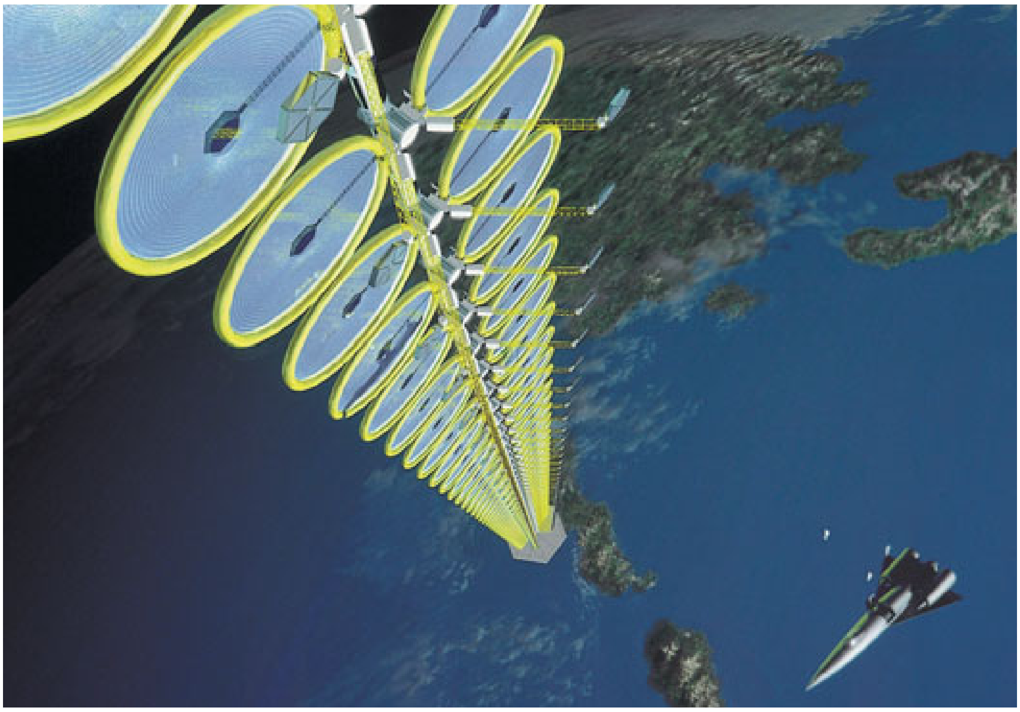
Energy and technological breakthroughs : science fiction or foreseeable future?

In the energy sector, a technological breakthrough can have considerable social and economic consequences, such as in real breakthroughs in energy storage.



Nasa's solar orbital power station. Launched at the end of the 'sixties, will the idea of sending the solar energy collected by huge panels of cells to Earth via microwaves become an everyday reality in the XXIst century?

Pat Rawlings/CIEL & ESPACE

In science, in technical matters or in economics, long-term prediction is difficult if not impossible. So much the better, since unexpected discoveries are often the most interesting ones! Simple extrapolation of a near future is a dangerous game. Suffice it to recall that, at the time of the first oil crisis in the 'seventies, economists had predicted a far greater electrical consumption in France for the end of the XXth century than has proven to be the case. Interesting as it may be to make predictions or to dream up scenarios, the reality is often a very different matter. Unpredictable technological or scientific breakthroughs can profoundly alter society's evolution and have a very significant impact on our daily lives: what springs to mind, among many examples, are the discoveries of the transistor, the laser, nuclear energy… To dream up such a breakthrough is more difficult than to extrapolate it. In the latter instance, the type of breakthrough and when it might emerge have to be planned. Twenty years ago, no one would have predicted that today it would be possible to move atoms one by one. And even if Jules Verne imagined Moon travel, the concretization of this idea took quite a bit of time. So, the goal of envisaging certain technological breakthroughs in the energy field and the influence that they might have give us food for thought. Just possibly, these considerations might have more in common with science fiction than with a foreseeable future.

No universal source

Energy is a complex field involving scientific, economic, political and environmental factors. There is no universal solution for a country's energy supply. It would be ideal if the desire to satisfy each energy need led to an optimization of available resources, as well as of their prices and their environmental impacts. It must be noted that diversification of energy sources contributes to ensuring a certain price stability as well as supply.

In addition to those that are currently accessible, there are a certain number of energy sources which could be envisaged for the long-term, starting with controlled thermonuclear fusion (see *Very long-term energy perspectives*). Others could eventually become usable – although currently a far cry from being economically viable – as in energy from waves, or that drawn from the differences in temperature between the surface and the depths of the ocean. This is also the case for spatial photovoltaic energy: cells in space would be permanently oriented toward the Sun, while the energy produced would be transferred *via* microwave beams to Earth, with a yield of around 50%.

A technological breakthrough allows for a substantial cost reduction on a given source, thus rendering it competitive. Earth's photovoltaic energy offers just one example. The current cost of kWh produced, close to ten times greater than the cost using fossil or nuclear fuel, only makes this type of energy of interest under specific circumstances, for example at isolated sites. If it were possible to manufacture photovoltaic cells furnishing one kWh at a competitive or even a lower price than that offered by other energy sources, they would play an important role in electricity production. Although prices are regularly decreasing, economic competitivity is still nowhere in sight. Such competitivity would require a technological breakthrough that could come from organic cells created by screen printing, thin mineral layers that are inexpensive to manufacture. Even if they are called upon to do more than injecting electricity produced within the network, cells are still only one of the components of a stand-alone photovoltaic system, and are only one-third of the total system price. Batteries, indispensable for storage and use in the absence of sun, are also an important factor. Thus, any and all advance that reduces cell costs and increases storage performance is worthwhile.

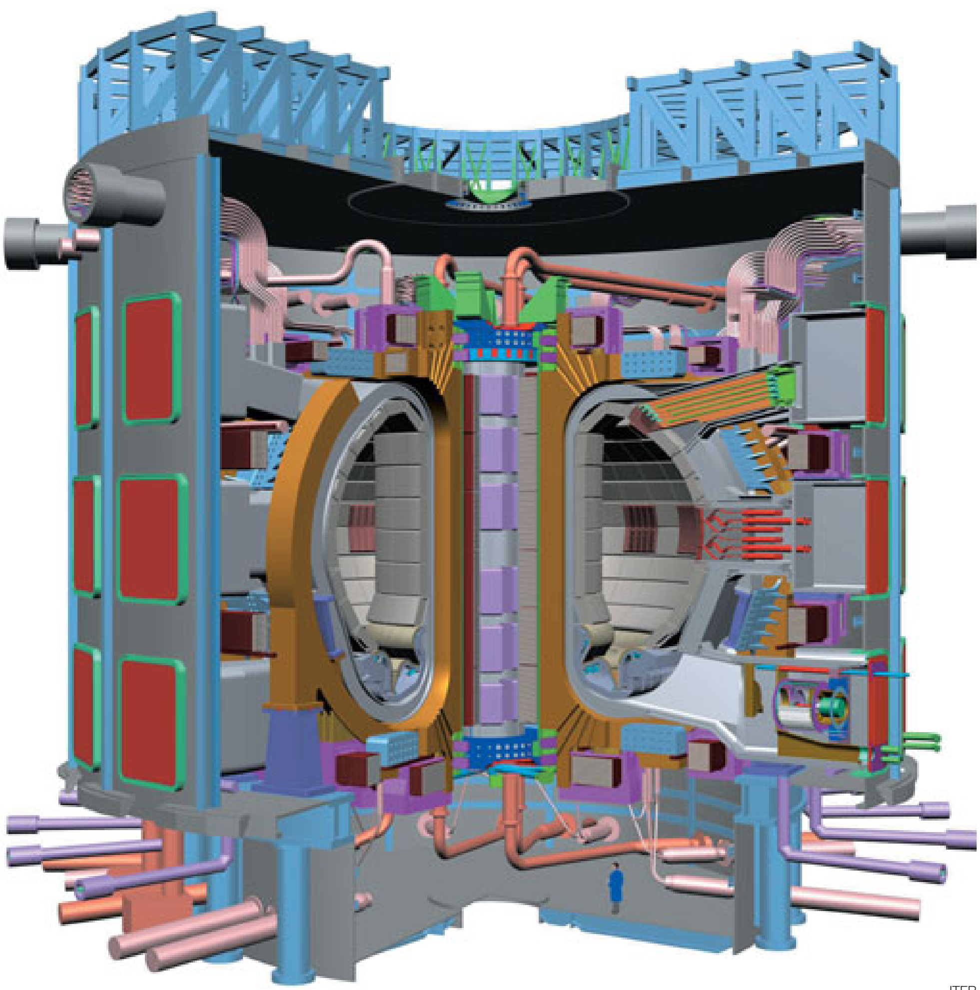
The current downside to using fossil energies is that they increase the greenhouse effect, which could bring about significant climatic alterations (box A, ***The greenhouse effect***). There have already been changes in the content of carbon dioxide over time; it is not so much the changes that matter, but rather the speed at which they are produced due to human interference. As has been seen in the past, if the change is produced slowly, nature has the time to adapt. If it occurs quickly, as appears to be happening at present, nature is put at significant risk. There are two extreme methods for avoiding this anthropic increase in the greenhouse effect. The first is to reduce emissions by optimizing user systems (for example, having cars emit less and less CO_2), and diminishing need, in particular through use of public transport, or by utilizing energies that give off less greenhouse gases, wherever possible. The second method is to trap the gas emitted by transformation into a non-polluting type, for example a solid, or in confining the gases underground, a solution which is currently being studied. The problem is a difficult one for emissions that spread out. If the trapping technologies were available at a reasonable price, clearly the problem of fossil energy use would be seen differently.

Storage: the weakest link

Hydrogen appears to be the energy vector of the future (see *The Promises of hydrogen*). Along with the conventional modes of production, the more futuristic methods based on hydrogenase must also be considered (see *Production of hydrogen from water and light via microorganisms*). Currently and self-evidently, electricity is the most used vector (and could also be used for hydrogen production). Unfortunately, it is difficult to store it in great quantity and it must be used immediately. Two technological breakthroughs would allow for its optimum use.

The first regards transportation, in the course of which a considerable amount of electricity is lost. These losses could be diminished through use of high-temperature superconductors, a solution that is not yet cost-effective. The second concerns storage, unquestionably the current weak link in the field of energy. At present, the only large-scale "storage" involves moving water into dams. New means of storage or a significant improvement in the technology would allow energy to be produced and used differently. If it were possible to have electrochemical or other batteries with a volume capacity greater than factor 10 of those currently available and at a competitive price, the electric car would be reality and its autonomy would be superior to that of current cars. Transportation pollution would be significantly lower, as would be the cost per kilometer traveled. This type of battery could also be used in the home. The energy would be sto-

View of the international experimental thermonuclear reactor ITER (in its ITER-FEAT economical version).



ITER

red during certain times, programmed, and then used throughout the day. This would allow peak time impact to be spread out and smooth out electricity use.

Another way of storing energy would be in the form of antimatter (see *Very long-term energy perspectives*). However as the research currently stands, infinitely more energy must be supplied in order to produce antimatter than can subsequently be recovered. Additionally, its storage in magnetic bottles is also energy consuming. Even if it were feasible to store energy in this form, the problem of recovery would be present, since annihilation of matter and antimatter, in particular, produces highly energetic photons.

"Nuclear" -style storage?

The energy liberated in elementary chemical reactions from oil, gas or coal combustion is of the order of electron volts (eV). The energy released in nuclear reactions corresponds to mega-electron volts (MeV), a million times greater. Thus, it is possible to produce – for the same mass – on the order of 1 million times more energy using nuclear energy. Energy storage through electrochemical reactions amounts also in eV for elementary reactions. What remains to be seen is whether "nuclear"-style storage can be achieved. This would represent a technological breakthrough of major interest in the energy field. The answer could lie in certain nuclei with **isomeric** states (shape isomers) at several MeV above the ground state, such as the hafnium 178 nucleus over a 36-year period in a state at 2.4 MeV above the ground state.

Rhenium 198 has a half-life of 300,000 years and could store 1 terajoule per liter for several thousand years! The problem is that, although it is known how to store that energy, it is not known how to recover it on demand. To do so, it would be necessary to be able to modulate the period of the shape isomer. If this were to be achieved, the process could then be generalized to other nuclear excitations. In this way, the problem of nuclear waste would be solved, as it would suffice to modulate the nuclei period to transform long-term waste into short-term waste. Could not the impossible for one generation of physicists be possible for the coming generation(s)?

Savings : yes, but…

Energy savings lower the consumption that corresponds to a given service. They also sometimes create the possibility of satisfying other needs, thus leading to an equivalent amount of consumption. So it was that a report by the Plan Commission showed that, whereas diesel engine cars consume less than gas engine cars, diesel drivers take advantage by driving more: Thus, the overall saving is practically nil. Electronics, with a major role to play in optimization of consumption, is still underutilized. Integrated circuits offer by far the best example of energy economy coupled with better and better performance. Finally, substantial savings could be made in business if, instead of making real meetings as we usually do, we would do virtual ones using all the technologies of virtual reality. Teleworking should thus allow for a reduction in travel, which would lead in turn to energy savings.

Breakthroughs and progress

As difficult as it may be to predict a technological breakthrough and its consequences, consideration must be given to the profound disturbances it may produce. The introduction of electronic calculators, which sounded the death knell for calculating rulers and books of numeric tables, illustrates this mechanism to a tee. Thus, where wealth steps in, the space in its wake is filled by poverty. It appears that this is always so with progress. With every advance, with every breakthrough comes a crisis and a global increase in wealth.

Christian Ngô
Technological Research Division
CEA/Fontenay-aux-Roses

Very long-term energy perspectives

Beyond what are sometimes incorrectly referred to as new energies, fundamental research offers a glimpse into a hypothetical and remote future of exotic energy sources, calling notably for antimatter. Meanwhile, it will be wise to have developed nuclear breeder reactors, already mastered, and to have demonstrated controlled thermonuclear fusion, which researchers hope will occur before the middle of the XXIst century.

The extremely fast evolution of knowledge makes any stab at long-term prospects for energy solutions extremely problematic. In order to grasp the incredible acceleration of knowledge in our generation, consider that the great majority of scientists throughout history are alive today. However, it is possible to attempt to carve out some guidelines that can, at the least, illustrate the path of future research into energy.

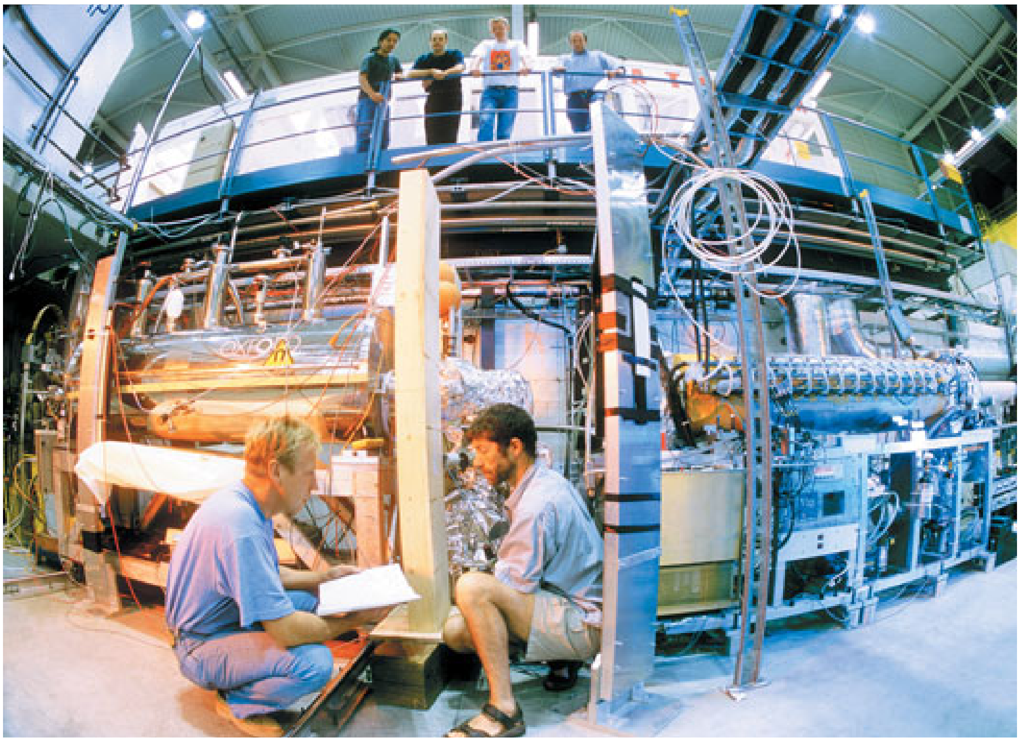
Today, Mankind uses its earthly resources with great abandon, not seeming to lose much sleep over very long-term solutions. Although there is no doubt that fossil energy reserves are today partially underestimated by *proven* reserves, it cannot be ignored that, in a very few years, there will be a drastic reduction in the number of countries producing oil and, to a lesser extent, in the number of countries producing natural gas. Thus, one of the major goals to be pursued must be research into lasting and accessible sources of energy. Today, with a reasonable extrapolation of knowledge, it would appear that there are several solutions either existing or apparently feasible.

Breeder reaction and fusion

The first of these solutions concerns breeder reaction. This must be envisaged if we hope for energy independence to take us through the millennium. Paradoxically, breeder reaction, a political and ecological hot potato, appears necessary in this day and age if there is to be an *ecological* exploitation of radioactive material resources found on Earth. A second line of research could be in controlled thermonuclear fusion, doubtless the future energy source. Its raw material reserves are substantial and can last into the millions of years. This very ambitious solution – to create a miniature sun in a controlled environment – requires, and doubtless will continue to require, the efforts of many generations of physicists and engineers before arriving at a viable solution for energy production. Beyond these relatively conventional solutions of breeder reaction and fusion, we must remain open to the idea that the energy of the future may call for radically new solutions. Even more uncertain than the prospective solutions outlined in the foregoing, the examples that follow can only be regarded as illustrative.

Hope for a full energy conversion

The recent announcement of the CERN, the European particle physics laboratory, of the implementation of the *Antiproton Decelerator* (AD), which slows and cools particles rather than seeking to speed them up, elicited several bold extrapolations as to the possible end uses of antimatter. However, as compared to conventional fuels, and even nuclear, the return in energy production when it encounters matter is optimal, representing as it does a full conversion to energy. Nuclear fuel only converts a very small fraction of its mass into energy. In spatial applications, for example, mastering such a compact source of energy would constitute tremendous progress. But it is clear that we are far from the *Star Trek* era, in which the space vessel is propelled by an antimatter reactor (at a speed faster than the speed of light!). CERN, whose energy consumption represents a not



CERN

The Athena experiment in antimatter (antihydrogen) production at CERN, near Geneva. The antiprotons coming from the antiproton decelerator are collected in the superconductor magnet (left). The positron accelerator (right) supplies the positrons.

unappreciable fraction of that of the Geneva city, has not been able, over its existence, to produce more than a microgram of antimatter, proof that there remains a long row to hoe in this field. In fact, antimatter, not existing in its natural state in our world, cannot constitute a direct energy source. However, it might be used for energy storage (see *Technological and energy breakthroughs: science fiction or foreseeable future?*).

Catalytic conversion from matter to antimatter?

Nonetheless, particle physicists are trying to understand the processes by which the "passage" is made between matter and antimatter. The first opening is in the standardization of the fundamental forces. Unfortunately, this passage appears to require a passage through a form that is very expensive in energy – the messenger X and Y bosons of grand-unified theories (GUTs) – which considerably slows down the disintegration process (happily for our survival). But the Russian physicist Valeri Rubakov quickly realized that a hypothetical particle, the magnetic monopole, would allow a spectacular catalyzation and acceleration of the passage between matter and antimatter. If we knew how to produce such a catalytic converter – which we are notably incapable of doing today – we would have a practically infinite source of energy, allowing us to transform specimens of matter into antimatter at will.

Black holes and vacuum energy

A second example of total conversion from matter into energy is given by the thermic emission of low mass black holes. Suggested in 1972 at Princeton by the Israeli physicist Jacob Bekenstein and theoretically proven in 1974 by Stephen Hawking at Cambridge, this emission might just appear as an intellectual oddity. Imagine, however, making an object the size of a mountain (approximately 10^{15} kilograms of matter) collapse under the weight of its gravity. A black hole of this size would emit extremely intense thermal radiation, around ten thermal gigawatts, without nuclear waste, as the emission would occur in the form of gamma radiation! This power, equivalent to that of 10 nuclear power plants, would be generated until such time as the mini-black hole were to be fully depleted by consuming itself, in a time frame far greater than the current age of the universe!

If this type of solution appears even today to be no more than a daring extrapolation of the physics predicted by our equations, it should be recalled that Einstein's famous $E = mc^2$ equation was also initially considered to be a theoretical relation that would have *a priori* no concrete application. In the same light, how could we dream today of mastering microelectronics without understanding the quantum behaviour of Fermi-Dirac's apparently esoteric solids and distributions? Likewise, we still do not have a complete and satisfactory understanding of the origin of particle masses, and we have no way of determining if what we call the "vacuum" might not in fact conceal a practically infinite source of energy, as this "vacuum" may in fact be **metastable**. Understanding this notion of vacuum energy and that of the generation of masses of particles thus represents one of the major objectives of subnuclear physics. This is all the more so because 1998 brought with it a great surprise: the experimental highlighting of what appears to be a long-distance gravitational repulsion.

Our goal here is not to propose examples of energy physics solutions that are immediately attainable. Rather, we are stressing the fact that the long-term energy independence of a country, as well as its ability to innovate in this field, may depend crucially on the reinforcement of its research and development effort.

Gabriel Chardin
Physical Sciences Division
CEA/Saclay