current challenges in energy

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Introduction

Growing worldwide demand for energy, and problems of scarcity and environmental impact associated with conventional sources are at the base of a very probable energy crisis in the next two or three decades. Petroleum will become increasingly expensive and scarce, while the climatic effects of massive use of all fossil fuels will by then be clearly felt. At the same time, current nuclear installations will have reached the end of their useful life. And it is not clear, especially in Europe, whether the power they will no longer provide when shut down, will be supplied by new nuclear plants.

At the present time, we cannot abandon any existing energy sources. They must receive the necessary modifications to eliminate or reduce their environmental impact, and new sources must be added, especially renewable ones. Below, I will describe the state of available technologies and the most promising developments in each of them, always on a time scale of the next few decades.

On a longer scale, nuclear fusion will be part of a catalog of more sustainable energy sources, but it will not be ready in the time period under consideration here and will thus be unable to help in resolving the crisis. That is why I will not address nuclear fusion here, although a powerful and interesting program is being developed on an international scale. The goal is to harness the reactions of nuclear fusion as an energy source, but foreseeable progress places it outside the time span we have chosen for the present analysis of energy problems.

Energy and civilization

Energy is a fundamental ingredient in human life. There is no industrial, agricultural, health, domestic, or any other sort of process that doesn't require a degree of external energy. Human beings ingest around 2,500 kilocalories of energy per day as food. But in industrialized countries, the average daily amount of supplementary (exosomatic) energy consumed in combined human activities (industrial, domestic, transportation, and others) is equivalent to 125,000 kilocalories per person. That is fifty times more, and in the case of the United States, the figure is one hundred times more (see, for example, British Petroleum 2008). In fact, there is a strong correlation between individual energy consumption and prosperity among different societies.

In figure 1, each country is represented in a diagram in which the "Y" axis specifies the Human Development

Index (HDI) for that country as determined by the UN using basic data on the wellbeing of its inhabitants. The "X" axis shows annual energy use per capita (in this case, in the form of electricity). Two interesting phenomena are observable here. In the poorest countries, the correlation is very strong, with energy consumption leading to clear improvements in the HDI. But in more developed countries, the very large differences in energy consumption do not significantly affect levels of wellbeing. This indicates that, for the latter countries, energy saving is a possible and desirable policy. In the most prosperous countries, saving is actually the cleanest and most abundant energy source. On the other hand, the necessary economic and social development of the comparatively poor countries that make up the greater part of the world's population will inevitably require greater energy consumption, so it is unrealistic to think that global energy use could diminish in the future. If it did, it would be an absolute catastrophe for the least-developed countries, which lack everything, including energy. Therefore, while energy saving must be a central aspect of active polices in first-world countries, from a global perspective, we must deal with the problem of a growing demand for energy.

Current energy sources

The primary energy sources are identified and it seems unlikely that any will be added in the foreseeable future. From the dawn of humanity to the beginning of the Industrial Revolution in the early nineteenth century, the only available sources of primary energy were wood and other forms of natural biomass, beasts of burden, and wind for maritime or river traffic. With the development of the first steam engines, coal entered use as an energy source and it continues to be an important source of consumed primary energy today. Later, with the widespread use of automobiles with internal combustion engines calling for liquid fuels, petroleum and its by-products became the preeminent source of energy. Finally, over the last half century, natural gas has become an important component in the generation of electricity and the production of heat for industrial and domestic uses.

These fuels—coal, petroleum, and natural gas—are found at different depths in the Earth's crust. They were formed in earlier geological epochs by natural processes in which organic materials—mainly plants and marine organisms—were subjected to high pressure and temperatures. That is why they are known as fossil fuels. Their contribution to the sum of primary energy consumed worldwide at the end of 2007 (British Petroleum 2008) was 35.6% for petroleum, 28.6% for coal and 23.8% for natural gas. Together, they thus represent 88% of the total. As we will see below, there are many reasons why this cannot be sustained, even into the near future. The rest comes from nuclear energy, which provides 5.6% of the total, and renewable energies, mostly hydroelectric.

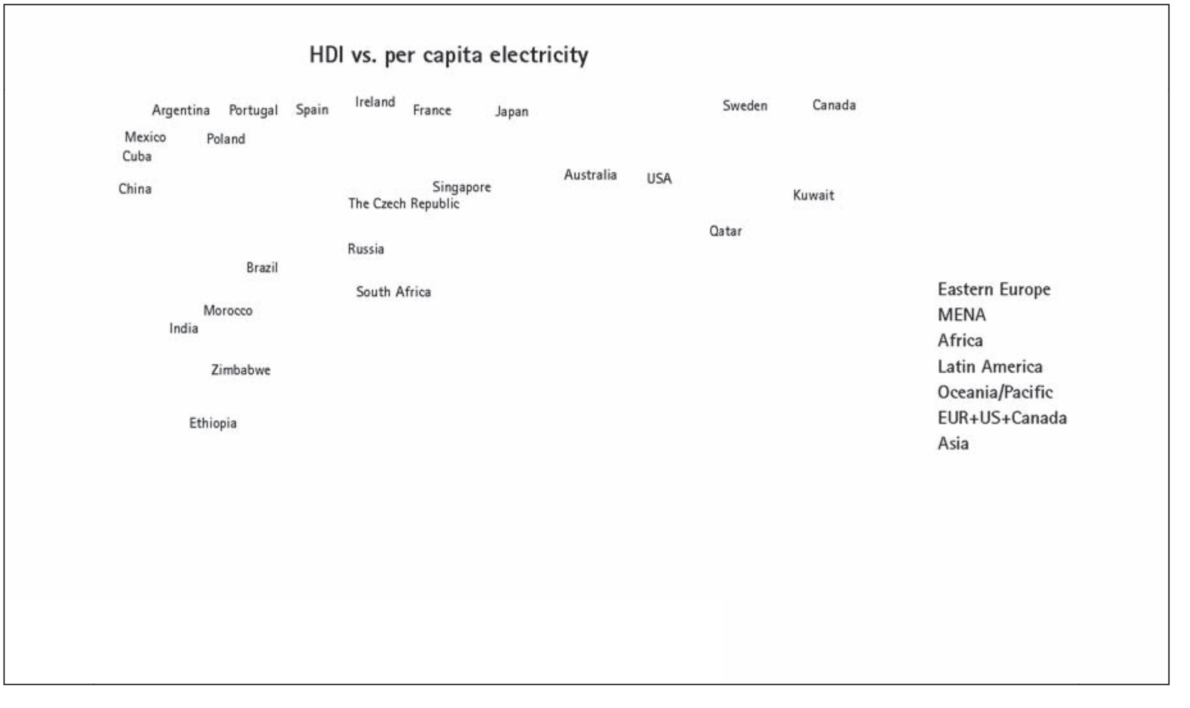


Figure 1. The Human Development Index (HDI) as a function of the amount of electrical energy consumed per person per year. Drawn up by this author on the basis of HDI data from the UN (UN 2006) and data on electricity use by the International Energy Association (IAE 2008).

Energy drawn from wind and the Sun in various ways is a marginal factor from a global perspective, but it is beginning to have a greater presence in some countries, especially Spain. So that is the global perspective; there are no more available sources of primary energy.

Of all this primary energy, an important part is transformed into electricity (about 40% in a country like Spain), while the rest goes to the transportation sector and other industrial and domestic uses.

Fossil fuels

The enormous predominance of fossil fuels as a primary energy source has some important consequences:

First, they are unequally distributed. Two thirds of the known reserves of petroleum, probably the most difficult fuel to replace, are under five or six countries in the Middle East, which implies a degree of dependence that is not especially compatible with a stable supply. Natural gas is also very concentrated in that area, and in the countries of the former USSR, while coal is more evenly distributed in all parts of the planet.

Second, these are non-renewable raw materials. They were formed over the course of dozens or even hundreds of millions of years and are thus irreplaceable. Moreover, they are limited resources. In particular, the use of petroleum as an energy source on which the lifestyle of industrialized nations is based, could be just a brief fluctuation in the history of humanity, limited to a period of about two centuries.

Third, these raw materials are scarce. There is some debate about the amount of available petroleum, but most geologists and petroleum experts agree that, at the current rate of consumption—no less than 85 million barrels of petroleum a day, which means burning a thousand barrels of petroleum per second—we only have enough for a few decades. It can be argued that the amount of petroleum extracted depends on the price and that, if it rises, there will be no practical limit to production. But this argument overlooks the fact that it takes more and more energy (in prospecting, pumping, treatment, and logistics) to extract petroleum from deposits that are increasingly deep or depleted. In the mid twentieth century, the energy required to extract a barrel of petroleum was equivalent to around 1% of the contents of that barrel. Today, that cost has risen to between 10% and 15%. When the energy needed to extract a barrel of crude oil comes close to the energy that same barrel could produce, no matter what its price, then it will have disappeared as a primary energy source, although it may continue to be useful, especially in the petrochemical industry, where it is used to synthesize a multitude of compounds that are fundamental to almost all branches of industry and agriculture.

At the current rate of consumption, proven petroleum reserves will last about 40 more years, while those of natural gas will last around 60 years. Coal reserves will last approximately a century and a half (British Petroleum 2008). There will be new discoveries, of course, and there are also the so-called non-conventional petroleums drawn from hydrocarbons dispersed in sand, bituminous schists, or heavy tars, but we must always remember the growing energy cost, and thus, their decreasing net yield and higher price. At any rate, there will not be a sudden end to supplies, passing from the current levels of use to nothing. There will probably be a progressive rise in price and, at some point, a progressive decrease in consumption and production as well.

Finally, we know that burning fossil fuels generates enormous amounts of atmospheric carbon dioxide (CO_2). This gas is one of those that produces the greenhouse effect and thus contributes to global warming. Given how fast this phenomenon is taking place (in geological terms), it could produce serious climatic disturbances that are potentially harmful for our civilization (not for life, as has frequently been alleged, nor for human life, but certainly for our complex and demanding social organization).

In sum, our social activity is based on fossil fuel use that, due to environmental concerns and limited supplies, must be limited in the future. Nevertheless, coal will continue to be a massive energy source for decades to come, but its use will only be tolerable if the contamination it produces can be palliated.

In consequence, the second energy challenge (the first is reducing consumption in developed countries) is to diminish the primacy of fossil fuels in energy production.

Preparing petroleum substitutes

Transportation depends almost entirely on liquid fuels derived from petroleum. Coal and natural gas are now important for electric production but they could conceivably be replaced by renewable or nuclear energy in the long term. However, it is not easy to imagine alternatives to the use of petroleum by-products for transportation. All of these involve very far-reaching changes.

The first possible alternative is the use of biofuels—bioethanol and biodiesel—to at least partially replace conventional fuels. But we have recently seen the collateral problems that can arise, especially in the area of food production, even when biofuel production is only just beginning. Of course, the influence of bioethanol production—the most controversial case—on food prices is limited and price rises coincide with other, deeper causes, some of which are momentary and others, structural. The only grain that is widely used to make ethanol is corn, while wheat and barley are employed in marginal amounts with regard to total production.

Rice is not used at all. And yet, prices have risen for all these grains, especially rice. Moreover, about half the current production of bioethanol comes from Brazilian sugarcane, and the price of sugar has not risen at all.

In any case, making ethanol from grains is the worst possible solution, not only because of its impact on food production, but mostly because of its poor energy yield. In fact, between fertilizers, seeds, harvesting, transportation, and treatment, the amount of energy contained in a liter of ethanol is barely more than that required to obtain it from cereals (see, for example: Worldwatch 2007; CIEMAT 2005). Therefore, from an energy standpoint, it is unreasonable to use this type of raw material. Environmental concerns associated with the use of water and tillable land also seem to discourage it (Zah 2007). On the other hand, the energy yield of sugar cane is much higher, and the yield of ethanol from what is called lignocellulosic biomass—present in woody or herbaceous plants and organic residues—is even higher. This is called second-generation ethanol. All of these conclusions appear in the interesting graph in figure 2, which is taken from Zah 2007. It offers all the data about fossil fuel consumption in the growing, harvesting, pretreatment, and other processes needed to obtain biofuels from different plant materials, as well as the overall environmental impact, compared to the direct use of petroleum by-products.

The third challenge, then, is to perfect the already existing technology to produce second-generation biofuels on a level useful to industry. This is not far off, and some pilot plants are already experimenting with various processes for generating ethanol from the sort of biomass that has no effect on food, requires less energy cost, and has less environmental drawbacks (see, for example: Ballesteros 2007; Signes 2008).

Thus, cane ethanol and second-generation biofuels could diminish petroleum dependence in the transportation sector, although they could not entirely replace it, due to the limited amount of tillable land and available biomass compared to that sector's gigantic fuel consumption.

It is easier, at least in principle, to replace fossil fuels used to generate electricity—resorting to renewable or nuclear sources—than to find substitutes for every petroleum product. Thus, in the long run, I think we will turn to electric vehicles, first as hybrids and later purely electric. The problem here is how to store the electricity. The batteries used at present are inefficient and very contaminating, but intense research into new devices for storing electricity is currently under way and will allow the construction of electric vehicles with adequate performance.

In general, we should say that energy storage, be it electricity, heat, hydrogen, or any other form,

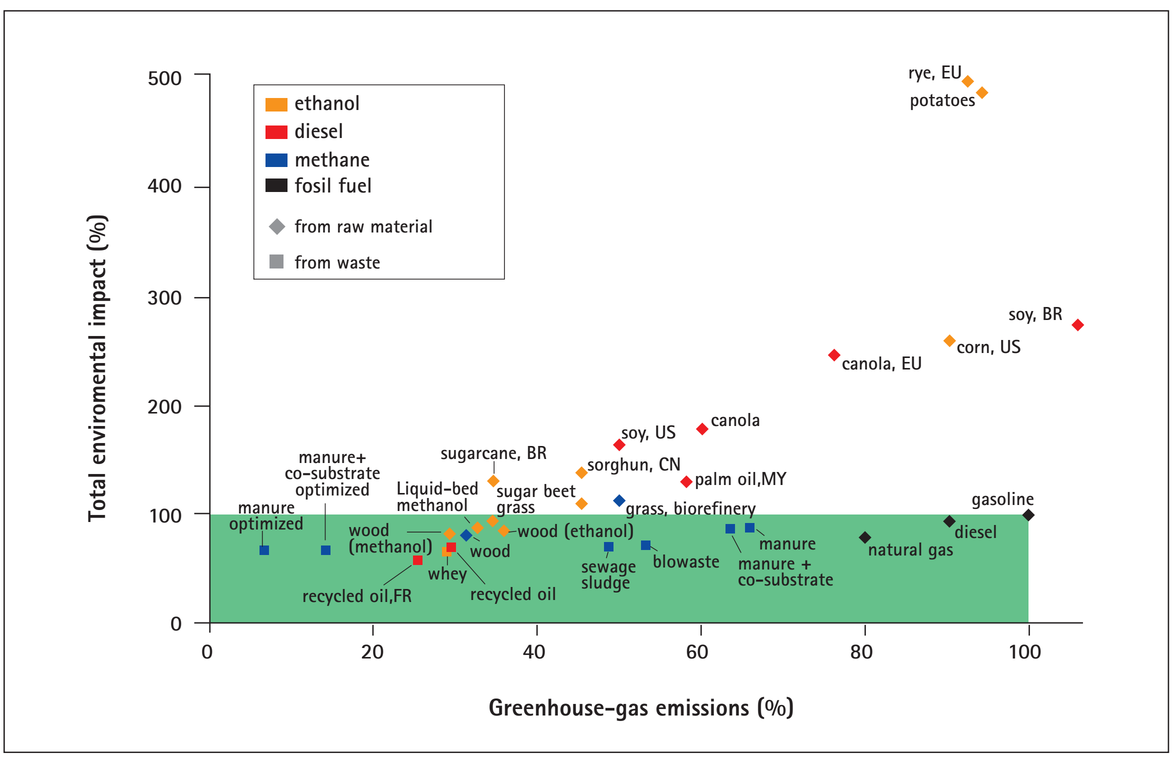


Figure 2. Environmental impact and consumption of fossil fuel in the production of biofuels as compared to the direct use of fuels derived from petroleum. (Zah 2007).

	Coal	Natural Gas	Nuclear	Hidraulic	Other Renewable	Others
World Average (06)	40%	20%	16%	16%	2%	6%
USA (06)	49%	20%	19%	7%	2%	3%
France (06)	4%	4%	78%	11%	1%	2%
China (04)	83%	0%	2%	15%	0%	0%
Spain (07)	24%	34%	18%	10%	11%	3%

Table 1. Percentages of total electricity generation from primary energy sources.

currently occupies a central position in energy research, both because of its importance to the future of the transportation industry and in order to solve problems derived from the intermittence of renewable sources, as we will see below. In other words, if we manage to improve electric storage technology (see, for example, José Luis Mata Vigi-Escalera, Club de la Energía 2008a), which is a formidable challenge if we want to reproduce the performance of a gasoline-based vehicle—then, an important portion of future vehicles will be electric. Therefore, below, I will concentrate on the production of electricity, which is shaping up to be the most flexible and adaptable energy, even for the future of the transportation industry.

Clean coal?

The electricity production scheme varies considerably from one country to another. In table 1, we offer some data about the relative makeup of energy sources used to generate electricity in Spain, some other countries, and the world average (IEA Statistics; Club Español de la Energía 2008a).

It can be seen that, with the exception of France, that relies very heavily on nuclear power, and partially Spain, which has an appreciable use of renewable sources, the basic energy source continues to be coal. And it will continue to be so for a long time, due to its abundance and its distribution on almost all continents. The case of China is particularly notable. According to the International Energy Association, in recent years, it has been opening a new coal-based electric plant every week. But coal is by far the most contaminating fossil fuel of all, spewing almost twice as much carbon dioxide into the atmosphere per energy unit produced as natural gas, and about 40% more than the gasoline used in internal combustion engines, not to mention its sulfur, nitrogen, and heavy metal components.

So, if we want to continue using coal as an energy source, we must develop procedures to eliminate or at least limit atmospheric CO_2 emissions (the other emissions are already controlled right in the power plants). This is known as Coal Cartridge Systems (CCS) and is still in its early stages. In particular, the capture of CO_2 emitted during coal combustion can be carried out with oxicombustion techniques that modify the composition of the air entering the boilers so that the gas emitted is almost entirely CO_2. That way, no separation is necessary. This can also be done by applying separation techniques to air-based combustion. Both methods generate additional energy costs and will need new physical-chemical processes, which have been tested in laboratories but not on the needed industrial scale. As to the CO_2 that is obtained as a result—we must find underground or underwater deposits hermetic enough that CO_2 injected into them will remain trapped there for centuries.

In reality, deposits of this type exist naturally. For example, deposits that have held natural gas for geological periods of time can be used to store carbon dioxide once the natural gas has been exploited. The same is true for exhausted petroleum deposits, sedimentary saline formations, and so on. In fact, most of the experiments with CO_2 storage around the world are associated with oil fields whose production is falling. The carbon dioxide is injected under pressure in order to improve production, obtaining crude oil that would not come out using conventional extraction techniques.

Another interesting experiment is being carried out at Sleipner, a gas production camp on the Norwegian coast of the North Sea. In that field, methane, the principal ingredient of natural gas, comes out mixed with significant amounts of CO_2. Once the two are separated in the extraction plant, the CO_2 is injected back into the seabed at a depth of about a thousand meters, in a bed of porous boulders with water and salts. They have been depositing CO_2 there since 1996, and data about how hermetic it is will be of great value when seeking new locations for massive use. At any rate, we should mention that the processes

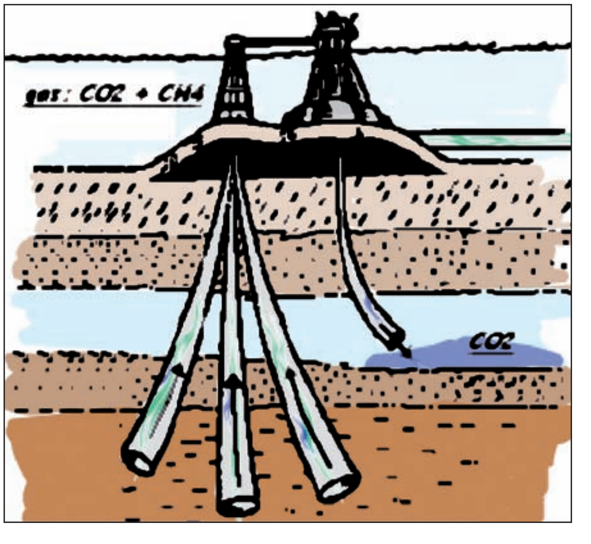


Figure 3. Sleipner Camp on the Norwegian coast of the North Sea.

of capturing and storing carbon dioxide will always signify additional costs, which must be added to the price of energy obtained from the clean use of carbon. Experts estimate that this cost will be between 30% and 100% of the cost associated with non-CCS coal use (Socolow 2005; Fundación para Estudios sobre la Energía 2008). Still, we must view this additional cost in the context of the rising price of both conventional and renewable energies, additional costs for CO_2 emissions, and aid for non-contaminating energy of the sort defined in Spain's Special Tax Code. The conclusion is that humanity will not stop using such an abundant and widespread energy source as coal, but its use has grave environmental consequences that it is extremely important to counteract with techniques such as CCS.

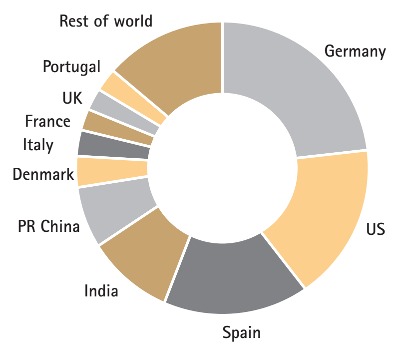
Renewable electricity. The wind

Perhaps the most important challenge for us in the next few decades will be significantly increasing the contribution of renewable energy compared to current levels, which are marginal on a planetary scale. Hydroelectric power has the greatest presence and its resources have been used in the most complete way, but other renewable energies, such as wind and solar power, have advantages and disadvantages. Their advantages are the opposite of the disadvantages to fossil fuels mentioned above—they are sustainable, unlimited, and hardly contaminate at all, even when we consider their complete lifecycle and their territorial distribution. Their disadvantages fall into two categories: high cost and intermittence.

One of the reasons why renewable electricity is so expensive is its degree of dispersion, which is an intrinsic characteristic offset only by its unlimited and sustainable character. However, it is reasonable to think that the expense of conventional energy will continue to increase as supplies diminish and environmental costs are figured in. In that case, its costs would converge with those of renewable energies at some point. The high expense of renewable energies is also due, in part, to the fact that the technology associated with it is still not very advanced. In that sense, the way to diminish costs derived from the lack of technological development is to create a worldwide market. That is the only way to lower the expense of producing the needed components, as it will lead to production of larger series, and to the emergence of more companies, ending the oligopolies currently existing in some key fields. Moreover, it will make it possible to implement improvements in the operation and maintenance of renewable energy plants, following a certain period of operating experience in conditions of industrial exploitation. Indeed, the different systems currently being activated to stimulate the spread of renewable energies are intended to broaden that market through the use of subsidies or other types of aid that compensate for initial difficulties.

As is well known, in Spain and some other countries that are advanced in this field, a special tax code has been enacted for renewable energies (and cogeneration), with the exception of hydroelectric power. This consists of a series of incentives or subsidies per kilowatt hour of renewable origin, intended to compensate for the greater current costs and thus stimulate growth in that sector. Special tariffs are different for each generating technology, reflecting the different costs at present, but they are supposed to diminish over time as costs decrease until they converge with conventional energies. This, and any of the other existing schemes, has already proved efficient in the first of the renewable energies that can be considered widespread on the worldwide market: wind power. In fact, at the end of 2007, the global figures for accumulated wind power were already 93,900 MW (Global Wind Energy Council 2008), which has made it possible to configure a dynamic industrial sector that is growing all over the world.

TOP 10 TOTAL INSTALLED CAPACITY



	MW	%
Germany	22,247	23.7
US	16,818	17.9
Sapin	15,145	16.1
India	7,845	8.4
PR China	5,906	6.3
Denmark	3,125	3.3
Italy	2,726	2.9
France	2,454	2.6
UK	2,389	2.5
Portugal	2,150	2.3
Rest of world	13,060	13.9
Total top 10	80,805	86.1
Total	93,864	100.0

Figure 4. Installed wind capacity as of 31 December 2007.

As can be seen in figure 4, the three countries with the greatest installed capacity are Germany, the United States and Spain, although, due to its lesser overall consumption, Spain is the one that obtains the greatest fraction of its electricity from that energy source—around 9%. In fact, Spain is second in the world, after Denmark, in both the total percentage of electricity from wind power, and the installed capacity per capita (European Wind Energy Association 2008).

With public support, the creation of a global wind-energy market is making headway, not only by creating new industrial activity and jobs, but also by progressively reducing the cost of energy thus produced. At the end of the nineteen seventies, when aerogenerators had a power potential of about 50 kW and a rotor diameter of about 15 meters, the unit price was about 20 to 40 euro cents per kWh. Now, aerogenerators have about 2 MW of power potential and a rotor diameter of nearly 100 meters, making the cost of energy production only slightly higher than conventional sources. The tariff of the special code for wind energy exceeds the conventional one by about 2.9 euro cents per kWh (about 2 cents per kWh in the United States).

Of course, they have gotten bigger, but there have also been many other technological improvements that affect their moving parts, the materials they are made of, their conversion, transformation and evacuation systems, and how they are manufactured and erected. The challenge in this field is achieve market expansion and technological improvements needed to bring the unit cost of electricity down to that of conventionally produced power. It is also a challenge to conquer the marine medium, with so-called off-shore wind power,

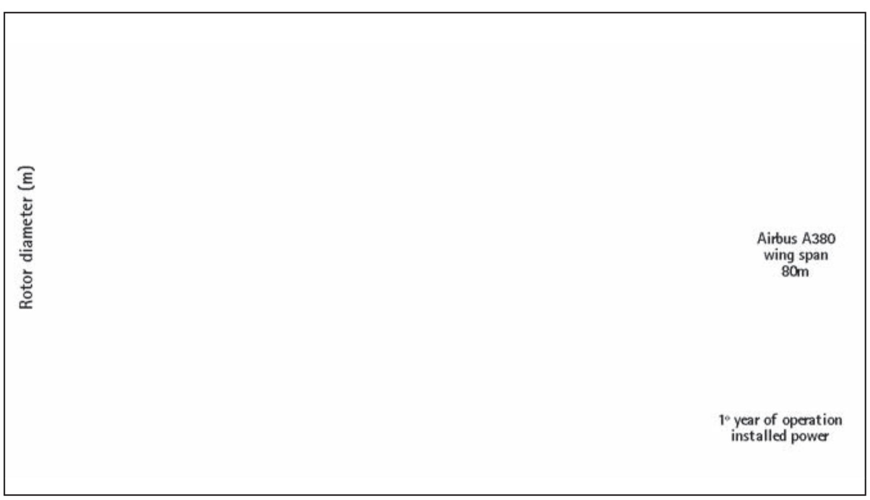


Figure 5. The progressive growth of aerogenerators. Power potential in MW and rotor diameter (twice the length of the blades) are indicated, along with the first year in which aerogenerators of each power level entered service. In Germany, there are now aerogenerators of up to 7 MW. To give an idea of their size, they are compared with an Airbus 380.

where the wind itself is better (sustained winds without turbulence), although there are considerable difficulties involved in anchoring and maintaining aerogenerators when the water reaches a certain depth, as well as evacuating the electricity they produce.

Thus, wind energy has a long way to go, both technologically and in terms of its territorial extension to other settings—the sea, of course, but also small-scale wind power, both in urban settings and in settlements that are outside the power network, or have a weak one. As happens with all renewable sources, the problem of intermittence has yet to be solved. Wind is discontinuous. In Spain, for example, wind parks only generate energy for an average of about 2000 hours a year, as can be seen in figure 6. That is something less than a quarter of the time.

Moreover, the time when electricity is being generated does not always coincide with periods of maximum demand. Nevertheless, in the windy month of March 2008, wind power counted for no less than 18.7% of the electricity generated in Spain that month, and for around 18 hours on 22 March, 9,900 MW of wind power was active, some 41% of the overall electricity being generated at that moment. And, during the entire weekend of 21–23 March, wind-powered electricity represented 28% of total production.

Solving the problem of intermittence calls for solving that of storage. The amounts of electricity we are dealing with here can be stored by pumping water into double reservoir dams, very few of which yet exist. Another system is to convert the electricity produced by aerogenerators into hydrogen that can later be converted back into electricity in a fuel cell, as needed. In fact, storing energy from renewable sources could be one of the applications for hydrogen as an energy vector. And, of course, if new devices are invented to store energy directly, such as a new generation of batteries, which we mentioned above in our discussion of transportation, then wind power could contribute to electric supplies in a manageable and still more significant way.

Renewable energy. The Sun

In terms of energy, solar radiation reaching the Earth's surface constitutes an average power of around one kW per square meter. If we average that out for all the hours of the year, in a sunny location like the south of Spain, it would add up to about 1,900 kWh per square meter per year. That is equivalent to the energy contained in 1.2 barrels of petroleum, or a coat of petroleum 20 centimeters deep. Given the enormous expanses of very sunny desert soil, as primary energy, sunshine on the Earth's surface is thousands of times greater than all the energy consumed worldwide.

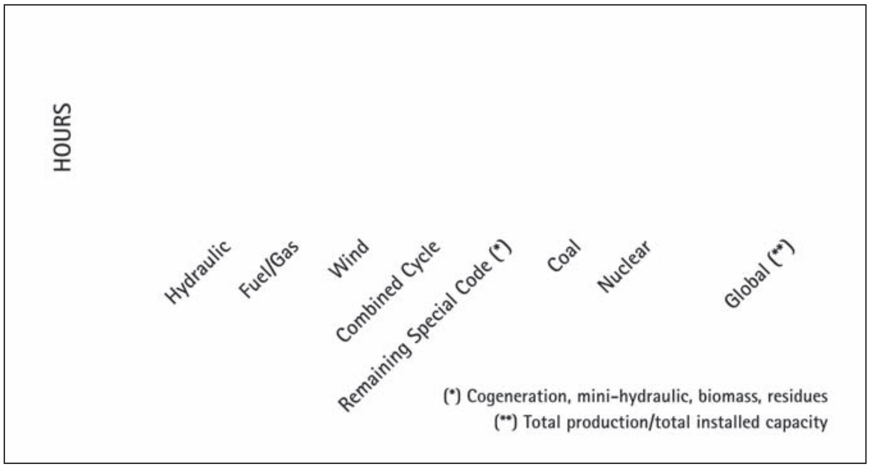


Figure 6. Functioning hours of electricity plants according to their source of primary energy in 2006 (Red Eléctrica Española).

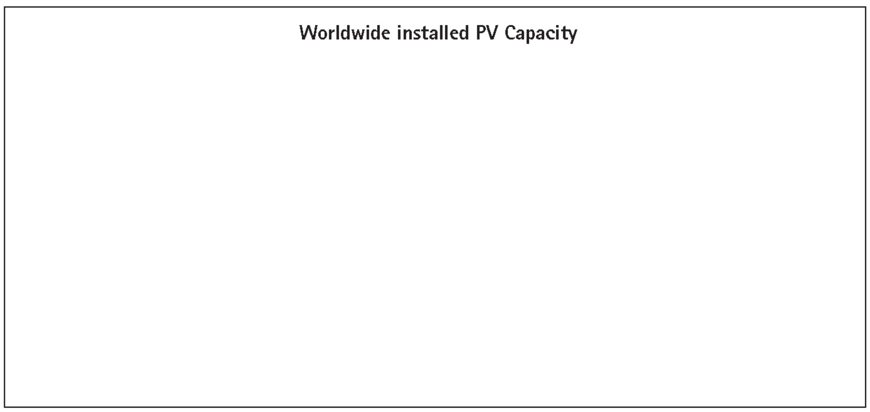


Figure 7. Installed photovoltaic capacity in the world (EPIA 2008).

There are two way of using solar energy. The first is to convert it directly into electricity using photovoltaic cells made from materials that transform the energy of the Sun's photons into electrons in a conductor. The second transforms radiant energy into high-temperature heat, which is then turned into electricity using a conventional turbine. That is known as thermoelectric solar energy.

Photovoltaic solar energy has the same drawbacks as the rest of the renewable energies: price and intermittence. The price comes from the cost of building photovoltaic cells, making it the most expensive of all renewable energies at the present time, requiring considerable public support. In fact, in systems based on special tariffs, photovoltaic energy is the one that receives the highest subsidies. On the other hand, photovoltaic technology is one of the most versatile and adaptable to urban settings due to its distributed character and the fact that it does not require large transformation systems, unlike thermoelectric devices. As to its diffusion, the total installed capacity generated by this method around the world is increasing at a dizzying rate in recent times, as can be seen in figure 7.

Germany is the country with the greatest installed capacity—3,800 MW—though Spain has undergone a very considerable expansion of photovoltaic installations over the last two years, with 630 MW at the end of 2007. That expansion, which would not be sustainable over time, is associated with a bonus of over 40 euro cents per kWh in the Special Tax Code, and the announcement that the amount of that bonus would be decreased in September 2008. Indeed, the level of the photovoltaic bonus is a good example of the importance of determining incentives in an intelligent manner. If they are too low in comparison to the real, foreseeable costs, they will not foster development of that technology, given that, as we saw above, the creation of a broad market is a necessary condition. But if the bonus is too high, it will not encourage technological advances needed to lower costs, which would in turn lower the amounts of bonus money associated with such costs.

Currently, most of the panels installed are composed of cells made from silicon, crystalline or polycrystalline wafers. The average yield of such devices in field conditions, that is, the fraction of solar energy deposited on the surface of the material that actually becomes electricity, is somewhere between 10% and 15%. There are other alternatives for improving that performance or for decreasing the cost of photovoltaic cells. One way is to explore other types of material and deposition techniques. These are known as thin-film systems, and they also use silicon—though less than conventional systems—or other more exotic and less abundant materials that improve photoelectric conversion. There are also multi-layer systems that allow the overlapping of materials sensitive to different frequencies of the solar spectrum, which increases total performance. There, the objectives are to find materials and cell-production procedures that use the smallest amount of materials, and to find materials that are cheap, do not contaminate, work well in different applications—in construction, for example—and seem best adapted to this kind of technology. Nevertheless, conventional solar panels based on silicon wafers are expected to predominate for many years to come.

Still, photovoltaic systems are expected to become more efficient quite soon, thanks to concentration techniques based on optical devices that direct solar radiation from a large area onto a much smaller photovoltaic surface, increasing its yield. At any rate, the fundamental goal of photovoltaic technology is to reduce costs, which are still very high in comparison to other renewable energies.

Another way of using solar radiation to produce electricity is thermoelectric technology. There, sunlight is concentrated on a receiver containing a fluid that heats up and then transfers that heat to a conventional turbine, generating electricity. This technology has been known for years, is straightforward and robust. And it has undergone considerable development in recent years, especially in Spain and the United States. Research into the shape of solar collectors and receivers has led to the design of a variety of devices, but here we will only consider the two most widespread technologies, cylindrical-parabolic collectors, and the tower or central receiver.

In the first case, the heat is concentrated in a tubular receiver containing fluid (normally a mineral oil with adequate thermal properties) that reaches a temperature of 400ºC, then passes through a heat exchange, generating high-temperature, high-pressure vapor that drives a turbine. In the nineteen eighties, following the second major petroleum crisis, a group of plants (the SECS complex) was built in California's Mojave desert, with a total power potential of 350 MW. It continues to work today, with no problem at all, furnishing not only electricity, but also valuable information about how such technology works. After they were put into use, and the crisis was over, no more were built. Meanwhile, in the same period, the Almería Solar Platform (PSA) was built. It is now part of the Center for Energy, Environmental and Technological Research (CIEMAT), a world-class laboratory that researches all kinds of thermoelectric technologies, trains personnel and tests all sorts of components and devices. The existence of the PSA is one of the factors that explains our country's leading role in this field.

Figure 8. The 64 MW Acciona-Solargenix Plant in Boulder, Nevada.

Figure 9. A view of the solar field at the SECS plants in Kramer Junction, California.

The second commercial plant in the world to use cylindrical-parabolic collectors is in the Nevada desert. It was built and is operated by Acciona. There are currently projects to built this type of plant in Spain, reaching a probable power potential of about 2,500 MW in the next four or five years. A considerable number will also be built in the United States, most with Spanish participation. For example, the so-called Solana Project was recently assigned to Abengoa, with two large thermosolar plants totaling 240 MW to be built in Arizona. Figures 8 and 9 give an idea of what this kind of plant looks like, and the sort of spaces in which it can be installed.

In Spain, among the numerous projects under way, is Andasol I. Nearly completed, this is the first 50 MW plant in a set designed by a consortium whose majority member is Cobra, of ACS, and a German firm called Solar Millennium. The Andasol plant, near Guadix in Granada, deals with one of the basic problems mentioned above with regard to the optimum use of renewable energies: storage. There, heat is stored, which has some advantages compared to storing electricity. In a plant with storage, when the sun is shining, part of the solar field feeds the storage device while the rest generates heat to produce electricity in the turbine. Thus, when the demand for electricity remains high after the Sun sets, it is possible to continue to generate electricity with the stored energy. In the case of Andasol I, the storage facility is able to continue generating electricity at maximum capacity for 7.5 hours, which makes the plant perfectly manageable and able to adapt its supply of electricity to meet demand.

The thermal storage employed in this type of plants is based on large quantities of melted salts (nitrates) that store heat by growing hotter, then release it again as they cool. It is a simple and safe system, although the levels of power being handled call for considerable amounts of salts. Specifically, Andasol I uses 28,500 tons of nitrates. There are other ways to store heat, including latent heat in materials that change phase, rather than heat that can be felt and is associated with temperature differences, or devices based on solids. These alternatives will be more clearly defined and improved as we gain more experience in this field.

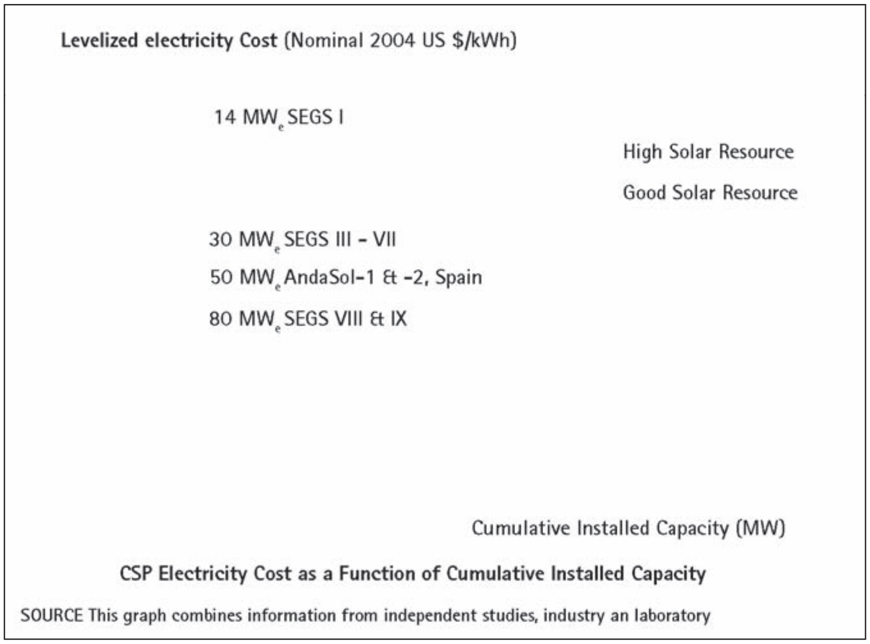


Figure 10. The estimated drop in the cost of thermoelectric electricity as a function of installed capacity according to CSP Global Market Initiative (SolarPaces 2004).

This type of solar energy is more costly than traditional energy, though less so than that of photovoltaic origin. Its bonus in the Special Tax Code is around 20 euro cents per kWh and, as with all renewable power sources, costs are expected to drop as the market expands. According to studies by SolarPaces, its cost will converge with those of conventional energy when around 15,000 MW have been installed, as can be seen in figure 10.

In order for this to happen, certain technological advances will have to be made, especially in the manufacturing of the absorption tubes, and the supply market will have to diversify. Its current narrowness impedes the development of the mechanisms of commercial competition that are essential for the improvement of fabrication processes. Improvements are also expected in heat-bearing fluids. As was mentioned above, a thermal mineral oil is currently being used, but it has the problem that, above a certain temperature (around 450º C), it decomposes. This makes it impossible to increase the working temperature, which would, in turn, increase performance when converting heat into electricity. Moreover, these oils are difficult to handle and contaminating. In that sense, there are already advanced programs to research the replacement of oil with another fluid, such as water or a gas that would allow the working temperature to be increased and simplify plant design, lowering its cost. These programs involve German and Spanish research groups working at the PSA, as well as the most important firms in that sector (see, for example, Zarza 2008). In sum, the challenges posed by the use of these technologies involve the optimization of tubes, of the heat-bearing fluid, of storage systems and collectors, and the expansion of global markets on the basis of public incentives.

Another technology being developed in the area of thermoelectric solar energy is based on a central receiver at the top of a tower. A field of rectangular heliostats focuses solar radiation on the receiver from which the resultant heat is extracted by a liquid or gaseous fluid. The first such plants operating commercially were built in Sanlúcar la Mayor (Seville) by Abengoa: PS-10 and PS-20, with capacities of 11 MW and 20 MW respectively. For the time being, their costs are higher than those of plants based on cylindrical-parabolic collectors, and their degree of development is somewhat slower. But they offer certain advantages, such as being able to operate at higher temperatures, and adapting to more irregular terrain. The process of improvement and optimization—still in its initial stages—is similar to what was described above, including the thermal storage devices, which are conceptually similar.

Nuclear fission

Along with fossil fuels and renewable energy sources, nuclear fission is presently an essential energy source in the most developed countries. In Europe, 30% of electricity is nuclear, while in Spain it is 20%. Nuclear energy has some advantages that make it attractive as part of the future energy menu. The main ones are its total independence of any kind of climatic or environmental conditions, which allows a plant to operate for a very high percentage of the hours in a year, as can be seen in figure 6. That explains how the nuclear sector in Spain, with an installed capacity of 7,700 MW, generated almost twice as much electricity as wind power, when the latter has a total installed capacity of 15,100 MW. Another positive factor to be taken into account is its relative independence from oscillations in the price of uranium because, over the useful life of the plant, fuel counts for barely 6% of the total building and operation costs. In figure 11, the cost of the raw material for nuclear plants is compared to that of other conventional energy sources.

Moreover, this is an industrial sector with considerable experience in safety, despite widespread opinion to the contrary. In fact, the most advanced and demanding safety protocols come specifically from the nuclear industry.

Its drawbacks are well known: from an economic standpoint, the enormous investments necessary to build the plants, with a very long period of depreciation, are the counterpart to the low cost of its fuel; from an environmental and safety standpoint, the potential seriousness of accidents when the plant is functioning—although there are very few—and, most of all, the generation of radioactive residues that are difficult to manage and store. The problem of residues is certainly the most serious drawback and, in public opinion, it has undoubtedly predominated over the more positive aspects of this energy technology. It therefore merits special consideration.

Generally speaking, there are two types of residues—short duration and long duration. Typically, the former have a half-life of 30 years (the half-life is the time that has to pass in order for a material's radioactivity to be reduced by half). The majority of residues fall into this category, and the universally accepted solution is to store them in a depository until their activity has dropped to the level of natural background radioactivity. El Cabril, in Cordoba, is a typical example of this sort of storage and, when properly managed, its effects on the environment are imperceptible.

The serious problem is residues with very long half-lives, measurable in tens or hundreds of thousands of years. That is the case of depleted fuel rods. Some countries have chosen to build Deep Geological Depositories (DGD) sufficiently hermetic to guarantee the stability of residues deposited there for geological time periods. Clearly, the difficulty lies not only in finding places that meet the necessary physical conditions, but also in getting a part of public opinion to accept this. Other countries, such as Spain, choose to build a Temporary Centralized Depository (TCD) at surface level, allowing safe custody of those residues for much shorter periods of time—about a century—while techniques are perfected for eliminating them or transforming them into inert matter. Indeed, the management or elimination of residues is one of the problems whose resolution is most pressing if we want nuclear energy to have a future. The principles of such a transformation are known—techniques of separation and transmutation—but their development is barely beginning. This is due to the complexity of the technology, and also the difficulty of experimenting with nuclear technology in the face of such strong public opposition.

In fact, the development of technology to neutralize the most dangerous residues is linked to what are known as fourth-generation reactors. Right now, there are 439 functioning commercial reactors in the world—104 in the United States and 59 in France—with a power capacity of 373,000 MW. Thirty-eight more are under construction in Finland, France, Eastern Europe and Asia (World Nuclear Association 2008). All of them are of second or third generation, operating with (slow) thermal neutrons and using the isotope ^{235}U for fuel. That isotope is very rare in nature, constituting only 0.7% of natural uranium. The most promising lines of the fourth generation operate with rapid neutrons and can use most existing residues for fuel, such as ^{238}U, which is the most abundant uranium isotope (it is the other 99.3%). They can even use thorium, which is even more abundant, and that alternative has been seriously studied in India. Fourth-generation reactors and devices using rapid-neutron technology—for example, accelerator driven systems (ADP)—could potentially solve many of the problems associated with residues and would be immune to an eventual long-term scarcity of conventional fuel (if we could use both types of uranium and not only the scarce fissionable isotope, reserves would automatically multiply by more than one hundred).

The unarguable challenges in the nuclear sector are thus the treatment of residues and fourth generation reactors, which are related to each other from a technological standpoint. But advances in this field take time and, at a level that can be exploited commercially, they will not be available for another twenty to thirty years. So most Western countries, with the noted exception of France and Finland, are faced with the difficulty of an improbable resurgence over that entire period, which could lead to a loss of knowledge and technical capacity. In contrast, many other parts of the world, especially Asia, will continue to build and operate second and third-generation nuclear reactors.

Conclusions

Given the situation described in the previous paragraphs, it seems neither realistic nor sensible to suggest abandoning any of the available energy sources, with the due precautions and in the time frames permitted by each technology. In the short term, there is a pressing need to prepare substitutes for petroleum by-products in the transportation sector, where we cannot avoid considering second-generation biofuels. Coal will continue to be an abundant, though potentially highly contaminating source, and it is necessary to make advances in its use with the capture and storage of CO_2.

But at this time, the most important challenge may well be to encourage renewable energies in order to make them a significant percentage of the total supply. This is still far from the case, but Spain is playing a leading role. Wind has proven its potential as a massive source of energy and must continue to broaden its presence on the global market. Solar energy is more abundant, but has the problem of dispersion discussed above. At some point in the near future, it will have to become the dominant and truly massive, sustainable

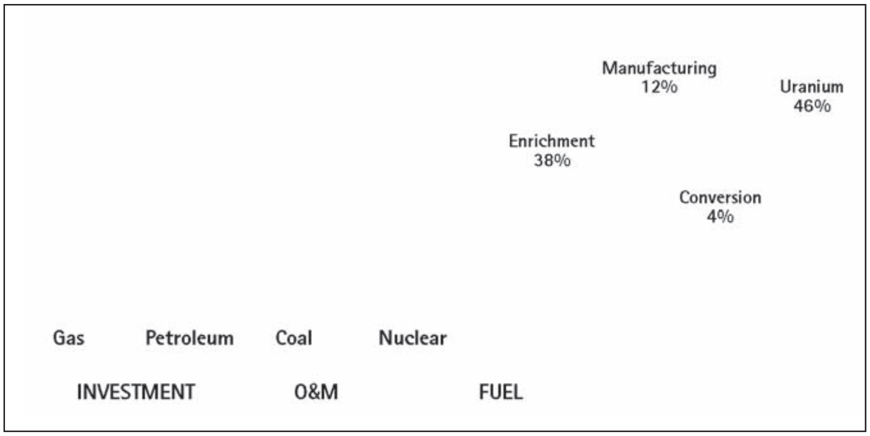


Figure 11. The distribution of costs in different types of electric power plants.

and unlimited renewable energy source. That will call for the solution of technological problems that limit its spread and affect its current high price, and will require decisive public support. In order to manage renewable energies and to meet the future needs of the transportation sector, energy storage technologies already occupy an outstanding place in energy research programs. So much so, that no sustainable scheme is conceivable without sufficient mastery of this sort of technology.

Unfortunately, nuclear fusion will arrive later on, and it is not likely to help alleviate the situation in upcoming decades. But fission reactors exist. They have been tested and have evolved toward ever-safer designs that use fuel more efficiently. I do not believe that it would be reasonable, in a period of energy crisis, to abandon this energy source, even though its survival largely depends on its public image. In the short term, the main problem is how to prolong the useful life of existing reactors and their replacement with third-generation technology. But the fundamental challenge in this area is to advance towards rapid fourth-generation reactors that make it possible to recycle residues and use fuel in an optimum manner.

No miracle has arrived to instantly solve the problem of supplying energy to humanity. It must be approached from all possible directions, and not only from a technological standpoint, as political and financial considerations are also important for each and every one of the available energy sources. Nor should we forget the educational and informational aspects, which are so important in a situation in which most of the population considers the energy problem to be solved and takes its continued supply for granted, yet refuses to accept the sacrifices inevitably associated with energy production from the standpoint of both economics and land use.

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