Chapter: intro

First, we will discuss the very notion of energy, which we will define as a universal quantity characterizing *transformations*, and motivate why it is worth spending a whole course on this notion. We will then introduce basic notions of energy balance inventory, which we use to look at the current situation and past evolutions of the energy sector worldwide. To have a look at the future, a lecture grid for the energy transition is proposed, with a clear distinction between aims (what do we want?) and means (what do we do?). Finally, an overview of usual units, indicators and orders of magnitudes is provided.

1 Energy: what and why?

1.1 A universal concept

Despite being used everywhere, the concept of energy remains a complex notion. Emerged only quite recently (first use in the current sens about 150 years ago).

Top-down approach The most basic approach of energy is not the easiest one to use for practical purposes. Energy is defined as the quantity which is globally conserved, whatever happens to the system under scrutiny. The very existence of such a quantity results from symmetry considerations, and in particular from time invariance (Noether's theorems). Energy is thus extremely well suited for physics, because it offers a baseline which allows to bring together phenomena which are seemingly completely unrelated. However, this perspective from basic principles offers very little indications on how to actually compute this quantity, or what to do with it.

> "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)

Bottom-up approach Energy appears everywhere when studying physics (which should not be a surprise considering the previous comments), and each physics course you have followed so far has certainly introduced specific expressions accounting for different forms of energy relevant to this or that field. Note that this approach allows to calculate "the energy of the system" in practical situations, but does not offer a global perspective on what energy actually is.

Kinetic	Rotation	Gravity	Electric	Elastic	Inductance	Capacitance	Electromagnetic	...
$\frac{1}{2}mv^2$	$\frac{1}{2}J\Omega^2$	mgz	qV	$\frac{1}{2}kx^2$	$\frac{1}{2}LI^2$	$\frac{1}{2}Cq^2$	$\frac{1}{2}\epsilon_0 E^2 + \frac{1}{2\mu_0}B^2$	...

Following the perspective offered by the "top-down approach", it appears that these expression for energy are defined up to a constant, and that what makes most sense from a physics perspective is the variation of the system's energy throughout a transformation.

A turning point in the elaboration of this notion is the construction of *thermodynamics*, which notably managed for the first time to offer a conceptual framework for *heat* (see Chapter XX). In modern physics, heat and work appear as two possible ways to exchange energy between systems, the overall amount of energy being conserved as required from first principles.

$$\text{Energy variation in the system} = \text{Work brought to the system} + \text{Heat brought to the system} \tag{1}$$

> "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, *On the Motive Power of Fire* (1824)

Corollary: energy as transformation In this course, energy will be essentially considered as a quantity characterizing *transformations*. Since energy is conserved, if we want to transform a system from an initial to a final state, we need to provide to this system an amount of energy corresponding to the energy difference between the final and initial state.

Providing energy to perform the transformation is a *necessary* condition, but might not be *sufficient*. We also need to provide the energy under the correct form. You won't turn on a computer by bringing kinetic energy to it, even if it is the same amount as the electrical energy required to power it. *Entropy* provides a way to take (partially) this additional constrain into account (see the thermodynamics chapter). However, energy conservation already provides a powerful way to account for sailient features of most transformations.

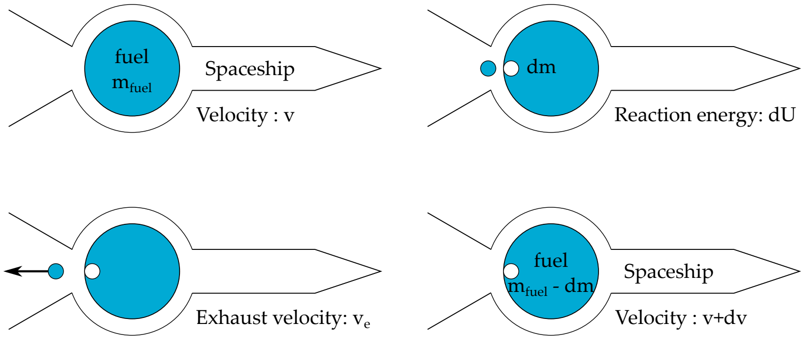
Corollary: energy doesn't care about details The energy involved in a transformation depends only the initial and final states of the transformation, and not on how the transformation is being performed. Energetic approaches thus offer analysis with a broad scope and depends only weakly on the technical details of the system.

Exemple (for fun) of a very broad statement which can be established through energy consideration: "it is impossible to perform interstellar travel with a standard combustion-based spaceship".

To demonstrate this very broad statement, we will show that a combustion-based rocket can never reach velocities close to the speed of light. The main reason is that the embedded fuel contributes to the inertia of the system, making it very hard to propel, and that the mass-to-energy factor for chemical reactions is too weak. And since the closest star is already few light-years away, a too low velocity forbids travelling between stars.

We first derive the relation between the amount of fuel loaded in the ship, and the final velocity reached once all the fuel has been used.

Consider a spaceship of mass m_{ship} carrying an amount of fuel m_{fuel} which is used to propel it. The fuel represents an internal energy U_{int}. Initially, the ship (and the fuel) flies at velocity v in a fix referential.



Between t and $t + dt$, a small fraction dm of the fuel reacts, decreasing the internal energy by an amount dU_{int}, and this enery is turned into kinetic energy for the exhaust fumes which reach a velocity v_e. Energy conservation leads to

$$U_{\text{int}} = (U_{\text{int}} - dU_{\text{int}}) + \frac{1}{2} dm\, v_e^2$$
$$\Rightarrow \frac{1}{2} dm\, v_e^2 = dU_{\text{int}}$$

The exhaust fumes are then expelled from the spaceship, changing the velocity of the ship and the remaining fuel to $v + dv$. From the fix referential, the expulsion velocity is $v - v_e$, and energy conservation leads to

$$U_{\text{int}} + \frac{1}{2} m v^2 = (U_{\text{int}} - dU_{\text{int}}) + \frac{1}{2}(m - dm)(v + dv)^2 + \frac{1}{2} dm\,(v - v_e)^2$$
$$\Rightarrow dv = v_e \frac{dm}{m}$$

Starting with an amount of fuel $m_{\text{fuel},0}$, the velocity reached when all the fuel has been used is given by the celebrated Tsiolkovsky rocket equation:

$$v_f = v_e \times \ln \frac{m_{\text{fuel},0} + m_{\text{ship}}}{m_{\text{ship}}} \tag{2}$$

Remarkably, the final velocity only increases in log with the initial mass of fuel - so increasing the amount of fuel won't help so much. The best we can do is use every atom in the universe ($\sim 10^{90}$ proton) to propel the lightest possible spaceship, consisting in just 1 proton

$$v_f \simeq v_e \times \ln 10^{90} \simeq 200\, v_e \tag{3}$$

We now turn to the estimation of the exhaust velocity v_e. To do so, we consider that the reaction energy dU_{int} can only be a fraction of the mass energy of the reactants:

$$dU_{\text{int}} = \alpha \left(dm\, c^2 \right) \Rightarrow v_e \simeq c\sqrt{2\alpha} \tag{4}$$

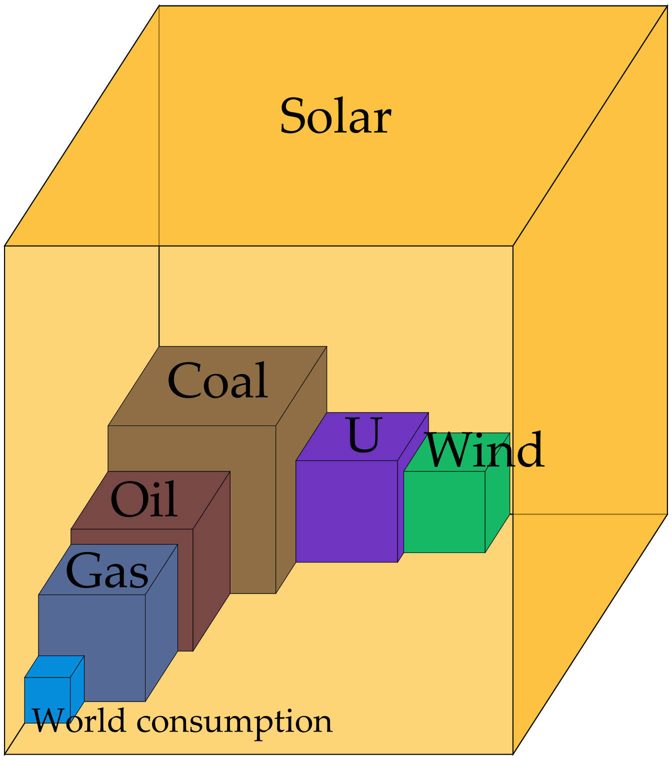
In chemical reactions, reactants are atoms ($dm\, c^2 \sim 1\,\text{GeV}$) and the energy per reaction is in the order of the electron volt ($dU_{\text{int}} \sim 1\,\text{eV}$, see section 4.2), so $\alpha = 10^{-9}$, leading to a final velocity for the spaceship

$$v_f \simeq c\sqrt{2\alpha} \times \ln 10^{90} = 0.01\, c$$

Even by using every atom in the universe as fuel, we won't reach 1% of the speed of light. The strength of this statement is that it does not rely on any technical or technological details of the spaceship.

Corollary: energy resources Considering energy as a quantification for transformations, we can understand what it means to count energy. The energy of a system indicates the amount of transformations that this system is able to perform. An energy source is a system which can be brought from a high energy state to a low energy state so as to provide the corresponding energy to a system we wish to transform. The amount and the form of the energy actually transferred may depend on the transformation undergone by the source.

Consider for instance an oil barrel as an energy source. This source can provide energy undergoing chemical transformations: the hydrocarbon chains are oxidized to CO_2, and the energy difference between initial



World use	Solar	Wind	Hydro	Biomass	Uranium	Coal	Oil	Gas
TWyr/yr	TWyr/yr	TWyr/yr	TWyr/yr	TWyr/yr	TWyr	TWyr	TWyr	TWyr
18.5	23 000	100	3	5	185	830	335	220

Figure 1: Primary energy resource. Flux energy: aggregated ressource over 1 year. Stock energy: estimated total stock. Solar energy received by emerged continents only, assuming 65% losses by atmosphere and clouds. Uranium does not include seawater reserve. More details in the original publication [15].

and final state is released as heat. But an altitute transformation could also be considered: the barrel was standing on a table and falls to the floor, providing kinetic energy. Or the barrel could be brought against an anti-barrel, releasing the mass energy mc^2.

Counting energy resources thus relies on conventions. "The" energy of an oil barrel corresponds to the heat released by fuel combustion. "The" energy of a water volume in a hydrostorage corresponds to kinetic energy released upon freefall. Figure 1 shows the energy resource corresponding to the main primary sources.

1.2 A strategic resource in any society

Seen as a universal ingredient for transformations, energy is obviously a required resource to any society.

Indeed, any adaptation of our environment to cover any of our needs require transformations, and thus energy: changing the ambient temperature to keep housings warm enough, changing a meadow into a crop field... The need for energy is significantly increased in an industrialized society, where raw materials are transformed into manufactured goods at large scales. Conversly, having access to more energy allows society to perform more transformations, and adapt more the environment to our needs and comfort.

Providing enough energy to a society is thus a strategic motivation of its own. Figure 2 shows the amount of energy used per capita in Europe since the middle age [10], and turning points in mankind history are clearly visible. Both the increase of available energy (kick off during the industrial revolutions) and the forced decrease of consumption (world wars, oil peaks) can be related to dramatic changes in daily lives.

A popular image, introduced by Buckminster Fueller, considers that the way society works is determined by the availability of energy, and compares the energy available per capita to the number of servants which would need to work full time to provide the same amount of transformations, and thus the same quality of life. Con-

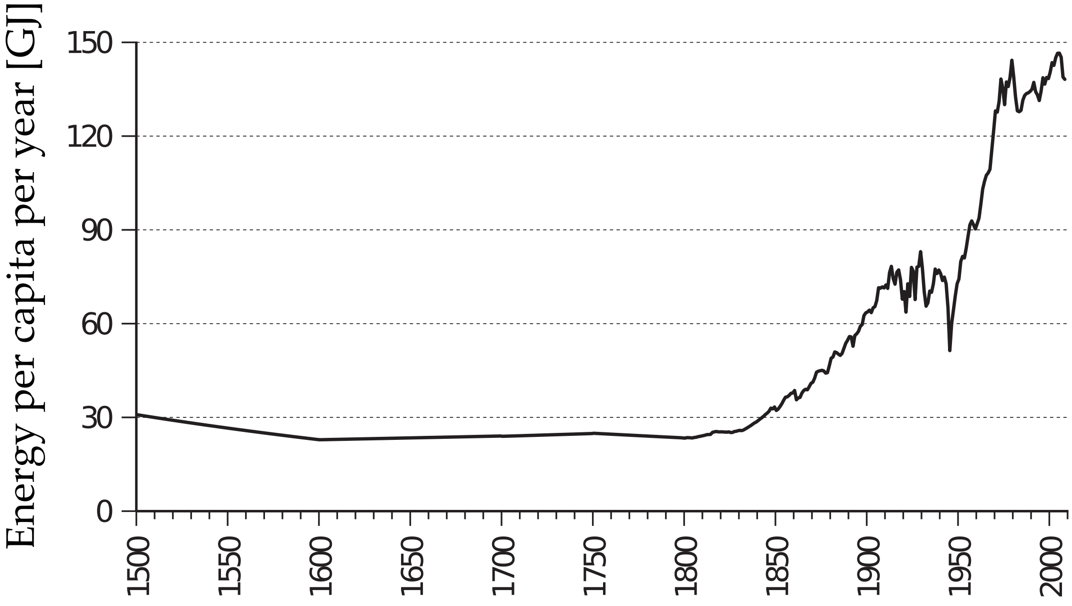


Figure 2: Average energy per capita in Europe overtime. Source: [10]

sidering that a human can provide a typical power of 40 − 100W (see 4.1) and that the world average energy consumption is 10 000 Mtoe per year for a population of 7 billion, the average human (which doesn't exist) benefits from about 50 "energy slaves". A complementary perspective offered by Ivan Illich [6] reverses the focus, and considers that energy needs are essentially determined by the way society works. Building on the example of transport, Illich estimates that the effective service brought by cars (taking into account not only the driving time but also the cost of fuel, insurance, maintenance...) is about equivalent to that of bikes. The energy need for the transport sector thus appears not to be determined by the desired amount of service, but by the rules of the society.

Note that the three sectors introduced in this section (buildings, industry, transport) are the main categories considered in most energy balance.

1.3 A powerful societal indicator

Besides the direct use of energy, the very broad scope of the energy concept makes it a powerful indicator, strongly correlated with many different aspects of any society. Looking at energy consumption of a society can thus give insight on how that society works.

Figure 3 shows two examples of such correlations.

The left plot shows that the fraction of workers employed in agriculture is larger when the available energy per capita is smaller. This correlation is usually interpreted by considering that agriculture transformations are needed to feed population, corresponding to a minimal amount of energy. If only little energy is available per capita, then many workers are needed to provide this amount. If more energy is available per capita, then fewer workers can perform the required transformations.

The right plot shows that the Human Development Index increases with the available energy per capita - no country with less then 1 ton of oil equivalent per capita per year reaches an HDI above 0.8. It is also worth noting that, above 2-3 toe/cap/yr, the correlation is significantly decreased. It seems that a minimum amount of energy is required to reach a satisfying HDI, but that above this threshold, more energy doesn't bring more happiness.

1.4 An impactful consumption

Energy consumption can have a large variety of impacts - not only induced by the transformations resulting from the energy use, but also by side effects of the energy source itself.

The most scrutinized side effect is certainly the emission of greenhouse gases, and particularly CO_2, induced

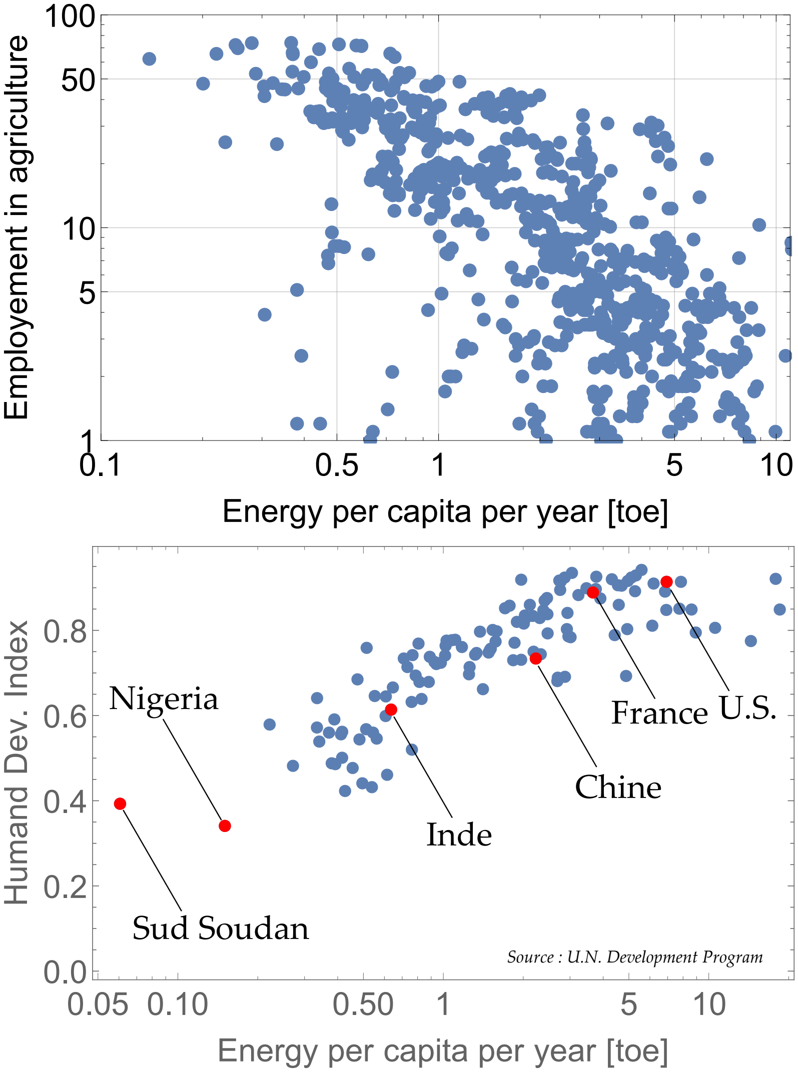


Figure 3: Correlations between energy consumption per capita and two societal indicators: fraction of total employment in agriculture (source: World Bank Data, 2018) and Human Development Index, which aggregates health, education and economical indicators (source: UN Development Program, 2018). Each point corresponds to one country.

	Primary	Secondary
Non Renewable	Coal(Hard coal, Brown coal, Peat), Oil(Oil shale, Crude oil), Gas, Nuclear heat, Industrial & Municipal wastes (partially), Heat from chemical processes	Coal products, Peat products, Refinery feedstocks, Oil products, Electricity and heat from combusted fuels of fossil origin, Electricity derived from heat from chemical processes and nuclear heat, Any other product derived from primary/secondary non-renewable products
Renewable	Biofuels (except charcoal), Municipal waste (partially), Heat from renewable sources (except from combusted biofuels), Electricity from renewable sources (except from geothermal, solar thermal or combusted biofuels)	Charcoal, Electricity and heat from combusted biofuels, Electricity from geothermal and solar thermal, Any other product derived from

Table 1: Cross-classification of primary/secondary and renewable/non-renewable products according to the International recommendations for energy statistics (IRES) [21].

by the combustion of fossil fuels (∼80% of the world energy supply). As a matter of fact, about three quarters of global GHG emissions are related to energy (see top of Fig.4), which is by far the first anthropogenic contribution to global warming.

However, this dramatic consequence of our energy supply should not conceal other impacts. The middle and bottom figure 4 shows for instance that the energy industry (especially coal in power stations) and residential energy supply (especially for cooking) are responsible for a large fraction of air pollution world wide. These environmental impacts also have social implications - notably considering that the cleanest form of energy are often the most expensive.

2 Today's energy situation

Now that we have set a definition for energy, and understood why energy is worth studying, let's see where the world is at today. To do so, we first introduce the basic vocabulary for energy balances, and present the energy inventory based on IEA data.

2.1 Energy balance vocabulary

Primary energy corresponds to raw commodities directly captured from natural resources, which have not been engineered or converted (but after removal of impurities (e.g. sulphur from natural gas)). Primary heat sources include notably coal (coking coal, steam coal, lignite, peat), oil (oil shale, crude oil), natural gas, nuclear, geothermal, biofuels and waste. Primary electricity sources include hydro, wind, solar, tide and wave power.

Total primary energy supply (TPES, or TES) is made up of production + imports – exports - stock changes - marine and aviation bunkers.

Secondary energy are obtained from transformations of primary energies, and are produced to respond to user needs, when primary commodities are not suitable (see Table 1). Of course, conversion losses can occur during the process - and the minimal amount of losses is set by thermodynamics.

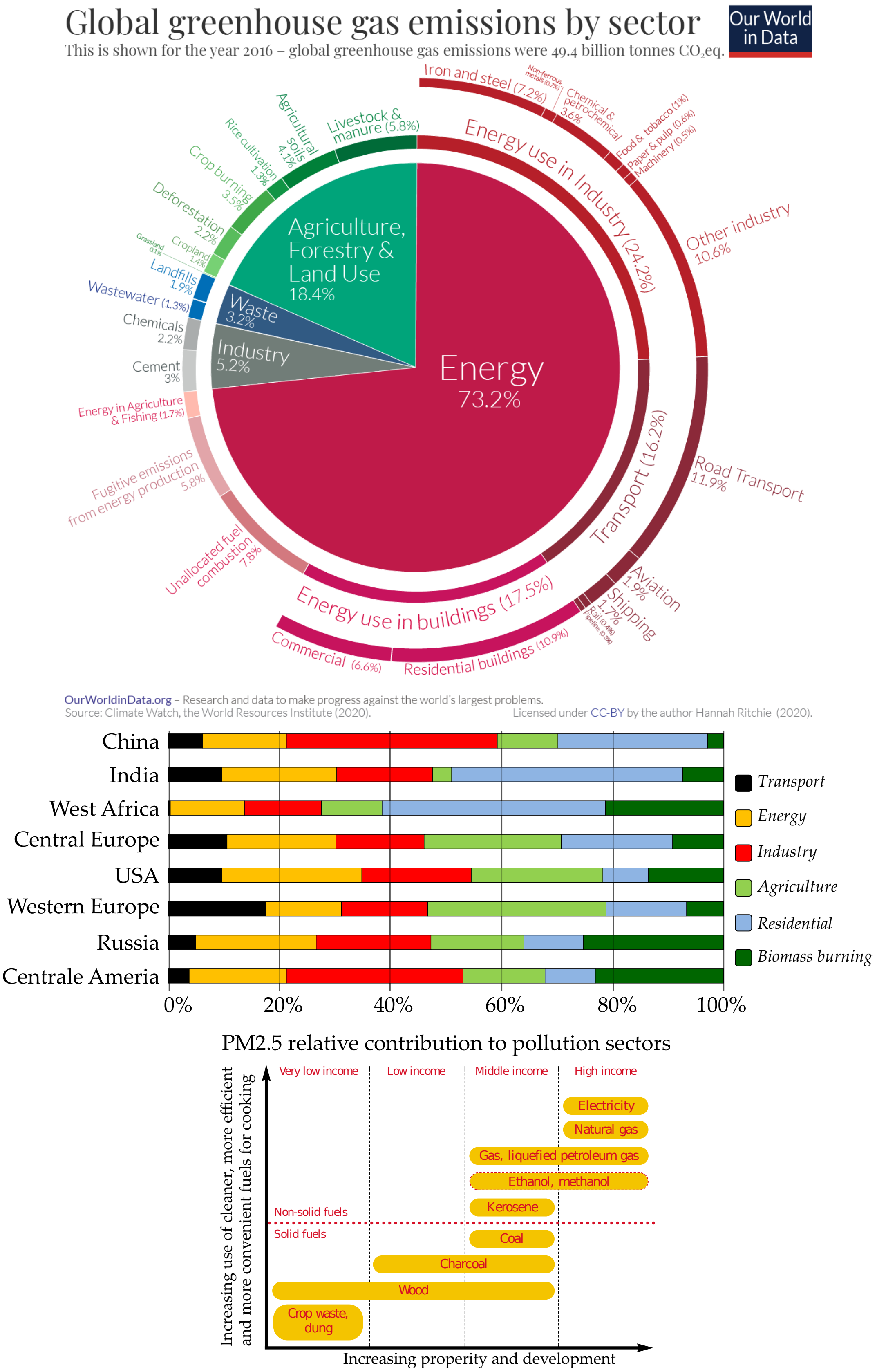


Figure 4: Top: Greenhouse gas emission by sector. Source: https://ourworldindata.org/emissions-by-sector. Middle: air pollution ($PM_{2.5}$) by origin for several countries or world regions (source : adapted from [11]). Bottom: type of fuel used for cooking as a function of property (source: [14]).

Final energy accounts for commodities which are actually purchased and used by end users, and can be analyzed by sector. The most usual categories are :

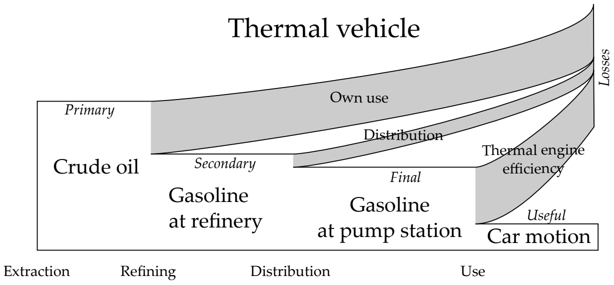
- Industry: iron and steel, chemical and petrochemical, non ferrous metals, non metalic minerals, mining and quarrying, wood and wood products, construction, food and tobacco, textile and leather...
- Transport: road, aviation, rail, navigation...
- Buildings: residential, commercial and public services
- Other: agriculture, fishing...

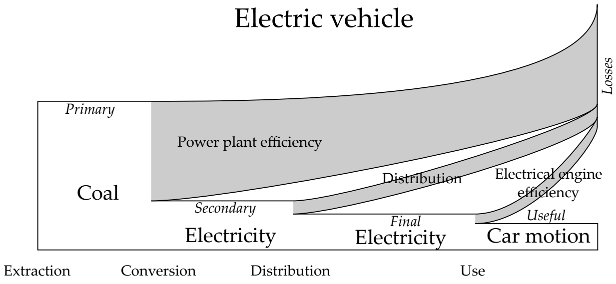
Non-energy use covers those fuels that are used as raw materials in the different sectors and are not consumed as a fuel or transformed into another fuel. Non-energy use also includes petrochemical feedstocks.

Energy industry own use (eg the energy required to power refineries) and losses (during conversion from primary to secondary, or during distribution) are usually counted separately from the Total Final Consumption (TFC).

Useful energy is usually not included in energy balance, but is an important notion. Only a faction is the final energy delivered to the end user will actually provide the desired service.

The exemple below shows a qualitative comparision between two cars. In this fictitious case, the useful energy is the same in both cases, and so is the primary supply, so the overall efficiency is the same. However, the distribution of losses are significantly different. For a thermal car, little energy is wasted during the refining of crude oil and most losses occur in the engine, when converting the heat produced by gasoline combustion into mechanical work. By constrast, for an electric car, the engine is very efficient at converting electricy into motion, and most losses come from converting the heat produced by coal combustion into electricity. Stoping the analysis at the *final* energy stage could lead to the misinterpretation that the thermal car have a much better efficiency than electric car: the energy loss from primary to final energy are much smaller for the thermal vehicle than for the electric one !





The main idea to keep from this discussion is that energy balances must be handled with care. Make sure you understand what is being counted, and what is not, to make sure that conclusions make sens.

2.2 Sankey diagram for world energy balance

The top figure 5 shows where we stand today. Don’t hesistate to play with data at https://www.iea.org/sankey !

- Fossil fuels (oil, coal and gas) account for >80% for the world energy supply.
- Carbon-based energy (fossil + biomass) reaches 90% of our energy supply
- Electricity is less than 20% of final energy consumption

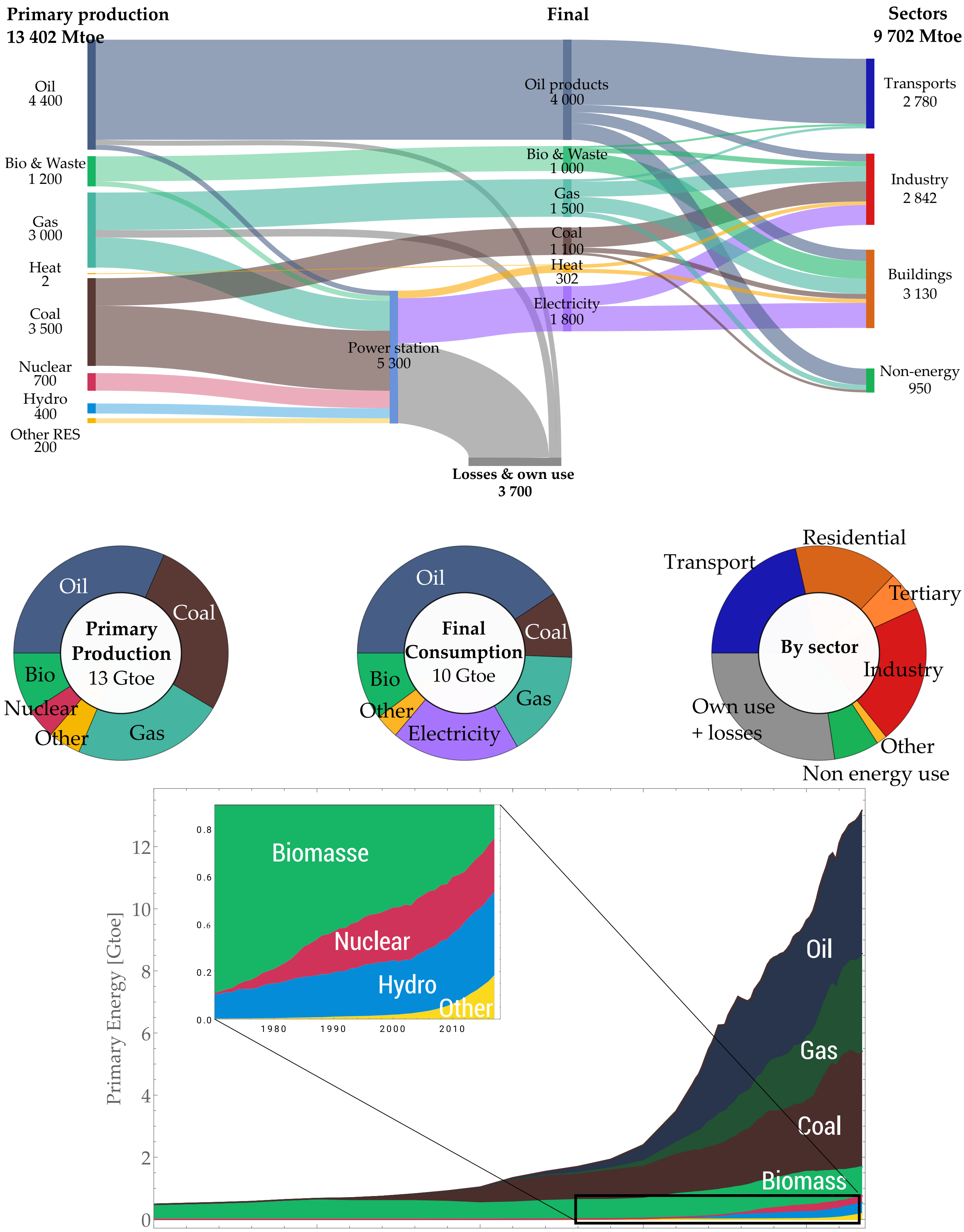


Figure 5: Sankey Diagram for the world energy balance in 2018. Adapted from https://www.iea.org/sankey/.

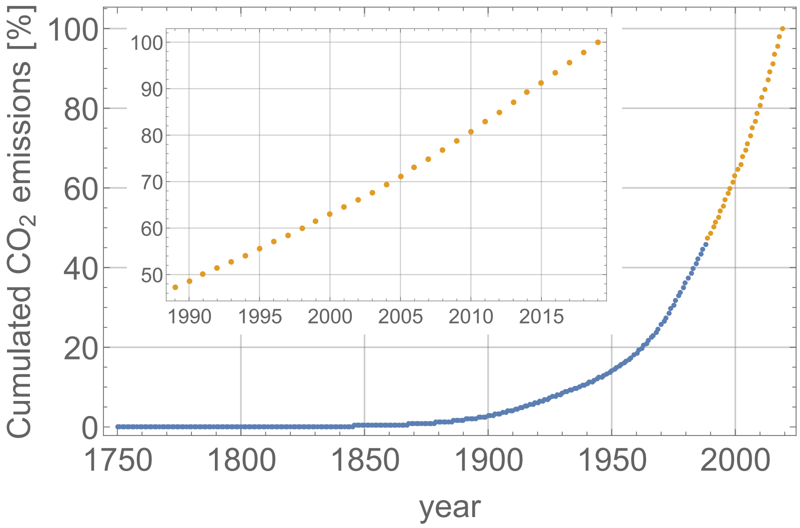


Figure 6: Cumulated world CO_2 emission. Adapted from [17].

The bottom figure 5 shows the time evolution of the world primary consumption.

- Over time, different sources of energy have been *added* to the stack, but never significantly removed. The first industrial revolution is not about replacing wood by coal, it's about adding coal to the list of possible supplies.
- The growth of new renewable sources (mostly wind and solar) is indeed exponential, but remains a very, very small fraction of the world supply (about 1.5%).
- Global energy supply keeps increasing, and this increase is largely carried by fossil fuels.

3 A framework for the energy transition: goals and means

The observation of today's energy situation and trends makes it obvious that this system cannot carry on forever - hence the need for an energy transition. However, the very topic of energy transition can be pretty messy, because this transition can aim at different targets, can use different tools - all tools being not necessarily well suited for every target.

This section proposes a lecture grid (see Fig. 7) to clarify (some of) the issues at stake in the notion of energy transition.

3.1 Goals: the energy trilemma

The World Energy Council offers an interesting lecture grid, which helps identifying three possible concerns for an energy policy.

Environmental sustainability evaluates the degradation of the environment induced by the energy system. Incidentally, sustainability determines the ability of the system to continue over long periods of time - i.e. to reach a stationary state. From a dynamic perspective, this implies that both inputs and outputs of the energy system are balanced. The notion can be divided into three considerations [3]:

- Renewable resources should be used at a rate slower than their renewal
- Non-renewable resources can be used in a sustainable way, provided alternative solutions are development simultaneously to replace them when exhausted

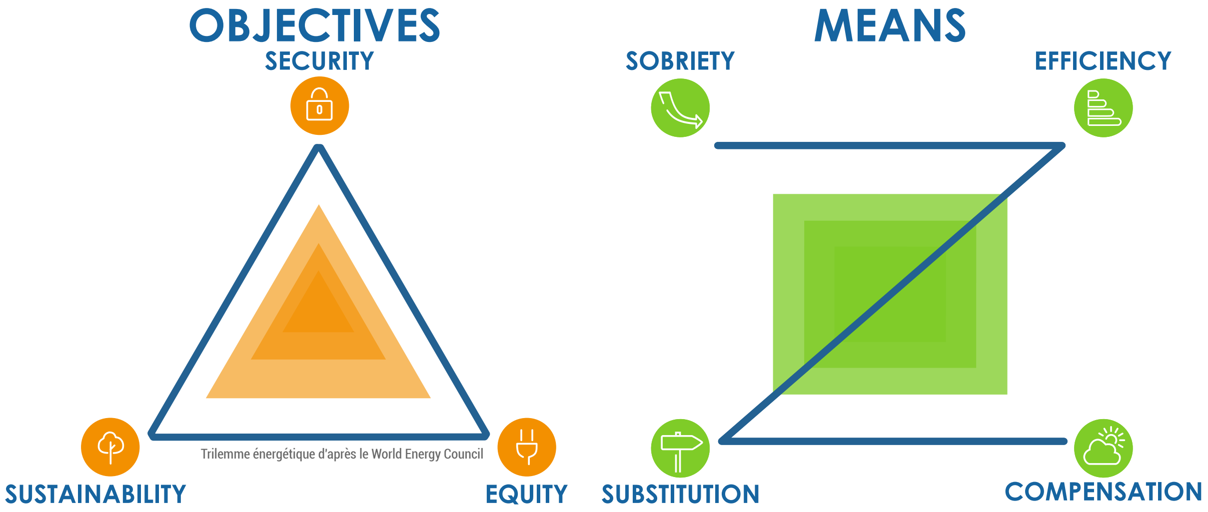


Figure 7: Goals and means for an energy transition.

- Wastes (= pollution, GHG...) should be produced at a rate slower than their elimination

Energy security concerns the conditions for the stability of the energy supply, now and in the future. This notion covers notably

- The security of energy infrastructures (explosions in mines, pipelines holdup, dam break down, power plants meltdown, power lines failure...)
- The energy dependence to foreign producers (fossil fuels, manufacturers...) or to foreign infrastructures
- The ability of the energy system to handle shocks (grid stability, strategic stocks...) and to recover from them

Energy equity considers the ability to provide universal, abundant and affordable energy. This issue addresses notably

- The very access to energy (electrification, cooking fuels...)
- The economical cost of energy (energy poverty...)

These three issues form a trilemma in the sense that all of them have to be addressed. If any single issue is neglected, the system would be problematic. A sustainable, fair but unsecured energy system, would leave the country at the mercy of adverse situations, be they geopolitical (it's hard to negotiate against somehow who can cut your energy supply out) or simply natural (you can't afford a blackout every time wind and solar productions drop down). A sustainable, secured but unfair system is unacceptable from a social perspective. A secured, fair but unsustainable system can only last for so long, before it destroys its own working conditions - as we are currently experiencing.

Note that this grid does not rank these objectives, and deciding where to set priorities is not a matter of physics.

3.2 Means

Once the objectives are decided, several means can be considered to achieve them. Most technical solutions can be classified in the following four categories.

Energy sobriety consists in cutting down uses. Reducing the speed limit, limiting long distance transportation, turning down the temperature, switching off the lights... are sobriety measures.

Energy efficiency aims at providing the same use for a lower energy consumption, without changing the use. Examples: improving the heat insulation of a building allows to maintain the same temperature with less energy. Changing an incandescent light-bulb by a LED to provide the same lighting with less electricity.

Energy substitution changes the energy vector consumed to provide the use, without changing the amount of energy required. Examples: replacing coal by wind and solar, switch from a diesel engine to an electric car.

Compensations tries to mitigate the negative social, ecological or economical consequences once the energy has actually been used. Examples: carbon capture and storage, afforestation, carbon tax...

Note that this grid doesn't say whether a specific solution is relevant for a specific objective, nor the conditions required for its implementation or the possible side effects. One of the most famous downside is the Jevons' paradox, or rebound effect, which states that any measure facilitating the use of energy will lead to an increase of energy demand, counterbalancing the initial gain. This idea was first introduced in *The coal question [9]* as a criticism of energy efficiency and remains to date a painfully relevant notion :

> «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.»

3.3 Another lecture grid: Kaya's identity

Another popular approach to energy policies has been suggested by the economist Yoichi Kaya in the 90s' [12], adapting the "IPAT" idea[1], which was first introduced in the 70s' to quantify the impact of human activity on the environment . Kaya's identity consists simply in highlighting arbitrarily four factors in CO_2 emissions:

$$\mathrm{CO_2} = \frac{\mathrm{CO_2}}{\mathrm{Energy}} \times \frac{\mathrm{Energy}}{\mathrm{GDP}} \times \frac{\mathrm{GDP}}{\mathrm{capita}} \times \mathrm{capita} \tag{5}$$

The first term corresponds to the carbon footprint of the energy mix (how many gCO_2 to produce 1 kWh ?); the second term corresponds to the energy intensity of the economy (how many kWh to produce 1€ ?); the third term is the GDP per capita; and the last one the population.

Kaya's identify offers a perspective on different approaches which can be considered to reduce CO_2 emissions: either by improving the carbon footprint of the mix, or by reducing the energy intensity of the economy, or by contracting wealth available per capita, or by reducing the population. It should however be noted that the simplicity of this approach can be misleading if considered as a proper demonstration. In particular, the factors introduced in this equation are arbitrary; the different terms are not independent from each other, and most importantly this approach considers aggregated averages (e.g. total GDP divided by total population), when inequalities are being increasingly identified as a key aspect of energy and climate issues (see Fig. 8).

4 Units, indicators and orders of magnitude

This last section aims at gathering numerical values and orders of magnitude for usual energy indicator.

Many energy-related quantities can be defined. Even before looking for the numerical value of an indicator, special attention needs to be given when *choosing* the relevent indicator to address a given question - and first of all, the question needs to be well identified.

For instance, when considering a power plant from an economical perspective, it can be more relevant to estimate and optimize the conversion efficiency of the plant of the fuel is expensive, or the power density of the installation if the infrastructure is expensive. The operation of the power plant will be different if we try to maximize the former or the latter.

As a rule, designing indicator is a tradeoff between something easy to compute, but providing limited depth of analysis (eg : energy per capita) and something offering a clear insight on a problem, but which is very difficult to compute (eg: the time evolution of residential energy consumption for heating, including climate corrections).

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[1] Impact = Population × Affluence × Technology

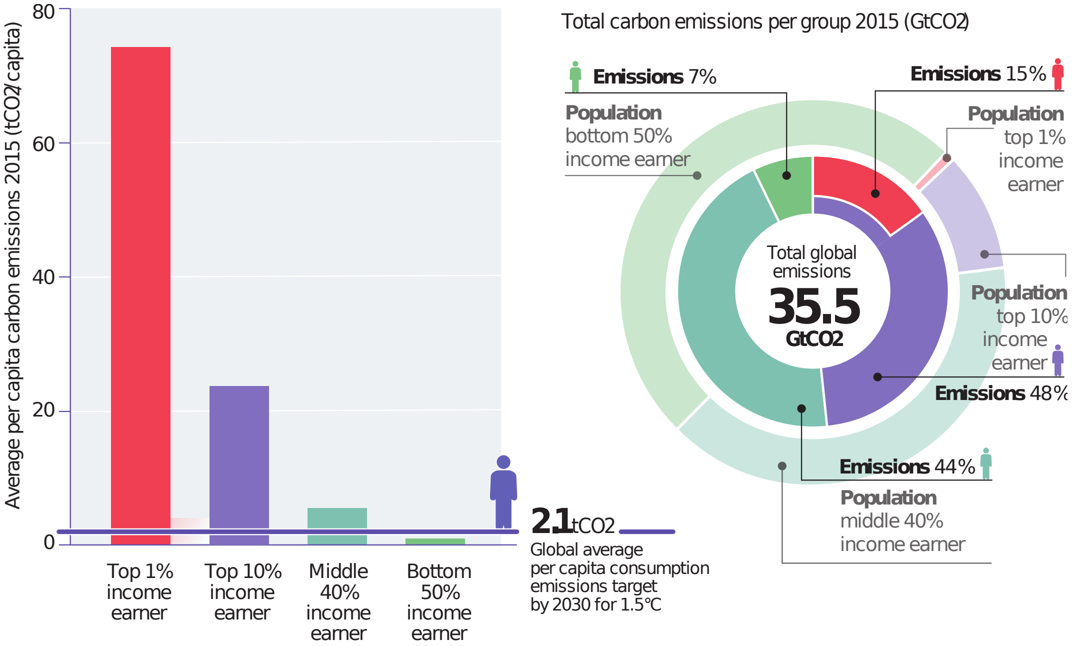

Figure 8: Per capita and absolute CO2 consumption emissions by four global income groups in 2015. Source: United Nations Environment Program [20]

4.1 Units

Conversion table (see Fig. 9)

	eV	J	kWh	toe
eV	1	1.6×10^{-19}	-	-
J	6.3×10^{18}	1	2.7×10^{-7}	2.3×10^{-11}
kWh	-	3.6×10^{6}	1	8.6×10^{-5}
toe	-	42×10^{9}	11 630	1

There is a large mess of units used to count energy, partly because of the large variety of situations where energy is a relevant concept. Here is a selected best-of energy units.

- The standard system unit is the *Joule*, defined as

$$1\,\mathrm{J} = 1\,\mathrm{kg.m^2.s^{-2}}$$

- For most microscopic systems, the relevant unit is the *electron-volt*, defined as the potential energy of an electron under a 1V potential difference

$$1\,\mathrm{eV} = 1.6 \times 10^{-19}\,\mathrm{J}$$

- The *Calorie* (or *kcal*) is mostly used in the food industry. It is defined as the energy required to raise the temperature of 1L of water by one degree Celsius at a pressure of one atmosphere. Not to be confounded with the *calorie* (lower case):

$$1\,\mathrm{Cal} = 1000\,\mathrm{cal} \simeq 4.2\,\mathrm{kJ}$$

- The British Thermal Unit follows the same idea, but using stupid units: it is defined as the amount of heat required to raise the temperature of one pound of water by one degree Fahrenheit[2] at a pressure of one

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[2] A story holds that Fahrenheit established the zero of his scale (0 °F) as the temperature at which a mixture of equal parts of ice and salt

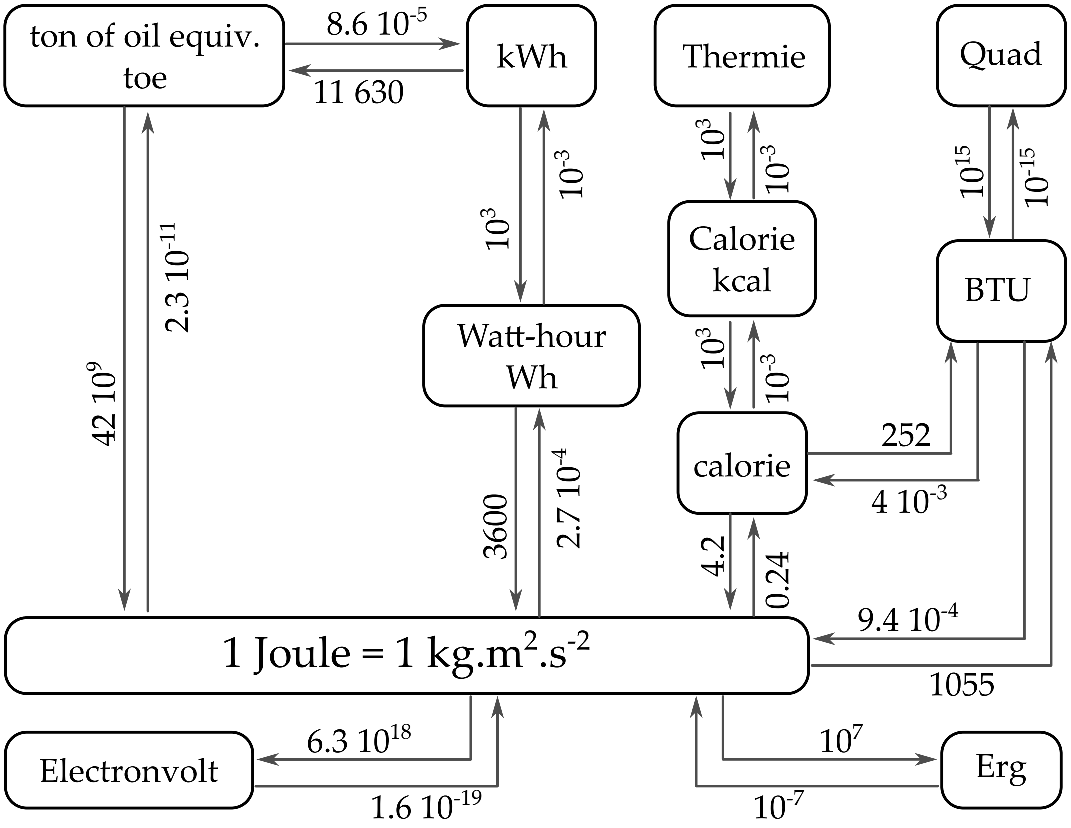

Figure 9: Energy units

atmosphere

$$1\,\text{BTU} = 1.060\,\text{kJ}$$

- The Quad is a large packet of BTU. It is notably used by the US Department of Energy to discuss energy budgets.

$$1\,\text{Quad} = 10^{15}\,\text{BTU}$$

- The *Watt-hour* (/!\ it's "watt times hour", not "watt per hour") is the power accumulated using a 1W source during 1h:

$$1\,\text{Wh} = 3.6\,\text{kJ}$$

  This unit (and its multiples kWh, MWh...) is usually used for electrical energy budget.

- The *ton of oil equivalent* is the amount of energy released by burning one tonne of crude oil:

$$1\,\text{toe} \simeq 42\,\text{GJ} \simeq 11.63\,\text{MWh} \qquad (6)$$

  It is the standard unit to discuss energy budgets for the IEA, for instance.

4.2 Densities

Gravimetric energy density, Specific energy [J/kg, kJ/mol] (see Fig.10) indicates the amount of matter required to obtain a given amount of energy. It is one of the most basic indicators, relating somehow the number of

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melts (some say he took that fixed mixture of ice and salt that produced the lowest temperature); and 96 degrees as the temperature of blood (he initially used horse blood to calibrate his scale). Initially, his scale contained only 12 equal divisions, but he later subdivided each division into eight equal degrees, ending up with 96. For some reason.

Energy (J)	
Ambient temperature	10^{-21}
Electron volt	10^{-19}
Visible photon	$2\,10^{-19}$
Binding energy per nucleon	10^{-10}
Daily nutritional need	10^{7}
Gasoline in a car tank	10^{9}
Lightning	10^{9}
1 ton of TNT	$5\,10^{9}$
1 ton of oil	$4.2\,10^{10}$
1 gram of Uranium	10^{11}
Tropical cyclone	10^{12}
Hiroshima bomb	10^{13}
Krakatoa Volcano	10^{17}
Tsar bomba	10^{17}
Valdivia Earthquake	10^{20}
World TPES in 2014	10^{20}

Power (W)	
Wind turbine (per m^2)	2
Human body (work)	40
Human body (heat)	100
Computer	100
Solar panel (per m^2)	20
Conso per cap. (Bengladesh)	300
Sprinter	700
Conso per cap. (World, China)	$2\,10^{3}$
Conso per cap. (Europe)	$5\,10^{3}$
Conso per cap. (US)	10^{4}
Car	10^{5}
Conso per cap. (Qatar)	$3\,10^{5}$
Nuclear plant	10^{9}
Total world consumption	10^{13}
Lightning	10^{14}
Solar flux on Earth	10^{17}
Total solar flux	$4\,10^{26}$

Table 2: Orders of magnitude.

elementary constituents of the system to the provided energy.

From that perspective, it is interesting to investigate why fossil fuels and uranium have such different specific energies. Both have roughly the same atomic density ($\sim 10^{30}/\mathrm{m}^3$) but the energies at stake are very different. The simple model of a potential well shows that the more tightly confined a system is, the higher the typical energy scale with $E \sim h^2/2mL^2$. For an atom, where electrons ($m \sim 10^{-30}$ kg) are confined in a volume of typical size $L \sim 10^{-10}$ m, the typical energy is $\sim 10\,\mathrm{eV}$. For an atomic nucleus, where nucleon ($m \sim 10^{-27}$ kg) are confined in a volume of typical size $L \sim 10^{-15}$ m, the typical energy is $\sim 100\,\mathrm{MeV}$. We thus expect a factor $\sim 10^7$ in specific energies between fossil fuels and nuclear fuels - which is indeed the case.

Specific energy is most relevant in situations where mass is a strong constraint (planes...). It is notably the case in many transportation systems: the heavier the system, the more difficult it is to move - so the mass of fuel should be as reduced as possible.

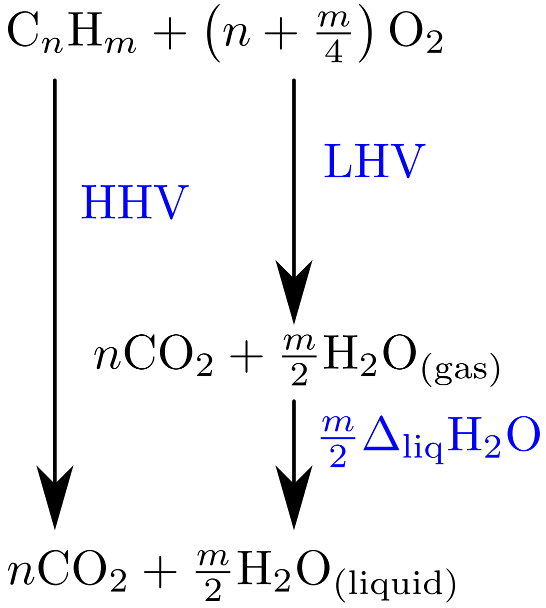
Volumetric energy density, Energy density [J/m^3, J/L] (see Fig.10) indicates the volume of matter required to obtain a given amount of energy. It is of course related to the specific energy through the density of the considered system:

$$\text{energy density} = \text{specific energy} \times \text{density} \tag{7}$$

This indicator is most relevant in situations where volume is a strong constraint. It partially explains why natural gas, despite having a very specific energy, is not widely use for transportation: it would require too huge tanks.

Comments on energy densities

- Warning: HHV and LHV. It is customary to distinguish the "higher heating value" (HHV, or gross calorific value) from the "lower heating value" (LHV, or net calorific value). The difference between these two quantities is simply whether water is considered as liquid or vapor in the final state. Vaporizing water costs energy, so liquefying vapor releases heat. HHV is thus larger than LHV by an amount corresponding to the latent heat of water molecules (44 kJ/mol). By default, numerical values in this lecture are given as HHV.



- Both densities (gravimetric and volumetric) are very well suited to address stock energies: a pile of coal, a bottle of gasoline or a pellet of uranium which can be measured (weight, volume...) before being burnt. It can be readily extended to storage devices. It is a bit more difficult to adapt to flux energies (solar, wind, hydro...). It can be done with a life-cycle analysis to estimate the total energy provided by these installations - but the interpretation of the obtained value is a little bit different from the stock situation.

Power density [W/m^2] (see Fig. 11) "informs us about the energy flux that can be usefully derived from a given area by a particular conversion, regardless of how close or how far apart the individual converting or extracting facilities maybe, and regardless of the commercial activity (if any) taking place in most of the area that is not occupied by structures or infrastructures indispensable for extraction or conversion." [19].

It is very well suited for flux energies (solar, wind...) and requires some adaptation to address stock energies. It can be done with a life cycle analysis, taking into account to total surface involved in power generation (mine, infrastructures, power plants...), the total energy provided over the lifetime of the installations, and the time required to produce all this energy.

4.3 Efficiencies

Conversion efficiency [%] (see Fig. 12) is the ratio between the useful output and the costly input of a converter[3]. These quantities are usually considered either as energies (basic thermodynamics of heat engines) or as powers (endoreversible thermodynamics).

One of the key results of thermodynamics is indeed that one form of energy cannot always be entirely converted into another form. The bottleneck is given by the second law, which prohibits the global decrease of entropy. The change in entropy depends on the amount of exchanged heat, and on the exchange temperature. It is thus possible to consider perfect conversions for specific cases, for instance when turning work into work, with no heat being exchanged. But in most cases, the relevant transformation considers turning heat (easy to obtain) into work (adapted to the actual need) - and such conversions have limited efficiencies.

Defining what the actual boundaries of the costly input, and possibly that of the useful output can be ambiguous. For instance, the "useless heat output" from a power plant can be used to heat houses, or greenhouses. In practice, special attention must thus be given to the exact definition of "efficiency".

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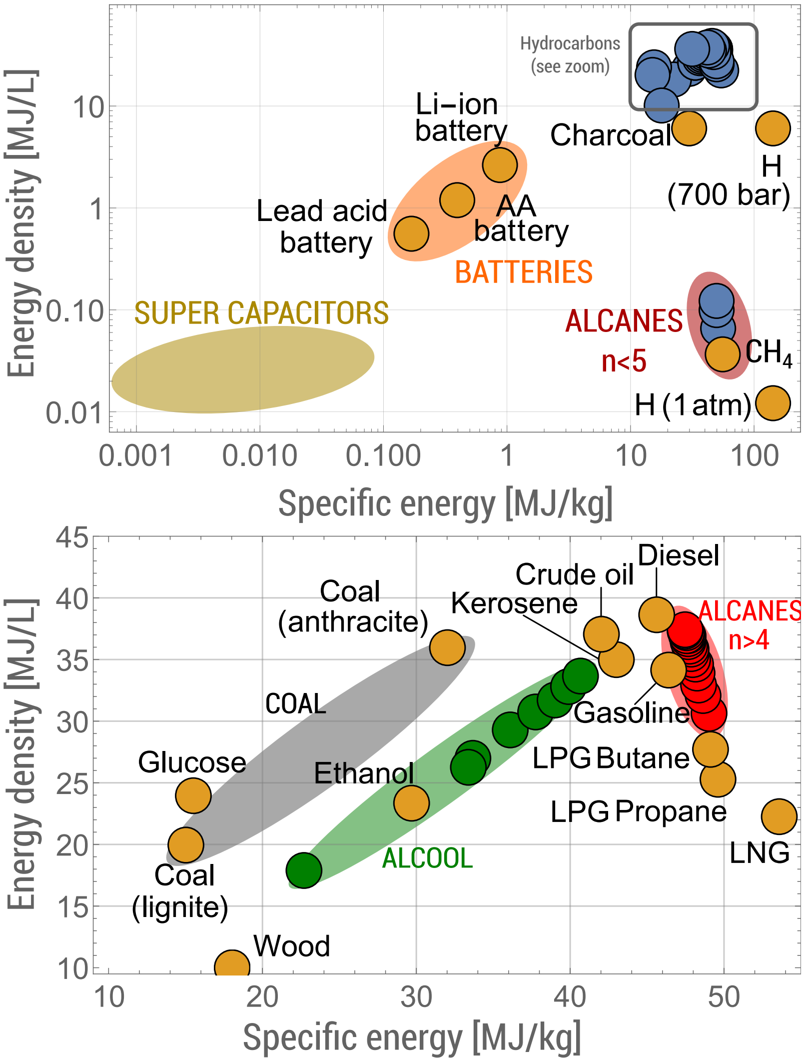
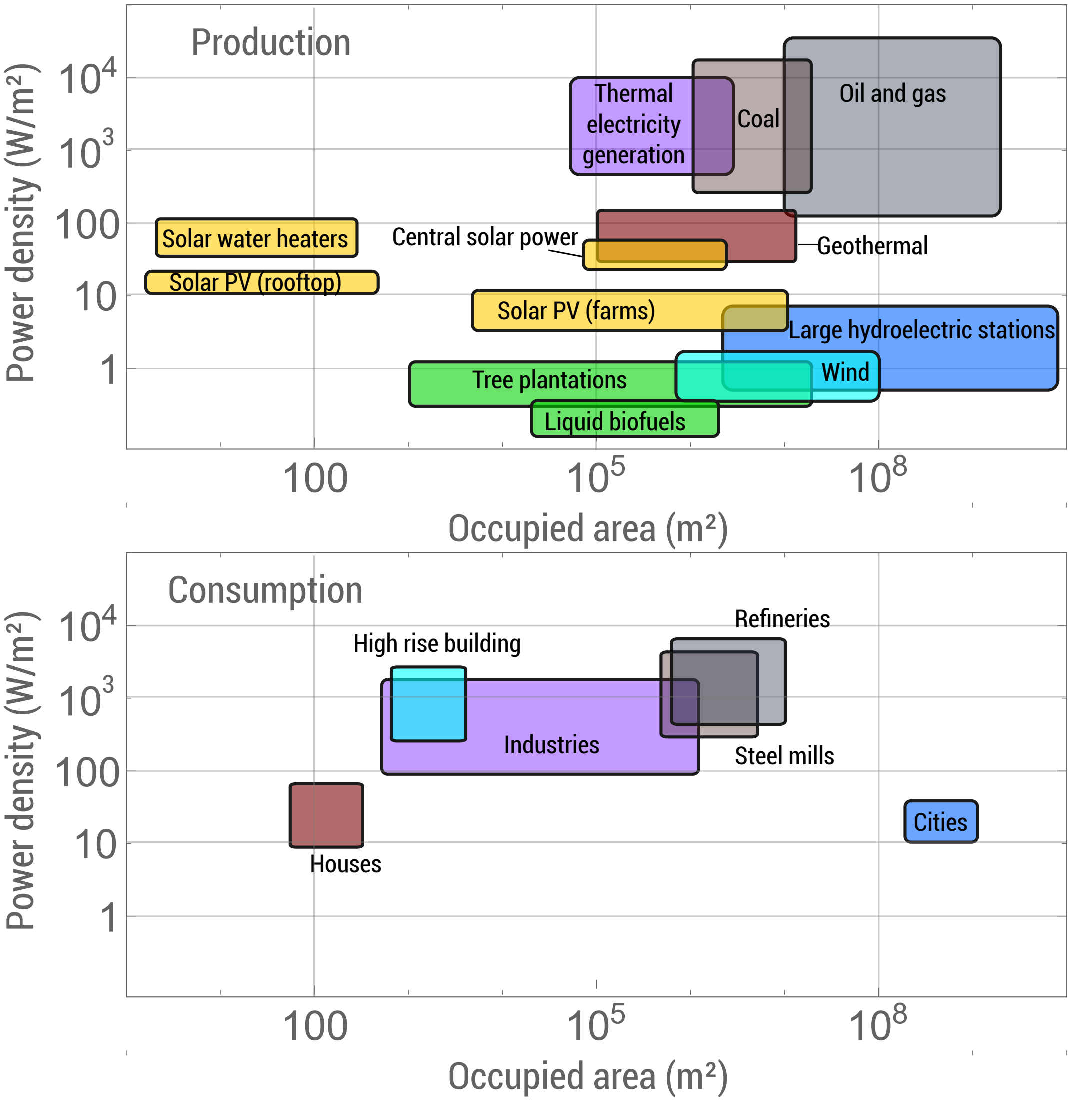
[3] Note that "input" and "output" are algebric values, and can be negative.



	MJ/kg	MJ/L
Alkanes		
CH_4 (gas)	55.4	0.04
C_3H_6 (gas)	50.3	0.1
C_4H_5 (gas)	49.5	0.12
C_6H_{14}	48.6	32
C_8H_{18}	48.2	33.9
Alcools		
Methanol	22.7	18
Ethanol	29.7	23.4
Bio molecules		
Glucose	15.5	24
Cellulose		
Wood	15	10

	MJ/kg	MJ/L
Fossil fuels		
Lignite	15	20
Anthracite	32	36
Charcoal	30	6
LNG	55	23
LPG Propane	49.6	25.3
LPG Butane	49.1	27.7
Crude oil	42	37
Gasoline	45	34.2
Diesel	46	38.6
Jet fuel	43	31
Storage		
H_2 (1 atm)	142	0.01
H_2 (700 bar)	142	6
Water falling from 100m	0.001	0.001
Super capacitor	0.002	0.02
Lead acid battery	0.1	
Li ion battery	0.36 - 1	
Nuclear		
Uranium	$8\,10^7$	$1.5\,10^9$

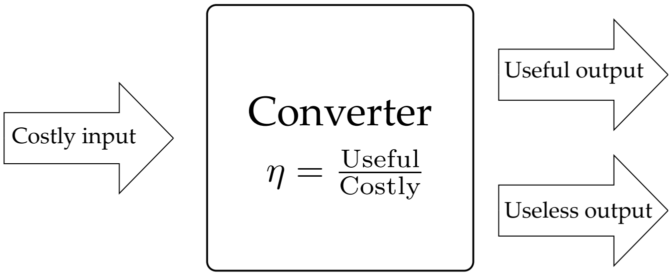
Figure 10: Energy densities. The typical density for Uranium is $\sim 10^8$MJ/kg and $\sim 10^9$MJ/L, completely off this chart. Source : [16, 18, 1]



Source	Wind	Hydro	Solar PV	Solar water heating	Biomass	Biofuels
Type	Elec	Elec	Elec	Heat	Heat	Heat
W/m^2	0.5-2	0.1-10	3-20	40-100	0.6-2	0.1-0.4

Source	Geothermal	Coal	Oil and Gas	Power plants
Type	Heat	Heat	Heat	Elec
W/m^2	40-100	200-10 000	1 000 - 40 000	400 - 5 000

Figure 11: Power densities, adapted from [19]. Comparing production and consumption values, both in terms of power density and occupied area, identifies which source is suited for which usage.



	Costly input	Useful output	Useless output	Efficiency
Motor, generator	Heat from hot source	Work output	Heat to cold source	$-W/Q_{\text{Hot}}$
Heat pump	Work input	Heat to hot source	Heat from cold source	$-Q_{\text{Hot}}/W$
Fridge	Work input	Heat from cold source	Heat to hot source	Q_{Cold}/W
Solar cell	Solar radiation	Work output	Cell radiation	$U \times I/P_{\text{sun}}$

Figure 12: Conversion efficiency.

	Converting from	Into	Efficiency		Converting from	Into	Efficiency
Steam turbine	Mechanical W	Electrical W	40 %	Combustion engine	Chemical Q	Mechanical W	10 – 50 %
Wind turbine	Mechanical W	Electrical W	(< 59 %)	Electric engine	Electrical W	Mechanical W	30 – 90 %
Water turbine	Mechanical W	Electrical W	90 %	Photosynthesis	Solar Q	Chemical Q	0.5-5 %
Solar cell	Solar Q	Electrical W	(<33 %)	Muscles	Chemical Q	Mechanical W	20 %

Installed / rated / nominal / nameplate capacity [W, W_{peak}] (see Fig. 13) estimates the maximal theoretical production of an installation.

For a solar panel, it corresponds to the expected power generation under standard conditions (∼ at noon, in summer, without clouds). For a wind turbine, it corresponds to the expected power when the speed of wind is not too weak and not too strong. For a power plant, it corresponds to power produced in full load operation.

No system runs at full capacity all the time, so the "installed" capacity does not reflect the power actually produced. However, it is a useful indicator to track the deployment of a technology.

Load / capacity factor [%] (see Fig. 13) is the ratio between the energy actually generated and the production corresponding to the installed capacity:

$$\text{CF} = \frac{\text{Yearly energy output [Wh]}}{8760\,\text{h/yr} \times \text{installed capacity [W}_\text{p}\text{]}} \leq 100\% \tag{8}$$

Equivalently, the system yield [h] corresponds to the yearly energy production per installed capacity - ie for that many Watt peak, how many Watt hours do you get at the end of the year? Or also: how many hours running at the full power correspond to the actual production?

$$\text{SY} = \frac{\text{Yearly energy output [Wh]}}{\text{Installed capacity [W}_\text{p}\text{]}} \leq 8760\,\text{h} \tag{9}$$

If the installation runs all the time at maximal capacity, which is never the case of course, the load factor is 1. A reduced load factor can be due to the way the installation is driven (e.g. gas turbine used only few hours a year to handle peak demand), to maintenance operations or to physical limitations of the generation (e.g. no solar production during the night, so the capacity factor is necessarily below 0.5).

Note that the capacity factor is an average value, which gives very little information about the time series of production. A capacity factor of 0.5 can correspond to power plant working all the time at 50% of its maximal power, or working half of the time at 100% and stopped half of the time.

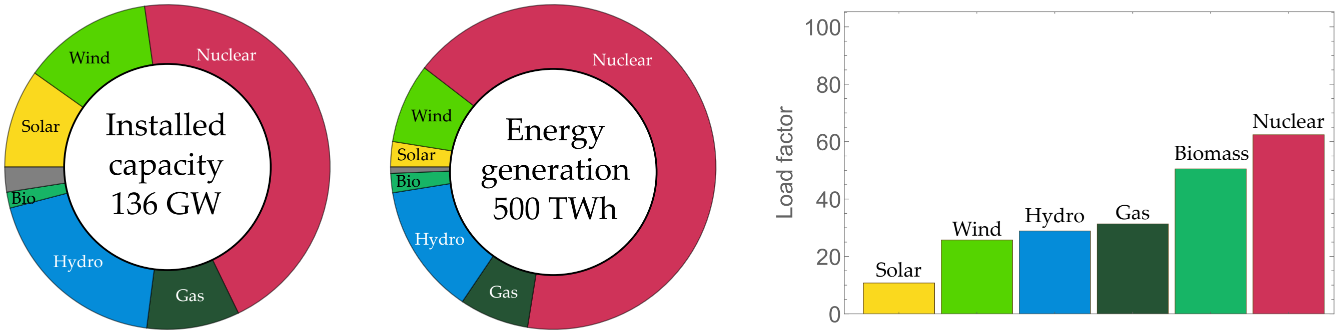


Figure 13: Installed capacity, actual energy generation and load factors for the French mix. Source: https://bilan-electrique-2020.rte-france.com/production-production-totale/

Performance Ratio [%] is the ratio between the energy actually generated and the expected production taking into account foreseeable deviations from the rated power.

$$\mathrm{PF} = \frac{\text{Actual energy output [Wh]}}{\text{Expected energy output [Wh]}} \tag{10}$$

For instance, for a solar installation, the expected production is the efficiency of solar panels multiplied by local yearly irradiation, taking into account the day/night cycle, the average cloud cover... but not the impact of parasitic shading, panel degradation... By contrast, the load factor would be the efficiency multiplied by an irrealistic constant illumination of 1000 W/m^2 24h a day all year long.

Performance ratio helps estimating whether an installation works as expected, or under-performs.

4.4 Life cycle indicators

A large variety of indicators are intended to account for what happens throughout the lifetime of an energy system. In this section, we first introduce basic notions of life cycle analysis, and present three usual indicators as illustration.

Life cycle analysis (LCA)

Life cycle analysis is defined as a “technique for assessing environmental aspects and potential impacts of a product or service” (ISO 14040). The international standard distinguishes four main processes in the analysis, which have to be performed iteratively until the study converges (see Fig. 14).

- Define the goal and scope of the analysis.

  Defining the goal should clarify the purpose (why is the study realized?), the intended audience (who is going to use it ?) and the intended application (typically, to decide among several options which one should be selected) of the analysis.

  The scope defines the studied system (product, service...), the system boundaries (see Fig. 14) and the *functional unit* - ie basic purpose which needs to be fulfilled by the system (produce 1 kWh of electricity, move 1 person by 1 km, ...). It also states the considered impacts (global warming, energy content, acidification, human health...), the data requirements (accuracy, precision...) and should make working assumptions explicit.
- Inventory analysis is the compilation and quantification of inputs and outputs for a product throughout its life cycle. Ultimately, this study leads to the estimation of all emissions required to generate the functional unit. In a linear approach, this step leads to the estimation of the *process vector* $\mathbf{p}$, which contains all relevant input required to produce the functional unit and of the *emission matrix* $\underline{E}$which

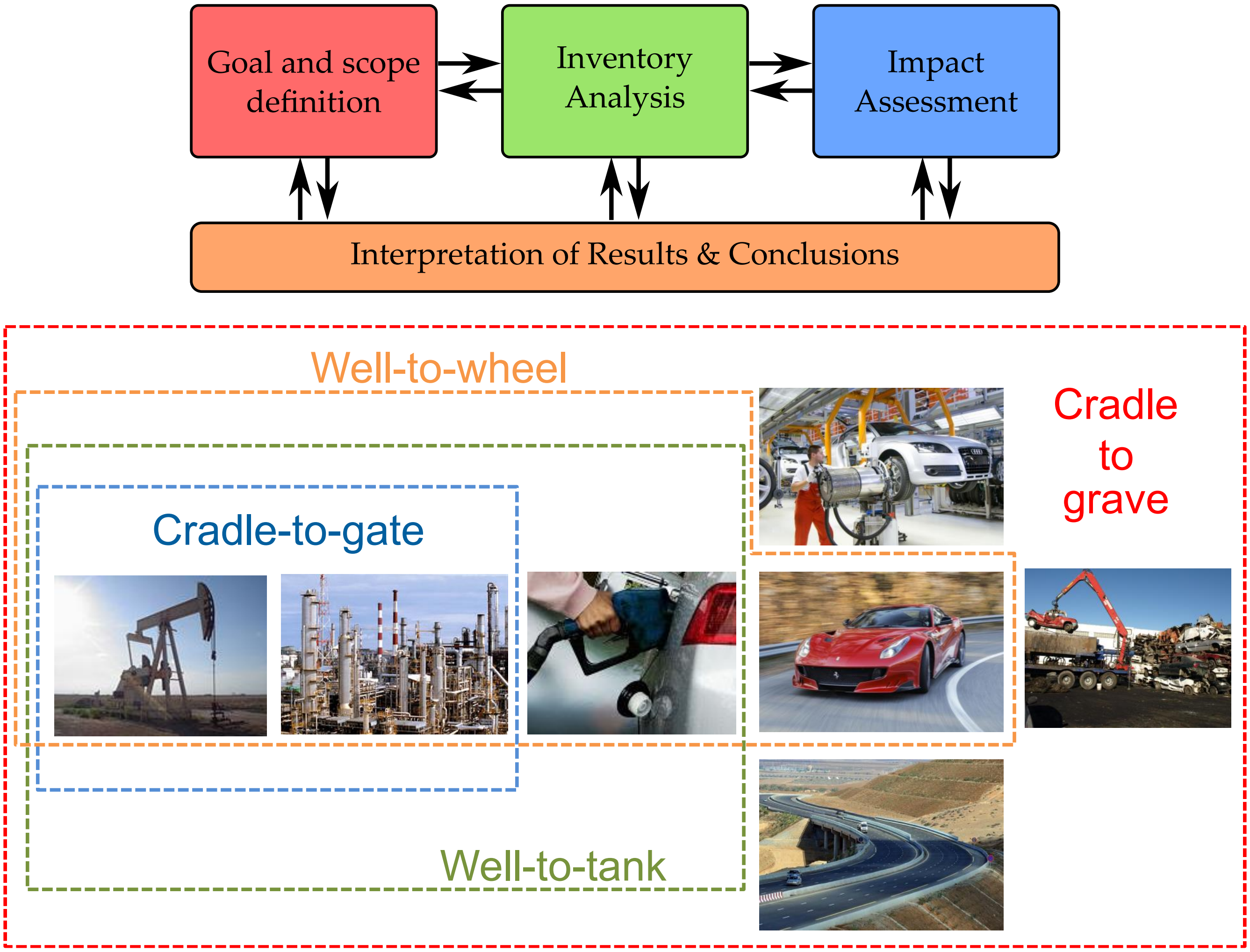


Figure 14: Top: main stages of a Lifecycle Analysis, following ISO 14040. Bottom: standard LCA perimeters. Courtesy to Paula Perez-Lopez

expresses the emissions induced by each ingredient of the process vector

$$\mathbf{p} = \begin{pmatrix} \text{X kg of steel} \\ \text{Y kWh of electricity} \\ \text{Z L of oil} \\ ... \end{pmatrix}$$

$$\underline{\mathrm{E}} = \begin{pmatrix} \mathrm{kgCO_2} \text{ for 1 kg steel,} & \mathrm{kgCO_2} \text{ for 1 kWh elec,} & \mathrm{kgCO_2} \text{ for 1 L oil} & ... \\ \mathrm{kgCH_4} \text{ for 1 kg steel,} & \mathrm{kgCH_4} \text{ for 1 kWh elec,} & \mathrm{kgCH_4} \text{ for 1 L oil} & ... \\ \mathrm{kgPO_4^{3-}} \text{ for 1 kg steel,} & \mathrm{kgPO_4^{3-}} \text{ for 1 kWh elec,} & \mathrm{kgPO_4^{3-}} \text{ for 1 L oil} & ... \\ ... & ... & ... & ... \end{pmatrix}$$

- Impact assessment classifies emissions according to impact categories (global warming, acidification, resource use...). Within each categories, emissions are *characterized*, ie compared to a chosen reference ($\mathrm{kgCO_{2,eq}}$ for global warming, $\mathrm{kgSO^-_{2,eq}}$ for acidification, ...). The characterization matrix converts all emissions in the chose equivalent units

$$\underline{\mathrm{Q}} = \begin{pmatrix} \mathrm{kgCO_{2,eq}} \text{ for 1 } \mathrm{kgCO_2}, & \mathrm{kgCO_{2,eq}} \text{ for 1 } \mathrm{kgCH_4}, & \mathrm{kgCO_{2,eq}} \text{ for 1 } \mathrm{kgPO_4^{3-}} & ... \\ \mathrm{kgSO^-_{2,eq}} \text{ for 1 } \mathrm{kgCO_2}, & \mathrm{kgSO^-_{2,eq}} \text{ for 1 } \mathrm{kgCH_4}, & \mathrm{kgSO^-_{2,eq}} \text{ for 1 } \mathrm{kgPO_4^{3-}} & ... \\ ... & ... & ... & ... \end{pmatrix}$$

so that the total impact of producing 1 functional unit is given by

$$\begin{aligned} \text{Impact for 1 functional unit} &= \begin{pmatrix} N\,\mathrm{kgCO_{2,eq}} \text{ (climate)} \\ M\,\mathrm{kgSO^-_{2,eq}} \text{ (acidification)} \\ L\,\mathrm{kgPO^{3-}_{4,eq}} \text{ (eutrophication)} \\ ... \end{pmatrix} \\ &= \underbrace{\underline{\mathrm{Q}}}_{\text{Characterization matrix}} \times \underbrace{\underbrace{\underline{\mathrm{E}}}_{\text{Emission matrix}} \times \underbrace{\mathbf{p}}_{\text{Process vector}}}_{\text{lifecycle inventory}} \end{aligned}$$

Finally, to allow a direct comparison between different options, the *weighting* step turns the impact vector into a single numerical value, by deciding (arbitrarily) how the different categories compare to each other. Would you rather emit 1 $\mathrm{kgCO_{2,eq}}$ and 2 $\mathrm{kgSO^-_{2,eq}}$, or 2 $\mathrm{kgCO_{2,eq}}$ and 1 $\mathrm{kgSO^-_{2,eq}}$?

- Interpretation of results and conclusions

Carbon intensity, emission factor [$\mathrm{kgCO_{2,eq}/J}$, $\mathrm{kgCO_{2,eq}/kWh}$] (see Fig. 15) counts the amount of greenhouse gases emitted to produce a given amount of energy. For fossil fuels, carbon intensity is related to the specific energy: both the mass of each molecule, the energy released upon combustion and the quantity of released CO_2 depend on the number of carbon atoms in the organic chain.

Two points of caution:

- Sometimes, only CO_2 emissions are considered (and not other GHG), sometimes carbon intensity is expressed in carbon mass (and not in CO2 mass), leading to a factor 3.6 difference.
- Sometimes, this quantity is estimated from a life cycle analysis (ie by dividing the total GHG emissions associated to an installation [infrastructures, fuels, maintenance...] by the total energy produced by the installation over its lifetime), sometimes it is simply a marginal value (ie GHG emissions for producing just one more energy unit, without taking infrastructures into account). Usually, electricity production is analyzed from a life cycle perspective, while fossil fuels are analyzed from a marginal perspective - which can be relevant, if emissions from fuel combustion largely exceed that of infrastructures.

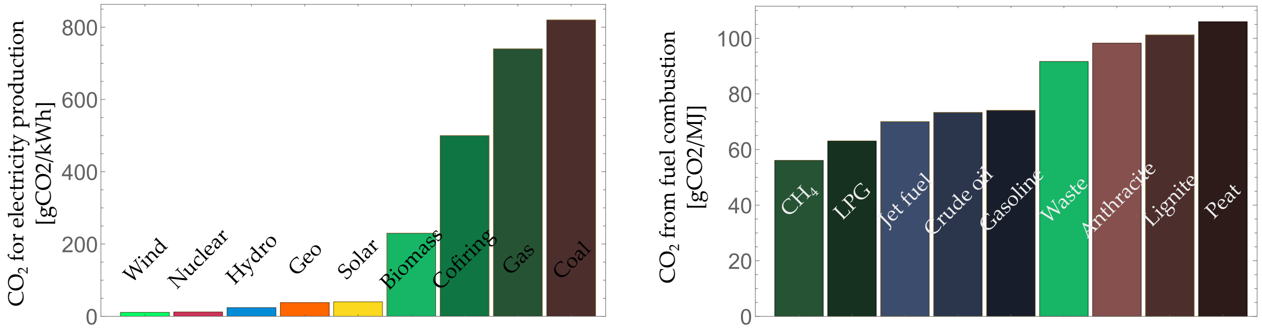


Figure 15: Emission factors from 2006 IPCC Guidelines for National Greenhouse Gas Inventories [7] and IPCC AR4 [8]

Energy Return On Investment (EROI) [-] (see Fig. 16) is the ratio between the energy produced by a system over its lifetime, and the energy required to create, maintain and operate the system.

$$\text{EROI} = \frac{\text{Generated energy}}{\text{Invested energy}} \tag{11}$$

For instance, it takes energy to drill a well and pump up the oil, then to refine crude oil into gasoline. How much energy is needed to produce 1 MJ of gasoline? It takes energy to purify silicon and process it into a solar panel. How much energy is needed to produce a solar panel ? How does this amount compare to the energy produced during ~25 years by the solar panel?

EROI is a powerful and popular indicator to quantify the ability of a source to contribute to society's energy supply. It is often interpreted as the fraction of the energy produced by a system which needs to be kept aside and re-invested to create a new system once the first one is exhausted[4]. What is available for society's consumption is the remaining fraction $1 - 1/\text{EROI}$. Think of an oil barrel: a fraction of what is pumped up needs to be used to power the pump which will bring up the next barrel and so on. An EROI ≤ 1 means that the source consummes more energy than it provides, as if 1 barrel of oil was not enough to pump up the next barrel of oil. The larger the EROI, the larger the fraction of the produced energy is available for the society (see Fig. 16).

The use and interpretation of EROI must however be taken with caution.

- A value of EROI is far from a being a universal constant. The perimeter for EROI calculation and the underlying assumptions can largely vary from one reference to the next one, leading to very different results (see Fig. 16 for an example).
- EROI is intended as a foresight tool, aiming at guiding long term decisions. But it is evaluated as a marginal quantity (how much energy is required to produce 1 more energy unit), making extrapolation tricky.

Energy Pay Back Time (EBPT) [yr] is defined as the time it takes for an installation to produce as much energy as it costed to create in the first place. The energy payback time is directly related to the EROI through the lifetime of the installation:

$$\text{EPBT} = \text{EROI} \times \text{lifetime} \tag{12}$$

Levelized cost of energy/electricity (LCOE) [\$/kWh] (see Fig. 17) accounts for the overall price of energy (and in

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[4] This fraction is actually $1/\text{EROI}$.

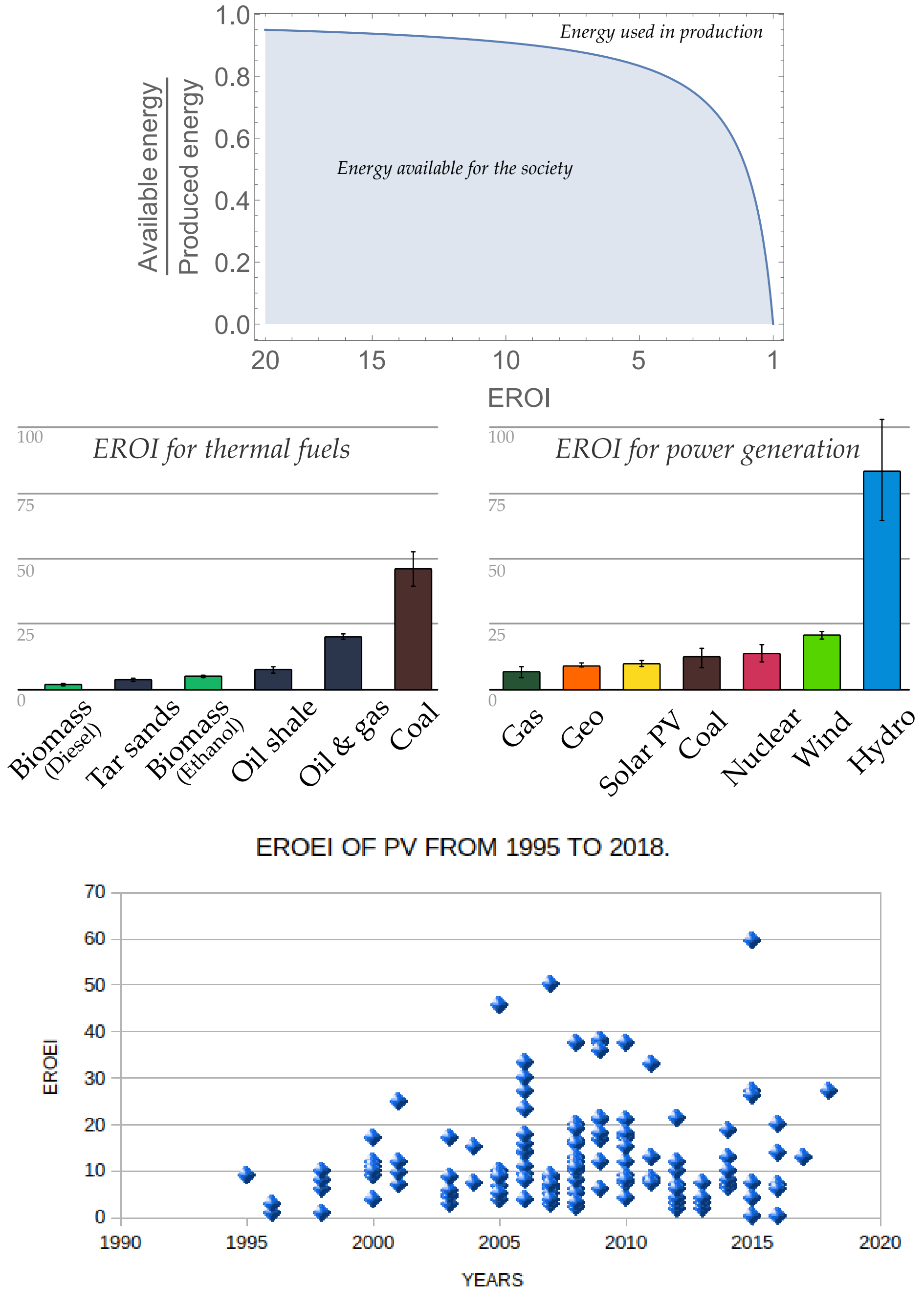

Figure 16: Top: EROI values from [4]. Bottom: Reported value for the EROI of solar PV from 74 publications between 1995 and 2018, sorted by publication date. Internship work by Fatoumata Diallo (2019).

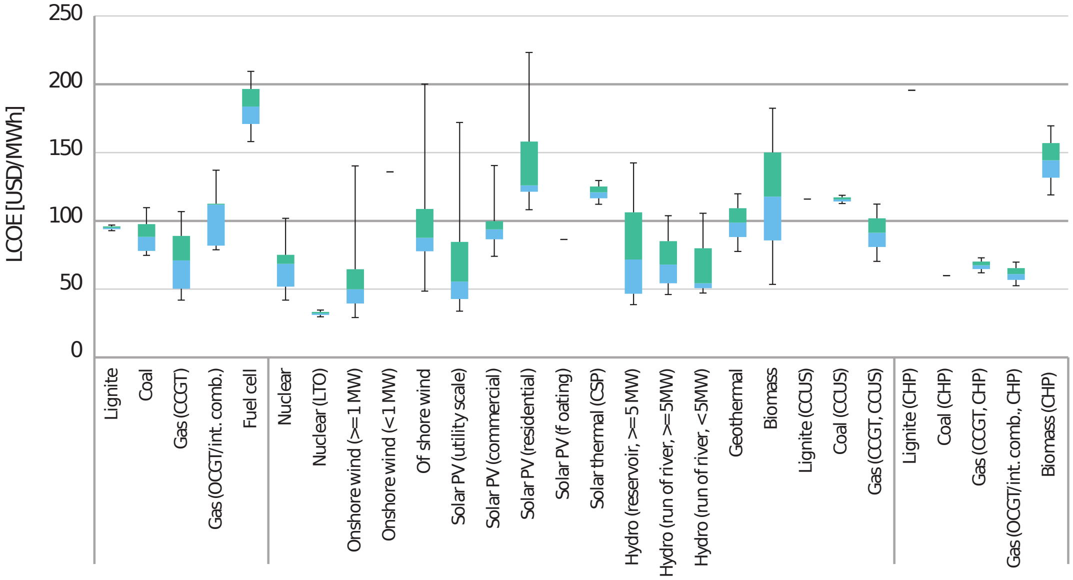

Figure 17: LCOE values from "Projected Costs of Generating Electricity", IEA 2020 [2]

particular electricity) generation.

$$\mathrm{LCOE} = \frac{\sum_{n=0}^{N} \frac{\mathrm{C}_n}{(1+d)^n}}{\sum_{n=0}^{N} \frac{\mathrm{E}_n}{(1+d)^n}} \tag{13}$$

where C_n is the total cost in year n (including investments, fuels, operation and maintenance), E_n is the total energy produced in year n and d is the discount rate.

A key aspect of LCOE is the notion of discount rate [= *taux d'actualisation*], which conveys the idea that spending the same amount of many tomorrow requires less efforts than spending it today. Note that the same discount rate is applied to the energy generation. A justification is given by [13]: "A discounting of power generation initially seems incomprehensible from a physical point of view, but is a consequence of financial mathematical transformations. The underlying idea is that the generated electricity implicitly corresponds to the revenue from the sale of this energy. Thus, the further this income is in the future, the lower the associated present value."

As discussed for EROI, the interpretation of LCOE should be done carefully. The underlying arbitrary assumptions, especially regarding the cost of capital [5], and the goal and scope of the calculation should be clarify before considering using the results.

5 Take home message

- Energy is a complex quantity, whose main property is to be conserved. As a consequence, it is a good quantity to study transformations. Energy analysis highlights necessary (but not always sufficient) conditions for a transformation to happen.
- The notion of energy is important because it offers a framework for addressing very different issues without relying on technical details, because it is a strategic resource for any society, because it is a powerful societal indicator, and because our energy consumption has severe consequences.
- Counting energy can be pretty messy: different units, different stages (primary, secondary, final), different natures (heat, work). In real life, there is not one single rigourous and rational way to count energy. When considering an energy balance, keep in mind that arbitrary choices had to be made.

- Our energy supply today relies heavily on fossil fuels. Several goals (sustainability, equity, security) and means (sobriety, efficiency, substiution, compensation) for an energy transition can be considered, and should be distinguished.
- Many energy-related indicators can be useful, none of them is perfect. Learn when to use which, and how to take their limitations into account. Orders of magnitudes are powerful tools to address new situations.

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