What is energy?

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Energy exists in various forms: mechanical, potential or kinetic energy, electrical, chemical, nuclear and finally heat. Energy is essential for all living beings, and first and foremost for plants, which convert solar energy into oxygen and nutrients for the benefit of animals. Among these, men, with their machines, consume much more energy than others. And this poses many problems, linked in particular to carbon dioxide pollution, the risk of accidents and, finally, the depletion of resources in the more or less long term. Some hope to find the solution to the problem in renewable energies and energy savings. Others believe that the massive use of nuclear energy, fission or fusion, is inevitable.

1. Energy in all its forms

1.1. nothing is lost, everything is transformed

A major principle of Physics is that a certain amount, called **energy**, is constant. Energy takes various forms that we will successively review: **potential** energy, **kinetic** energy, **heat**, etc. Energy passes from one form to another without creation or disappearance: it is the principle of **energy conservation**.

Let's start with the **potential energy** associated with a force (see "The Laws of Dynamics" for an introduction). The potential **gravity** energy of an object at height h above the ground is (with one additive constant) the **work of** the weight P of this object when it falls from height h, either $W_{pot} = Ph$. The weight is proportional to the mass m, or $P = mg$, where g is the **acceleration of gravity** (or gravity). If the object is an elevator, it requires **electrical energy** at least equal to mgh to bring it to a higher floor, which is actually higher because the elevator wastes energy (i.e. it also converts part of the electrical energy into heat). If the object is now an apple perched in its tree at height h0, it may happen that the apple comes off and falls. It then loses height, but acquires a velocity $v(t) = -dh/dt$ which depends on time t, and consequently a kinetic energy $W_{cin} = mv^2(t)/2$. The principle of energy conservation tells us that the total energy $mgh(t)+mv^2(t)/2$ is constant. Its derivative with respect to time is therefore nil, i.e. $mgv(t) = mv(t)\, dv(t)/dt$ and by simplifying: $dv(t)/dt = g$. The constant g is therefore an acceleration.

Figure 1. Representation of Newton, a fraction of a second before his discovery of the law of universal attraction.

In the 17th century, it is said, the Englishman Isaac Newton saw such an apple fall (Figure 1) while meditating on the movement of the planets, which the German Johann Kepler had solved a few years earlier. He then had a brilliant idea: weren't the fall of the apple and the ellipse described by the planets around the Sun two aspects of a universal phenomenon? The calculation confirmed Newton's intuition that two objects of masses m and m' at a distance r attract each other with a force F equal to Gmm'/r^2, where G is a universal constant, the same if the two objects are the Sun and the Earth, or the Earth and the Moon, or an apple and a piece of Earth. This phenomenon is called **gravitation**. To this force F corresponds a potential energy $Wpot = -Gmm'/r$, which is the mechanical work of the force F when the two objects are brought closer together, initially at an infinite distance from each other. In other words, $F = -dWpot/dr$. The gravitational force is attractive. A general rule is that force tends to decrease the potential energy.

Figure 2. The Happy Haphazards of the Escarpolette, by the painter Fragonard. When the swing goes down, the potential energy decreases and the kinetic energy increases. It's the opposite when the swing goes up.

The fall of the apple illustrates the conservation of the total energy $Wtot = Wpot + Wcin$, called **mechanical energy**. Another less ephemeral example is the oscillation of a swing (Figure 2), which allows us to observe alternately the growth of kinetic energy at the expense of potential energy, and then the opposite phenomenon. Similar oscillations can be achieved by attaching a mass (not too heavy) to a coil spring. Let's pull a little on the spring and let go: it contracts, then stretches, then contracts, etc. Here again, the sum of potential and kinetic energies is constant, or at least would be if the spring did not absorb the energy (i.e.

it converts part of the energy into heat). The potential energy *Wpot* here is **elastic** in nature, proportional to the square of the difference δz between the spring length and its equilibrium value: $Wpot = \gamma \delta z^2$.

Thus the energy is expressed by different formulas depending on the case. Often we prefer to express the **power** supplied or absorbed, i.e. the energy per unit of time. Thus, if we connect an appliance (our elevator for example) to a current source with a **voltage** $V = 220$ V, and a current I flows through it, the power expended is $W = VI$. If our elevator takes a time $t = 20$ seconds to climb, the energy that will have to be paid to the electricity supplier will be VIt.

1.2. The heat

But the energy provided by this supplier is not only used to run engines. It allows us to heat ourselves, because we can transform it into **heat**. The heat stored by air is essentially the sum of the kinetic energies of the molecules, *(*$mv^2/2$ ñ for a molecule of velocity v ñ and mass m). Since it is not a question of knowing the speeds of the millions of billions of billions of molecules contained in a room, we prefer to say that the heat stored in a body is a function of its **temperature** and **pressure**, a function that can be calculated at least approximately (read "Pressure, temperature and heat").

This is an opportunity to return to the examples mentioned above, and to ask ourselves why the spring stops oscillating quickly enough, as well as the swing, if we do not maintain its movement. It's that there are **frictions** and they generate heat, even if we don't notice it. The energy is constant, but some of it is **dissipated** as heat.

1.3. Matter, reservoir of electrical and nuclear energy

A century after Newton discovered the law of gravity, the French physicist Charles Coulomb established a similar law for the interaction between two **electrical charges** q and q'. The force is thus proportional to the product qq' and inversely proportional to the square of the distance [1]. However, unlike mass, the charge can be either positive or negative: the force is then attractive if the charges are of opposite signs, but repellent if they are of the same sign.

In an electric battery or other generator, positive sign electric charges are distributed on the positive pole while negative sign electric charges are distributed on the opposite pole. An electron or any other charge q' moving in the electric field thus produced has a potential energy that it can convert into heat (in a resistance) or mechanical energy (in a motor). The **electrical potential** is obtained by dividing this potential energy by the charge q'. This is the equivalent of the gh product for the gravity field. For a potential difference V, the available energy is therefore Vq' and the power expended VI, where the current I is the charge per unit of time travelled the circuit between the two poles.

In addition to its manifestations in electricity, this "**Coulombian**" interaction is responsible for the stability of the material. The nuclei, with a **positive** electrical charge, attract **negative** electrons, which leads them to form atoms that themselves attract each other. In addition, when a chemical reaction occurs, it results in a reorganization of nuclei and electrons and a modification of Coulomb energy. This is called **chemical energy**. A fuel such as coal, gasoline or hydrogen, is a reservoir of chemical energy, but this energy is nothing more than Coulomb energy. The elastic energy of the spring mentioned above is also a consequence of the Coulomb interaction.

An interesting exercise is to compare the gravitational force $Fg = Gmm'/r^2$ and the Coulombic force $F_{el} = qq'/(4\pi\varepsilon 0 r^2)$, between an electron and a proton at a distance of 0.1 nm. The gravitational constant is G = 6.67 x 10-11 N.^{m2}.kg-2. The masses are m = 1.67 x 10-27 kg and m = 0.91 x $^{10-30}$ kg. From this we deduce Fg = 10-47 N. In addition, $1/(4\pi\varepsilon_0) = 9 \times ^{109}$ N. $^{m2/C2}$, the load being expressed in **coulomb** (C). The charge of the proton, opposite to that of the electron, is q =- q' = 1.6 x 10-19 C so that F_{el} = 2.3 x 10-8 N. We see that the gravitational force is totally negligible, in a ratio of 2.3 x ^{1039}!

Within **atomic nuclei,** there are also **nuclear** interactions, which are very short-range and therefore only important within these **nuclei**. They bind **nucleons** together, i.e. **protons** and **neutrons**. We can thus release enormous energy by combining light nuclei (which is what we do in an H-bomb by **nuclear fusion**). Huge energy is also obtained by splitting heavy nuclei such as uranium, which is done in an A-bomb or nuclear reactor by **nuclear fission**. It is then the electrical force of repulsion between protons that takes over and releases the Coulomb energy (see "Radioactivity and nuclear reactions"). In both cases, the potential energy, nuclear or coulombic, is converted into kinetic energy of the nuclei and then into heat.

1.4. Light energy

There is yet another form of energy: that carried by light and more generally by **electromagnetic radiation**. It is subject to the strange laws of **quantum mechanics** and **relativity**. Quantum mechanics requires that light energy can only be absorbed in finite quantities or **photons**, each photon having an energy $h\nu$, where ν is the frequency (related to color) and h is the Planck constant. Relativity makes it possible to understand how photons can have both an energy and a zero mass m. If the kinetic energy is $mv2/2$, and if m =0, the photon should have zero energy even if its velocity c= 300,000 km/s is not zero. The solution to the mystery, found by Einstein, is that the formula $Wcin=mv2/2$ is only an approximation valid for small v speeds compared to that of light. The correct (relativistic) formula leads to an infinite increase in energy when approaching the speed of light, so that a particle with zero mass like the photon has non-zero energy at the speed of light.

Another Einstein discovery is that a mass particle *m* has an energy even at rest (if *v=0*), equal to *W=mc2*. This famous Einstein formula[2] is confirmed by nuclear physics: if two light nuclei combine to form a heavier one with energy emission, the large nucleus is a little lighter than the sum of the masses of the two small nuclei, and the difference is equal to the energy emitted. That's the secret of the H-bomb.

2. Units and orders of magnitude

What are the energy units? In the international system it is the **joule**. It is worth one kg.m2/s2. Another important unit of the international system is the **watt** (symbol W), a unit of power. The power supplied or expended is the energy supplied or expended per unit of time. One watt is therefore equal to one joule/second.

For example, to move a mass elevator *m* = 200 kg up to the third floor at height *h* = 10 m, it is necessary (assuming that the elevator does not waste any energy at all) to have an energy *W* = *mgh*, with g = 9.81 m/s2. That's about 20,000 joules.

The annual global energy consumption is about 0.6 x ^{1021} J, which represents 1/10,000 of the total energy radiated by the Sun on Earth, but nearly 1/5 of the total energy of photosynthesis, the source of all terrestrial life. As for the kinetic energy of rotation of the Earth on itself, it is in the order of ^{1029} J.

For more or less justifiable reasons, physicists, chemists and engineers readily use various units other than the joule. For example, electricity suppliers charge in **kilowatt-hours**, kWh. The conversion is quite simple: 1 hour = 3600 s, so 1 kWh = 3 600 000 watt.second = 3 600 000 joules, and our 20 000 joules mentioned above are therefore (2/360) kWh, or a little more than 0.005 kWh. Economists often use the **tonne of oil equivalent** (toe): it is the heat produced on average by the combustion of one tonne of oil, estimated at 42 x ^{109} joules.

Physicists, on the other hand, readily use the **electron-volt** (eV) and its multiples (KeV, MeV, GeV) or submultiples (milli-eV or meV). The electron-volt is the variation in energy of an electron that passes through a potential difference of one volt. The **volt** (V) is the unit of electrical potential, and therefore corresponds to a joule/coulomb. The charge of an electron being 1.6 x 10-19 C, it results in 1 eV = 1.6 x 10-19 coulomb-volt = 1.6 x 10-19 J.

But some scientists use other units as well, for example:

Calorie, which is often used to measure heat. It is worth 4.18 J.

The **Kelvin**. It is then necessary to multiply by the Boltzmann constant to obtain joules (see "Pressure, temperature and heat").

3. No life without energy

3.1. The contribution of plants

The appearance of life on Earth is a miracle that was only possible thanks to an extraordinary combination of favourable conditions (see "The biosphere, a major geological actor"), in which the Sun's energy played an essential role. This energy is nuclear and results from the fusion of light nuclei, but it comes to us in the form of light radiation. Its role is first and foremost to maintain an appropriate temperature, but this is obviously not enough. An extraordinary effect of sunlight is **photosynthesis**, thanks to which plants produce the oxygen needed by animals. The sequence of chemical reactions is complex but can be summarized globally as follows:

6 CO2 + 6 H2O → C6H12O6 + 6 O2

Thus the plant produces both oxygen O2, and glucose C6H12O6 which is for it an energy reserve. For her... and also for men, hungry for energy. Plants do us a huge service: transforming intermittent solar energy into chemical energy, which can be stored and used whenever and wherever we want.

3.2. The conquest of energy by man

But what to do with this chemical energy? Absorbing it by eating plants is a good solution, within reach of any animal. Only one animal has been able to do better, it is man. And in many ways. First through the domestication of fire, hundreds of thousands of years ago, more recently applied to ceramics manufacturing and metallurgy (the oldest metallurgical remains found date back about 10,000 years).

Figure 3. Don Quixote and the mills, engraving by Gustave Doré

Man has also been able to take advantage of the energy of water - water mills appeared shortly before the Christian era - and wind - the windmills dear to Cervantes (Figure 3) date from the Middle Ages. These industrial machines probably contributed to the decline of slavery in the Christian world before it reappeared in the colonies. They provided immense services until the 19th century, when **thermal machines** became widespread, already the subject of research in the 17th century and whose first prototypes appeared in the 18th century. A thermal machine heats material (e. g. water) and transfers heat from this "hot source" to a "cold source". As we pass, we take some of this heat and transform it into mechanical energy or electricity. Unfortunately, only part of the heat can be transformed, all the more so as the temperature difference between hot and cold sources is greater (link to *thermodynamic* article).

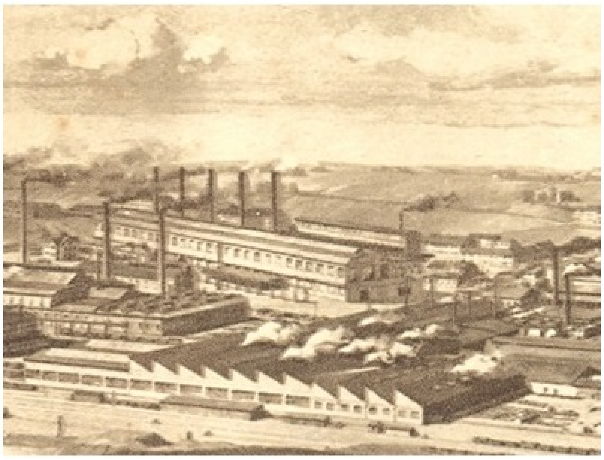

Figure 4. The Henrichshütte factory in the Ruhr in 1880 [Source: Slg. LWL-Industriemuseum) http://www.zeitreise-ruhr.de/chronik/420-politische_wirtschaftliche_entwicklung_1850-1890.html]

It was in the 19th century that industry began to transform certain landscapes and factory chimneys began to pollute in a worrying way (Figure 4). This 19th century was also the century of major research on **electricity**, marked by the discoveries of Ampère, Volta, Faraday, Maxwell. The use of electricity in industry became widespread in the second half of the 20th century. Electricity is less polluting than 19th century coal-fired machines, but how is it produced in the 20th century? Most often, by coal, which only displaces the source of pollution. We also use the potential energy of the water coming down from the mountains (the amount *mgh* by which this article begins). This is called **hydroelectricity**. But this is not enough to feed the appetite of an ever-increasing number of people and an ever-increasing demand for energy.

3.3. The control of nuclear energy

It was also in the second half of the 20th century that **nuclear energy** began to be used, the same energy source that forced Japan to surrender in 1945. The principle of a nuclear reactor and the 1945 bomb is more or less the same (see "Harenessing Nuclear Energy"): heavy nuclei are used (e. g. isotope{ind-text}the isotopes of an element are nuclei with the same number of protons, and therefore of electrons in the neutral state, but different in the number of neutrons. The isotopes of an element have similar chemical properties (these being determined by electrons), but differ in their nuclear properties. {end-tooltip} ^{235}U of uranium) that are bombarded with neutrons. Neutrons cause the uranium nucleus to split into two lighter nuclei, with the emission of a few neutrons (about 3). If the piece of uranium is not too large, the neutrons escape into the atmosphere and nothing happens. If the uranium block exceeds a certain critical mass, the neutrons are likely to cause further fission, there is a chain reaction that releases more and more heat and finally an explosion that, on the one hand, ends the reaction and, on the other hand, causes more or less significant damage. In an atomic bomb, we make sure that this damage is as great as possible. In a nuclear reactor, on the other hand, efforts are made to control the chain reaction, so that the critical mass is reached but never exceeded. It is not easy, and there are sometimes accidents, some of which are serious.

Instead of using the fission of heavy nuclei, we can consider using the fusion of light nuclei. That's what happens in an H-bomb. This is also what the Sun does to illuminate and heat us. We do not yet know how to control the nuclear fusion reaction and make electricity. Indeed, light nuclei are willing to combine if they are very close; they then release an enormous amount of energy; but it is very difficult, on Earth, to bring them close enough. The Sun is much larger than the Earth, and gravity imposes an enormous pressure that, at the centre of the star, exceeds 200 billion times that of the Earth's atmosphere. On Earth, the march towards the industrial use of fusion is slow; the current stage is represented by the ITER reactor, which will be commissioned in the coming years. Thanks to ITER, we hope to demonstrate the "feasibility" of the project.

3.4. Innovative alternatives

However, there is a risk of a shortage of raw materials. Oil and gas reserves, which are very convenient fuels, are likely to run out before the end of the 21st century, at least the easy-to-exploit reserves from groundwater. We are therefore looking for more hidden reserves, those that impregnate certain rocks. The United States is firmly committed to this path. Should France follow their example and exploit its shale gas? The issue is controversial, as it involves inflicting treatments on our basement that can compromise its stability. On the other hand, the extent of the resources is not known.

Biofuels are another temptation: instead of growing plants to eat them or have them eaten by animals, they are grown to make alcohol for fuel. It would obviously be dangerous to go too far in this direction. There is an optimum to be sought: part of the soil must be devoted to cultivation, but plants have other functions, including feeding us, as they have done for millennia. And, of course, to renew our oxygen.

More innovative are **fuel cells** [3]. As a thermal machine can do, they use chemical energy, but they transform it directly into electrical energy without raising the fuel to a high temperature. The process can be more efficient.

The **heat pump** can also be an interesting new feature. It is used for heating. The heat is pumped out and transported to the house to be heated. It is the same function as that of a refrigerator that takes heat from a chamber that you want to cool and transports it outside; the operation of a heat pump is therefore that of a refrigerator. This heat transport requires energy, which we have to pay to our electricity supplier. But you have to pay less for a given result if the energy we buy supplies a heat pump than if it is completely transformed into heat. At least if it's not too cold outside.

Wood heating is also a technique that has improved considerably recently. With the methods used for centuries, most of the energy was wasted. Better efficiencies can currently be achieved, and smoke pollution limited, by optimising the recovery of the heat produced.

3.5. Renewable energies

Figure 5. A mill on the Cher, in Touraine.

Most of the so-called renewable energy sources use the Sun's energy, either directly or through the atmospheric or hydraulic movements it generates. The most common method is the use of river water (**hydroelectric** power) or wind (**wind** power). Solar energy is also directly exploited: we can use solar radiation to heat water, we can use the same heat to operate a thermal machine that will produce electricity, we can finally use **photovoltaic** cells that transform solar energy into electricity. Tides are also exploited and marine swells are being considered.

Most of these techniques have one disadvantage: **intermittency**. There are days without wind, and at night there is no sun. It is therefore necessary to be able to store energy. However, if you produce electricity, this form of energy has everything to please you, except that it is very difficult to store. It must be transformed into mechanical or chemical energy. For example, we can raise the water from the dams during the day and lower it at night. Or water is electrolyzed during the day to produce hydrogen: globally 2 $H_2O \rightarrow 2 H_2+O_2$. And at night, the reverse reaction restores energy, either through a thermal machine or fuel cells.

Figure 6. Wind turbines in Pellafol, Isère department [Source: Diverticimes, www.diverticimes.com].

A simpler solution is to transform solar energy directly into chemical energy, easy to store. This is what nature does very well, through photosynthesis. Unfortunately, the process is a little slow for the busy animals that we are. The problem of energy **storage** has not yet been satisfactorily solved, which is why solar and wind energy can currently only make a small contribution compared to other sources: coal, nuclear energy, oil, and even hydroelectricity.

4. The environment pays the price

The most visible effect of energy production machines was first and foremost the transformation of the landscape. A transformation that is often harmonious. Windmills, like riverside mills, were often very beautiful (Figure 5), and our current wind turbines are not so bad (Figure 6). However, they are accused of scaring away some animals and even being a deadly danger to others, such as bats, thereby endangering biodiversity and consequently the ecological balance.

Since the end of the 19th century, the industry has been responsible for accidents and pollution, lasting or temporary, of the air, water and soil. The production and creation of energy is not always directly responsible, but it is often so. Accidents at nuclear power plants are of particular concern because of the high number of such plants in some countries (United States, Japan, France, etc.). The most serious was that of Chernobyl, in Ukraine, in 1986, responsible for thousands of deaths and massive radioactive pollution, which makes the surroundings uninhabitable even thirty years later. Dam failures are at least as dangerous. The Malpasset dam in southeastern France killed more than 400 people in 1959. This dam was not so much intended to produce energy as to regulate the region's water supply, but the danger obviously threatens all dams, and defies any prevention if the failure is due to a major earthquake.

While such accidents are exceptional, pollution from industry is chronic. The most characteristic is that of coal-fired power plants. The most widespread is that due to motor traffic, particularly in large cities. Among other things, it produces sulphur dioxide (SO2), which causes lichens to disappear. The concentration of this gas in Paris in 2000 was almost twice as high as they can tolerate. In some English and American cities, smog is a combination of fog, dust and gases such as sulphur dioxide. Some anti-pollution measures have been taken, and smog is declining. Sulphur dioxide disappears fairly quickly after forming sulphuric acid that combines with the first organic or inorganic body it encounters. The same is not true for carbon dioxide (CO_2). This gas is produced in very large quantities in thermal power plants by burning coal or oil and by transport (gasoline combustion). It is decomposed by plants, and they do so with considerable efficiency during their lifetime; but after their death they reconstitute, by fermentation, most of the carbon dioxide they had decomposed. CO_2 is also partially absorbed by the seas, but this only limits the increase in atmospheric concentration (Figure 7). This results in effects on the climate and in particular a warming (greenhouse effect).

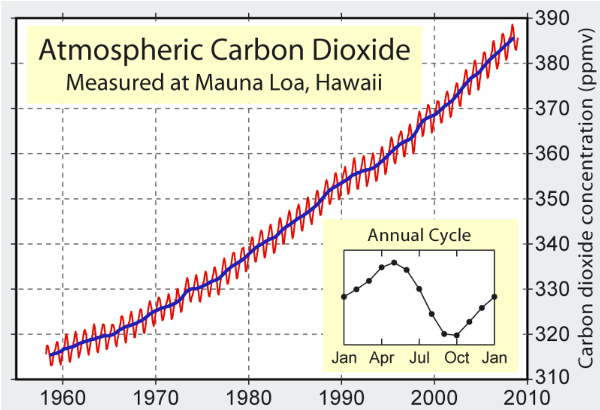

Figure 7. Evolution over 57 years of the concentration of CO_2 in the air at the Mauna Loa observatory. The insert figure details the seasonal drop in CO_2 during the growing season (April to October) and its elevation in autumn/winter in the northern hemisphere (terrestrial vegetation is more important in the northern hemisphere). [Source: Delorme. Personal work. Data from Dr. Pieter Tans, NOAA/ESRL and Dr. Ralph Keeling, Scripps Institution of Oceanography]

And then the accumulation of carbon dioxide in the oceans could eventually disrupt marine life. This pollution is in addition to many others, which are not directly related to energy.

Nuclear power plants are currently low polluting. However, they accumulate radioactive waste that is beginning to cause problems (see "Harnessing Nuclear Energy"). On the other hand, nuclear power plants are often located on the banks of rivers, which serve as a cold source for the thermal machine, and are thus subject to local warming.

5. How to reduce pollution

It is obviously desirable to develop renewable energies: mainly solar and wind energy. Tidal and wave energies also deserve to be developed, but their possibilities are more limited. As for dams on rivers, they are not far from reaching their limits. The main obstacle to the development of solar and wind energy is related to their intermittent nature, as the problem of energy storage does not currently have a satisfactory solution. However, some countries such as Denmark and Germany have already undertaken an "energy transition" to increase the share of renewable energy. The development of this company deserves to be monitored with interest (Figure 8).

In addition, energy savings are possible. First, the efficiency of the installations can be improved.

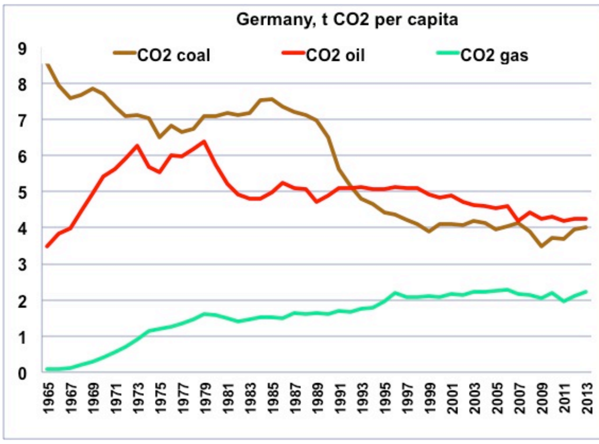

Figure 8. Fossil CO_2 emissions per person in Germany from 1965 to 2013. Reunification was followed by a significant reduction in pollution. [Source: Jean-Marc Jancovici - http://www.manicore.com/documentation/transition_germany.html]

The pollution they impose can also be reduced. Thus, after the reunification of Germany, the old coal-fired power plants of the German Democratic Republic were replaced by modern plants that polluted significantly less. We have also seen that the efficiency of our ancestors' wood heating can be considerably improved. The use of innovative devices, such as heat pumps and fuel cells, is also a way to save energy. Other paths require a transformation of our way of life. We have become accustomed to staying very far from work, which is a waste of time and energy. We have become accustomed to going to bed well after the Sun and rising after it. Changing this habit will be difficult, but it may be necessary to come to it. Already, in our cities, residents have massively resumed using public transit instead of their cars, reducing smog.

Finally, the need for economic growth can be questioned. Our economists and politicians are currently unable to design an economy without growth in activity and energy consumption. This is an effect of technological progress, which makes it possible to increase yields and automate more and more activities. This reduces the burden on workers, but in the absence of growth, unemployment increases. And the growth in energy consumption has the deleterious effects mentioned above, in terms of pollution, impact on the climate and the environment. Moreover, can growth continue indefinitely in a finite world where resources are limited and starting to run out? Some economists are aware of the problem and are thinking about it.

6. What does the future hold for us?

Where are the resources now?

Oil and gas? It won't be long now: a few decades, counting only the easily exploitable groundwater. A day will come when our cars will only be able to be electric, or use an artificial fuel (hydrogen, perhaps).

Coal? There are several centuries of it, even counting only proven resources, but its exploitation is highly polluting, hardly conceivable unless a way is found to "sequester" the carbon dioxide emitted.

Uranium? There are for two or three centuries, or a few millennia with breeder reactors. But the storage of waste, the dismantling of old power plants and security requirements will make energy more expensive.

How to do this? Nuclear fusion can be a solution. But probably not until the end of the twenty-first century. Renewable energies can be part of the solution. Energy sobriety, another one. In any case, the energy transition is necessary and will significantly change our way of life.

References and notes

Cover photo: Wind turbines and high voltage lines near Rye, England[source: DAVID ILIFF. CC BY-SA 3.0 license].

[1] The force between two distant charges of r is expressed as $|qq'|/(4\pi\varepsilon_0 r^2)$ (in vacuum) and the corresponding Coulomb

potential energy is $W_{el}=qq'/(4\pi\varepsilon_0\, r)$. The universal constant ε_0 is called dielectric permeability of vacuum (the factor 4π in the denominator was arbitrarily introduced into this formula by 20th century physicists in order to make it disappear in other formulas).

[2] According to relativity, the energy of a particle of mass *m* and velocity *v* is *W(v)*=mc2 /(1-v2/c2)$^{1/2}$. The kinetic energy is therefore *Wcin=W(v)*-mc2=mc2/(1-v2/c2)$^{1/2\text{-mc2}}$. If *v/c* is much lower than 1, it is reduced to *Wcin=mv2/2.*

[3] Chatenet M. and Maillard F. "Les cellules à combustible".

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