The energies of today and tomorrow

If the world wants long-lasting development for all of its inhabitants, it must reduce its reliance on fossil energies in favour of energies that are less polluting and consume fewer resources. Only renewable and nuclear energies provide sufficient prospects in this area.

coal	496 billion oil equivalent tonnes
lignite	110 billion oil equivalent tonnes
oil	137 billion oil equivalent tonnes
gas	108 billion oil equivalent tonnes
oil shale + tar sand	hundreds of billion oil equivalent tonnes
methane hydrates	more than 1 000 billion oil equivalent tonnes
uranium (in water reactors)	80 billion oil equivalent tonnes
uranium (in breeder reactors)	8 400 billion oil equivalent tonnes

Table 1: Order of magnitude of energy reserves in billions of tons of oil equivalent (Gtep). (Source: WEC 1993: latest data considered as reliable on a global scale).

	low hypothesis	high hypothesis(1)
coal	860	1 290
natural gas	480	780
hydraulic	4	18
nuclear	8	59
wind	11	75
photovoltaic solar	30	280
biomass	0	116

Table 2: Content in CO_2 equivalent per kWh generated (in g).

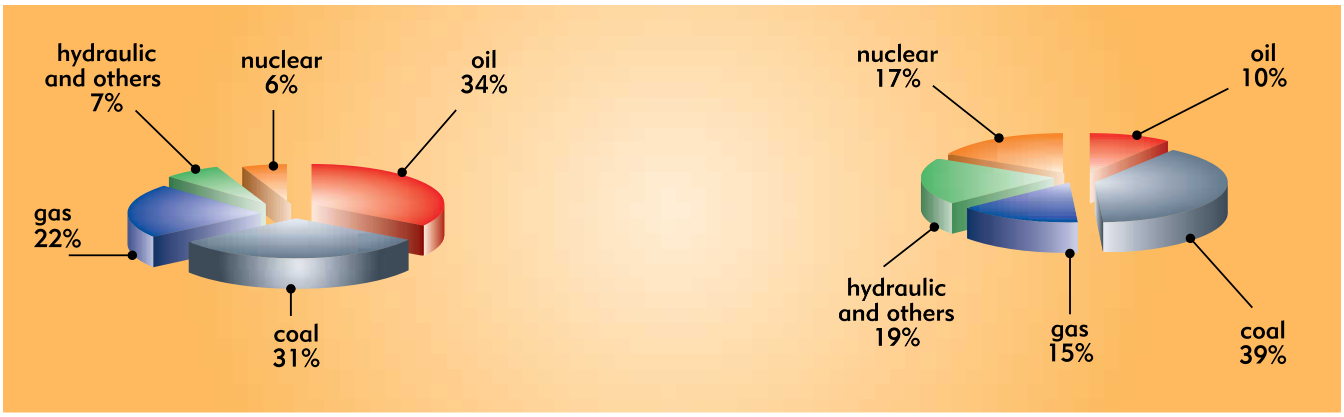
(1) High hypothesis correspondence: coal – due to poor quality and long transportation; gas – due to CH_4 leaks over long distances (the case for Russia); hydraulic – due to the production of CH_4 during the opening of a dam; nuclear – due to the enrichment obtained *via* coal-based electricity (the case for the United States); wind and photovoltaic solar – due to electricity based on natural gas as a complement to intermittent production; biomass – due to the absence of forestation.

Whether one considers the upward curve of the earth's temperature increase due to greenhouse gases (box A, ***The greenhouse effect***), the fossil energy reserve limits (table 1), or the progressive rise in energy demand on a worldwide scale, it is now clearly urgent, following the environmental awareness conference in Kyoto in 1997, to develop energy sources so that environmental requirements and economic constraints in relation to the use of natural resources can be met.

At the same time, consumption must be optimised in order to obtain a given service with the minimum quantity of energy.

An inevitable increase in demand

Energy consumption can only increase, for two reasons: one is the accelerated population growth, which should reach 10 to 12 billion people by the year 2100, and the other is the fact that developing countries cannot improve their standard of living except unless they considerably increase their energy consumption. Although the annual electric consumption of the worldwide population is around 12 000 terawatt hours (TWh), two people out of three consume less than the average 230 watts, four times less than the quantity used by a French person who, with 940 watts, is among the 10% of Earthlings who exceed 7 000 kWh/year. However, the infant mortality rate increases when energy consumption declines: for the lowest figures it is multiplied by 70, and life expectancy



Source: OECD

The greenhouse effect

A

The solar energy which reaches the ground heats the Earth and is transformed into infrared rays. Like the glass panes of a greenhouse – hence the name given to this mechanism – the gases in the atmosphere trap part of these rays and they in turn heat up the atmosphere. Thus, in terms of power, the Earth receives on average a little more than 240 watts/m^2. Without the greenhouse effect, the average temperature on Earth would be -18 °C and there would be very little water in liquid form. Therefore, this effect is beneficial, since it enables our planet to maintain an average temperature of 15 °C.

However, since the beginning of the industrial era, i.e. more than a hundred years ago, man has discharged gases (carbon dioxide, methane, nitrogen oxides, etc.) into the atmosphere and these artificially increase the greenhouse effect; since 1750, this increase for well mixed gases has been 2.43 W/m^2. With an "additional radiative forcing" of 1.46 W/m^2, carbon dioxide (CO_2) alone accounts for more than a half of this "additional greenhouse effect", far ahead of methane (0.48 W/m^2), halocarbons (chlorofluorocarbons CFC, hydrochlorofluorocarbons HCFC and hydrofluorocarbons HFC) with 0.34 W/m^2 and nitrogen dioxide with 0.15 W/m^2. Besides, tropospheric ozone has a *positive* radiative forcing of 0.35 W/m^2 (the observed depletion of the stratospheric ozone layer from 1979 to 2000 is estimated to have caused a *negative* radiative forcing of 0.15 W/m^2).

This increase to the natural greenhouse effect (155 W/m^2) is slight, corresponding to a rise of around 1 %. Nonetheless, it is believed that it has contributed to increasing the average temperature of our planet by approximately 0.5 °C. And this has been noted throughout the twentieth century. If nothing is done to reduce these emissions, the concentration of carbon dioxide in the atmosphere may more than double by the year 2100. Based on current worldwide consumption(1) of fossil fuels (7 700 million oil equivalent tonnes), it is easy to calculate the amount of CO_2 which is currently produced: 20 billion tonnes per year!

This could lead to a substantial increase in the greenhouse effect and, through non-linear amplifying effects, to serious climatic changes. Most models forecast that, by the end of the twenty-first century, twice the present concentration of carbon dioxide would lead to a temperature increase of around 2 to 3 °C. Some models even suggest a range of between 1.4 and 5.8 °C, involving spectacular consequences on the environment such as a significant rise in the sea level.

These figures may well seem small with insignificant consequences on the climate but, in fact, nothing could be further from the truth. In order to be convinced of this, one has only to remember that during the "Small Ice Age", between 1450 and 1880, the average temperature in France fell by only 1 °C. Six to eight thousand years ago, when western Europe experienced a warmer period, with an average temperature 2 to 3 °C higher than today's average, the Sahara was not a desert at all but a place of rains. However, this increase in temperature is less worrying than the actual speed of climatic variations (in a century). The major variations already seen in nature occurred over much longer time scales, at least for those of a global nature. Thus, the last glacial period lasted 100 000 years and the corresponding deglaciation lasted 10 000 years. The rapid variation which we are experiencing may lead to substantial, unexpected disturbances in the climate and the ecosystem, which will not always have time to adapt.

(1) CEE DG XVII (1996), "Traditional Wisdom" scenario.

Main conferences on the global environment

Changes in the global environment have acted as an impetus to the organization of large conferences over the past decade.

The United Nations Framework Programme on Climatic Change was signed at the Earth Summit in **Rio de Janeiro** (June 1992). This convention, which came into effect on March 21st 1994, adopted the objective of stabilising greenhouse gas emissions.

The protocol for the global reduction in the emissions of these gases was signed at the **Kyoto** Conference (December 1997); this convention stipulated a 5.2% average reduction between 2008 and 2012 in relation to 1990 for OECD countries and countries in Eastern Europe (including Russia). The targets for the European Union and France are a reduction of 8% and 0%, respectively. The means to achieve these targets were the object of unsuccessful discussions at **The Hague** in November 2000.

Stemming from the United Nations programme for the environment, problems relating to the substances that damage the atmospheric ozone layer were discussed in **Vienna** (1985) and, above all, in **Montreal** (September 1987), where the protocol requiring a reduction in the production and use of chlorofluorocarbons (CFC) was signed. This protocol was amended in **London** (1990), at which point CFC's had to be abandoned on January 1st 2000, and the regulations were extended to include other products in **Copenhagen** (1992), in **Montreal** (1997) and in **Peking** (1999).

drops abruptly when the power used is less than 180 watts. Although such facts and figures are not only the consequence of the under-consumption of energy, this under-consumption does reflect just how destitute part of mankind really is.

Exhaustible and renewable energy sources

Non-renewable energy sources (coal, oil, gas, uranium) are gradually being exhausted, contrary to hydraulic, solar, wind and biomass energy sources, which will be available for approximately another 5 billion years, before the Earth disappears. However, worldwide energy consumption (on the left in the figure below), like generation of electricity (on the right in the figure), is largely dominated by fossil energies (oil, **natural gas** and coal) which represent more than 85% of **primary energy** (box B, ***chains and energy systems***). Gas has become particularly competitive with the development of gas turbines and "combined cycle" technology, which have taken the cost of the kWh down. However, the gas itself accounts for 70% of this cost, which means that it is difficult to stabilise prices over long periods of time.

Finite reserves and the greenhouse effect

The extensive use of fossil energies puts the earth under two main types of pressure: increase in the greenhouse effect on a relatively short-term basis, and exhaustion of reserves in the longer term. It is not possible

Photovoltaic modules for the energy supply of a building near one of the highest peaks in the western Himalayas, the Dapsang (K2). Solar energy is especially recommended in isolated sites.

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to entirely separate these effects. In fact, carbon atoms extracted in the form of natural gas, oil or coal lead to the inexorable production of carbon dioxide (CO_2), with the most hydrogenated sources being those which emit the least (table 2).

We are living in a period of abundant energy, paying less for energy than we should be if we had a responsible attitude with respect to natural resources and future generations. As of the second half of the 21st century, gas and oil will become increasingly scarce and more expensive. Eventually, it will be necessary to reserve them for more noble uses than combustion, such as chemistry. For coal, the reserves should last several centuries. With respect to nuclear energy, the reserves are assessed in thousands of years for "fast" reactors, which enable more than 50% of the energy to be extracted from the fuel, whereas the time scale for "slow" neutron reactors, which exploit only 0.5 to 1%, is about the same as for hydrocarbons. And one day it may be worth our while to use other sources of uranium, such as seawater.

In the longer term, thermonuclear fusion would ensure reserves for several hundred million years. Far from being controlled by industry, the development of this source of energy depends on intensive research work being carried out within the framework of the Euratom-CEA association and of the ITER international project. Lastly, the planet's methane hydrate reserves, which are greater than those of coal, oil and gas reserves combined, will doubtless be useable in the future.

Renewable, but not yet competitive

There is renewed interest in energies that are *apparently* inexhaustible and cause less damage to the environment than fossil energies. Their major advantage is that they contribute little to the increase in the greenhouse effect. Their drawback is that they are diluted, not always available, and, for the most part, not yet competitive in most situations. Only **hydraulic energy**, which enables inexpensive electricity to be obtained at the price of costly investments, is used on a broad scale. This may result in nuisances, environmental disturbances[(1)], or even accidents. It should be remembered that when the Morvi dam burst in India in 1979, 30 000 people lost their lives.

Although the major source of electricity in France in 1960, hydraulic energy accounted for no more than 12% in the year 2000. Nonetheless, the price of the hydraulic kWh remains particularly low, once the investment has been made. It has a high potential in Asia, South America and in the former Soviet Union. Hydraulic energy is also the energy of tides and waves (1 watt per square meter), and, with a potential that is one hundred times greater, the very costly thermal energy of the oceans.

Most forms of renewable and fossil energies come from the Sun. Solar energy, in the broad sense of the term, covers all forms of energy at work in the terrestrial atmospheric machine: solar energy, in the strict sense of the term, wind energy, hydraulic energy, photosynthesis and wave energy. It includes neither tidal energy, generated by lunar movements, nor geothermal energy, which comes mainly from terrestrial radioactivity and represents 0.06 watt per m^2 (around 3 500 times less than solar radiation). The total power received by the Earth from the Sun amounts to 170 000 TW: over 2 500 times the worldwide consumption of electricity on the continents alone! But although renewable energies are "free", their recovery is not!

Strictly speaking, **solar energy** can be used directly (thermal) or transformed into electricity (**photovoltaic**). But there is a hitch here since the cost per kWh is still ten times higher than that obtained from gas or nuclear energy. Although it has advantages for isolated sites (savings in connections), it is not appropriate when substantial amounts of power are involved, and also generates waste, especially where the production of solar cells is concerned. Greatly reducing the cost of photovoltaic modules requires technological breakthroughs such as the production of thin mineral or organic layers, and this is something the CEA is working on right now.

Wind energy, which involves 1% of the energy received on the Earth being transformed into mechanical energy, is expanding remarkably, but produces a kWh at a price still 2 to 4 times greater than that of nuclear or gas energy. A windmill supplies power which is proportional to the cube of the speed of the wind. A 750 kW facility provides this power with a wind of 15 m/s (force 7) but delivers no more than around thirty with a wind of 5 m/s (force 3), and zero when there is no wind at all: a site with a lot of wind can supply 20 to 30% of the *installed* power. Wind turbines can be placed offshore where the winds are stronger and more regular. Their drawbacks (surface area, visual appearance and noise) are better known than advantages like the hedge effect, used in farming.

The **biomass** is a good means of storing diffuse and intermittent solar energy, but its efficiency is low: 1% or less in temperate areas. Plants consume carbon dioxide, which partly compensates what is emitted during their combustion. For wood, the CO_2 budget is 7 to 12 times less than that of gas. But ways of improving low energy density biomass combustion are currently being studied and, again, this is a subject that the CEA is working on. As with other sources, it is important to evaluate the balance before talking about efficiency: for example, it takes 1 litre of fossil fuel to produce 1.5 litre of

(1) The beneficial effects include regulation of the river network.

bio-ethanol or 2 litres of ester from rape seed. But it is possible to recover hydrogen from the by-products of the transformation. Lastly, although the objective is above all to destroy it, reduce it or make it inert, **waste** may represent an additional source of energy (at best, 1% of French consumption).

Difficulties relating to transport

Oil is currently irreplaceable in transport, accounting for 95% of the sector's needs. In France, the energy consumption of this sector represents 25% of total consumption and is increasing even faster. Current technology will not be able to hold out much longer due to its contribution to the greenhouse effect (an automobile releases around 1 tonne of CO_2 into the atmosphere every 5 000 kilometres), as well as the increasing scarcity of fossil energies and rise in prices.

For automobiles, one way forward may be the **hybrid** car equipped both with a heat engine and an electric **battery**. In the longer term, hydrogen will doubtless supply either an internal combustion engine directly or a **fuel cell** of an electric car.

J.-C. Raoul/ THE MEDIA LIBRARY EDF

EDF nuclear power plant in St-Laurent-des-Eaux. The stable cost of the nuclear power kW remains a long-term advantage.

Hydrogen, the energy vector of the future

Hydrogen should soon become the second biggest energy vector after electricity. The CEA, aware of these prospects, is increasing its research in this field as well as in that of fuel cells, which may have many uses on top of transport, e.g. in stationary applications as a source of electricity and heat, or the mobile sector in the supply of "nomad" devices (telephones, computers, etc.).

The need for electricity and also for production of hydrogen (initially *via* water electrolysis) will mean producing considerable quantities of energy. It would be logical for at least part of this to be produced using nuclear energy, as this has no impact on the greenhouse effect.

The nuclear energy of the future

In addition to its highly competitive price, above all during off-peak periods (less than 10 centimes per kWh), and the independence which it provides, nuclear energy generates a large part of its added value in the user-country. It must therefore contribute and be part of long-term development projects.

The nuclear energy of the future will have to satisfy five conditions, including that of producing a kWh at a price less than or equal to other energy sources. It will have to be safer, even if most types of reactors belonging to previous generations have a very satisfactory safety level, and it will have to generate more power with the same quantity of fuel. It will have to generate less waste, especially long-life radioactive waste(2), be capable of burning part of the waste from older reactors and not be used in military applications.

Energy savings: "negawatts"

It is also very important to use generated power in the best possible way. Optimisation of systems, with smart systems, provides the same service using less energy. Much remains to be done in the field of energy savings in which the CEA has already acquired extensive experience. The micro-electronics industry has the finest example of reduced energy consumption (and prices), combined with an excellent increase in performance levels. The decrease in consumption contributes to creating negawatts (non-consumed watts) without downgrading either the service provided or the level of comfort.

(2) These waste are perfectly localised, when the greenhouse gas pollution is a planetary one; It should also be noted that, when operating normally, even a coal-fired power station produces much more radioactive waste than a nuclear power plant.

An energetic role to play in future research

The CEA has contributed considerably to setting up the type of nuclear reactor that currently supplies 78% of French electricity at a price that will remain stable for a long time. Thanks to its expertise and know-how, the CEA was able to invest in areas such as energy system optimisation and photovoltaic energy very early on. It contributes to research work aiming to reduce the high cost of renewable energies. The CEA is also focusing on developing new vectors and **energy converters**, by working on the production and storage of hydrogen, but also on fuel cells, with the aim of substantially lowering their costs and increasing their reliability, on batteries, in order to improve their capacity and service life, and on technologies based on lower energy consumption. The following pages give an overview of this non-nuclear based work, the objective of which is to find new technological breakthroughs and pave the way for part of the future's energy systems.

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B

Chains and Energy Systems

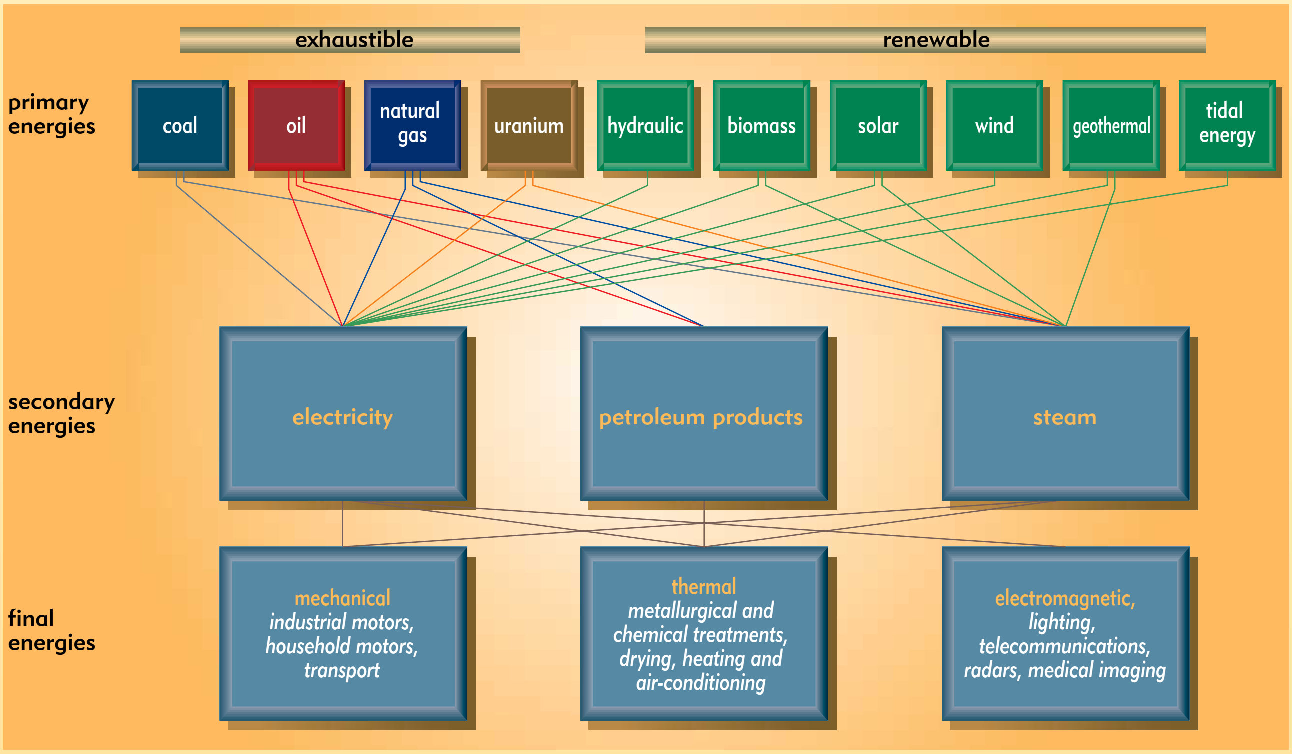
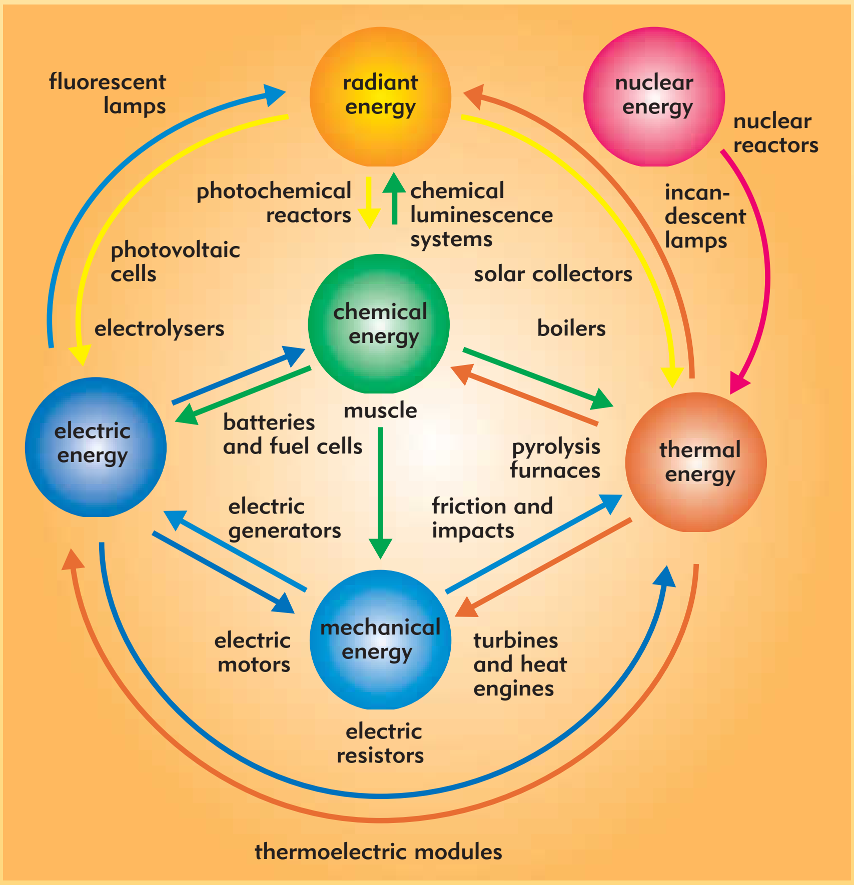


Figure 1. Energy system diagram.

The simplest energy system is the one man has been using for thousands of years: wood to cook food or keep warm and the strength of animals or wind to grind grain or transport goods or people. From the primary energy sources to be found in nature, wood and wind in the case in point, man drew on useful energy for a given service such as heating or movement. It is only in the 18th century that the notion of energy began to take shape. Energy has become an essential driving force of the economy. In fact, it assumes numerous forms: chemical energy in **fossil fuels** or the biomass, kinetic energy in waterfalls or the wind, electromagnetic energy from the Sun, nuclear energy in uranium, as well as the electrical or thermal energy that is put to numerous uses (figure 1). The many transformations from one form to another give unity to this concept, but the quantity of energy remains unchanging, according to **the first law of thermodynamics**.

These different forms of energy do not have the same quality. Neither can they be entirely transformed (figure 2). When the chemical energy contained in coal is transformed into electric energy in a power station, this electric energy accounts for only a fraction of the initial energy (approximately 42%); the rest is changed into low temperature thermal energy in the condenser and disappears into the environment. The energy is kept



Source : CEA/DSE/SEE

Figure 2. Conversion of the six main energy forms and examples of energy converters.

B

unchanged in quantity but, as **the second law of thermodynamics** explains, partly reduced in quality. Any transformation that is not strictly reversible results in useful energy losses in relation to the target optimum use.

With the development of industry and the appearance of new technologies, the energy system has become very complex: knowledge of this system is behind all studies on energy. The system has several levels.

The **primary** level is comprised of all non-transformed energy sources that can be found in nature, and which are subdivided into exhaustible energies (coal, crude oil, natural gas, natural uranium) and renewable energies (hydraulic, solar, wind, biomass, geothermal, tidal). Of course, in the strict sense of the term, no energy is really "renewable". This is why the Sun will eventually burn out, the Earth cool down and rotate slower and slower taking the tidal energy forces along with it.

The **secondary** level concerns conversion (figure 2) and transmission of energy after a given stage of transformation, and eventually its storage. It is at this level that power is actually generated, but it also includes the refining of oil, the production of industrial steam and, in the future, the production of hydrogen, destined to become a major **energy vector** alongside electricity.

The **final** level covers the ways the end-consumer uses energy (petrol at the pump, electricity at the meter). These can be grouped into three categories that span all sectors of the economy: mechanical energy, thermal energy and radiation. At this level, there is a difference between the *final* energy that is actually consumed and the *useful* energy required for the service provided. This difference corresponds to the various losses arising from the specific appliance used. In relation to useful energy, accounting for just a little more than one-third of the primary energy used, the losses are broken down as follows: 24.5% in conversion, 4.4% in distribution, 34.4% in end use, i.e., around 63%.

Any quantity of energy that moves from the primary energy stage to another stage follows a series of transformation and transmission processes, i.e. they follow an energy chain. An energy system is made up of a large number of possible chains, but not all of them are viable from an economic or environmental point of view.

Energy choices: issues at stake and means

Energy choices correspond to complex socio-political, economic and industrial issues which are often in contradiction with each other. Their assessment integrates more and more factors, and their implementation implies new means for decision-makers.

NOVOSTI/SIPA PRESS

Fumes from an industrial complex in the Kouzbass basin (western Siberia). The assessment of an energy chain must take account of all losses between primary energy and useful energy.

The economic assessment of energy systems is quite subtle even when based on statistics, as shown by the estimate of the worldwide system made by the World Energy Council (WEC) for the year 1990, the last year in which the whole Earth was taken into account and not only OECD countries like the more recent statistics (table 1). The values given are for information only: they depend on equivalence conventions between energy forms that are approximate and not universally admitted and, although it is relatively easy to assess commercial energy in numerical terms, this is not the case with the biomass (mainly wood), which is an essential resource for 2 billion people.

Although there may be no cause for concern with respect to the overall volume of energy resources available, the significant inequalities between the distribution of hydrocarbon resources and the consumption levels of rich versus poor countries are problematic (see *The energies of today and tomorrow*). Downsizing such inequalities must play a central role in any good energy policy as they give rise to conflicts. Moreover, any choice in this field must take into account the adverse effects of energy consumption on the environment.

With all this in mind, possible *energy chains* have to be examined from one end to the other and from all points of view in an effort to keep production costs and environmental impact to a minimum (table 2). No energy is exempt from random economic elements or dangers. The various assessment criteria have to be applied at local, national, regional or international level. The factors involved in choosing an energy source are numerous, sometimes contradictory, and often have a long-term effect owing to project fulfilment schedules and the service life of generation and transmission equipment.

Electricity has come to occupy a very important place in modern economies. On average, it accounts for 13% of final energy at worldwide level and 40% in industrialized countries; its growth (3.2% between 1995 and 1996) remains higher than that of energy (2.9%). How electricity is generated is thus a central issue in any country's energy policy, all the more so in that this form of energy provides considerable flexibility in its production means as well as a multitude of uses, whether captive or competitive.

The production cost of a kilowatt-hour (kWh) has long been subject to in-depth analyses. But it is not reasonable to focus one's thoughts on a single segment such as the one represented by the power station. It thus appears that the gas chain is as capitalistic as the nuclear energy chain, and that, from this point of view, although it has the advantage of being less demanding on the electrician, on the other hand the corresponding added value is not as good for the national economy. Moreover, the stability of the cost of a hydraulic or nuclear kWh is a significant factor for any industrialist. In the long term, other aspects are to be taken into consideration such as supply reliability and geopolitical implications, even though no one wants to neglect them on the pretext of liberalizing the market.

energies	coal	oil	natural gas	nuclear	hydraulic	biomass	electricity	heat	total
1996 (9.5 billion oil equivalent tonnes)	22.7	34.6	19	6.3	6.5	10.8*			100
1990 (9 billion oil equivalent tonnes)									
primary	24.6	30.8**	18.9*	5.1	5.7	14.9			100
final	9.7	24.8	10.8			14.3	9.4	2.1	71.1
of which:									
industry	6.7	4.1	5.9			0.8	4.6	1	23.1
transports	0.3	15.9	0			0	0.2		16.4
residential ***	2.7	4.8	4.9			13.5	4.6	1.1	31.6
useful	6	8.2	8.1			5.4	7.5	1.5	36.7

Table 1. Energy consumption in the world (in %).
Primary energy consumption in 1996 came to around 9.5 billion oil equivalent tonnes. *Source:* AIE *(1996) WEC (1990)*
** biomass and geothermics*
*** outside use as raw material in the chemical industry*
**** residential, service industry and farming*

The consequences on the environment are also part of electricity generation economics. The cost of waste and its contribution to the cost of the nuclear kWh are correctly estimated. On the other hand, until now the cost of the fossil fuel kWh has not reflected the consequences of greenhouse gas emissions, nor the cost of eliminating them. Hence the importance of more recent studies that also take account of these "externalities" so as to compare various scenarios for renewing the means for energy production. Thus, the authors of the economic study, *Prospective de la filière électrique nucléaire* (Prospects of the nuclear power industry), submitted to the Prime Minister(1) last July, estimated that in case of a substantial increase in the price of fossil energies, the cost is lowest in cases where a large part of the nuclear equipment is renewed.

New instruments

Whatever the case, new economic instruments must be set up in order to apply the Kyoto protocol (box A, ***The greenhouse effect***). Taxation on greenhouse gas emissions is a simple, flexible and efficient means of reducing them, but it may lead to economic disturbances as well as to distortions in competition among countries in the absence of serious international co-ordination.

(1) Report prepared by Jean-Michel Charpin, Plan Commissioner, Benjamin Dessus, director of the Ecodev program (CNRS), and René Pellat, Atomic Energy High Commissioner.

Another instrument would consist of an emission permit market: polluters would be allotted CO_2 emission quotas which they could subsequently trade in, with each CO_2-emitting party being responsible for ensuring that it holds as many emission permits as gases emitted. If the party did not hold the right permit it would have to either reduce its emissions or buy the relevant permit from a country with an unfilled quota thanks to efforts to control emissions. Nonetheless, the implementation of such a market, the idea of which was accepted at the Kyoto conference and discussed at The Hague, raises considerable problems, especially on an international scale. Energy and economic questions currently overlap to such an extent that the most relevant way to compare policies is to assess their macroeconomic consequences using an adequate model, e.g. the type the CEA has been building for the past ten years. Not only does such a model enable one to estimate the eventual development of the main macroeconomic aggregates, such as GDP, balance of payments, employment, etc., but also the effects of tax redistribution or eventual emission permits.

A different, but absolutely essential, way forward is to invest in research in renewable energies and energy savings, and to set up industrial subsidies. This would reduce greenhouse gas emissions and, ultimately, lessen Europe's vulnerability as regards energy supplies, as well as promote the right type of technologies for developing countries. This effort would help curb the production cost of new energies by improving their performances and through the economies of scale expected from such an industrial program. In fact, these energies, like the others, will eventually be subject to market criteria. Taxation on greenhouse gas emissions or the emission permit market will place them in front of fossil energies, at least insofar as they are shown to be efficient through a complete assessment based on an energy chain analysis. One of the important aspects of the question is the greenhouse gas content per kWh produced by primary energies, expressed in equivalent CO_2. Table 2 of the previous article shows the disparities and possible variations according to the actual conditions prevailing from one end to the other of the energy chain.

This is why the assessment of electricity **energy converters** such as fuel cells must include an analysis of their specific energy chain, in this case that of hydrogen the energy vector of the future. Should this not prove wholly satisfactory from an economic or environmental point of view, the undeniable advantages of these converters, in relation to their ease of use or improved quality of air in cities thanks to their use in the electric car, would nonetheless render them acceptable and promote their growth.

Whatever the case, the future demand for energy, especially in poor countries, is likely to be enormous. Finding technological breakthroughs in new energies to make them attractive and competitive are thus important issues for French research and industry, just as nuclear energy activities continue to be.

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Table 2. To produce 1 000 electric megawatts during one year, one needs:

photovoltaïc	100 square kilometres (efficiency: 10 %, Central Europe)
windmill	5 600 wind turbines (availability: 30 %, North Sea)
coal	2 600 000 tonnes
oil	1 800 000 tonnes
nuclear fission	25 tonnes of uranium with an enrichment of 4 %
thermonuclear fusion	100 kg of deuterium and 150 kg of tritium

(Source : CEA/DRFC)