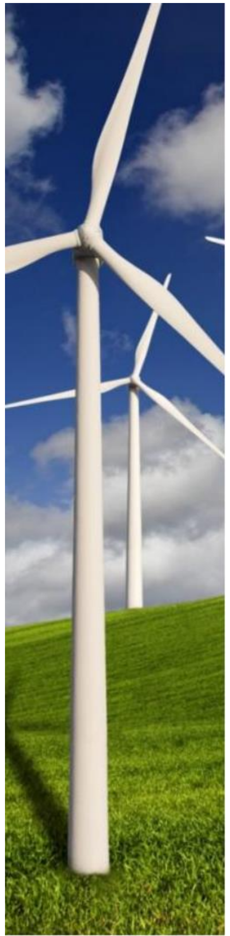
Achieve the same service, with less energy consumption





Substitution

Consume the same amount of energy, from another source



Compensation

Use the same source, balance the downfalls

Environnement. En Turquie, 11 millions d'arbres plantés en novembre sont presque déjà tous morts

MOYEN-ORIENT 〉 ENVIRONNEMENT 〉 TURQUIE 〉

Courrier international

Publié le 30/01/2020 - 15:10

Question toolbox

OBJECTIFS

MOYENS

Which priority?

Technical feasability?

Means adequate to tackle objectives ?

Context?

Indirect effects?

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)

Lecture 1 Introduction

I. Energy : what? why?

II. Energy accounting : how much of which energy ?

III. Energy today : balance and diagrams

IV. Energy transition : where to go, how to get there?

V. Thermodynamics reminders

1st law of thermodynamics

H. Callen, Thermodynamics and an introduction to thermostatistics

Energy is a conserved quantity

Energy now = energy before + energy input – energy output

Properly speaking, energy is never created or consumed – only exchanged

Energy can be exchanged through heat or work

$$\Delta E = W + Q$$

Energy Work Heat

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

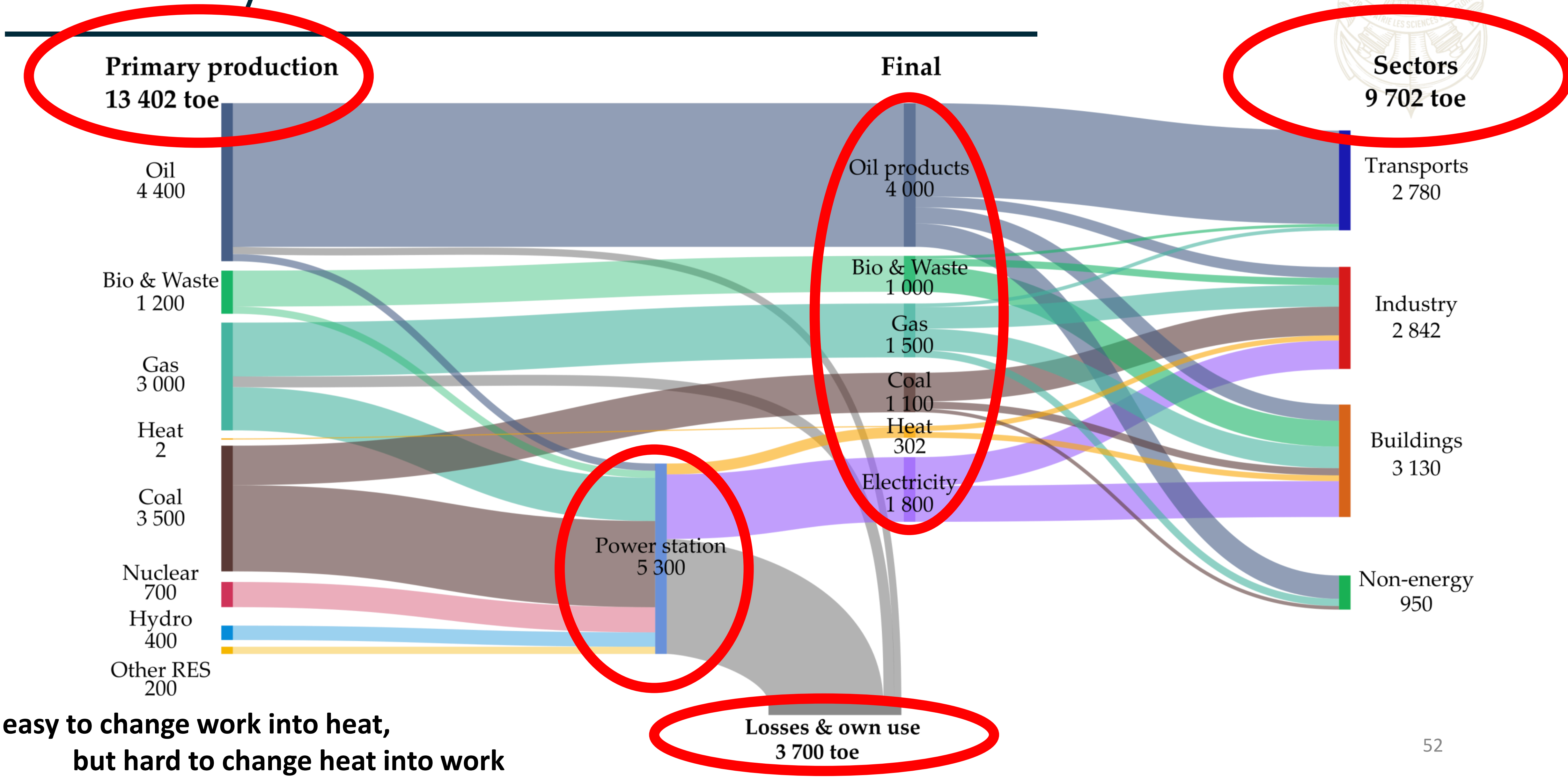
« Heat is work and work is heat »

“Heat is nothing else than motive power, or rather, a motion which has changed its form. [...] Whenever motive power is destroyed, there is, at the same time, a production of heat in quantity precisely proportional to the quantity of power destroyed. Reciprocally, wherever there is destruction of heat, there is production of power of motion. We may then state as a general law, that motive power is, in nature, invariable in amount; that is, is never, properly speaking, either created or destroyed. In fact, it changes form.”

Carnot, *manuscript notes* (c.1927)

Sadi Carnot
by Louis Léopold Boilly

Sankey & thermo



It is easy to change work into heat,

but hard to change heat into work

2^{nd} law of thermodynamics

Entropy measures the disorder of a system. Microcanonical postulate : maximize entropy.

Entropy can be created, but never destroyed $$dS_{\text{created}} \geq 0$$

Every heat transfer comes with an entropy transfert $$dS_{\text{exchanged}} = \frac{\delta Q}{T_{\text{ext}}}$$

Consequences

- Thermodynamic identities
$$dU = TdS - pdV + \mu dN + ...$$
$$dH = TdS + Vdp + \mu dN + ...$$

- 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

2^{nd} law of thermodynamics

“The production of motive power is then due in steam-engines not to an actual consumption of caloric, but **to its transportation from a warm body to a cold body**, that is, to its reestablishment of equilibrium. […] The production of heat alone is not sufficient to give birth to the impelling power: it is necessary that there should also be cold; without it, the heat would be useless”

Carnot, *On the Motive Power of Fire* (1824)

Sadi Carnot
by Louis Léopold Boilly

$$\eta = 1 - \frac{T_{\text{cold}}}{T_{\text{hot}}}$$

→ A car in a hot atmosphere cannot drive

Energy source **and its environment**

- Which one would you rather have ?

N moles of gas Ambient T p = 1 bar	N moles of gas Ambient T p = 8 bar

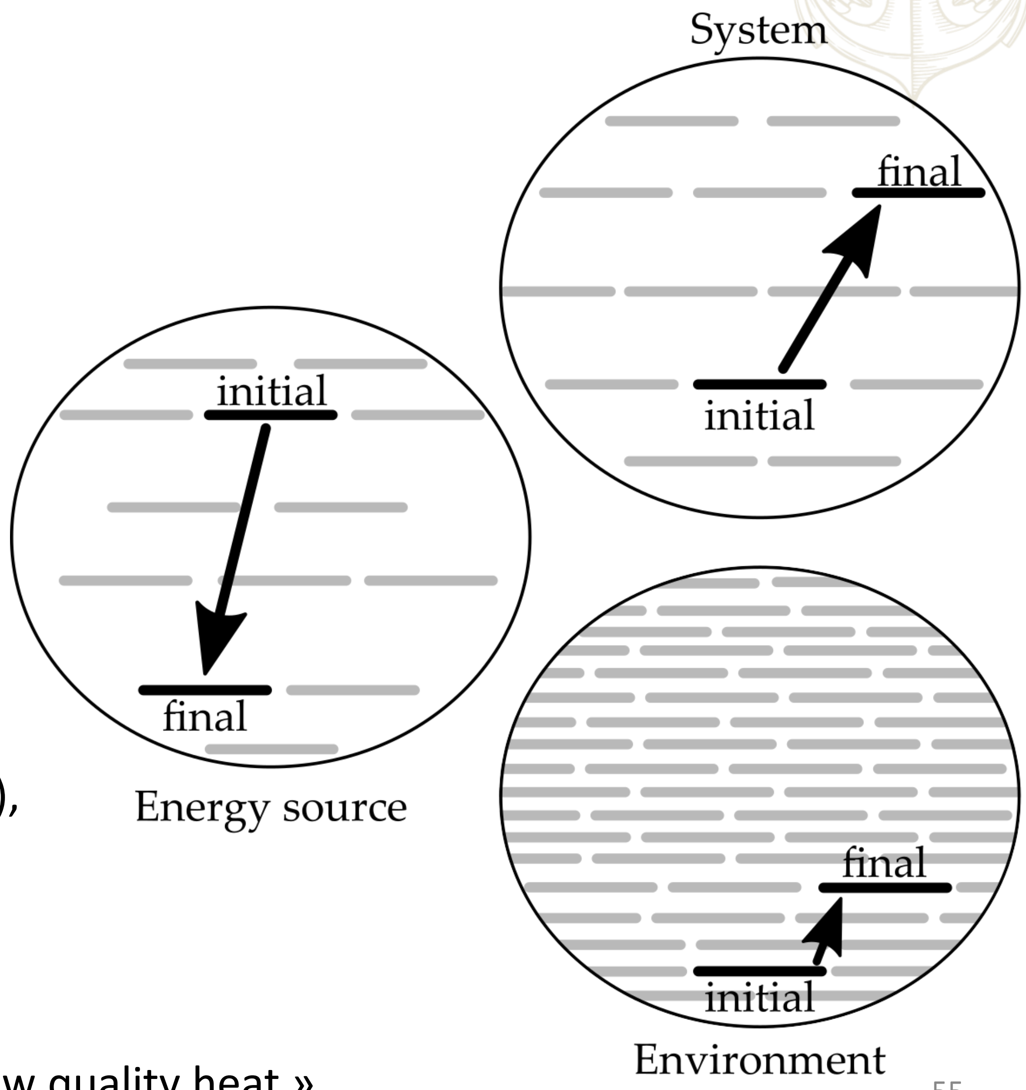
General idea

Take a system out of equilibrium with the environment (T,p,µ…),

Let it relax towards environmental conditions (dead state),

Collect energy along the ride.

Get rid of entropy with heat, use whatever remains as work.



« High quality heat » versus « low quality heat »

Go with the flow

Out of equilibrium with the environment

↓

Gradient of something (potential)

↓

Flow of something else

Need good insulating materials

to maintain gradient

Need good conducting materials

to allow transport

Need materials

Gradient

Flux

	Displacement gradient (Solid strain)	Hydraulic gradient	Chemical gradient	Electrical gradient	Thermal gradient
Solid stress	**Hooke's law**	Effective stress principle	Adsorption-induced stress	Piezoelectric effect	Thermal stress
Fluid flow	Skempton's effect	**Darcy's law**	Chemo-osmosis	Electro-osmosis	Thermo-osmosis
Species transport	Strain-induced adsorption	Streaming current	**Fick's law**	Electrophoresis	Soret effect
Electric current	Piezoelectric effect	Streaming potential	Diffusive current	**Ohm's law**	Seebeck effect
Heat transfer	Coupled thermoelasticity	Thermal filtration	Dufour effect	Peltier effect	**Fourier's law**

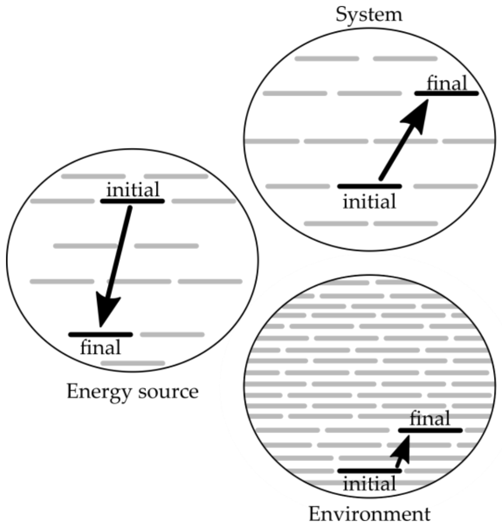
Take home message

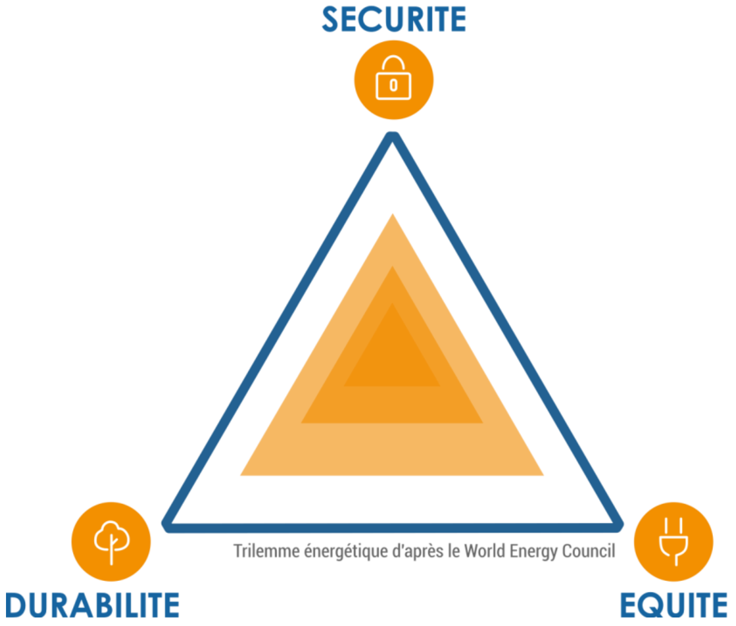
Energy is a complex concept. For PHY555 : energy ↔ transformation

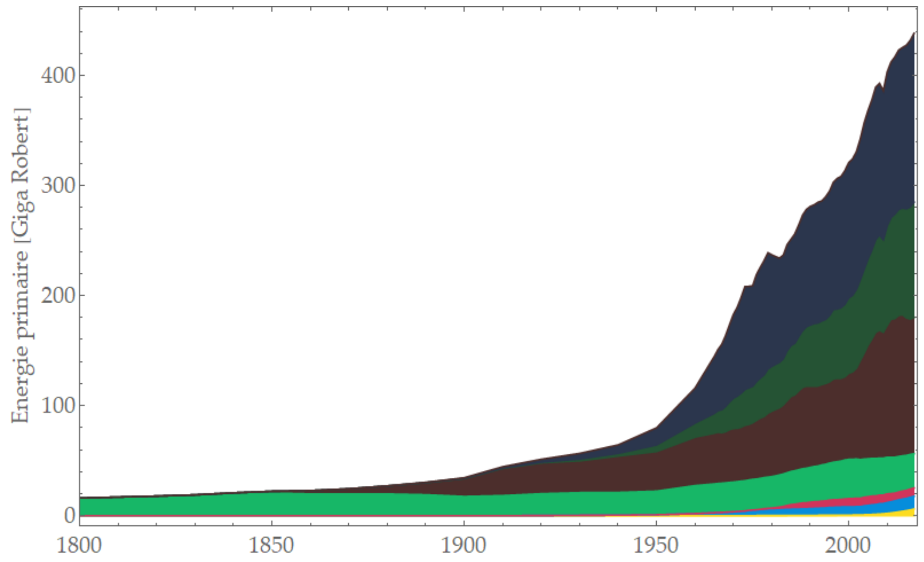
Units, primary / secondary / final / useful energy

Energy has technical, environmental, economical and social implications → trilemma

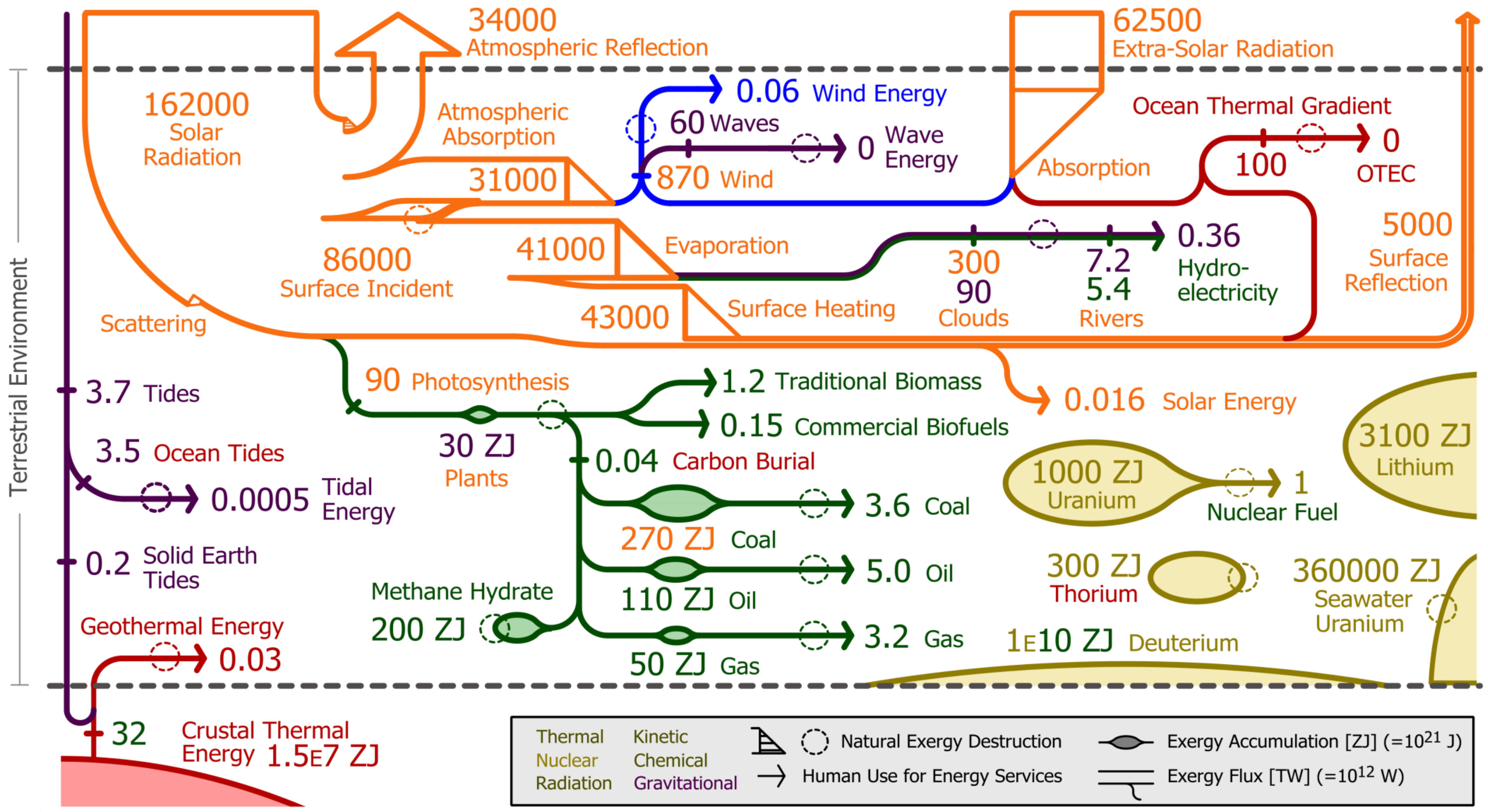
Thermodynamics offers the basic framework to address energy issues (+basic applications)







How much energy? Resource side



"Quantifying global exergy resources"
W. Hermann, Energy **31** (2006)

Kaya’s equation

“IPAT” analysis

Impact = Population × Affluence × Technology

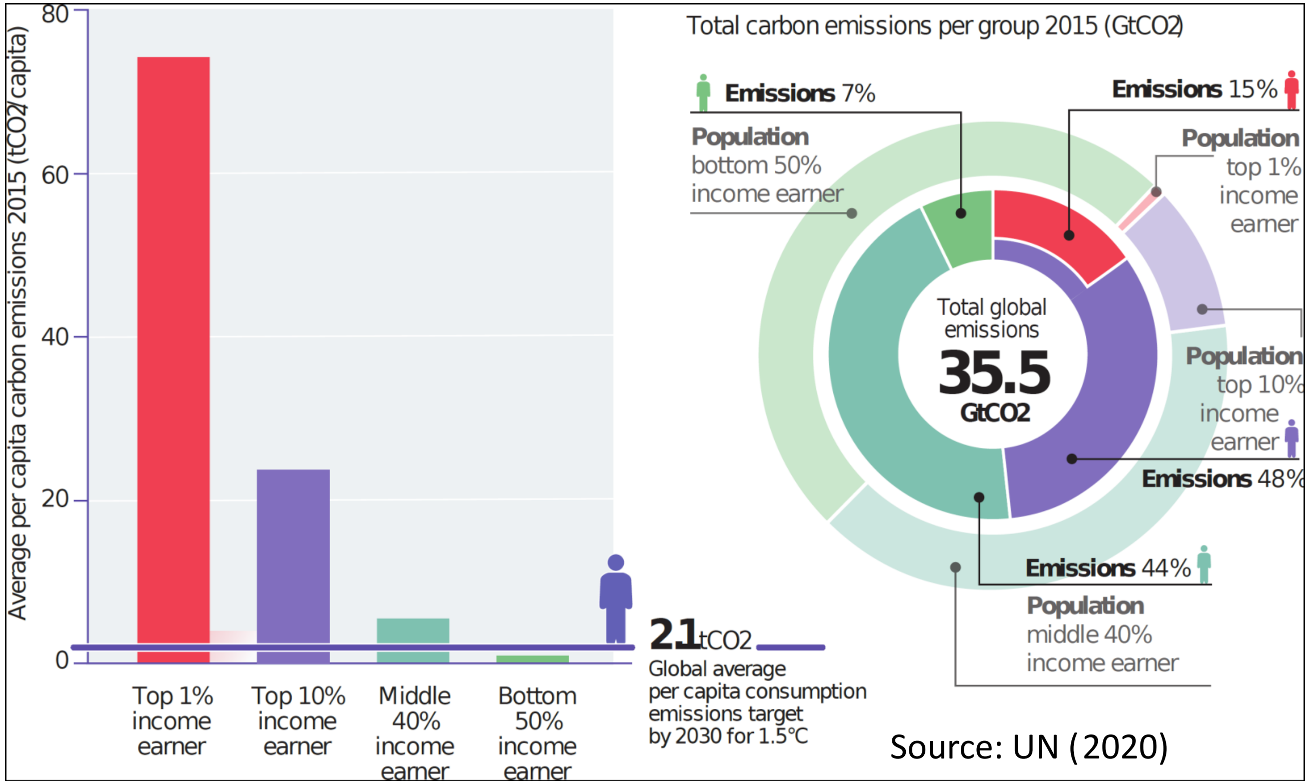
Ehrlich and Holdren (1971)

Be careful with
over-interpretation !

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*



Source: UN (2020)