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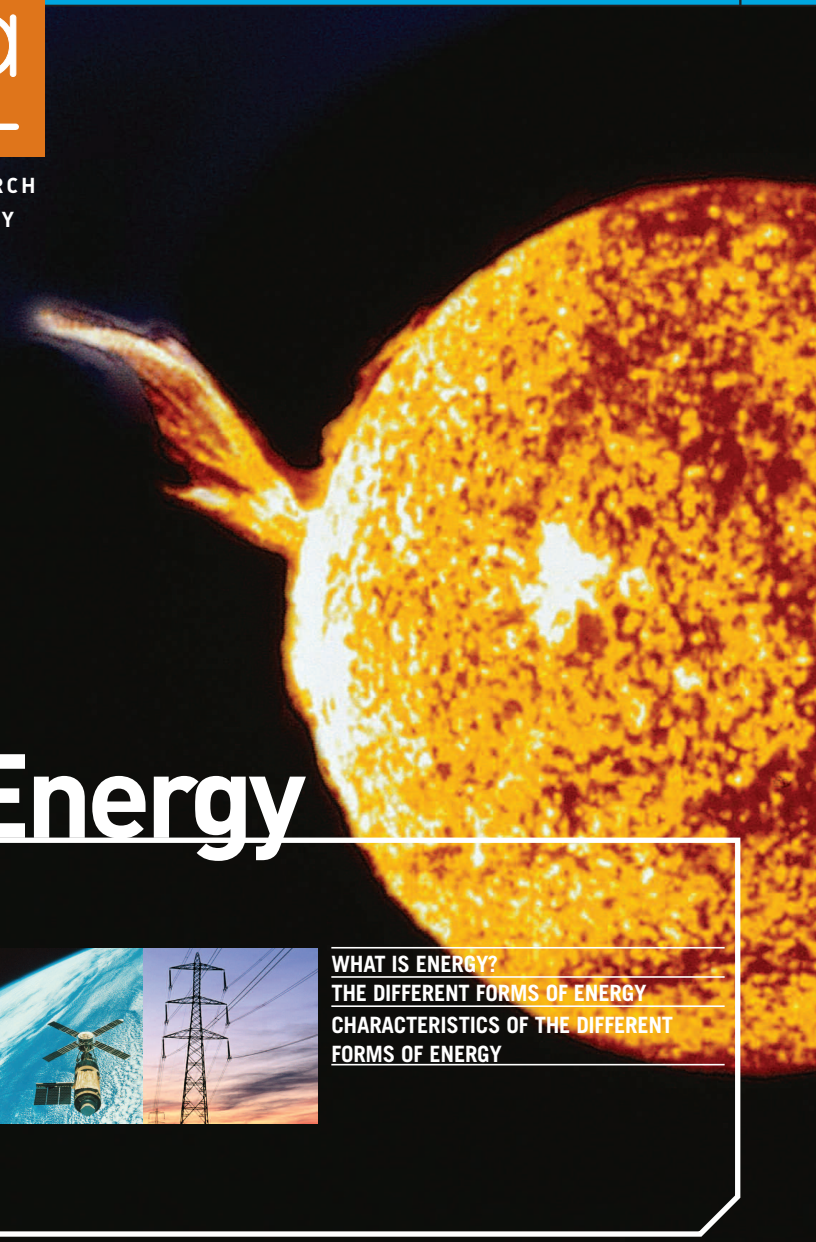
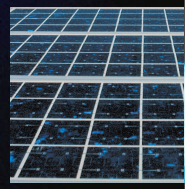
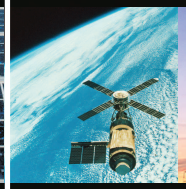
FROM RESEARCH TO INDUSTRY

→ From natural sources to production challenges



4 → Energy





WHAT IS ENERGY?
THE DIFFERENT FORMS OF ENERGY
CHARACTERISTICS OF THE DIFFERENT FORMS OF ENERGY

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Communication Division
Bâtiment Siège - 91191 Gif-sur-Yvette cedex
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The wind is one of many sources of energy.

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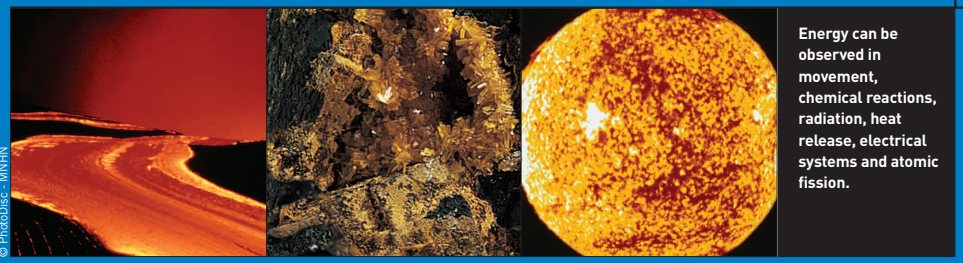

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Energy can be observed in movement, chemical reactions, radiation, heat release, electrical systems and atomic fission.

"Energy is essential for mankind. It represents a major political, economic, scientific and environmental challenge."

introduction

Human beings have always needed energy to feed themselves and move about. Energy can be found in various forms. Today's technologies are capable of tapping all possible resources (e.g. fossil fuels, water, wind, sun) to produce large quantities of energy. Now, at the start of the 21st century, energy remains a major political, economic, scientific and environmental challenge. Of the many properties found in material objects, energy is not only one of the most important but also one of the most abstract, since it is not actually tangible.

An abstract concept, energy comes from the Greek word "energia", meaning "strength in action".

What is energy?

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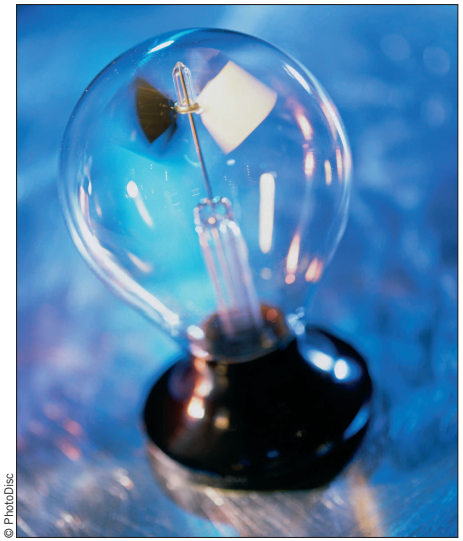
DIFFERENT LEVELS OF ENERGY

The existence of energy can appear under different guises, depending on the situation. The faster a car is traveling, the more energy it has; but it carries less energy than a truck traveling at the same speed. When a spring is compressed, it has more energy than when it is released. A battery has more energy before it is used than when it has been discharged. The energy in a saucepan of water increases when it is heated.

Thus energy appears in very different forms. For each of them, comparisons show how the amount of energy in a physical system depends on the state of that system. In the above examples, this state is characterized by the speed and mass of the vehicle, the shape of the spring, or the charge of the battery. As we will see, different types of energy can, at least in part, take many other forms. These energy transformations are used in everyday life, but they all generate losses.



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In a bulb, electrical energy is converted into light and thermal energy.

ENERGY CAN CHANGE

Energy can be transmitted from one system to another: it is transferred as heat from a radiator to the air in a room. It can also change to take on a different form. In a mechanical toy, the spring unwinds causing movement. The energy associated with the movement of your bicycle is converted into heat in the brake blocks and wheel rims when you brake. The energy stored in a flashlight battery is transformed into electrical energy when you close the circuit. This in turn is converted into light and thermal energy in the bulb. In a thermal power station, the energy stored in the fuel (chemical energy in coal and oil or nuclear energy in uranium) is transformed (by combustion or nuclear reaction) into heat; part of this heat is then recovered in turbines as mechanical energy; finally, this mechanical energy is converted into electrical energy in the alternators. We perceive energy through these transformations and transfers.

"Energy can never be destroyed: none of it can be lost and none created. This is the primary principle of thermodynamics."

ENERGY CAN NEVER BE DESTROYED

The most remarkable characteristic of energy is that it can never be destroyed. When it is transferred from one system to another, or when it changes nature, no energy is created or destroyed. If an object loses energy, the same amount of energy must have been gained by another object linked to the first. Similarly, when energy changes form, the amount remains exactly the same.

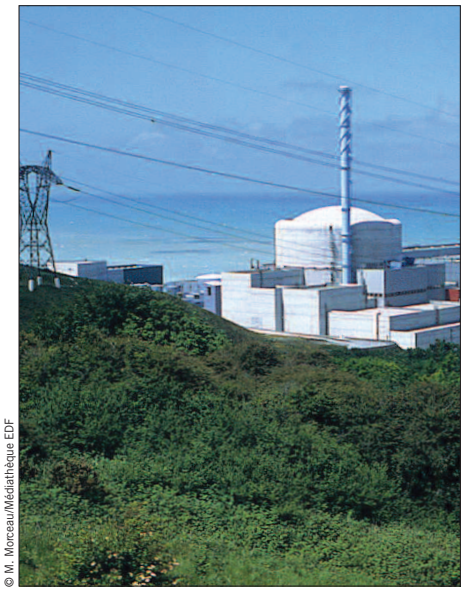
Therefore, terms such as "energy production" or "energy loss" used by journalists, economists and politicians are in fact inaccurate, because energy can be neither created nor lost. In a thermal power station, energy is not "produced"; rather, chemical or nuclear energy is transformed into electrical or thermal energy. The overall amount of this conversion is described as the efficiency. The efficiency of a power station is 33%, which means that for every 33 units of electrical energy sent over the electricity grid, 100 units of nuclear energy were consumed and 67 units of heat produced.

This heat, which is released into the environment, for example as steam from cooling towers, is generally lost. However, some power stations recover some of it to heat homes or greenhouses.

We will see later that, although energy can never be destroyed, its different forms are not actually equivalent, because not all the transformations we can imagine are possible.

ENERGY CAN BE MEASURED

As energy cannot be destroyed, its different forms can be measured using a single unit. The kinetic energy associated with the movement of an object of mass m and velocity v is equal to $E = 1/2\ mv^2$. When this mass is expressed in kilograms and the velocity in meters per second, this formula gives energy in joules (J), a legal unit in the International System of Units (SI).



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When a power station – here the EDF power station at Penly (Seine-Maritime) – "produces" electricity, it is really transforming nuclear energy into electrical energy.

Before heat was recognized as a form of energy, the study of thermal exchanges had led to the introduction of a unit of heat, the calorie, defined as the quantity of heat needed to raise the temperature of one gram of water by one degree Celsius. Experience has shown that transforming mechanical energy into heat, and the reverse, always gives the same ratio, i.e. 1 calorie to 4.18 joules. These two forms of energy (mechanical energy and heat) are therefore equivalent. For this reason, the calorie was abandoned and heat and all other forms of energy are now measured in joules.

POWER

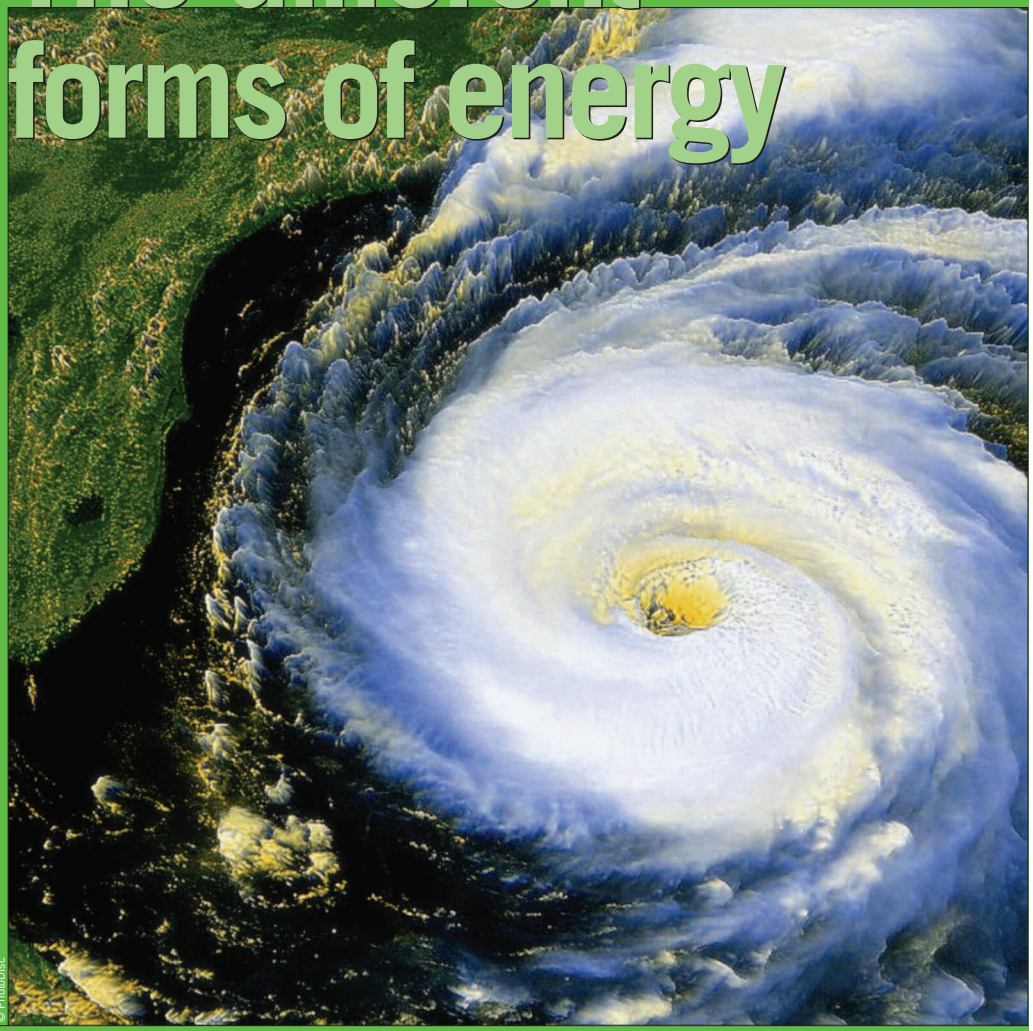
Energy exchange is characterized not only by the amount of energy transferred or transformed, but also by the duration of the process. The concept of power is thus defined as the amount of energy exchanged per unit time. The unit of power, the watt, is therefore the joule per second. Therefore, in one hour (3,600 seconds), 3,600 x 1,500 J = 5,400,000 J of electrical energy is transformed into thermal energy. This example shows that the joule is really too small a unit of energy for everyday use. In practice we often use the kilowatt-hour (kWh), the amount of energy used by a device rated at 1,000 W in one hour. One kWh is thus equivalent to 3,600 x 1,000 J = 3,600,000 J. In one hour, the electric heater used in the example above, consumes 1.5 kWh and obviously radiates 1.5 kWh of thermal energy in the same period.

"An American consumes on average about twice the amount of electricity a French person consumes, who in turn consumes fourteen times more electricity than an African."

The average annual consumption of electricity per capita in France is more than 7,000 kWh, in the US it is twice that at 14,000 kWh and in Africa it barely exceeds 500 kWh. Nuclear power plants account for three quarters of the electricity produced in France; the remaining quarter is split between hydroelectric and thermal (coal and oil). But this electricity represents less than half our total energy consumption. The rest comes from the direct use of oil (gasoline and fuel oil), gas and coal. One third of our consumption is used for heating, and one quarter for transport.

Energy can be observed in movement, chemical reactions, radiation, heat release, electrical systems and atomic fission.

The different forms of energy



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KINETIC ENERGY

Kinetic energy is the energy associated with the movement of an object. We know that energy is proportional to the mass m and the square of the velocity v of an object (provided that the velocity is well below the speed of light, i.e. 300,000 km/s).

GRAVITATIONAL ENERGY

Two massive bodies attract each other. This phenomenon, known as gravitational force, is weak for small objects but becomes very strong for stars and planets. The Sun and the Earth, and the Earth and Moon, attract each other; gravity is the gravitational force exerted by the Earth on objects in its vicinity. Gravitational energy corresponds to this force and is greater when bodies are farther away from each other than when they are close together. Gravitational energy is called potential energy because it is only perceptible when converted into another form of energy. The potential energy of an elevator car is greater on the sixth floor than on the ground floor because on the sixth floor it is farther away from the center of the Earth, which attracts it. If you cut the cable and released the safety brakes, the car would fall, accelerating all the time, and its potential energy would change into more visible kinetic energy. Similarly the energy of a 1 kg mass of water on the surface of a lake behind a dam is greater than its energy when it is at the foot of the dam. For a difference in altitude of 100 m, its difference in potential energy is 981 J. It is this energy that is exploited in a hydroelectric power station, where the falling water turns the turbines that drive the alternators.

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Dams offer the advantage of being both sources and reservoirs of energy.

ELASTIC ENERGY

This is another type of potential energy, in this case associated with the deformation of elastic objects, e.g. the tension in a spring or the compression of a gas.

WORK

This term refers to the transfer of energy that occurs when a force is applied to an object and the point of application of the force moves. When a weight is lifted or when water is raised from the bottom of a dam to the top, work is done, enabling the object in question to acquire

"Energy can change form. For example, oil combustion converts it into heat."

greater potential energy. The work done on a pump compressing a gas increases the elastic energy of that gas and heats it.
The forms of energy described so far are mechanical energies.

THERMAL ENERGY

On an atomic scale, heat appears as the disordered, fairly rapid movement of molecules. As we perceive it, it is the form of energy involved in temperature variations or when materials change state (e. g. when ice melts or water evaporates). It can be transferred between two objects without changing into another form of energy (thermal conduction). It can also be converted into mechanical energy, in a turbine, a steam engine or a jet engine, although this conversion can only be partial, as shown later.

ELECTRICAL ENERGY

Charged particles exert electrical forces on each other. Just as gravitational potential energy is associated with gravitational forces or gravity, electrical potential energy is associated with the electrical forces between charges. When these move around a circuit, fairly rapid transfers of energy take place, measured by electric power. Electrical energy can be transformed into heat in a resistor (e.g. a heater), or into work in a motor.

RADIATION ENERGY

Radiation carries energy, even across a vacuum. The Sun transmits about 1 kW per square meter of power as visible light and infrared radiation.

A radiator conveys its heat to us not only through the surrounding air, but also directly as infrared radiation. In the filament of an electric bulb, the electrical energy is transformed into heat, and this heat is given off principally as radiation energy, both visible light and infrared. A microwave oven transfers heat to food starting with electrical energy, which is converted into "microwave" radiation, similar to that of a radar. Conversely part of the light energy from the Sun can be converted into electrical energy using photovoltaic cells. Radio waves also carry energy, at a weak level but with sufficient strength to carry sound, images or information.

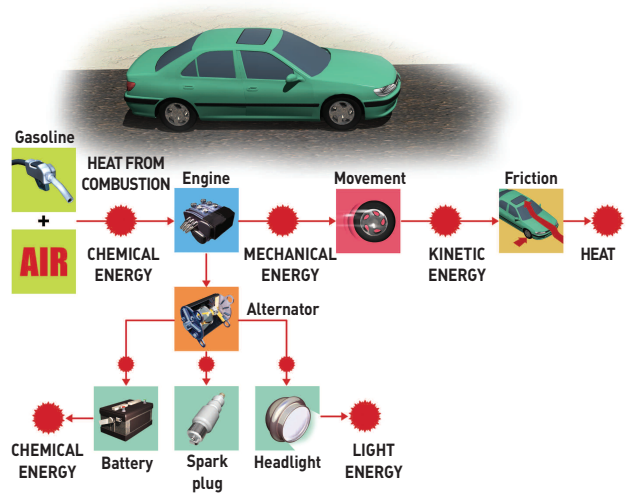
CHEMICAL ENERGY

Chemical energy is associated with the bonds of atoms inside molecules. It is greater when these atoms are separated than when they are bound as molecules, and the greater the binding energy, the greater the difference in mass. Chemical reactions change the chemical energy of bodies and therefore often transform this energy into other forms of energy, usually heat. A gas fire produces a certain amount of thermal energy, equal to the difference between the chemical energy of the gas and oxygen consumed, and that of the combustion products (steam and carbon dioxide). In a coal- or oil-fired power station, only a fraction of the heat from combustion is converted into electrical energy. In an accumulator or electric battery, part of the chemical energy released by the reaction is directly recovered as electricity.

Here, by way of example, are the energy transformations produced in a car:

- **The chemical energy of gasoline and air is transformed into heat by combustion. This is transmitted, by the production of hot gases, first to the cylinders and then to the pistons. At this stage, it is transformed into mechanical energy and starts to move the car, which acquires a certain amount of kinetic energy.**
- **The friction of the air against the bodywork and the wheels against the ground transforms all this energy into heat (on a flat road at a constant speed).**
- **Some of the energy from the engine is converted into electrical energy, which drives an alternator. The current produced is used to make the spark plugs spark to light the fuel, and to recharge the battery, thereby increasing its chemical energy. It is also used to light the headlights to emit light energy. Thus, at a given speed, we consume slightly more gasoline by night than by day.**

Transformation of energy



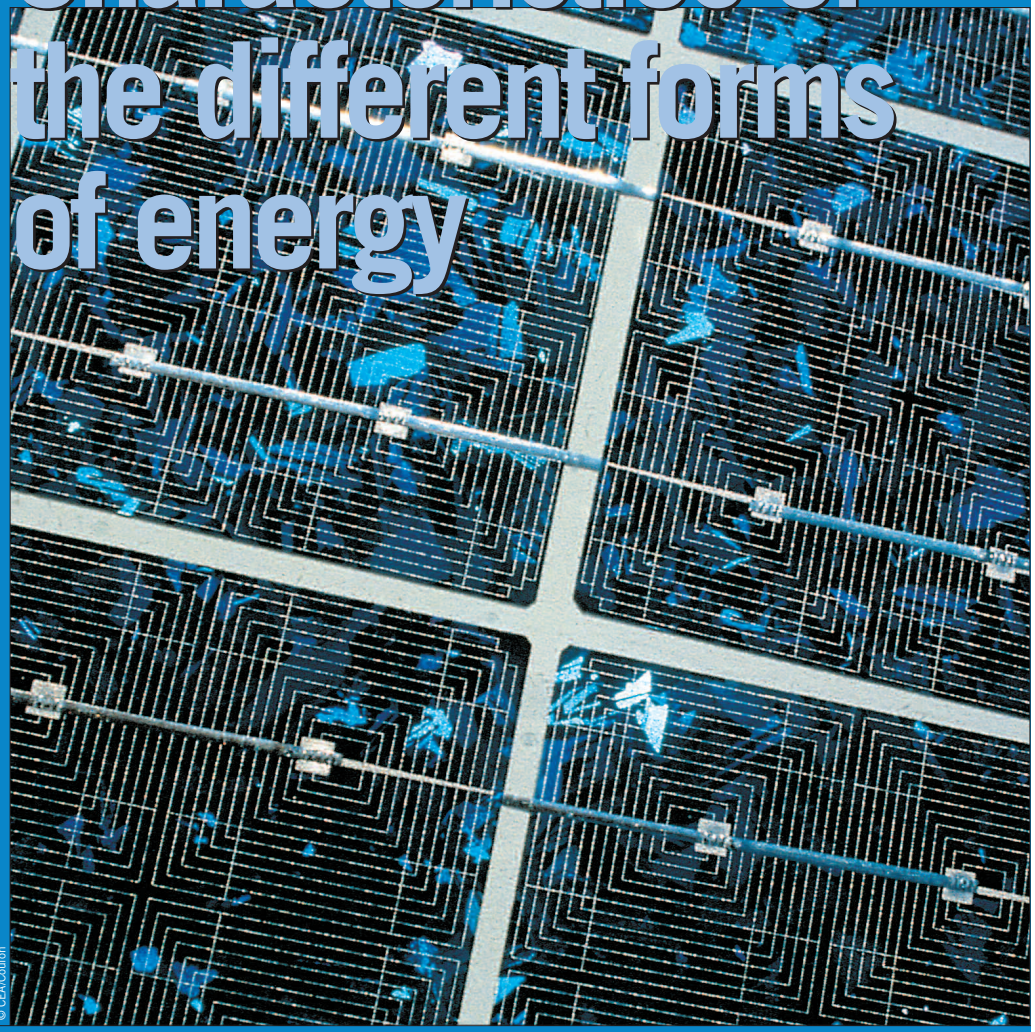
Although they seem different, thermal, electrical, radiation and chemical energy actually all have the same source: on a microscopic scale, they are all connected to the electrical forces between charged particles.

NUCLEAR ENERGY

Nuclear energy is located in atomic nuclei. These nuclei, which are 100,000 times smaller than the atoms, are made up of more, very tightly bound, fundamental particles, called protons and neutrons. Just as the bonds between atoms to form molecules are a source of chemical energy, those created by nuclear forces between protons and neutrons to form nuclei provide nuclear energy. As they transform the structure of atomic nuclei, nuclear reactions release heat. This is the mechanism at work within the Sun's core, which produces the heat radiated by the Sun through the fusion of hydrogen nuclei into helium nuclei. In our nuclear power plants, another nuclear reaction is used, namely the fission of uranium nuclei, which splits each nucleus into two different nuclei approximately twice as small. Some of the heat produced (33%, as seen on page 6) is converted into electricity.

POWER, "LOSS" AS HEAT, CAPACITY FOR RENEWAL... THESE ARE THE CHARACTERISTICS THAT DETERMINE HOW WE USE DIFFERENT ENERGIES.

Characteristics of the different forms of energy



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Although energy is a single physical variable, its various forms have very different characteristics. In practice, the choice of energy used depends on the intended purpose. For a particular purpose, for example electrical energy production, it is essential to weigh up the pros and cons of each potential solution; there are many selection criteria.

DILUTED AND CONCENTRATED ENERGY

Just as a $50 bill is worth the same as fifty $1 bills, some forms of energy are concentrated in a much smaller volume than others. In this respect, there are three categories corresponding to the three types of force seen earlier.

Gravitational energy

The amount of gravitational energy available is only significant if huge masses are involved. It was demonstrated earlier that 1 kg of water falling from a height of 100 m only represents 981 J of energy (see page 9) and 1 kWh is equivalent to 3,600,000 J (see page 7). To release only 1 kWh, 3,600,000 J/981 J/kg, or 3.67 metric tons of water, must be dropped 100 m. Hydroelectric power stations are therefore not very efficient in this respect. The mechanical energies at work in our everyday life are also on a very small scale. The kinetic energy of a car weighing 1 metric ton traveling at 100 km/h is only 0.1 kWh.

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The middle category, between the diluted and concentrated energies, includes thermal, electrical, radiation and chemical energy. Example: oil or gas combustion.

Thermal, electrical, radiation and chemical energy

The middle category features thermal, electrical, radiation and chemical energy, which for everyday use can be measured in kWh per kg of matter. It takes 0.1 kWh to melt 1 kg of ice, or 0.7 kWh to evaporate 1 kg of water at 100°C. Domestic appliances consume between 0.1 and 5 kW of electrical power. The combustion of 1 kg of oil or gas provides

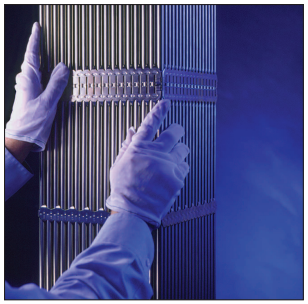
approximately 12 kWh. We human beings make biochemical energy from the food we eat and the air we breathe. We use this energy to maintain our body temperature at 37°C and engage in activity; the corresponding power we use is 100 W at rest and 500 W during physical activity.
The difference between these first two categories can be illustrated as follows: if the mechanical energy of an egg dropped from the top of the Eiffel tower were entirely transformed into heat and used to heat the egg, its temperature would only increase by 0.7°C.

Nuclear energy

Nuclear energy is a far more concentrated form of energy. One kilogram of natural uranium provides 100,000 kWh of heat in today's nuclear power plants, while burning 1 kg of coal supplies only 8 kWh. That is why we handle only fairly small masses of nuclear fuel in electricity production. A nuclear power plant with a power rating of 1,000 MW (10^9 W) uses 27 metric tons of enriched uranium per year, a quarter of its loading, while a thermal power station with the same power rating burns 1,500,000 metric tons of oil per year. In fact, we can only extract by industrial means a very small proportion of the nuclear energy stored in matter. Nuclear reactions in the Sun transform hydrogen into helium. In this way, 1 kg of hydrogen generates 180 million kWh.

Most French nuclear power plants are equipped with pressurized water reactors (PWRs).

Fuel assembly.



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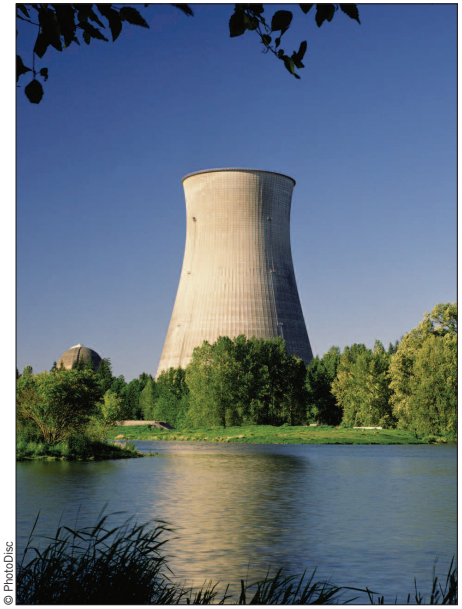
Nuclear energy is one of the most concentrated forms of energy.



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CALCULATING TOTAL ENERGY

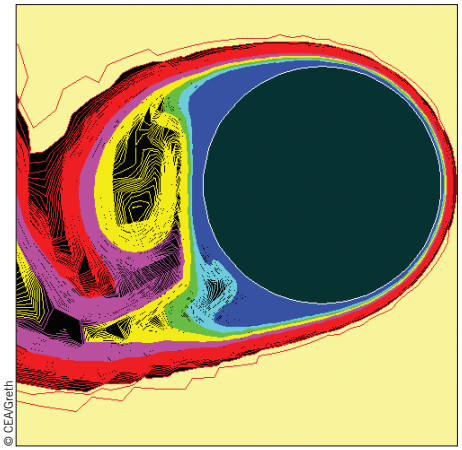
In the Sun, 1 kg of hydrogen produces 180 million kWh. These high energy levels are upheld by Einstein's famous equation $E = mc^2$, which states that the total energy of a body is proportional to its mass, a new equivalence; but the conversion factor is enormous because the speed of light, c, is 300,000 km/s. This means that a mass of only 1 mg is equivalent to 25,000 kWh. In a nuclear power plant, the transformation of 1 kg of natural uranium into other elements reduces the nuclear energy of the fuel by 100,000 kWh, and therefore its mass by 4 mg.

DEGRADATION

Experiments have shown that a physical system naturally tends to become spontaneously more and more disordered. Among the different forms of energy, heat corresponds to the chaotic movement of molecules. The other forms of energy, sometimes described as the "noble" or "available" forms, are ordered at the microscopic level and thus tend to change into heat. This phenomenon is known as dissipation, and we say that heat is a degraded form of energy.
It is easy to produce heat from an equivalent amount of a noble energy, for example in electric or combustion boilers and ovens, or in solar collectors for water heaters. However, the reverse transformations are impossible. A given amount of heat cannot be totally converted into mechanical, electrical or chemical energy using a closed-cycle apparatus, returning periodically to its initial state. This impossibility is one of the fundamental laws of physics, confirmed by countless experiments: nature allows us to convert only a fraction of the heat available into another form of energy, and this fraction can never exceed a certain maximum value. This limits the efficiency of steam turbines in power stations, car and airplane engines, and all other machines generating mechanical energy from the thermal energy of a hot gas.
Heat often appears as a "loss", when other forms of energy are handled (except of course, for domestic or industrial heating). In order to exploit nuclear energy or chemical energy in a power station or a car, we use a nuclear or chemical reaction to generate heat, only some of which can then be converted back into electrical or mechanical energy. The best situation is the direct conversion of mechanical energy into electrical energy, and vice versa. But even in these cases, it is difficult in practice to prevent part of these noble energies from turning into heat. If the shaft of an electric motor is driving the shaft of an alternator, the motor is converting electrical

"Nature only lets us convert a fraction of heat into other forms of energy."

Study of thermal exchanges by simulation.



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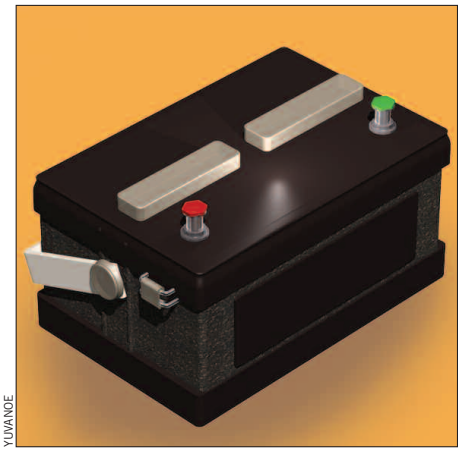
The battery: a method of storing electrical energy as chemical energy.



YUVANOE

energy into mechanical energy, and the alternator is converting this back into electrical energy. But overall, less energy is recovered than was initially supplied; the difference is accounted for by a release of heat through the joule heating in the coils, or through friction in the bearings, and this is impossible to eliminate totally.

The equivalence between energies can be compared to the equivalence between convertible currencies, with 1 dollar worth 0.98 euro for example. Dissipation as heat plays the same role as bank commission charges, which prevent us from recovering the amount we started with if we change dollars into euros and back. The same overall value or energy still exists, but not in our pockets.

STORAGE

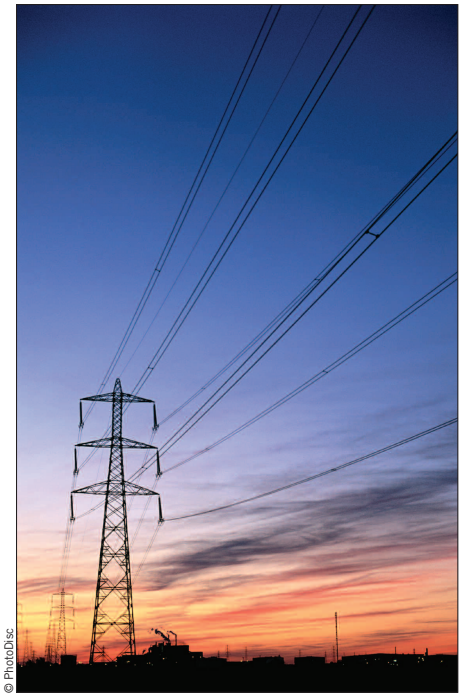
It is difficult to store energy in any sizeable quantity except in certain forms. Storing and recovering it involve conversions, and therefore dissipation. Electrical energy can be stored in accumulators as chemical energy. But discharging an accumulator provides less electrical energy than it was charged with, because the electrochemical reactions that occur involve quite significant heat degradation. Moreover, accumulators are costly and heavy because they can only store 0.1 kWh per kg, which, along with price, has been the principal obstruction to the development of an electric car.

Our electrical power consumption varies throughout the day, rising sharply, for example, in the evening. It is hard for nuclear power plants to keep up with these variations. Because of low energy loss in electromechanical exchanges, dams are used not only as sources of hydroelectric energy, but also as reservoirs of energy. At off-peak times, water is pumped up from the bottom of the dam using electricity from nuclear power plants, and at peak times this water is let down again, operating the power station's turbines and generating electricity. Because this form of storage uses mechanical energy at one stage, it requires the movement of very large masses of water – several metric tons per kWh stored.

Chemical and nuclear fuels store energy efficiently, but we can only recover such energy as heat.

TRANSPORTING ENERGY

The relative ease of storage and also of transportation over long distances of coal, oil and gas has been one of the key factors of industrial development over the last two centuries. The increasing use of the car is also due to its ability to carry enough fuel to travel several hundred kilometers. However, electricity is the only form of energy that can be converted almost entirely into any of the others and transported over long distances in large quantities at relatively low cost. Nevertheless, energy losses due to heat from high voltage lines and transformers reach 8%.



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Electricity can be converted almost entirely into any other type of energy, and can be transported at a relatively low cost.

RESERVES

Energy sources can be divided into fossil energies and renewable energies. The first rely on the use of minerals and fuels formed throughout the Earth's history and only exist in limited quantities. Considering rising consumption and

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Wind turbines exploit a renewable source of energy but only produce a small amount of power.

the possible discovery of new deposits, estimated global reserves stand at a few decades for oil, about a hundred years for gas and uranium, and a few centuries for coal. The development of technologies such as breeder reactors, however, would multiply our nuclear energy reserves more than a hundredfold.

Renewable energies

Renewable energies reach us directly or indirectly from the Sun through the constant radiation it emits. They include solar, water and wind energy, and also the chemical energy built up in plant life, which can be used for fuel (timber, waste, alcohol). However, the total amount of power drawn from these renewable energies is limited. Forests should not be burnt more quickly than they can grow. Although renewable energies constitute a useful top-up, they can only replace a small proportion of fossil energies.

HAZARDS

Handling all types of energy has, to some degree, harmful effects on our environment, and these must be individually assessed.

Certain combustion residues of coal, oil, gasoline or even gas if it does not burn properly, are harmful to human health. Carbon dioxide is the gas emitted in the greatest quantity. It builds up in the atmosphere and is in danger of affecting our climate by increasing the greenhouse effect. Nuclear reactions generate radioactive waste, which must be processed or reduced, especially long-lived waste. Hydroelectric power stations have a negative impact on valleys. Wind turbines are noisy and do not guarantee continuous production. They also take up a great deal of space for the rather small amount of power they provide. Photovoltaic cells have the same drawback and are very expensive. The conversion of solar energy into electricity is therefore only suitable for supplying very isolated dwellings, or for operating small portable devices such as pocket calculators. Furthermore, a lot of energy is required to manufacture photovoltaic cells.

Thermal pollution

Thermal pollution is the consequence of energy degradation and all non-renewable energy sources. Most fossil energies used are eventually converted into heat. An earlier example demonstrated how a car operates by converting chemical energy supplied as gasoline into heat released into the environment. Even though this thermal pollution is too slight to influence the climate, it can have local effects: a thermal or nuclear power plant cooled by water from a river increases the downstream temperature of this water significantly, and can thus modify its ecological balance. Significant savings can be made by recovering this lost heat. Half the energy we consume is intended for domestic or industrial heating, making use of coal, gas, fuel oil or electricity. This could be reduced through more efficient use of the heat from power stations. Average per capita energy consumption reflects not only standards of living, but also the amount of energy wasted. This example illustrates a key point: the many sources of energy reflect the diversity of uses, and a global approach to energy problems is essential.

“Renewable energies are those that reach us directly or indirectly from the Sun, the wind, etc.”