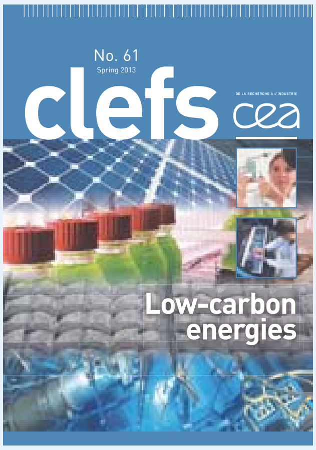
No. 61
Spring 2013

clefs

DE LA RECHERCHE À L'INDUSTRIE

Low-carbon energies



Clefs CEA No. 61 – SPRING 2013

Main cover picture
To break the shackles of its dependence on fossil energy, France must begin an energy transition to achieve energy savings and energy efficiency, based on synergy between nuclear energy and the renewable energies (low-carbon energies). CEA is actively involved in this process.
L. Chamussy/Sipa-CEA – G. Lesénéchal/CEA – P. Avavian/CEA – P. Allard/REA-CEA

Inset
top: Installation of characterization tools in one of the experimental houses on CEA's Incas platform at the French National Solar Energy Institute (Ines: *Institut national de l'énergie solaire*).
P. Avavian/CEA

bottom: Development and validation of the battery pack management system for the CEA demonstrator vehicle.
P. Avavian/CEA

Pictogram on inside pages
© Spécifique

Review published by CEA
Communication Division
Bâtiment Siège
91191 Gif-sur-Yvette Cedex (France)
Phone: + 33 (0)1 64 50 10 00
Fax (editor's office): + 33 (0)1 64 50 17 22

Executive publisher
Xavier Clément

Editor in chief
Martine Trocellier
martine.trocellier@cea.fr

Scientific committee
Susana Bahri, Bernard Bonin, Hélène Burlet, Gilles Damamme, Catherine Fillet, Étienne Klein, Fabienne Lebrun, Gérard Sanchez

Iconography
Florence Klotz

Production follow-up
Lucia Le Clech

Subscription
Subscription (printed French version) to *Clefs CEA* is free.
Requests for subscriptions should be addressed, preferably *via* Internet, by using the form available at the site: http://www.cea.fr
or by fax to: + 33 (0)1 64 50 20 01

Translated into English by
AéroTraduction

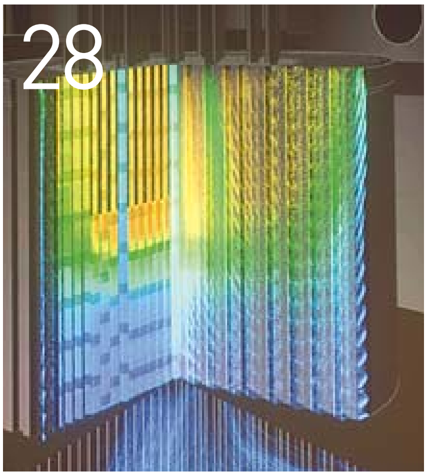
ISSN 1625-9718
Clefs CEA (Web)

Design of electronic media
Calathea - Paris
Phone: + 33 (0)1 43 38 16 16

RCS Paris B 775 685 019
Head office: Bâtiment Le Ponant D,
25, rue Leblanc, 75015 Paris (France)

Low-carbon energies

I. ENERGY PRODUCTION



II. TRANSFORMATION, STORAGE, TRANSPORT AND DISTRIBUTION

III. IMPROVED USE OF ENERGY

CEA, a major player in the field of research, development and innovation

Standing as it does as a major player in the field of research, development and innovation, the French Alternative Energies and Atomic Energy Commission (CEA) is active in four main areas: low-carbon energies (nuclear and renewable), information technologies and health technologies, the design and operation of very large research infrastructures, and defense and global security. For each of these four main fields, CEA relies on first-rate fundamental research and offers support to industry.
CEA operates 10 research centers in France, distributed across the country. It is developing numerous partnerships with other research organizations, local authorities and universities. In this respect, CEA is a stakeholder in national alliances coordinating French research in the fields of energy (Ancre), life and health sciences (Aviesan), digital sciences and technologies (Allistene) and environmental sciences (AllEnvi). Particular emphasis is also placed on education and information of the public at large, in order to promote the transfer of knowledge and foster the science-society debate.
Widely recognized for its expertise in its areas of competence, CEA is fully engaged as a player in the European Research Area and is making its presence increasingly felt on the international scene.

Foreword

As we all know, the availability of sufficiently abundant, easily mobilized and competitive energy is a primary condition to the economic and social development of a country. In spite of sobriety efforts and improvement of energy efficiency, the world is bound to face increasing energy needs. By 2050, the population of the planet will have increased by more than 30%. More than one billion people legitimately yearn to strongly increase their consumption and reach satisfactory standards of living. The constraints are very severe – more than 80% of the world's primary energy consumption now relies on fossil fuels, when their depletion and their price increase are unavoidable and their massive consumption increases health, environmental, and climate change risks. The proof is that demand increased by more than 25% between 2002 and 2010.

France imported 23 billion euros of fossil fuels in 2005. In 6 years, our country almost trebled its expenditures to reach 62 billion euros in 2011, that is, 90% of our 2011 trade deficit. In the mid- and long run, the price of fossil fuel can only become more disadvantageous to our country. The production of shale gas and tight oil – if it is indeed carried out – will only postpone the deadline to a few decades at most. The world must reduce its fossil fuel consumption as soon as possible and turn to domestic, carbon-free energy – in France's case, to renewable energies and nuclear energy. We will benefit from this transition. It will result in significant improvement of our trade balance, strong reduction of health, environmental and climate change impacts, and the extension of the availability of fossil fuels, so that we can keep on using them for uses for which they are not easily replaceable. I strongly defend the idea of an energy mix based on nuclear energy and renewable energies that would use both sources complementarily in the best possible way. We must make up our mind soon and progressively secure the necessary funding, and develop, thanks to our R&D investments, the indispensable technological solutions that will highlight our assets.

> **"I strongly defend the idea of an energy mix based on nuclear energy and renewable energies that would use both sources complementarily in the best possible way"**

Under the current debate on energy, it is essential that we consider a wide range of solutions and develop synergies between energy sources. Nuclear energy would constitute a continuous, massive and programmable source of electricity and heat, and meet the basic energy needs that cannot be reduced of highly urbanized and industrialized areas. Renewable energies would constitute an intermittent and diffuse source and meet – when combined with adapted storage capacity that reduces the size of interconnected networks – more flexible needs. The local consumption of renewable energies in close proximity to production must be encouraged.

In 2010, CEA became the French Alternative Energies and Atomic Energy Commission. It participates actively in the thought on energy transition through the French National Alliance for Energy Research Coordination (Ancre: Alliance nationale de coordination de la recherche pour l'énergie) and contributed directly to the French thought on the "Energy Roadmap 2050" in fall 2011. We will continue our work in this direction with the national debate on energy transition launched in November 2012. Under this debate, the Minister for Ecology, Sustainable Development and Energy asked Ancre to shed light on potential future solutions for France in an international and European context. The approach should focus on scientific and technological aspects and highlight the potential solutions offered by disruptive technologies and innovations. The energy transition is an inevitable change to which CEA, thanks to its expertise, wishes to contribute as a major player in energy research and innovation.

CEA manages research in the field of nuclear energy. Even after the Fukushima accident, we must keep in mind that nuclear power remains a promising energy. We must draw all lessons from this accident so as to guarantee, in all circumstances, the perfect safety of the operation of facilities.

Studies are actively carried out on fission energy through the ASTRID Generation IV reactor prototype project, and on fusion energy to support the ITER project.


L. Godart/CEA

CEA manages with the same determination research on traditional and concentration photovoltaics, solar thermodynamic power, and solutions for thermal storage.

To facilitate the instantaneous adaptation between electricity supply and demand, CEA has made a top priority of the development of smart electric grids and the various massive or dispersed electrical energy storage systems. Electrochemical storage systems (batteries, fuel cells, etc.) are the objects of intensive research.

This innovation-focused approach is based on disruptive technologies with the use of nanomaterials and disruptive systems.

In the field of transportation, the aim is to replace heat-powered engines with electric or hybrid vehicles, to develop the use of hydrogen, the performance of fuel cells, second-generation biofuels (especially with the Syndièse project) and third-generation biofuels with, for instance, microalgae, which are other large-scale storage solutions for renewable energies.

The possibilities of smart coupling various technologies often come from a thorough analysis of lifestyles. The coupling of photovoltaic solar panels installed on roofs to provide electricity for parked electric vehicles is an excellent example. This experiment is carried out at the French National Solar Energy Institute (Ines: Institut national de l'énergie solaire).

Last but not least, the thought and research conducted at CEA focus on the optimized and efficient use of energy by using nuclear heat, bio-inspired materials or nanosciences, in fields that represent the largest share of our fossil fuel consumption such as transportation, industry, or housing.

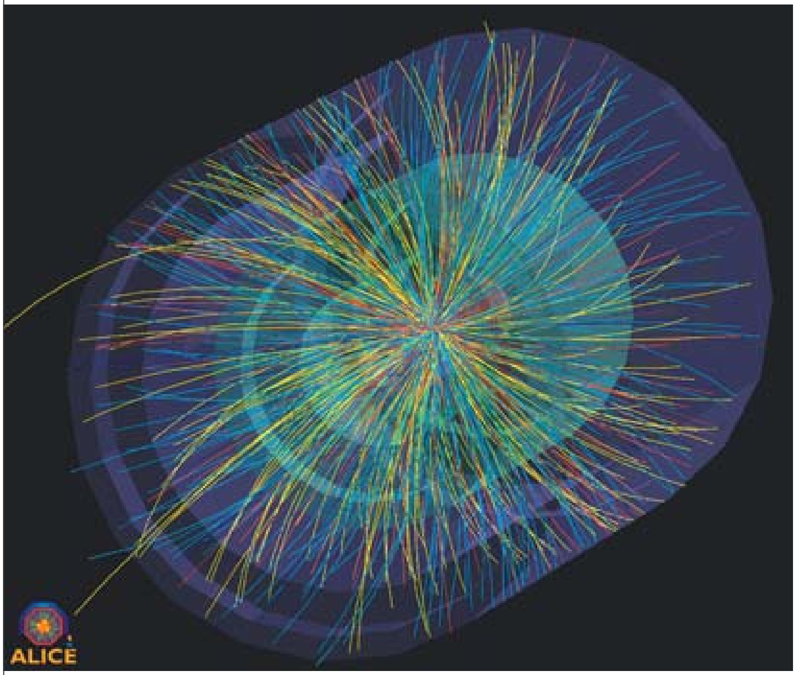
The actual national objective is to replace fossil fuels – which constitute today two thirds of France's energy consumption – with renewable energies, provided that we significantly improve their economic competitiveness. In 2013, the cost increase generated by renewable electricity will amount in France to at least 3.6 billion euros (about 4% of the total consumption) and to at least 18 billion euros for our German neighbors (about 18% of their total energy consumption). The increasing use of renewable energies, which are mostly used for electricity production, will inevitably lead to an increase in the share of electricity in our consumption (today about 50%) and automatically reduce the share of nuclear power – 79% in 2012 – even if nuclear-generated electricity production remained close to current volumes.

I would like to thank everyone who contributed to this fascinating issue of *Clefs CEA* and invite you to examine CEA's involvement and achievements in the field of low-carbon energies. The energy challenges we have to face deserve that each one of us be fully informed of the prospective scientific and technological developments in the fields of nuclear and renewable energies. There is no doubt that both these energy sources will be complementary components of increasing importance in the French and international energy mixes.

> **Bernard Bigot**
CEA Chairman

The power of the **concept of energy**

Energy is an abstract concept whose applications transformed our lives and which occupies a central position in the field of physics. **It is a value with a multitude of forms which obeys the law of conservation** – it cannot be destroyed nor created from nothing – and its understanding is the result of a conceptual process that has taken more than two centuries, based on the labors of a whole host of researchers, physicists and mathematicians.



©2010 Cern

Consequence of the conservation of energy, the invariability of physical laws over time enables the physicists to recreate the primordial universe by causing particle collisions, such as those caused here between heavy ions in the Large Hadron Collider (LHC) at the Cern in Geneva.

The word energy has been in the vocabulary of physics, or more precisely in that of mechanics, for about three centuries, although it was of humble origins.

18th century mathematicians introduced it into French. Jean Bernoulli was probably the first to have used this term. In a letter written to the Jesuit father Pierre Varignon, dated 26th January 1717, the Swiss physicist and mathematician defined energy as the product of the force applied to a body by the displacement experienced by this body under the effect of this force, what we today call **mechanical work**. This initial scientific definition of energy, applied only to static forces and equilibrium, was however too limited to be able to colonize the entire world of physics. Consequently, energy only became a core concept of this science a century and a half later, when it was clearly established that it obeyed an unbending rule, that of a law of conservation.

The conservation of energy

When two systems interact, they exchange energy. During this interaction, the sum of the energy variations in the first system is always the opposite of the sum of the energy variations in the second, such that the **total energy is conserved**. Thus, a ball falling through the terrestrial atmosphere transforms its weight energy into heat. This heat is transmitted to the air *via* the friction forces due to electromagnetic force. The potential energy of the ball's gravitational force is converted into electromagnetic potential energy and then into the kinetic energy of the air molecules.

German physicist Max Planck, future inventor of the quantum, was the first to understand the essential scope of this law: in addition to its various empirical manifestations, energy must first of all and above all be abstractly considered as a value which is conserved. In a work published in 1887, entitled *Das Prinzip der Erhaltung der Energie* (*The Principle of the conservation of energy*), he wrote: "I will only speak of the concept of energy in that it can be linked to the principle which gives its title to this essay, assuming therefore that the meaning of the concept of energy in physics is derived above all from the principle of conservation which concerns it(1)". This thus leads to the formal modern definition of **energy**: a quantity


S.P.L./COSMOS

Max Planck (1858-1947), the father of quantum theory, according to which energy exchanges between radiation and matter are not continuous, but in packets or quanta, and Albert Einstein (1879-1955), the primary developer of this theory, who in particular demonstrated that mass is one of the forms of energy.

---

(1) Quoted by the science historian Yehuda ELKANA in "The Conservation of Energy: a Case of Simultaneous Discovery?", *Archives internationales d'histoire des sciences*, Paris, 23, 1970, p. 31-60.

which can be associated with any system and which depends on various parameters characterizing the status of this system at the time in question. It in particular depends on the positions and speeds of the parts of the system and their mutual interactions. Its most fundamental property is to remain constant over time when the system is isolated.

This discovery was the culmination of a lengthy and laborious process, taking no less than 40 years. It cannot be really attributed to a single author, but rather to several researchers working in relative isolation and with widely differing preoccupations. Faraday, Carnot, Joule, Mayer, Helmholtz, Thomson and Rankine are among the best-known of them.

Force, power and energy

As is often the case in physics, where the name plays an essential role, the clarification of the concept of energy triggered an intense semantic debate, punctuated by theoretical advances, after which the words force, power and energy, which for so long had been jumbled together, were each given a separate, precise definition.

In 1847, the German Hermann von Helmholtz published a memorandum entitled *Über die Erhaltung der Kraft* (*On the conservation of force*) in which he lays out what was subsequently to become the **first principle of thermodynamics**, that is the conservation of energy. However, Helmholtz does not talk of energy, but of power or force, this latter term having had a two-fold meaning for a long period of time: both the ability to produce movement and a reservoir of potential. Considerable conceptual work into heat and how it is exchanged between systems was to be necessary for a clear distinction to be made between these notions(2). **Power** is the flow of energy, the rate at which it is delivered. More precisely, it is the quantity of energy per unit of time supplied by one system to another. The consequence of this definition is that two systems with different power will be able to perform the same work (the same energy), but the more powerful system will do so more rapidly than the other. From a mathematical viewpoint, power is equal to the product of an **effort** (a force, a torque, a pressure, a voltage, etc.) by a **flow** (a speed, an angular velocity, a flow rate, a current).

Noether's theorem: the invariability of physical laws

In the early 20th century, a crucial theorem further consolidated the conceptual strength of the law of conservation of energy. In 1918, the German mathematician Emmy Noether established that any invariant according to a symmetry group must necessarily be associated with a quantity that is conserved in all circumstances, in other words a law of conservation.

Let us, for example, state that the laws of physics are invariable with the translation of time, in other words, that they do not change if the choice of the moment of reference, the origin from which the durations are measured, is modified. This means that the laws governing any physical experiment can never depend on the particular moment at which the experiment is carried out: as far as they are concerned, one moment must be the same as any other, such that there is no particular moment that can serve as an absolute reference for the others. If Noether's theorem is applied to invariance by translation of time, it then follows that its direct corollary is the conservation of energy. Let us imagine, however, that the force of gravity were to vary periodically, being very weak each day at midday and very strong at midnight. It would then be possible to raise a load to the top of a building at midday and drop it at midnight. The energy thus gained would be greater than the energy expended. There would no longer be any conservation of energy.


Office of Press- and Public Relations, University of Göttingen

German mathematician specializing in abstract algebra and theoretical physics, Emmy Noether (1882-1935) demonstrated in 1918 that physical laws and therefore more particularly the law of the conservation of energy, are invariable over time.

The law of conservation of energy thus has a theoretical depth which goes far beyond its usual formulation: it expresses the **invariability of physical laws**, in other words their permanence over time. Physicists in particular use this to explore the early universe: by causing violent collisions between particles, they create – or more accurately recreate – in a very small volume and for a very short period of time, extreme physical conditions (very high temperature and very high energy density) which were those which prevailed in the distant past of the Universe. As physical laws have not changed, the particles generated by the shock energy(3) relive the same violent kinematic turmoil(4) which is exactly the same as that

---

(2) In common parlance, a degree of confusion persists, with the notions of energy and power still not being clearly differentiated. It is thus that the popular imagination sees TNT as the symbol for chemical energy. However, one kilogram of TNT contains ten times less energy than one kilogram of petroleum. This does not mean that significant power cannot be obtained from it: in contact with air it explodes, so that all of its energy is released in a very short space of time. One kilogram of petroleum contains more energy but releases it more slowly: the corresponding power is thus far lower.

(3) By applying the formula $E = mc^2$, whereby mass is one possible form of energy.

Fundamental interactions and energy

What quantity of matter is needed to provide a given quantity of energy? The answer to this question is heavily dependent on the interaction used. Let us assume that we want to obtain 1 kWh, in other words the kinetic energy of a ten-ton truck moving at 100 km/h.

If **gravitational interaction** is used, or other mechanical forces, the quantities of matter necessary are of several tens of tons. Thus 10 tons of water must be dropped from a height of 40 meters to obtain 1 kWh of electrical energy in a hydro-power plant, in which the efficiency is 85%. To obtain the same quantity of energy with a wind turbine, one would need to collect all the kinetic energy from 20,000 m^3 of air – or 27 tons – arriving at a speed of 60 km/h.

If one is using **electromagnetic interaction**, the quantities of matter to be used are about one kilogram. For example, the combustion of fuels provides heat, at about 1 kWh per tenth of a kg. Figures comparable to those of biological or heating energy: a good meal, or one kilo of food, provides about 1 kWh, which is then burned off by the organism, and 1 kWh of heat is required to melt 10 kg of ice or boil 1.5 kg of water.

For **strong interaction** (nuclear interaction), the quantity of matter necessary is even smaller. During the fission reaction in a nuclear power plant, 10 mg of natural uranium are required (it contains 0.71% uranium 235) to obtain 1 kWh of heat. This figure can be divided by a factor of 100 in the case of a breeder, by recovering the plutonium fission energy produced by neutron capture by the uranium 238. Finally, in the case of fusion, such as D-T (deuterium-tritium) fusion, which takes place in a tokamak, one milligram of fuel is enough to obtain 1 kWh.

experienced by their counterparts when the Universe was in its infancy, thus spectacularly rejuvenating an infinitely small portion of space-time(5).

The forms of energy

As the energy of an isolated system remains constant over time, one should not really talk of the production or consumption of energy, even though this is all too often the case, because energy cannot emerge from nothingness and cannot disappear. In any case, there are only changes in the form of the energy or transfers of energy from one system to another.

Producing electrical energy in a hydro-power plant in fact means that the potential energy of the water in the dam is transformed into kinetic energy in the penstocks, and this kinetic energy is then transferred to the turbines and to the generator rotors, before finally being transformed into electrical energy. The viscosity of the water, friction and the Joule effect subtract a small part of the energy from this flow, which is converted into heat.

Similarly, consuming electrical energy to operate a television set in fact means transforming it into the light energy emitted by the screen (*via* the kinetic energy of the electrons output by the cathode), the acoustic energy emitted into the ambient air (*via* the kinetic and potential energy of the loudspeaker diaphragm) and above all into heat of no use at all (primarily by the Joule effect).

Of the various forms of energy liable to be transformed into one another, a distinction can be made between those which are stored in matter and those which are manifested during a transfer from one subsystem to another.

Of the energies stored in matter, we could mention the internal energy of a fluid, which is dependent on its temperature and pressure, the chemical energy of a fuel, the nuclear energy of a piece of uranium, the electrochemical energy of a battery, the potential energy of the water in a dam before falling, or the kinetic energy of a vehicle. Most of these energies are only very indirectly accessible.

In the second case, this is for example the heat radiated into the air by a radiator, the work exchanged between a piston and the fluid it is compressing, or the electrical energy circulating along a line.

Controlling and using forms of energy

The purpose of the energy technologies is to control the various energy transformation processes in order to reduce the share of unusable energy forms and increase the share of the form one wishes to extract. The first principle of thermodynamics drastically limits the possibilities, with the conservation of energy demanding that equilibrium be achieved. Other constraints come from the **second principle of thermodynamics** whereby a closed system loses its capacity for change as and when it changes (its entropy can only increase). Finally, others are linked to the hierarchy of the intensity of the forces of nature (box).

In short, in order to talk about energy in physics, one really needs to talk about physics as a whole.

> Étienne Klein
Saclay Institute of Matter and Radiation (Iramis)
Physical Sciences Division
CEA Saclay Center

---

(4) Kinematics is the study of the movement of a body through space as a function of time, without considering the causes of this movement.

(5) In quantum physics, a void is not empty: it contains particles said to be virtual, which are present but which do not have enough energy to really exist. If two particles from a high energy accelerator collide, they deliver their energy to the quantum void. Consequently, the virtual particles it contained become real and escape. The vacuum which was cold owing to the expansion of the Universe, the temperature of which has been constantly falling, suddenly warms up and the particles which were dormant in it regain the vitality they enjoyed when the Universe was in its infancy.

Searching for the **ideal energy mix**

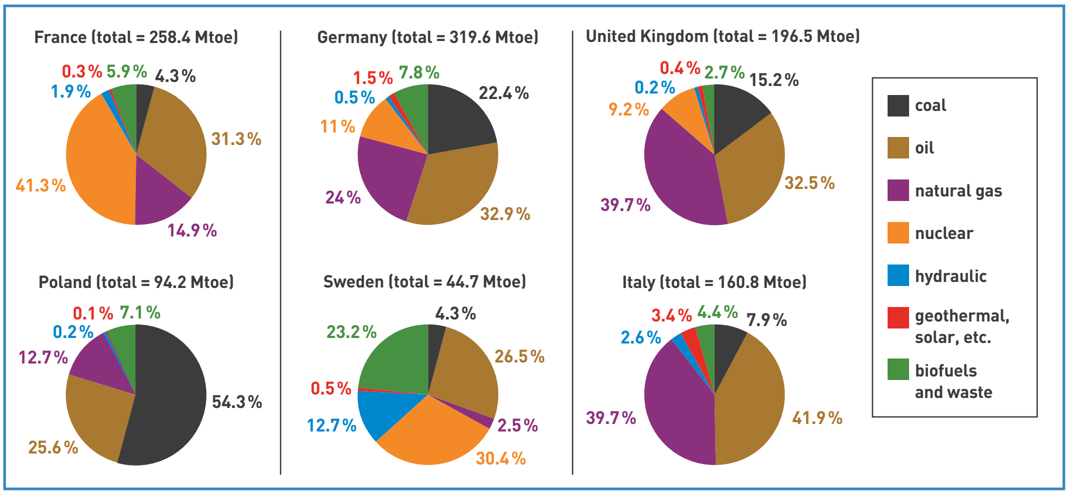
The concept of an ideal energy mix might at first glance appear relatively simple. Misleadingly simple. **Depending on the chosen criteria – reduction of greenhouse gas emissions, technological reliability, energy costs, security of energy supply, acceptance by society, and so on – and the respective weight given to each one, there are in fact a range of ideal mixes.** For France, which is still 50% dependent on fossil energies for its primary energy consumption, the Government has decided to initiate a process of transition, boosting the share of low carbon energies, but with which mix? The work and the studies carried out by the researchers at CEA make a significant contribution to answering this question and underline the importance of the technical-economic assessment when defining the "target" for the French energy mix.

The ideal energy mix is without doubt a social and political concept. It depends on priority goals such as reducing greenhouse gas (GHG) emissions. The present process of the National Debate on Energy Transition in France could promote such an ideal mix. This debate, initiated by the Government, following the first Environmental Conference on 14 and 15 September 2012, was launched on 29 November 2012. It was organized into three phases: an "information phase", a "general public consultation phase" completed in June 2013, and a "summary and definition of recommendations phase", which will lead to a planning Bill in the end of 2013. The organization of this debate, with the very large space given to discussions among the different stakeholders, highlights the social need of sharing views, objectives, and visions of the society around energy future.


P.-F. Grosjean/CEA

In order to break out of its dependence on fossil energies, France must initiate an energy transition based on energy economy and efficiency, through synergy between nuclear energy and renewable energies. CEA is working actively on this. R&D into nuclear reactors of the future is thus essential, in order to design the generation IV reactors which will consume the depleted uranium present on the French territory and the plutonium from the spent fuel of today's nuclear power plants, thus potentially supplying the NPP fleet for 5,000 years without having to import any new fuel. Here, adjustment of valves in the IRINA facility located in the CEA Cadarache Center, for sodium tests.

In addition, the target itself is moving: the "weights" of the different criteria at the root of the ideal mix are changing. At any given moment, and provided that it is officially defined, this ideal mix or, more pragmatically, this target mix, involves the definition of the objective of the economic, technical (R&D) and regulatory policies enshrined in a program. It is preferable for this ideal/target mix to be fine-tuned gradually and smoothly, in order to prevent waste of resources and potentially very high economic costs. In recent years, three principles have emerged from the work being done on such a mix: the importance of the long-term, that of taking account of uncertainties



F. Thais/I-tésé/CEA

Figure 1.
Primary energy mix of several European countries per type of energy in 2009 (source: International Energy Agency IEA). The total supply of primary energy, expressed in Mtoe, does not take account of heat and electrical exchanges. The primary mixes of the European countries have widely differing structures. They remain primarily carbon-based.

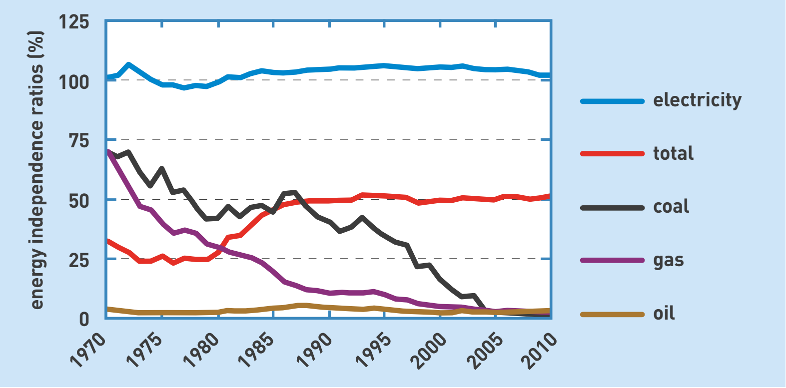


Figure 2.
Development of French energy independence. In 2010, the level of energy independence (ratio between national production of primary energy and primary consumption uncorrected by climatic variations) stood at 51.2%, as against 50.3% in 2009 and 50.9% in 2008. It benefits primarily from the good level of electricity production.

France energy balance for 2010, General Commissariat for Sustainable Development, Observation and Statistics Department (SOeS), 2011

and risks, and the need for economic cost-benefit studies in order to assess them. In operational terms, even if the essential role of R&D in attaining the targets has been clearly established, it still needs to be better quantified.

The French mix is still primarily fossil

The energy mix of a State is often represented by the balance of the primary energies(1) consumed (primary mix).

An initial observation is that similar economic conditions in the European countries have not today led to similar mix structures (figure 1). From this, one must deduce that the energy targets themselves remain very closely linked to the specificities of each individual country, even if a semblance of convergence was given shape in the Climate and Energy Package.

A second observation is the still carbon-intensive nature of the mixes, including in France. The total primary energy consumption of France amounted to 265.8 Mtoe in 2010, 43% of which came from primary electricity(2) of nuclear origin, 31% from oil, 15% from natural gas, 7% from renewable energies (EnR) and waste, and 4% from coal. The final consumption(3) amounted to 170 Mtoe.

Thirty-five percent of the French primary mix is consumed by the energy sector. If we exclude the 5% utilized for non-energy uses (chemical industry, naphtha for plastics, bitumens for roads, etc.), the rest (considered as 100%) can be broken down as follows: 43% in the residential-service sector, 32% in transports, 22% in industry and 3% in agriculture.

The final electricity is produced by nuclear sources (75%), renewables (14%, mainly hydro-power) and fossil energies (11%).

Over the past 20 years, a gradual slowdown in the rise in final energy consumption has been observable: whereas it progressed by an average of 4 Mtoe per year during the 1990s, it was only 2 Mtoe in 2001 and 2002. It then stabilized and dipped significantly in 2009. Today, the economic crisis involves a decrease of this consumption.

These structural changes were accompanied by a significant improvement in energy independence as of the 1980s, with the ramp up of the nuclear power plant fleet (figure 2).

The energy mix assessment criteria

Despite a very low-carbon electricity sector (see *Electrical energy and CO_2 emissions*, p. 11), the energy mix of our country is heavily dependent on fossil energies. It has two major characteristics: the emission of a large quantity of GHG (more than 5 tons/inhabitant per year, as against a global world average of 4.3 tons) and the need for large-scale imports of energy products, as France has virtually none, other than renewables and nuclear power. Thus in 2012, our energy bill was 62 billion euros, which should be compared with that of our trade deficit, standing at 70 billion euros.

This observation itself contains two of the main criteria for assessing the mix in our country: reducing GHG emissions and controlling import levels. There is a relatively broad consensus among all the stakeholders concerning the identification of all these criteria. The *Commission Énergies 2050*(4) (the "Energies 2050" French Commission), which recently studied this question on behalf of the Government, used a chart comprising the following criteria:

- reduction of our GHG emissions;
- control of imports and guaranteed security of supply for the country;
- feasibility (realistic technologies at a given date, investments that can be funded);
- enhancement of our competitiveness (lower total cost of electricity production, which has an impact on GDP (Gross Domestic Product), jobs, the competitiveness of our industries which consume large quantities of electricity, and so on);
- flexibility, including with regard to the various technological options;
- social acceptability (liquid hydrocarbons, shale gas, nuclear, etc.).

Behind all of this lies the core question of the sustainability of a mix. Many of these criteria are linked to this point.

The uncertainties: from the ideal mix to the target mix

Implementing a policy aiming for the ideal mix is now and will in the future be faced with a certain number of challenges and uncertainties concerning:

G. Rolles/REA

Construction and transports, two sectors that are major consumers of fossil energies in France and the cause of more than 50% of carbon dioxide (CO_2) emissions, are the primary targets for the development of renewable energies. The integration of solar energy into buildings is one of the key areas in which CEA is concentrating. Here, a low-consumption house installed on the Incas experimental platform on the French National Solar Energy Institute (Ines: Institut national de l'énergie solaire) site in Chambéry (Savoie *département*). It is fitted with photovoltaic and thermal solar panels and a local energy management system.

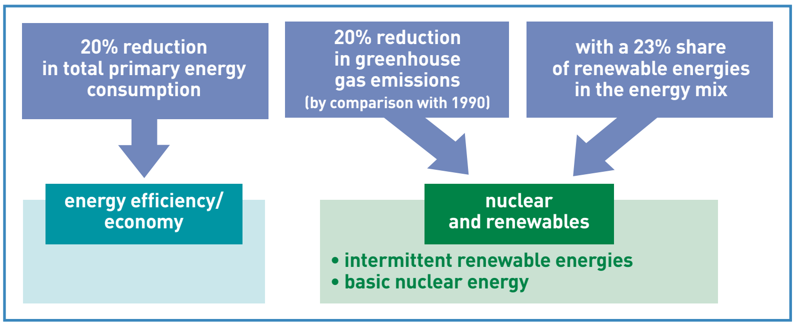
---

(1) Primary energy: energy usable prior to any transformation. This includes fossil energies (coal, oil, gas), nuclear energy and renewable energies (hydraulic, solar, wind, geothermal, tidal power, biomass) and waste.

(2) Primary electricity: electricity produced by the primary energies.

(3) Final energy consumption: all energy consumption by the end-users (residential-service, transport, industry, agriculture, etc.). It is equal to the primary energy consumption minus the energy consumption necessary for the transformation of primary energies into energy products usable by the end consumers.

(4) *Commission Énergies 2050*: created in October 2011 by Éric Besson, at the time Minister for Industry, Energy and the Digital Economy "in order to conduct an analysis of the various possible energy policy scenarios for France with regard to the 2050 time-frame".



CEA

Figure 3.
The main objectives for French energy mix development. A basic energy functions all year round.

- world energy prices and the geopolitics of resources;
- the world's economic context;
- energy risks and accidents;
- technological developments (shale gas and oil, energy storage, carbon capture and storage);
- changing public perceptions of energy issues;
- the level of success of the new energy strategies (e.g. in Germany).

The ranking of the above criteria and the sensitivity to these uncertainties mean that there are many differences in the way the possible mixes are assessed and thus in how one attempts to define an ideal or more practically an optimum mix (if it does exist). Preferences vary widely from country to country, from one group of individuals to another, between locations (town or countryside), between levels of development (Northern and Southern countries), domestic resources (availability of gas, **uranium**, etc.), the vagaries of history (West and East Germany) and so on. There is thus no single mathematical function of well-being that can be maximized: no identical preferences and no fully transparent weighting method between these preferences, neither geographically, nor in terms of time-scale.

Over and above these criteria, it is important to consider flexibility and robustness, which are often poorly understood. The guarantee of good resistance to shocks, sometimes referred to as resilience, is another parameter taken into consideration in energy policies. It can lead to particular choices, not only in terms of diversification, or supply structures and energy system technologies, but also in terms of R&D, so that, when the time comes, a wide range of national or European technologies and skills is available.

Last but not least, the concept of the ideal energy mix is not an abstract idea, because energy is not the first question to which our societies are attempting to find an answer. Therefore the search for an ideal mix must be seen, at any given time and place, as a path to a target mix, a moving and often hazy target… in order to remain flexible. The ideal/target European mix will not be defined tomorrow: however, a set of goals and of different possible paths matching these goals!

What ideal/target mix for France?

The ideal/target mix is a useful concept for guiding the nation's long term efforts. The experts are looking at a dual future. For the next twenty years (the 2030 mixes), one will have to implement the best of existing technologies or those directly derived from them, given the time-scale of an energy system. In forty years' time (the 2050 mixes) technologies will have changed considerably and the socio-economic system may also have been extensively transformed.

Indeed, the ideal mix is not a prescriptive concept in our country. However, many commitments can be considered as roots of the major trends of the ideal mix, as a philosophy of action. This in particular concerns the commitments which apply European GHG emissions reduction targets. They are generally well-known (figure 3). We should simply recall that they comprise targets for 2020 (the 3 x 20 rule in the Climate and Energy Package) and for 2050 (factor 4 reduction of GHG emissions).

This leads to a range of targets (such as those of the multi-year program for electrical production investments set by the French Government – *Programmation pluriannuelle des investissements de production électrique*), economic policy instruments (subsidies, taxes, purchase prices, etc.) and rules and standards applicable to these targets. Simulations are being carried out by specialized institutes to illustrate the possible ways to be taken, in accordance with the public will (figure 4). But a quite large room may remain with respect to the practical path of the economy, along the trends. The approach followed by the authorities consists in establishing an economic framework within which the players make a number of choices in accordance with the economic rules of the European Union. Nonetheless, this approach in certain cases considers quantitative targets (wind and solar farms in **MW**, contribution of biofuels in %, etc.) and aims to implement instruments to ensure that the economy converges on the specified values. These targets are defined per energy source and per sector:

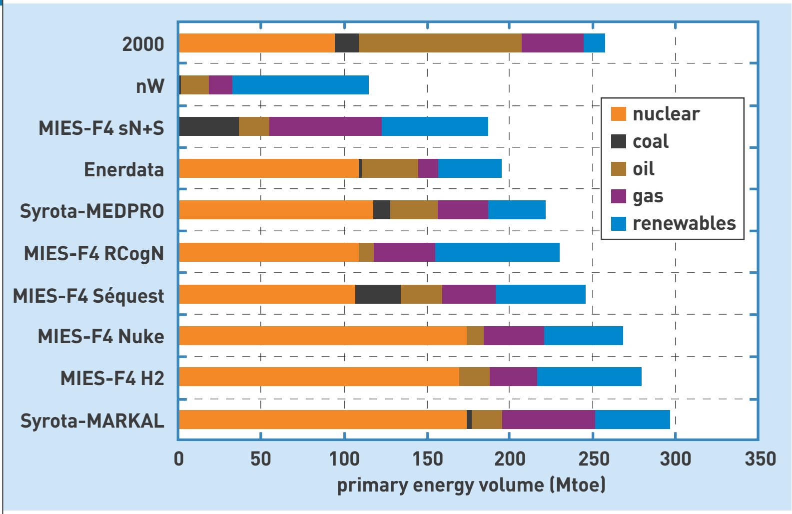
- in all the sectors, reducing of the total energy consumed as much as possible (efficiency, economy, alternatives), maximizing the share of domestic energies and reducing the carbon level of the mix;
- in the electrical sector, increasing the share of renewables and **cogeneration** for the share using fossil fuels, the volume of which will have to diminish;
- in transports, reducing consumption, increasing the share of 2nd and eventually 3rd generation biofuels, electrifying the fleet and considering the question of hydrogen, which has recently found itself back under the spotlight;
- in the residential-service sector, making greater use of decentralized renewables, insulating, renovating, improving building construction methods, controlling and regulating consumption and replacing old heating methods by more efficient systems, such as heat pumps;
- in industry, promoting efficiency, replacing the least-efficient energies and processes...

Given the relative weight of these sectors in French energy consumption, it is mainly the carbon footprint of transports (70% of energy consumption of petroleum products) and the residential-service sector that needs to be reduced. The electricity sector, which is the subject of particularly close attention, has an excellent level of performance, due to the position of nuclear and hydro power.

In short, a low number of studies show that the energy mix of the future is not an "energy cake" of a given size, to be shared by the primary energies. This view is often implicit in the debates on the respective shares of low-carbon energies in electricity. This is a two-fold

© PhotoDisc

The transports sector, which is 95% dependent on oil, is also a key target for increased use of renewable energies. CEA is in particular working on 2nd and 3rd generation biofuels. A pre-industrial pilot for the production of 2nd generation biofuels from lignocellulosic biomass (forestry residues, agricultural waste), is currently under development (Syndièse project).



CIRED

Figure 4.
The French primary energy mix in 2050 according to various scenarios, with the goal of dividing GHG emissions by four:
- 2000: situation of the mix in 2000.
- nW: scenario established by négaWatt for the Government in 2006, based on non-renewal of the nuclear power plants, energy economy and efficiency, and the deployment of renewables.
- MIES: exercise conducted by Pierre Radanne for the Interministerial Mission on the Greenhouse Effect (MIES: *Mission interministérielle sur l'effet de serre*) in 2004, according to five scenarios. MIES-F4 sN+S: abandoning the nuclear option with carbon dioxide sequestration (CO_2); MIES-F4 RCogN: balance between the use of nuclear power and the development of cogeneration and renewables; MIES-F4 Séquest: development of CO_2 sequestration; MIES-F4 Nuke: increased development of nuclear energy and electricity penetration in all uses, including transport; MIES-F4 H2: development of a hydrogen sector supplied by the nuclear power plants.
- Enerdata: in this scenario established by Enerdata for the Government in 2005, emissions continue to rise until 2030 and then fall even more sharply. This study illustrates a post-Grenelle trajectory.
- Syrota-MEDPRO and Syrota-MARKAL: study submitted to the Government in 2007 by a commission at the Strategic Analysis Center (*Centre d'analyse stratégique*), chaired by Jean Syrota, using the MedPro (coupled with POLES) and Markal-Times models.

error because, on the one hand, electricity production can be all the greater as it helps reduce the carbon footprint of sectors such as transport or industry and, on the other, the synergies between low-carbon energies create value when developed jointly.

Figure 4 presents the trends highlighted by various exercises to model France's ability to meet the “Factor 4” target in 2050(5). These scenarios indicate that relatively differing paths will be able to attain the targets set, determined primarily by the available technology and the behavior of the economic players. In these scenarios both the size of the cake and the components of the cake are different. In addition, these scenarios also have to be economically acceptable.

The central role of R&D

In the conclusions of its report(6), published in February 2012, the French *Commission Énergies 2050* highlighted the role of R&D in the development of the French energy mix. According to this commission, it is essential to use R&D to obtain room for maneuver with the technologies which will be maturing as of 2030. One of the keys to success lies in the development of new areas of excellence and the preservation of those which are strong today. R&D and training are another two key areas. R&D would thus appear to be an essential aspect, for reasons ranging from the operational availability of new technologies to the strategic importance, for the country and for Europe, of developing innovative technologies that will stimulate growth and create jobs (figure 5). The scenarios developed by the French National Alliance for Energy Research Coordination (Ancre: Alliance nationale de coordination de la recherche pour l'énergie), show in addition that matching the factor 4 goal will need to implement fully new technologies (or “Game Changers”), which do not exist today(7).

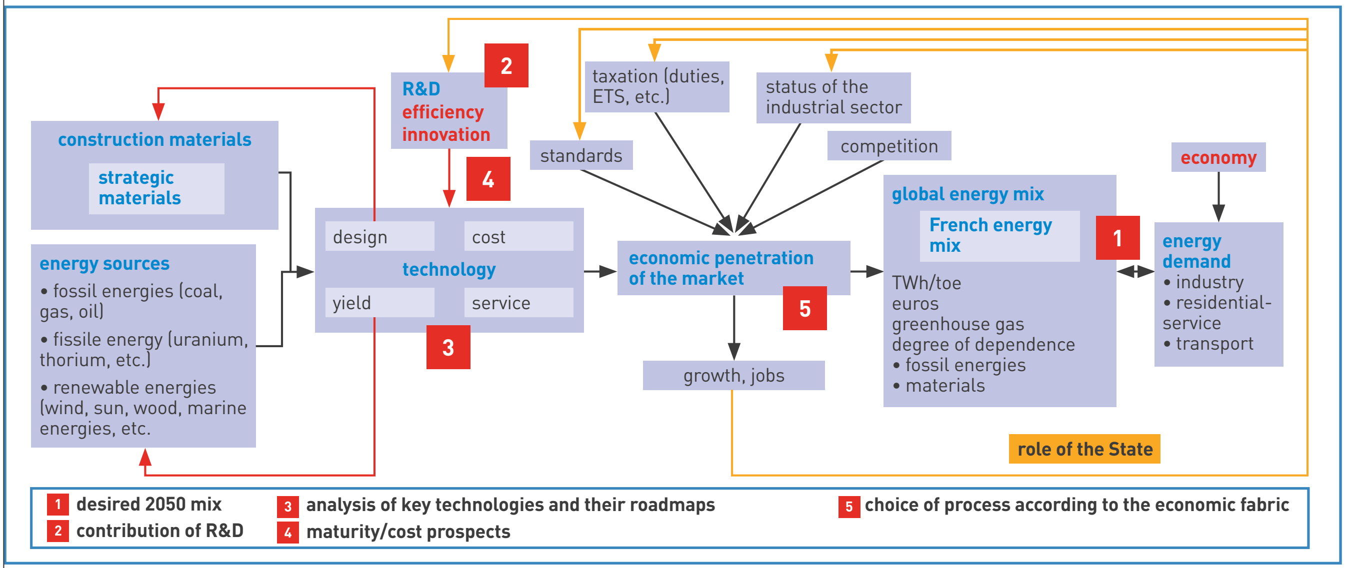
These concerns and findings are at the heart of CEA's research in the field of energy. Its R&D work is almost

---

(5) Sandrine Mathy, Meike Fink and Ruben Bibas, “Quel rôle pour les scénarios Facteur 4 dans la construction de la décision publique ?”, *Développement durable et territoire*, Vol. 2, n° 1, 2011. Can be downloaded from: http://www.imaclim.centre-cired.fr/IMG/pdf/20110924-MathyFinkBibas-RoleF4ScenariosInPublicDecisionMaking.pdf.

(6) Jacques Percebois and Claude Mandil, “Rapport énergies 2050”, 2012. Can be downloaded from: http://www.strategie.gouv.fr/content/rapport-energies-2050.

(7) Can be downloaded from: http://www.allianceenergie.fr/presentation-des-scenarios-energetiques-de-l-ancre.asp.



I-tésé/CEA

Figure 5.
Links between R&D and energy mixes. This diagram presents the role of R&D in the process to define the mix of the future. It underpins the technological development of the energy system and is also one of the levers available to the public authorities for promoting progress towards the chosen target mix.

exclusively focused on non-fossil technologies, such as nuclear energy, solar energy or the use of biomass and hydrogen techniques, without forgetting energy storage and grid management.

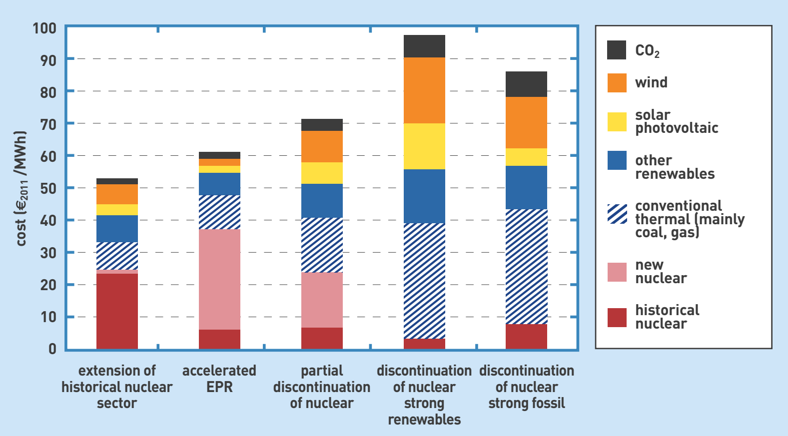
CEA's actions consist in plotting a course for a low-carbon future in complete transparency, with a highly ambitious goal for the decades 2030-2050, or even beyond, with fusion as a complement to the generation IV nuclear technology. It is part of a vision of an overall energy system, deploying considerable means to support management of energy demand and management of physical flows and also information (process control, smart grid, etc.). Finally it enables advantage to be taken of the possible synergy between the various low-carbon energies, in particular nuclear and renewables: management of intermittence, optimization of storage *via* hydrogen or biofuels, improvement of the photovoltaic solar lifecycle through refining of the silicon of the cells by nuclear electricity…

Even if the role of R&D is well recognized, its quantification nonetheless remains one of the major challenges for this period. Work drawing on the new models for the future is in progress but has yet to deliver its full potential.

Economic assessment of energy choices is needed

The sustainability previously mentioned comprises a strong economic component. A technology will only have a chance of developing if its cost eventually becomes low enough to be accepted at the main levels of society, whether directly, by bringing down household and corporate costs, or indirectly, by minimizing the impact on the country's balance of trade and creating jobs. If we consider the cost of electricity (for example, in €/MWh), it would appear that this varies significantly depending on the electrical mix scenario chosen (figure 6).

The importance of the technical-economic assessment led CEA to create the Institute for Techno-Economics of Energy Systems (I-tésé). This dedicated institute has the ability to build and assess a variety of mixes, for the short and above all the medium and long terms. One of its priorities is to take greater account of the role of R&D in defining and then attaining the ideal/target mixes for the country.



Commission Énergies 2050

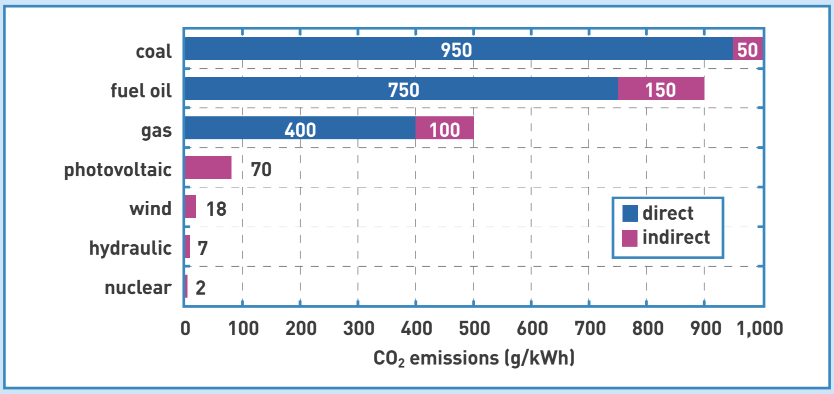
Figure 6.
This example, borrowed from the *Commission Énergies 2050* report[6] , illustrates one of the approaches to the selection of the mixes by the public authorities. Various electrical mix scenarios in 2030, for a given economic environment, were evaluated. The criterion utilized is that of the updated average cost per MWh produced. For carbon dioxide (CO_2), the cost of the tax, or ETS (European Union Emissions Trading System) amounts to 50 euros per ton. The ratio between the cost per MWh is nearly 2 when comparing the choice of continuing the operating life of the historical nuclear power sector and that of developing an energy base consisting of low-carbon technologies, without nuclear energy. The choices and the time-frame play a key role: rapid shutdown of today's nuclear reactors does not make it possible, in this scenario, to take advantage of competitive renewables, because the substitution takes place too early, or to benefit from large scale synergy between renewables and nuclear energy, as this latter would no longer be in use.

An example of the I-tésé ability to manage these questions is, within the framework of Ancre, the role of our experts for proposing and characterizing possible energy transition scenarios. These scenarios have been retained by the secretariat of the national debate, and one of them (the "energy diversity" scenario) became the reference of the "Diversity" scenario family established for the debate[7].

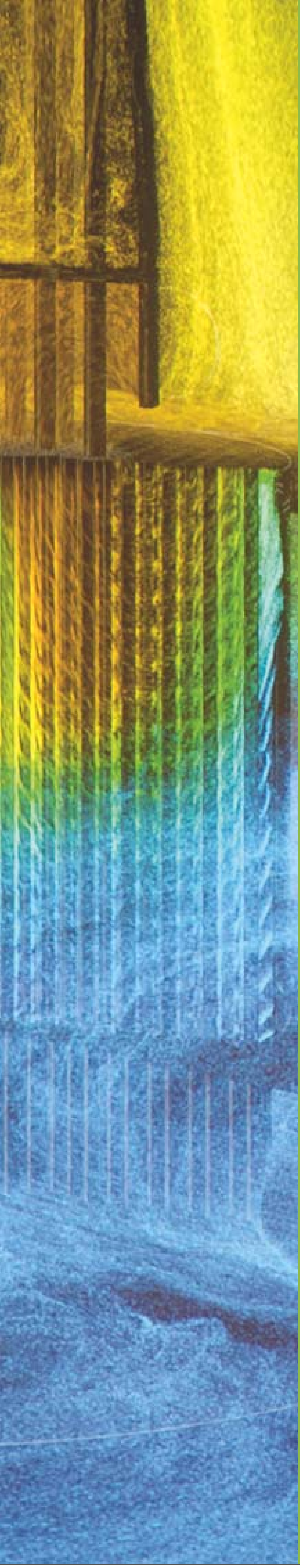
> **Jean-Guy Devezeaux de Lavergne**
Institute for Techno-Economics
of Energy Systems (I-tésé)
Nuclear Energy Division
CEA Saclay Center

Electrical energy and CO_2 emissions

Together with transports, the electricity sector is one of the world's main emitters of greenhouse gases (GHG). Coal-fired plants are the most polluting, with 1 kg of carbon dioxide (CO_2) per kWh produced, twice as much as gas, commonly used in cogeneration. Whereas nuclear and renewable energies do not emit CO_2 during operation, an analysis of their lifecycle shows that they consume energy, mainly during the construction phase. Emissions referred to as indirect are evaluated and compared with the electricity production throughout the lifetime of the plant. In France, the electricity sector is low-carbon owing to production that is primarily from nuclear energy (75%, emission of 2 g/kWh of CO_2) and renewable energies (14%; emission of 7 g/kWh of CO_2 for a hydro-power plant for example).



> **Henri Safa**
Scientific Division
Nuclear Energy Division
CEA Saclay Center



Simulation, displayed on the video wall at the Nuclear Energy Division, for the design of generation IV fast neutron reactors.

P. Stroppa/CEA

I. ENERGY PRODUCTION

After the planning Act setting the energy orientations in 2005, the Grenelle Environment Summit implementation Acts and the "Climate and Energy Package" action plan adopted in early 2008 by the European Commission, France has initiated a new energy transition debate, which will lead to the energy transition planning Act in the autumn of 2013.

Although energy savings remain a core aspect of energy policy, renewable energies and nuclear energy are still the cornerstone of the low-carbon electricity production capacity, with amplification of the diversification process that was started in 2005. The incentives for the development of solar photovoltaic and wind power bear witness to the desire on the part of the Government to move towards the target of 23% electricity from renewables in 2020. To this can be added the objective of a 10% biofuels share of gasoline and diesel supplies by 2015. The nuclear sector, for which some countries expressed serious doubts following the Fukushima power plant accident, still enjoys firm support in France, with an expected 50% share of electricity production in 2025. All of these orientations help reduce our dependence on imported fossil energies and thus our balance of trade deficit.

So what exactly are the fields for research in the main energy technologies?

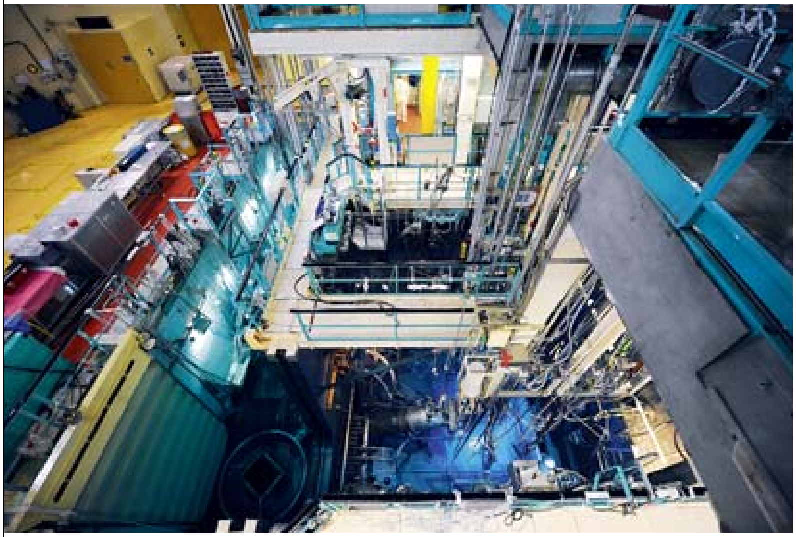
For solar energy, the goal is to improve the efficiency of photovoltaic cells, bring down their cost and develop the potential of thermodynamic concentrated solar power for high-efficiency electricity production or high-temperature heating for industry. For biomass, an initial challenge is being addressed by the BioTfuel and Syndièse demonstrators, with the development of 2nd generation processes capable of converting green waste into diesel and kerosene, with the possible addition of petroleum residues. Another challenge is to make progress towards the 3rd generation biofuels by enhancing the ability of microalgae to produce hydrogen or energetic carbon compounds. For nuclear fission, the challenges are to learn the lessons of the Fukushima accident in order to continuously optimize the safety and economic competitiveness of reactors and, with the ASTRID technology demonstrator, prepare for the next generation of fast neutron reactors with the goal of achieving a sustainable and uranium-thrifty nuclear industry with reduced ultimate radioactive waste disposal needs. Finally, for nuclear fusion, the goal is to demonstrate control of a thermonuclear plasma in ITER and then to produce power in a demonstration reactor leading, in the last quarter of the 21st century, to a first power generating reactor.

All of this research is being accompanied by studies and cross-cutting technological developments in order to maximize the benefit gained from each technology and optimize how they interface. As shown by the following articles, CEA plays an active role and also takes part in the technical-economic studies to evaluate the viability of these technologies as part of an overall energy production system capable of meeting all the requirements.

> **Frank Carré**
Scientific Division
Nuclear Energy Division
CEA Saclay Center

The nuclear sector **post-Fukushima**

In the wake of the Fukushima accident in Japan, many nuclear-related fears have resurfaced. While some countries, such as Germany and Italy, have announced their intention to give up nuclear power and Japan, where virtually all reactors are currently shut down, has not yet made a final decision, other countries are still banking on nuclear energy to underpin their energy independence and meet greenhouse gas emissions reduction targets. **Learning the lessons of Fukushima means increasing the safety** of the plants in operation, assessing their ability to withstand extreme situations, choosing the 3rd generation for reactors to be built and improving performance, especially in terms of safety, made possible by the new technologies being implemented in the design of the generation IV reactors.



L. Bonaventure/AFP/CEA

View of the pool and the Osiris research reactor (CEA Saclay Center). Following the accident which struck the Fukushima nuclear power plant in Japan, the French Nuclear Safety Authority (ASN) was tasked with performing stress tests on the 150 French nuclear facilities, including those operated by CEA. The purpose of these tests was to determine the strength margins of the facilities to extreme hazards and whether improvements were necessary. CEA thus set up a specific organization comprising a steering committee, a reading committee, two "hazards" and "equipment" working groups, and editorial groups. The stress tests for the Osiris reactor were carried out in 2011. In its report, issued in December of the same year, ASN concluded: "For the Osiris reactor at CEA-Saclay, in the event of total loss of cooling and total loss of electrical power supplies, the time before core melt is considerable and is compatible with the arrival of the off-site emergency response services".

On 11 March 2011, a powerful magnitude 9 earthquake shook north-eastern Japan, followed by a 10-metre high tidal wave which devastated the coastline, triggering the world's third major nuclear accident, after Three Mile Island (1979, United States) and Chernobyl (1986, Ukraine). The shock-wave rapidly went beyond Japan's borders and fuelled anti-nuclear criticism. Increasing numbers of radical viewpoints were heard. For example, on 24 May, one could read: "nuclear energy is dead" (Jeremy Rifkin, Chairman of the Foundation on Economic Trends) and "Fukushima in no way compromises nuclear energy" (Henri Proglio, CEO of EDF). But no-one can as yet accurately measure the damage caused by the accident. It is actually impossible to exhaustively identify all the consequences, and it is probable that some of them will remain visible for decades. There is thus a before Fukushima and an after Fukushima.

Before Fukushima

In early 2011, according to the data from the International Atomic Energy Agency (IAEA), 441 nuclear reactors were operational worldwide, representing a net installed power of 374 GWe. Nuclear power plants were generating 2.7 billion MWh annually, or more than 13% of the world's electricity(1). This contribution needs to be compared with that from fossil fuels (67%) and renewable energies (20%, of which 16% comes from hydro-power alone).

2011 DigitalGlobe/Getty Images

Satellite image of the Fukushima Daiichi site (Japan), taken on 18 March 2011, after the exceptional earthquake and tidal wave that struck on 11 March.

(1) 2009 statistics from the International Energy Agency (IEA).

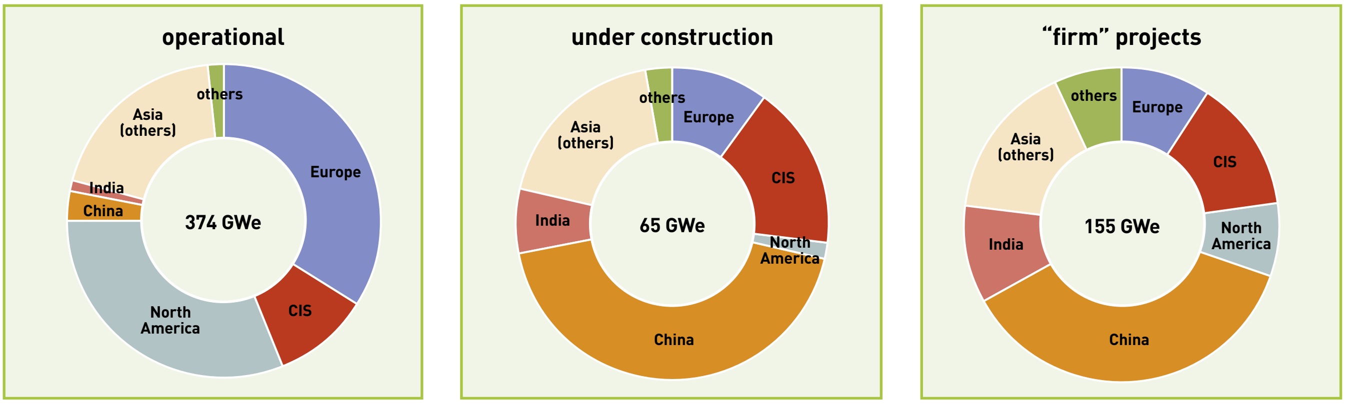


Figure.
Breakdown of plants under construction and planned in 2011. In early 2011, before the Fukushima accident, many countries had expressed the political desire to commit to nuclear electricity production, hence a significant change in the geographical distribution of the new plant units by comparison with the reactors already in operation. Whereas these latter were mainly located in Europe, North America and the Far East (Japan, South Korea), most of the new plants were being or were to be built in the emerging countries, in China, India and Russia. The CIS (Community of Independent States) consists of 11 of the 15 former Soviet Republics, with Estonia, Latvia, Lithuania and Georgia not being or no longer being members.

Under the combined effects of increasing global energy demand and the aim of reducing CO_2 emissions, a revitalized nuclear sector was presented as an absolute certainty. This was borne out by the 68 units then under construction and the 450-500 reactors planned or proposed worldwide, even if these reactor proposals needed to be treated with caution, as they are generally nothing more than declarations of intent on the part of the national authorities.
Many countries had expressed a political desire to opt for nuclear electricity production, thus leading to a significant change in the geographical distribution of the new units by comparison with those already in operation (figure).
However, this nuclear renaissance, allied with the need for low-cost energy production, did however raise questions concerning the regulatory framework and the safety standards that would apply to the development of these new plants. Most of the plants for which the industries in the emerging countries are opting are "entry level", which can be offered cheaply, but without necessarily providing the appropriate safety guarantees.

After Fukushima

For the time being, and if one looks simply at the facts, the Fukushima accident will have led to the following:

- permanent shutdown of 12 reactors: the 4 damaged Japanese reactors and 8 German reactors, making a total capacity of 11 GWe, or 3% of the world's nuclear capacity;


RWE Power

The Biblis nuclear power plant (Hesse), in Germany. Following the Fukushima accident, Germany finally shut down 8 reactors and decided to abandon nuclear power by 2022. The two reactors of the Biblis plant, which output a power of 2.4 GWe, were closed on 18 March 2011.

- prolonged shutdown of virtually all of Japan's reactors, representing more than 40 GWe, or more than 10% of the world's nuclear capacity. No date has yet been announced for a restart;
- a virtual freeze on the construction of new reactors. In 2011 and 2012, construction work began on only 7 units (totaling less than 6 GWe) of the forty or so scheduled (about 45 GWe). The postponed Chinese projects alone represent more than 20 GWe;
- a clear slow-down in the commissioning of new units in 2011 and 2012: 9 reactors (6 GWe) instead of the 22 units scheduled (20 GWe).

Official declarations

In the months which followed the accident, several European countries announced their intention to abandon nuclear energy.
This is the case with Germany, with the decision taken by the Federal Government on 30 June 2011 to shut down the 9 reactors still in service (12 GWe) by 2022. This decision is basically a return to the nuclear exit consensus which had been adopted in 2001 by the Social-Democrat / Green party coalition.
The same applies to Switzerland where, just a few weeks earlier, on 25 May 2011, the Federal Government had announced the gradual abandonment of nuclear energy by 2034 (5 units, 3.2 GWe).
In Italy, the referendum of 12 and 13 June 2011 prolonged the decision already taken in 1987, following a first referendum in the wake of the Chernobyl disaster. It sounds the death knell for the nuclear investment program supported by the President of the Council (13 GWe were to have been built between now and 2030).
Finally, in Belgium, the political parties involved in forming the new Federal Government confirmed in November 2011 the principle of abandoning nuclear energy as of 2015, as stipulated in an Act passed in 2003. However, the closure of the 7 Belgian reactors (5.8 GWe) will be dependent on the country finding alternative energy sources to nuclear energy.
On the other hand, having learned the lessons of the accident in the Fukushima nuclear power plant, other countries have made clear their keen desire to continue with the development of a nuclear energy

sector. According to the declarations of Sergeï Kirienko, General Director of Rosatom, at the IAEA general conference in Vienna, Russia "will continue to develop civil nuclear energy". China could issue permits for new projects in 2013, after freezing them in the aftermath of the accident, in order to carry out inspections on the country's facilities. India is continuing to consider nuclear energy as an essential component of its energy mix, able to support its strong growth. Generally speaking, all the countries which are aiming to adopt nuclear energy for the first time are continuing to show interest in it.

Japan is in a particular position, because in the short term, it is committed to the accelerated closure of its nuclear reactors, for reasons that are both technical and political. In September 2012, the Japanese Government adopted a stance in favor of renouncing nuclear technologies within the coming thirty years. At the same time, the Government has decided to restart some of the reactors shut down, provided that their safety can be guaranteed, and has authorized the continuation of work on two reactors that were under construction.

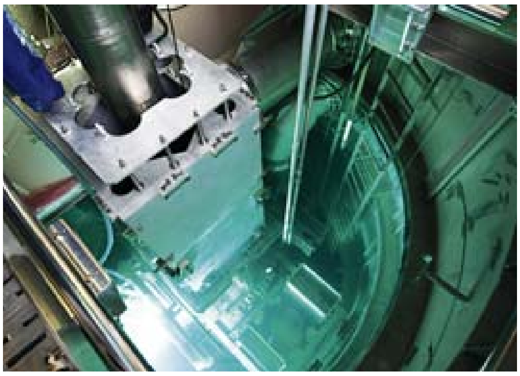
The steps taken

All the nuclearized countries claim to have run tests to check the safety of their NPPs in the light of the events at Fukushima. The 55th General Assembly of the IAEA thus ratified an action plan aimed at reinforcing the safety of the plants in operation around the world, asking countries to agree to more inspections by international experts. However, under pressure from certain countries, in particular the United States and China, nuclear safety tends to a large extent to remain a question of national sovereignty.

On 24 and 25 March 2011, the European Council asked that all European reactors undergo tests to assess their ability to withstand extraordinary events, such as those which occurred in Japan (earthquake, flooding, etc.), or other extreme situations which could lead to the simultaneous loss of several safety functions. The results of these stress tests were peer reviewed under the aegis of the ENSREG (European Nuclear Safety Regulators Group), whose report was published in April 2012.


Council of the European Union

Meeting of the European Council in Brussels on 24 and 25 March 2011. During this session, the European Council asked that all of the nuclear facilities in the European Union be checked by means of a comprehensive and transparent assessment of the risks and of safety (stress tests).


G. Lesénéchal/CEA

Cabri research reactor pool (CEA Cadarache center).
This reactor, designed to study the consequences of certain accident situations on the behavior of the fuels used in nuclear power plants, is one of the facilities which underwent stress tests in 2012. The licensees submitted their reports to ASN on 15 September 2012.

In France, the Nuclear Safety Authority ASN (Autorité de sûreté nucléaire) organized complementary safety assessments (CSA) which were in fact two-fold: on the one hand, an audit of the nuclear safety of the French civil nuclear facilities in the light of the events at Fukushima, which the Prime Minister instructed ASN to carry out on 23 March 2011 and, on the other, the performance of the stress tests requested by the European Council. The conclusions were made public in early 2012 after the CSAs on the priority facilities: "ASN considers that the facilities examined offer a sufficient level of safety such as not to warrant the immediate shutdown of any of them. At the same time, ASN considers that their continued operation requires that their robustness to extreme situations be increased as rapidly as possible, beyond their existing safety margins".

Nuclear energy is still a credible option

The Fukushima accident occurred at a crucial moment, at a time when nuclear energy was enjoying a major renaissance, with the sale of new plants and life extensions for existing reactors. Unlike the Chernobyl accident, which was seen to be a disaster created by a system which did not have the safety rules and the technological quality of Western designs, Fukushima showed that a major nuclear accident could happen in one of the world's most developed nations, even one which enjoyed such a reputation for technological sophistication. Although this accident was the result of quite exceptional conditions, the world realized that, despite all the precautions taken, an accident felt to be highly improbable can occur. In the various declarations made, opinions therefore converge on how to learn the lessons from such events, in order to reinforce the continuous safety improvement approach and to refuse corner-cutting solutions. Henceforth, only the 3rd generation reactor projects should see the light of day, with the possible consequence being an erosion of the economic advantages of nuclear energy when compared with the other electricity production technologies. Hence the goal announced by China of developing a modern, safe and inexpensive 3rd generation reactor technology, both for its domestic market and for export. Two EPRs, for which commissioning is scheduled in 2014 and 2015, are currently being built. It is clear that the Fukushima accident in no way alters the fundamentals of energy demand: the rising need for electricity, the increasing scarcity of fossil resources and the need to reduce CO_2 emissions are as topical as ever. Nuclear energy without doubt remains a credible response able to address all these fundamentals. This is why, with the exception of the few European countries we mentioned and possibly Japan, the question of the short-term nuclear future cannot be simply to stop everything or to carry on as before. Now is not the time for an energy revolution, even if a number of changes to the global energy mix are probable. One could therefore continue to believe that the future of nuclear energy will still be driven by the emerging countries, led by China. If the Governments meet their climate change mitigation undertakings, one must expect a rise in nuclear power generated electricity (+ 70% by 2035 according to the estimates from the International Energy Agency (IEA)). Even in this case, the nuclear share globally would remain more or less constant and modest (14% of electricity production).

Nonetheless, in its annual report published in November 2011, the IEA also considered a hypothesis in which the Fukushima accident had greater repercussions. This “low nuclear” scenario mainly postulates that no new reactor is built in the OECD (Organization for Economic Cooperation and Development) zone and that the non-OECD countries halve their construction projects. The nuclear energy share would then drop from today’s 13% to 7% in 2035. Many observers found this scenario to be overly pessimistic, even if it is primarily designed to alert the Governments to the significant repercussions of reducing reliance on civil nuclear energy, in particular on the climate.

Towards generation IV

Over and above the various declarations, it is still premature to try to measure the true consequences of the Fukushima accident on the future of nuclear energy globally. It today remains a fundamental component of the energy mix needed to meet the growing demand for electricity, while minimizing CO_2 emissions. However, one must not underestimate the impact of the accident, both on the investors and on public opinion and therefore on political decision-makers. The additional safety requirements will inevitably weigh on the cost of electricity production. It is probable that nuclear power will remain attractive as long as fossil fuel prices continue to rise. However, we can already see that this advantage tends to fade wherever fossil energies are cheaper (such as gas in the United States).

The Fukushima accident revived a whole host of the fears, myths and worries that accompany the use of the atom. It has triggered new questions about the civil nuclear risk, which are difficult to answer, other than by announcing measures which go even further towards the goal of maximum safety. How will the political leaders balance these legitimate concerns against the environmental advantages and energy independence offered by nuclear energy? We do not yet really know the answer. This accident will in any case have confirmed the need for greater safety and justified intensified research into nuclear safety. Therefore, in France, it was felt to be important to review the methodology for assessing the effects of earthquake and flooding on the nuclear facilities, to improve the understanding of the phenomenology of severe accidents and their potential consequences, and to study the possible means of mitigating their impacts.

These events recalled how important it is to work on innovative technologies offering increased performance in terms of safety, security, reliability, economic competitiveness, waste management, optimization of natural resources and combating proliferation. This is the subject of the studies carried out on the fourth generation nuclear systems (see *ASTRID, Generation IV advanced sodium technological reactor for industrial demonstration*, p. 26). In one of its declarations, the Generation IV International Forum recalled the need to increase safety efforts: “ …the forum considers that it is essential for the 4th generation systems, for which commercial deployment is planned for the 2030 time-frame, to be the best the world can offer in terms of safety”.

> **Alain Leudet** and **Alain Porracchia**
Innovation and Nuclear
Support Division (DISN)
Nuclear Energy Division
CEA Saclay Center

C. Abou/CEA

The Verdon facility. Installed in two hot cells of the CEA Cadarache center, the Verdon facility can be used to melt fuel samples in a controlled atmosphere induction furnace, in order to reproduce severe accident configurations and study the release of fission products and their transport in the primary system of a reactor.

Looking at the nuclear lifecycle means considering not only that of the nuclear facilities, from the design phase right up to dismantling, but also that of the materials, from the initial use of the uranium in the reactors to handling of the waste. **These two aspects have been an integral part of the R&D work carried out by CEA since it was created**. With regard to fuel, the generation IV nuclear systems will lead to a reduction in the volume and toxicity of the ultimate waste, by means of a closed cycle where most of the material is recycled. As for the nuclear facilities, with more than sixty years of experience, CEA is able to oversee their cleanup, decommissioning and delicensing, in the best possible conditions. A prime example of this is the Passage project, which succeeded in transforming the Grenoble CEA center, which was originally dedicated exclusively to atomic research, into a leading technology center working on micro- and nanotechnologies, the new energy technologies and biotechnologies.

The **nuclear lifecycle**

The nuclear fuel cycle

More than thirty years ago, France decided on a closed cycle for its nuclear industry, consisting in reprocessing spent fuels in order to separate out the reusable materials from the waste. Optimizing the materials cycle, as already implemented industrially, and preparing the materials management options for the future reactor fleets, are thus two key areas for work by CEA. This work is carried out with a view to developing a sustainable, safe and economically competitive nuclear sector.

S. Le Couster/CEA

Remote-manipulator work on the shielded process line (CBP) in the CEA Marcoule Center's ATALANTE facility. Demonstration of the technical feasibility of many processes, such as the SANEX, DIAMEX, GANEX and EXAm processes, was carried out on this shielded line.

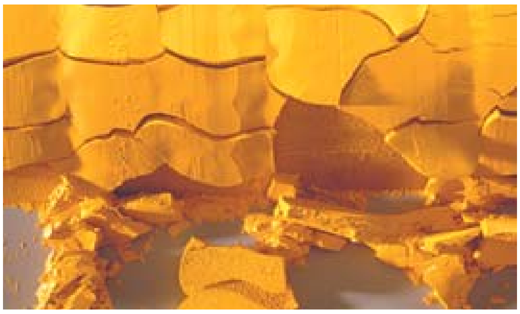
Managing materials before and after burn-up in the nuclear reactors is an essential aspect of the technologies in this sector. Upstream, from the mine to the reactor and through a whole series of transformation processes, this involves extracting, purifying and enriching the uranium (U) and then manufacturing the fuel assemblies. Downstream, this involves managing the spent fuels, taking account of their energy capacity, which remains considerable, as well as their potential harmfulness, because they contain radioactive elements, some of which have very long half-lives.

The options selected for the fuel cycle, in particular the back-end of the cycle, are decisive when designing sustainable nuclear systems. The recycling of reusable materials, both fissile and fertile, in reactors able to make best use of them, is the focus of the research being carried out in this field.

The materials cycle, as today practiced in France, represents a sound basis for the development of future nuclear systems. The technologies employed give not only remarkable performance, but are opening the door to highly interesting new prospects within a development context aimed at better meeting the needs for rational and economic use of resources and for safe management of ultimate waste, offering the highest guarantees in terms of non-proliferation and enhanced economic efficiency.

The materials cycle

The materials used in the French nuclear power plants (NPPs) are managed in a closed cycle (figure 1).


Philippe Lesage/Areva

The front-end of the fuel cycle. After extraction from the mine (open-pit or underground mining), the uranium ore is processed to obtain a uranium concentrate, or yellow cake.

The annual loading of the 58 Pressurized Water Reactors (PWR) with about 1,000 tons of enriched uranium oxide (UOX) requires about 8,000 tons of natural uranium (which means that nearly 7,000 tons of depleted uranium has to be stored). The values given below, expressed in tons of heavy metal, are only approximate, as the actual operating conditions can vary from one year to another.

Most of the materials contained in the 1,000 tons of UOX unloaded are reused. The approximately ten tons of plutonium (Pu) extracted during the reprocessing operations, are recycled in the form of MOX(1) fuel in certain reactors in the fleet (about 120 tons per year). The recovered uranium, or URT (reprocessed uranium) – nearly 950 tons – can be re-enriched. We then obtain about 150 tons of URE fuel (re-enriched uranium), which are then reloaded into several reactors in the fleet, and about 800 tons of depleted URT, which are stored. The remaining materials, fission products and minor actinides (about 40 tons) constitute the ultimate radioactive waste, which is vitrified and stored to allow radioactive decay, pending deep geological disposal.

At present, the spent MOX and spent URE fuels are not recycled. They are stored under water for subsequent reprocessing and recycling of the materials they contain in the generation IV reactors of tomorrow.

The spent fuel reprocessing and recycling operations have today reached full industrial maturity, following decades of R&D which have profoundly transformed the utilization of the PUREX(2) process. They enable very high recycling ratios to be achieved (higher than 99%) while generating only very little secondary waste. About 25,000 tons of spent fuels were thus reprocessed in the La Hague plants (Manche *département*), and nearly 2,000 tons of MOX were fabricated.

The fuel cycle strategy currently developed for the French NPPs offers four key advantages:

- savings in natural uranium resources of up to 25% if all the uranium and plutonium is recycled;
- safe conditioning of the ultimate waste without plutonium. Conditioning of fission products in glass is an international standard, for which the long-term alteration mechanisms are well understood, with an extremely low estimated corrosion rate in disposal conditions (about a few microns over several centuries);
- control of the plutonium inventory. All the plutonium recovered in the reprocessing of the spent UOX fuel is recycled in the form of MOX fuel;

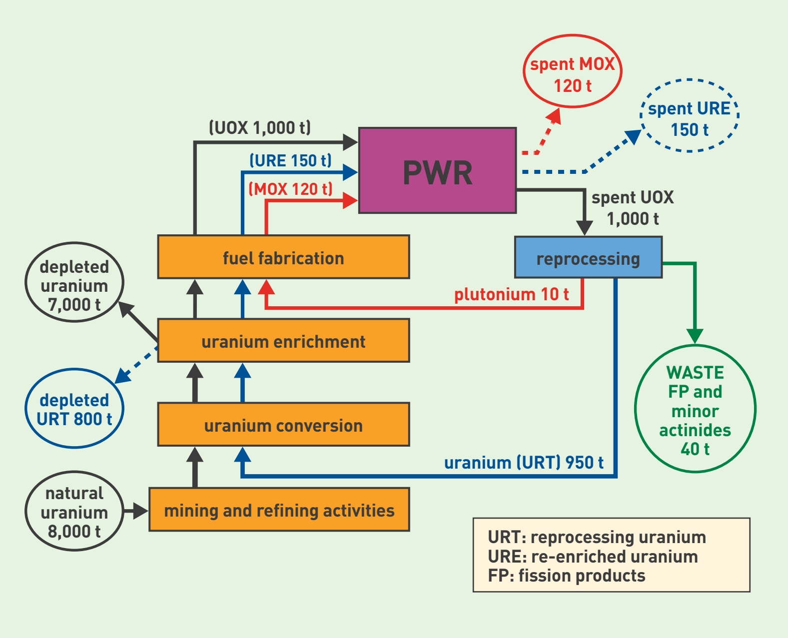


Figure 1.
The materials cycle in the French NPP fleet (in indicative annual flows for production of about 400 TWh/year).

- the stock-piling of a reserve of plutonium which will constitute a resource for future generations of nuclear reactors. The plutonium contained in the spent MOX fuels is thus stored in a safe, concentrated form, that can be easily reused subsequently.

This materials management strategy could continue after renewal of the current NPPs, with the deployment of 3rd generation reactors (EPRs). It also opens the door to fully sustainable nuclear systems, with the advent of new reactor technologies.

The nuclear systems of the future

The fuel cycle options are crucial in being able to address the issues of preserving natural resources, mitigating the environmental impact and controlling the risk of proliferation. Recycling reusable materials is vital for long-term utilization of uranium and plutonium, which are today stored in "second round" spent fuels (spent MOX, spent URE). This is a means of making best use of the fissile materials (^{235}U and ^{239}Pu) and the fertile materials (^{238}U, in particular through the reuse of very large stocks of depleted uranium).

To achieve this, not only must one have highly efficient recycling processes, but one must also be able to recycle the reusable materials in reactors able to make best use of them. In this respect and although they offer extremely interesting properties, the Light-Water Reactors (LWRs) currently in operation around the world, would not appear to be able to handle by themselves this very long-term sustainable development challenge. Certain unavoidable characteristics such as the unfavorable deterioration of the isotopic carrier(3) during the course of successive reprocessing operations, pose problems for the repeated effective recycling of plutonium

---

(1) MOX (Mixed OXides): mixture of uranium and plutonium oxides.

(2) PUREX (Plutonium Uranium Refining by EXtraction): hydrometallurgical process for separating out the uranium and plutonium contained in the spent fuel.

(3) The isotopic carrier describes the respective fractions, as a percentage, of each isotope of a chemical element.

and uranium in these reactors. Sooner or later, the introduction of **Fast Neutron Reactors** (**FNRs**), whose characteristics are far more favorable in these respects, will be necessary in order to make full use of the material recycling options (figure 2).

The recycling of nuclear materials in FNRs would therefore appear to be a key component of the nuclear systems of the future. This is the principle underlying the development of the generation IV systems in which numerous States are currently involved, in particular those which are looking at large-scale deployment, such as China and India, and which in France is being addressed by the ASTRID prototype (see *ASTRID, Generation IV advanced sodium technological reactor for industrial demonstration*, p. 26).

FNRs can go even further and propose even more sophisticated recycling options. Their ability to enhance the **fission** of the minor actinides (neptunium Np, americium Am and curium Cm) means that it could be possible to recycle these elements in addition to uranium and plutonium (figure 3).

So what could be gained from this? The main benefit would be to improve the management of ultimate waste. It would be possible to reduce its long-term radio-toxicity by removing the minor actinides, which are the primary contributors, and also to reduce the decay heat of the waste and the volume of disposal (in the long-term thus preserving the "rare resource" that is the disposal sites).

The **Act of 28 June 2006** calls for an assessment of the "industrial prospects of the **transmutation** possibilities" and, together with **Areva** and **EDF**, CEA has carried out studies to deliver an estimate of the potential gains, costs and drawbacks linked to the use of such options, that is as complete as possible.

S. Le Couster/CEA

Preparation of a glove box test for the COEX™ process in ATALANTE. Oxalic acid is added to a purified solution of uranium and plutonium resulting from the coextraction cycles. Coprecipitation of the two radionuclides takes place. We obtain a mixed oxalate co-precipitate which, after heat treatment, gives a mixed uranium and plutonium oxide, which is recycled in a new MOX type fuel.

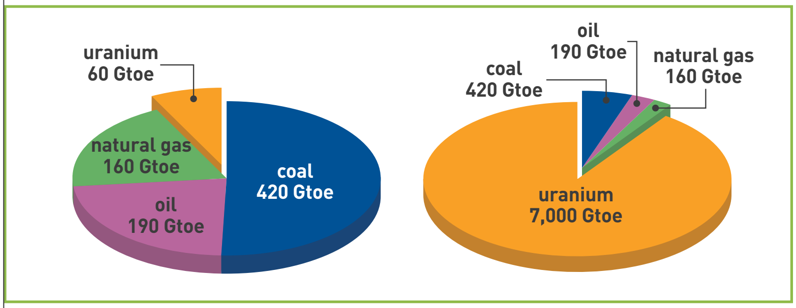
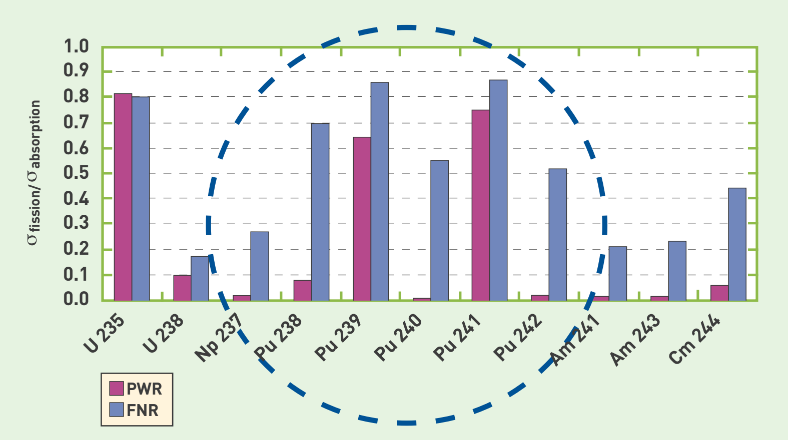


Figure 2.
Relative shares of fossil resources and uranium, when this latter is used in a LWR (left) and multi-recycled with plutonium in a FNR (right). The global reserves considered (conventional resources identified) are of 189 Gt ($189 \cdot 10^9$ tons) for oil, 860 Gt ($860 \cdot 10^9$ tons) for coal, 187 Tm³ ($187 \cdot 10^{12}$ m³) for natural gas [*BP Statistical Review of World Energy*, June 2011] and 4 Mt ($4 \cdot 10^6$ tons) for uranium [*Red Book*, 2009 edition (RRA)].



Robert N. Hill/Argonne National Laboratory, ACS meeting, 2007

Figure 3.
Ratio between the effective fission sections $\sigma_{fission}$ (probability of interaction of a neutron with a nucleus, leading to its fission) and the effective neutron absorption sections $\sigma_{absorption}$ (probability of absorption of a neutron by a nucleus, then leading to its fission, or not) for isotopes of uranium (U), plutonium (Pu) and minor actinides (neptunium Np, americium Am and curium Cm) in a PWR and FNR.

What directions for research?

The performance of the technologies used today is remarkable, both in terms of the quality of the products generated and the conditions in which they are obtained. R&D in this field is based on four main areas: adapting the technologies, improving them, supplementing them and, finally, exploring new concepts.

Technology adaptation

Adapting the technologies to possible or probable changes in fuel, context or management strategies is a first challenge. For example, the deployment of FNRs obviously means systematic recycling of their fuel. Even if the oxide form persists, these fuels have a number of particularities when compared with water reactor fuels. Although it has in the past been demonstrated that **hydrometallurgical** processes, such as those currently used, could be applied to reprocessing FNR fuels – more than 20 tons of fuel unloaded from the **Phénix** reactor have been recycled – their implementation would have to be optimized for any large-scale deployment.

Technology improvement

The aim is not so much to look to raise the existing fabrication and reprocessing performance levels – which are more than adequate, even excellent and which are not really a research issue – but more to aim to further reduce the cost, the waste and the associated releases, and to offer the best guarantees of protection against the risk of proliferation. This is part of a continuous progress approach, which has already given remarkable results. Prime examples are CEA's development of the COEX™[4] process (in partnership with Areva) or of cold-crucible vitrification, which are two major steps forward. This approach can and must be pursued, because there is still considerable room for improvement, in both the front-end and back-end cycles: simplification of processes, progress in operations safety, greater compactness of the facilities, reduced consumption of reagents and releases into the environment, deployment of even more effective and efficient tools for enhanced control of the processes.

Supplementing existing processes

As enshrined in the Act of 30 December 1991, the search for additional steps in the recycling of the minor actinides, has entailed particularly intense activity over the past fifteen years. New molecular architectures, with selective affinity for these elements, were thus synthesized, experimented and then integrated into steps supplementing the PUREX process, as part of an extensive cooperation program. In the laboratory, on spent fuel samples and *via* technologies similar to those usable on an industrial scale, the CEA researchers demonstrated that these new concepts were compatible with the various means that could be envisaged for recycling of the minor actinides (figure 4). The following were thus developed:

- the DIAMEX and SANEX processes for recovery of americium and curium, downstream of the reprocessing stage (experimented in 2005);
- the GANEX process (Global ActiNides EXtraction) which, after separation of the uranium, allows grouped extraction of all the transuranic elements[5], including plutonium (experimented in 2008);
- the EXAm process, for recovery of americium alone, with the curium remaining with the fission products and not being recycled (experimented in 2010).

Cédric Helsly/EDF Médiathèque

MOX fuel storage pool in the Tricastin NPP (Drôme *département*). The spent MOX fuels are stored under water in complete safety for reprocessing at a later date. The plutonium they contain, which is in pre-concentrated form, will constitute a resource for the nuclear reactors of the future.

Research is continuing in order to gain a clearer picture of the conditions for industrial implementation of these concepts (large-scale synthesis of new extractants, radiation resistance, management of by-products, development of control systems, etc.).

---

[4] COEX™ (COEXtraction): this process, which is a development of PUREX, allows the joint extraction of uranium and plutonium and then their co-precipitation, with subsequent calcination to produce the mixed oxide used to fabricate MOX type fuels.

[5] Transuranic elements: radioactive chemical elements whose atomic number (number of protons of the nucleus) is greater than that of uranium, *i.e.* 92. They in particular include the isotopes of neptunium, plutonium, americium and curium.

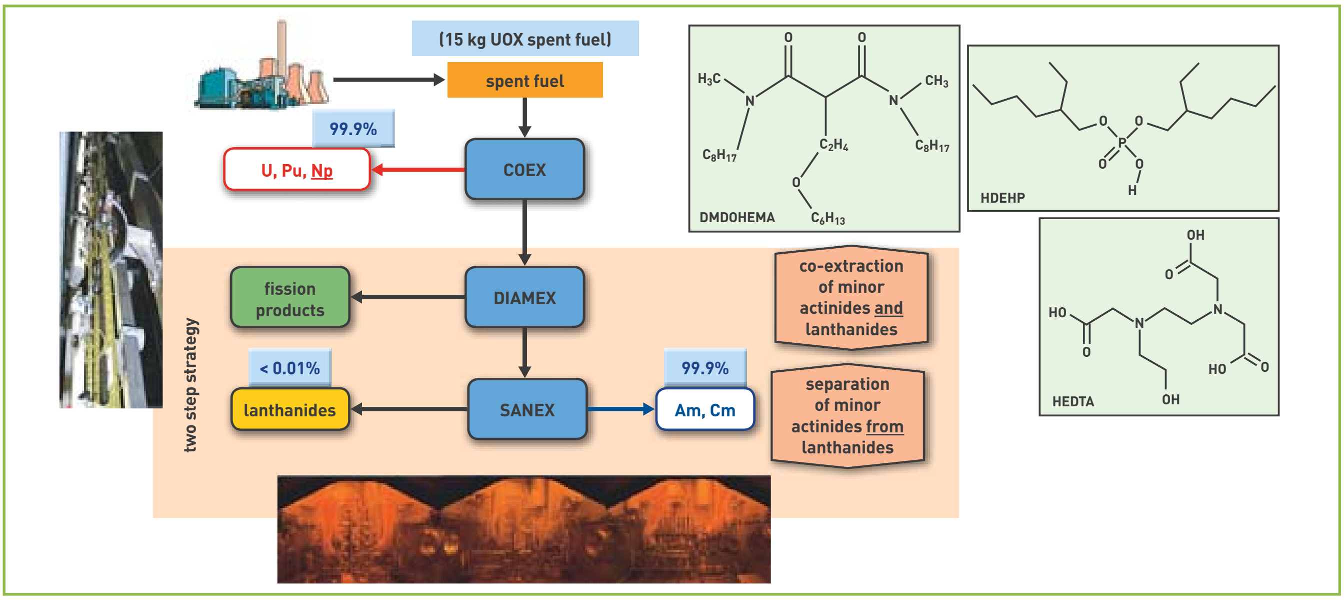


Figure 4.
Minor actinides separation tests performed in the ATALANTE facility (CEA Marcoule Center). Once the plutonium has been removed, the minor actinides constitute most of the residual radioactivity in the spent fuel. The separation of minor actinides, to reduce the volume and above all the toxicity of the ultimate waste is thus a key element in the work being done by CEA. Hydrometallurgical processes complementing PUREX – and COEX™ – have been developed. After extraction of more than 99% of the uranium (U) and plutonium (Pu) from the spent fuel, the DIAMEX process allows co-extraction of 99.9% of the minor actinides and the lanthanides. In the next step, SANEX, 99.9% of the americium (Am) and the curium (Cm) are separated from the lanthanides.


P. Dumas/CEA

Advanced vitrification prototype (PEV) equipped with a cold crucible furnace, installed in CEA Marcoule Center. In this technology, developed by CEA, the glass is heated by direct induction. The unheated crucible is cooled by a circulating water system. A fine layer of set glass then forms on contact with the cold crucible, separating it from the molten glass and thus preventing it from corroding. This technology opens up significant prospects in terms of increased capacity or conditioning of waste containing potentially aggressive elements.

Exploring new concepts

The development of new concepts, quite unlike today's technologies, is an area of research being actively explored. In the United States, teams from the **DoE** (**US Department of Energy**) have launched a wide-ranging program, although without yet having selected any particular options, with the time-frame being 2050 for industrial implementation. Many countries are looking at pyrochemical reprocessing, which consists in extracting elements at high temperature in a molten salt medium. Considerable potential is claimed for this system: compactness, ability to reprocess metal, refractory or very hot fuels, etc. However, for most of these processes, an industrial application is still a long way off, with the question of technological waste linked to the use of high temperatures and particularly aggressive media, remaining one of the more challenging issues. Whatever the situation, the experience of the decades of R&D needed to bring the PUREX process to its current level, starting from a very simple concept, which is selective extraction at ambient temperature, shows us that the road from laboratory concept to industrial technology is a long one. It is however important not to lose sight of the emergence of these new concepts. This is in fact one of the main objectives of the Marcoule Institute for Separative Chemistry (**ICSM: Institut de chimie séparative de Marcoule**, in the Gard *département*), where the French National Center for Scientific Research (**CNRS: Centre national de la recherche scientifique**), universities and CEA are working together in what will be a "laboratory for new ideas" for the cycle processes of the future.

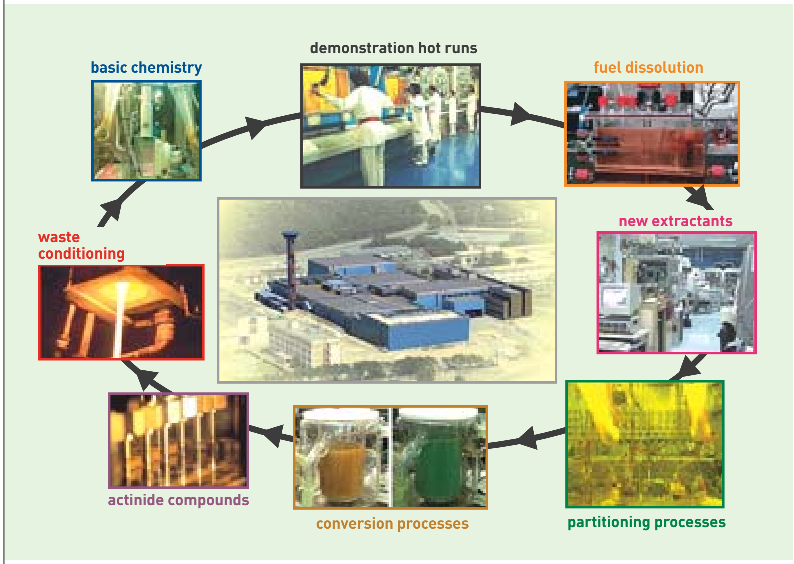


Figure 5.
The ATALANTE research facility. The ATALANTE facility is located in the CEA Marcoule Center and is CEA's primary research tool in the back-end of the nuclear fuel cycle. Several R&D programs have been carried out in it since 1992, in particular following the Act of 30 December 1991 concerning research into the management of radioactive waste. Its modular construction comprises a series of laboratories, equipped with glove boxes and shielded cells, plus common service facilities, so that a given area can be reconfigured to meet the needs of various research programs.

A future marked by sustainability

The technologies currently employed in the fuel cycle mean that the French NPP fleet is today built on remarkably solid foundations and is coherent. They are also preparing for the possible future deployment of even more sophisticated options, for the advent of systems that are fully sustainable over the very long term. Preparation for these next steps is a key challenge and, backed by the progress accomplished so far, maintaining an intense research effort in this field would seem to be vital. Two points are worthy of particular attention: the need to develop flexible technologies, which can be implemented in a changing fleet, and the importance of the research infrastructures. The ATALANTE facility (CEA, Marcoule) is able to conduct research into several areas of the materials cycle at various scales, from fundamental aspects up to experimental demonstrations, using several kilograms of material (figure 5). The pertinence of its design has in just a few years made it an essential and valuable tool for the CEA research teams because, here as in many other fields, anticipation is the watchword.

> **Bernard Boullis**
Innovation and Nuclear
Support Division (DISN)
Nuclear Energy Division
CEA Saclay Center

Cleanup and dismantling of nuclear facilities

The nuclear lifecycle is intimately linked to that of its facilities. As a nuclear licensee, CEA is responsible for the cleanup and dismantling of its end-of-life facilities, as well as for managing the resulting waste. These operations must be performed in compliance with the safety rules, while minimizing their environmental impact, with a view to sustainable development and meeting cost and deadline constraints.

For CEA, carrying out nuclear research necessarily means having a constantly changing equipment fleet, which is permanently adapting to the research challenges. New requirements are appearing, the processes developed are increasingly sophisticated and safety demands are ever-tighter. It is therefore necessary to run facility construction and refurbishment programs in parallel with the cleanup and dismantling of end-of-life facilities.

Dismantling operations

At the end of their service life, nuclear facilities undergo a series of operations allowing final shutdown, then dismantling and final cleanup prior to delicensing. Dismantling in particular comprises disassembly of equipment, cleanup of premises and demolition of civil engineering structures. These operations generate waste, which may or may not be **radioactive**, which then has to be processed and conditioned for disposal.

The general term of dismantling covers all technical or administrative activities leading to a predetermined final status for the facility, in order to obtain its statutory delicensing and its administrative removal from the list of basic nuclear installations.

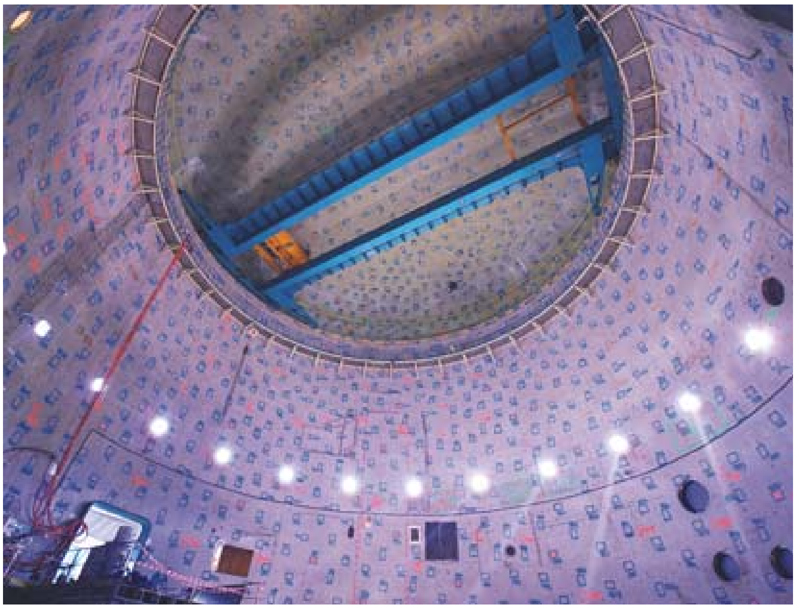
CEA's strategy is in line with the recommendations of the French Nuclear Safety Authorities: **ASN** (**Autorité de sûreté nucléaire**) with regard to nuclear civil applications and **ASND** (**Autorité de sûreté nucléaire de défense**) for defense applications. It consists in dismantling nuclear facilities as soon as possible after their final shutdown, in order to reduce the radiological risks as rapidly as possible and benefit from the expertise of the employees still present.

The Nuclear Energy Division (DEN) is responsible for all of these operations on the Cadarache, Marcoule, Grenoble, Saclay and Fontenay-aux-Roses sites. The complexity and duration of these operations depend on the history of the facilities and indeed on the envisaged fate of the site.

There are no prohibitive technological obstacles to the dismantling of nuclear facilities. These operations can be performed in good conditions of safety and radiation protection through the use of remote-operated devices when the radiological environment so requires.

The Act on Transparency and Security in the Nuclear Field of 13 June 2006 (TSN Act) and its implementing decrees are the benchmarks for improved monitoring and management of the dismantling operations, management of waste and transport of radioactive substances. Each nuclear licensee draws up a dismantling plan for each of its new facilities, as of the creation phase and, for those that already exist, no later than three years before final shutdown. This plan specifies the dismantling procedures. In this plan, the licensee explains the intended final status of the facility (building reused, environmental monitoring in the event of residual radioactivity, etc.).

The dismantling process is included in the design of a facility. For example, the scientists designing the **ITER** facility close to the Cadarache site are already looking at its dismantling in around 2050, and at the best way of designing it in order to limit the dismantling costs.


CEA

Dome 2 of the Siloé reactor, located in the CEA Grenoble Center, after cleanup and dismantling operations. Radiological checks are carried out on the entire floor and on thousands of points on the walls and ceiling, defined randomly and identified by blue marks.

Operational oversight

As of the 1950s, nuclear facility dismantling operations began in France, mainly by CEA, in particular on the first **plutonium** plant in Fontenay-aux-Roses and two small research reactors, César and Peggy, in Cadarache. Over the past fifteen years, dismantling activities have accelerated, because many of the nuclear facilities built between the 1960s and 1980s have gradually been closed down.

To deal with this wide-ranging change, a project-based oversight organization for dismantling activities was set up at the DEN in 2001. This operational oversight organizes CEA's dismantling activities and enables the organization and performance of the cleanup and dismantling work to be entrusted an industrial infrastructure qualified by CEA, guaranteeing compliance with the regulations.


CEA

Those Passage project stakeholders were convened on 1 July 2011 by the CEA Chairman, Bernard Bigot, and the Directors of the DEN (Nuclear Energy Division) and DRT (Technological Research Division), in the presence of André-Claude Lacoste, Chairman of the French Nuclear Safety Authority (ASN) at the time.

This oversight also aims to manage and control the quantities of radioactive waste produced during the operations, sending it to existing recycling and disposal routes or, for the most radioactive waste, to interim storage facilities on the site, pending deep geological disposal.

Many facilities are concerned

The dismantling of the civil nuclear facilities (Cadarache, Grenoble, Saclay, Fontenay-aux-Roses sites, the Phénix reactor and the Marcoule pilot facility), and of the former UP1 military plant in Marcoule, is being handled through 24 DEN projects. These facilities are extremely diverse: particle accelerators, research laboratories, effluent and waste treatment plants, reactors of various types. They all have different histories and types of operation. This means that a broad range of technologies needs to be utilized.

CEA has defined three projects that are priorities, owing to their strategic nature:

- dismantling of the nuclear facilities on the CEA Grenoble site (Passage project);
- dismantling of the nuclear facilities on the CEA Fontenay-aux-Roses site, as part of the Aladin project where, as in Grenoble, activities other than nuclear are to be developed in a densely urban area;
- dismantling of the former UP1 spent fuel reprocessing plant in Marcoule.

Dismantling of the CEA Grenoble site: a rite of Passage

In strict compliance with the scheduled time-frame (master plan in figure 1), about twelve years were needed to successfully complete the Passage project. This vast nuclear facilities cleanup and dismantling project for the CEA Grenoble Center was completed in December 2012, with the end of the dismantling work on the last unit, the Active Materials Analysis Laboratory (Lama).

The CEA Grenoble Center was set up in 1956 by the Nobel prizewinner for physics, Louis Néel. It was originally devoted exclusively to atomic research. Three experimental reactors, called Siloëtte, Mélusine and Siloé, and an active materials analysis laboratory, Lama, were built there in the 1950s and 1960s, with a corresponding waste and effluent treatment plant (STED).

In 2001, the decision was taken to group most of CEA's civil nuclear activities in the Saclay, Cadarache and Marcoule centers. The final shutdown of the Grenoble facilities was thus agreed, paving the way for their dismantling. The objective was two-fold: to manage the end-of-life phase of these five nuclear facilities and to free up space for other non-nuclear research activities that were strategic for the CEA Grenoble Center. The Passage project is original in that it deals with all the nuclear facilities on a CEA site up to and including delicensing, within a relatively short space of time. This emblematic project is monitored at the highest level within CEA so that experience feedback can be put to good use by the various CEA centers, but also by other nuclear activity sectors in France.

Passage is now completed and the time has come to analyze the results. In terms of safety, CEA's

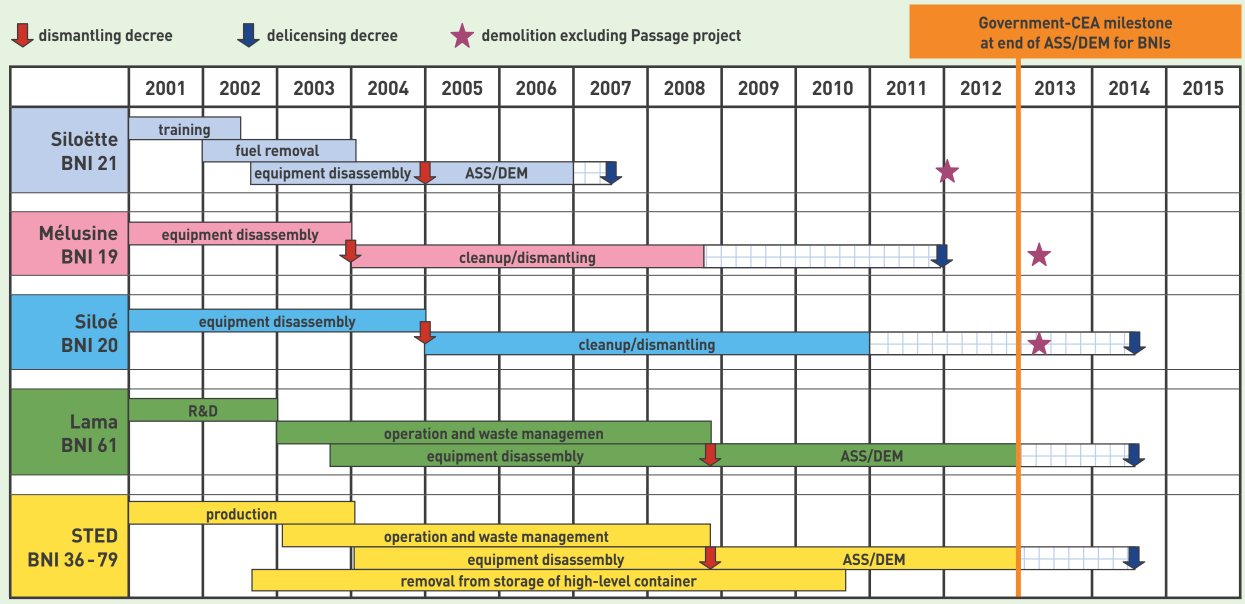


Figure 1.
Schedule for the cleanup (ASS) and dismantling (DEM) project for the basic nuclear installations (BNI) of the CEA Grenoble Center (Passage project).


1988 1994 2003 mid-2005 2008

CEA

The stages in dismantling of the Mélusine reactor in the CEA Grenoble Center. 1988: the reactor hall in operation; 1994: disassembly of experiments and associated protocols; 2003: reactor pool at the end of cleanup after drainage; mid-2005: final checks on the pool after peeling of the concrete; 2008: reactor hall after removal of the pool block and internal structures (physical state of the BNI at the moment of its delicensing in late 2011).

primary concern, one can only be satisfied by the small number and the relatively minor nature of personnel accidents, owing to the good oversight of the operations carried out and the preparatory work and preliminary analysis of the envisaged scenarios.

In terms of environmental impact, the air and water analyses and fauna and flora measurements in the environs of the site show that the radioactive discharge levels are extremely low, well below the authorized limits.

Dismantling will have generated about 25,000 m^3 of radioactive waste, including about 22,000 m^3 of very low level (VLL) waste, 3,000 m^3 of low and intermediate level waste (LLW-ILW), which is sent to existing disposal facilities operated by the National Radioactive Waste Management Agency (Andra: Agence nationale pour la gestion des déchets radioactifs), and 20 m^3 of high level waste (HLW). This latter is currently being stored in dedicated facilities at Saclay and Cadarache, pending the opening of a deep geological disposal repository.

Communication with and information of the regional players and media are also keys to the success of the project.

In human terms, most of the 150 CEA staff who were working on these facilities in 2001 have been able to take part in the new activities on the Grenoble site, after retraining. Others, based on their experience, have joined or will be joining Marcoule, Cadarache or Fontenay-aux-Roses. From the outset of the Passage project, CEA has taken steps to manage the skills necessary for the success of the project and prepare for retraining of the staff. Experience feedback in this respect is extremely positive.

Finally, the budget for the Passage project, amounting to 267 million euros, was kept under control. Spending was spread over a period of time, as shown in figure 2.

The CEA Grenoble Center today primarily focuses on technological research (micro- and nanotechnologies, new energy technologies and biotechnologies). It is also carrying out fundamental research in life and physical sciences.

By enabling the Grenoble Center to focus on these strategic activities, the Passage project is a clear demonstration that the reversibility of nuclear facilities is a reality.

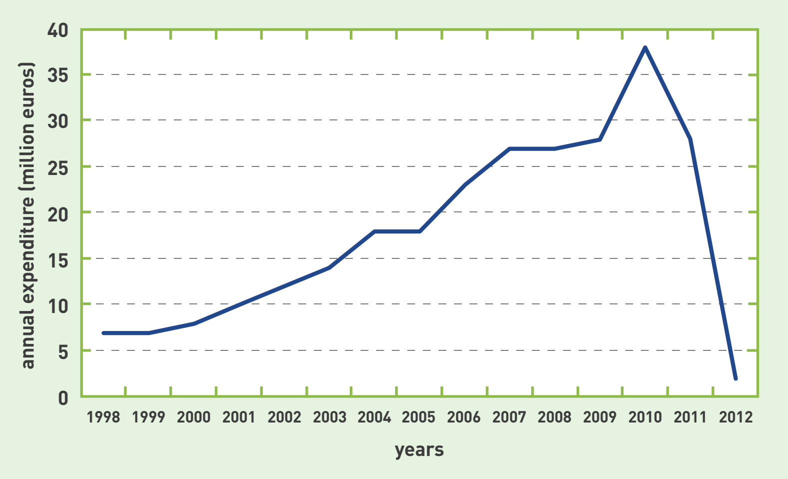


Figure 2.
Spending trends for the duration of the Passage project. They remained within the anticipated budget (267 million euros current basis).

> **Didier Dall'ava**[1], **Frédéric Tournebize**[2], **Bernard Comte**[3] and **Didier Lelievre**[4]

[1]Nuclear Cleanup and Dismantling Division (DADN)
Nuclear Energy Division
CEA Saclay Center

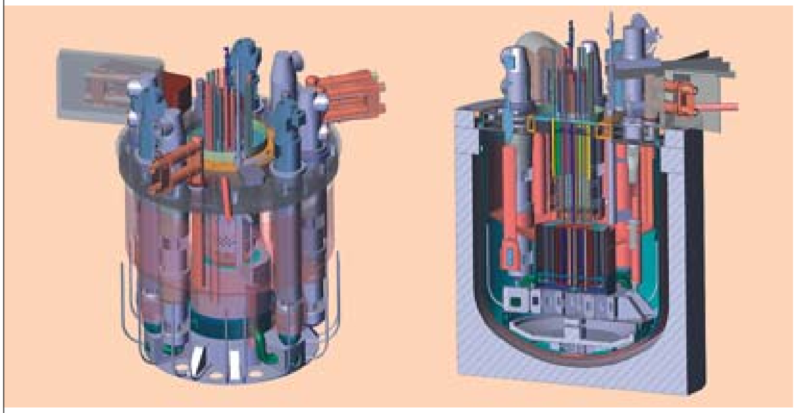
[2]Cleanup-dismantling Projects Department
Nuclear Energy Division
CEA Grenoble Center

[3]Leti Institute (Laboratory of Electronics and Information Technologies)
Technological Research Division
CEA Grenoble Center

[4]Quality and Environment Division (DQE)
Nuclear Energy Division
CEA Saclay Center

ASTRID, Generation IV advanced sodium technological reactor for industrial demonstration

Contribution to sustainable energy development, economic competitiveness, improved safety and reliability, combating proliferation. These are the key goals that will have to be met by the generation IV nuclear reactors. CEA is closely involved in the design of the nuclear systems of the future and is in particular focused on developing a 4th generation sodium-cooled fast neutron reactor, the ASTRID prototype. **ASTRID will incorporate a range of innovative technologies that will all be decisive steps forward by comparison with its predecessors. It will be a true demonstrator of the industrial operability of the generation IV reactors.**


CEA/Areva

ASTRID reactor whole and cross-section views (primary system). Sodium-cooled fast reactor with an electricity generating power of 600 MWe, ASTRID is an integrated technology demonstrator designed to demonstrate the operability of the innovative choices enabling fast neutron reactor technology to meet the Generation IV criteria.

While the 3rd generation of nuclear reactors is currently being industrialized, in particular with the construction of several EPRs, in Europe and China, the 4th generation is being prepared under an inter-governmental association launched in 2000, the Generation IV International Forum (GIF).

With a view to the sustainable development of nuclear energy and faced with the risks of climate change and the depletion of fossil and uranium resources, the GIF set a number of targets for the nuclear systems of the future. They will have to be able to recycle the plutonium with no limit on the number of recycling operations (multi-recycling), to be able to maximize exploitation of the uranium resource and, if this option is chosen, be capable of transmuting certain of the minor actinides. This implies designing reactors operating in the fast neutron spectrum, coupled with a closed fuel cycle. The generation IV reactors will also be required to provide a level of safety at least equivalent to that of the 3rd generation and integrate the experience feedback from the stress tests performed on the French nuclear power plants following the Fukushima accident in Japan. Finally, their economic competitiveness will have to be satisfactory for the service provided and they must offer guarantees that they can counter the risks of nuclear proliferation. The GIF therefore selected six reactor concepts: four using fast neutrons and two using thermal neutrons⁽¹⁾. An R&D plan was defined in order to achieve the innovations necessary for their deployment.

The technological maturity of the systems chosen by the GIF varies widely. CEA focuses primarily on two technologies: the Sodium-cooled Fast Reactors (SFRs) and, to a lesser extent, the Gas-cooled Fast Reactors (GFRs), with particular emphasis on materials innovation.

The advantages of fast neutron reactors

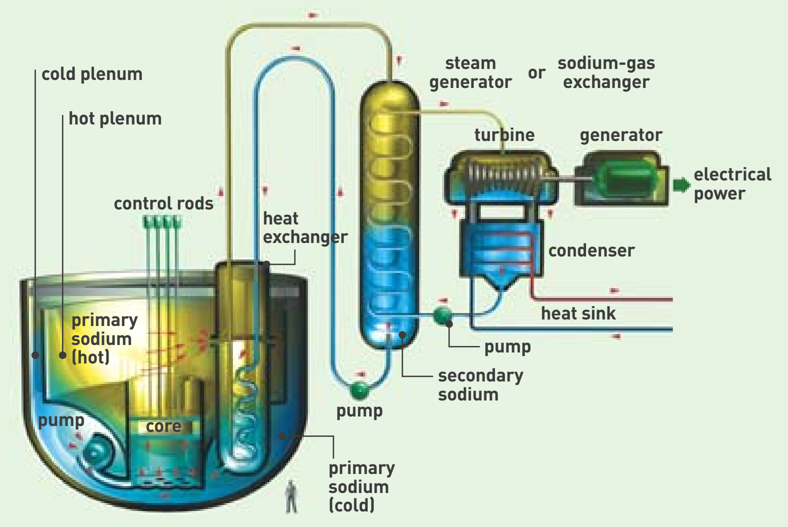
FNR technology has major advantages when it comes to sustainable energy. Firstly, it offers excellent utilization of the uranium resource, allied with the ability to multi-recycle the plutonium. Whereas the reactors currently in service in France and the future EPRs only utilize about 1% of the natural uranium, the FNRs can consume more than 80% of the resource. With the stock of depleted uranium at present available in France, it would thus in theory be possible to supply an FNR fleet for several thousand years. The FNRs are also a source of intensive energy, whose operation emits no greenhouse gases. Finally, they are able to burn the minor actinides and produce electricity, hence a considerable reduction in the quantity and lifetime of the ultimate radioactive waste.

The choice of sodium as the coolant fluid to cool the reactor core is the result of a multi-criteria analysis. Apart from the fact that it does not slow down the neutrons – an essential precondition – liquid sodium

(1) Fast neutrons: **SFR** (Sodium-cooled Fast Reactor, RNR-Na in French); **GFR** (Gas-cooled Fast Reactor, RNR-G in French); **MSR** (Molten Salt Reactor, RSF in French); **LFR** (Lead-cooled Fast Reactor, RNR-Pb in French). Thermal neutrons: **SCWR** (Super Critical Water-cooled Reactor, RESC in French); **VHTR** (Very High Temperature Reactor, RTHT in French). On this subject, see *Clefs CEA* N° 55, Summer 2007, p. 6-7.

exhibits good thermal properties (conductivity, heat removal) and good viscosity, leads to little activation under the effect of the neutrons, is compatible with steels, etc. Its main drawbacks are its opacity and its significant chemical reactivity with water and air.

The SFRs (figure 1) were the subject of numerous projects worldwide and have enabled more than 400 reactor operating years to be accumulated.



Yuvanoé/CEA

Figure 1.
Operating principle of an integrated type Sodium-cooled Fast Reactor (SFR). By comparison with a standard design Pressurized Water Reactor (PWR), several points should be remembered: the reactor's primary system is integrated into the main vessel, which contains not only the core, but also the intermediate heat exchangers and the primary pumps; there is an intermediate sodium system acting as a barrier between the primary sodium and the energy conversion system; the primary system is not pressurized and has considerable thermal inertia; finally, the general architecture of the reactor offers excellent radiation protection for the workers.

Increasing SFR safety

For a number of years, in partnership with EDF and Areva, CEA has been devoting efforts to strengthening the lines of defense and the robustness of the safety demonstration, in order to raise SFR technology to a level consistent with that required for the generation IV reactors. These efforts primarily concern the design of the core, the means of removing the decay heat and resolution of the problem linked to the reaction between sodium and water.

CEA and its two partners are thus working on the design of a low void effect core (CFV) which, unlike those previously designed, has the particularity of a very low or even negative(2) sodium void coefficient. By controlling the reactivity of the reactor, this core represents a decisive step forward in terms of safety. With regard to decay heat removal, it is important to recall the role of thermal inertia and the margin with respect to coolant boiling: the higher they are, the more the reactor will be able to withstand a temperature rise in the event of loss of its decay heat removal sources. An SFR has a thermal inertia multiplied by the margin at boiling nearly 20 times greater than on a standard design Pressurized Water Reactor (PWR). In addition, the SFRs comprise a combination of redundant and diversified passive and active systems allowing the removal of decay heat as soon as the control rods drop, even in the event of total loss of electrical power supplies and heat sink. Some of these systems in fact use natural passive circulation (thermosiphon) and use the atmosphere as the heat sink (figure 2). Their effectiveness was checked several times during tests on the Phénix and Superphénix reactors.

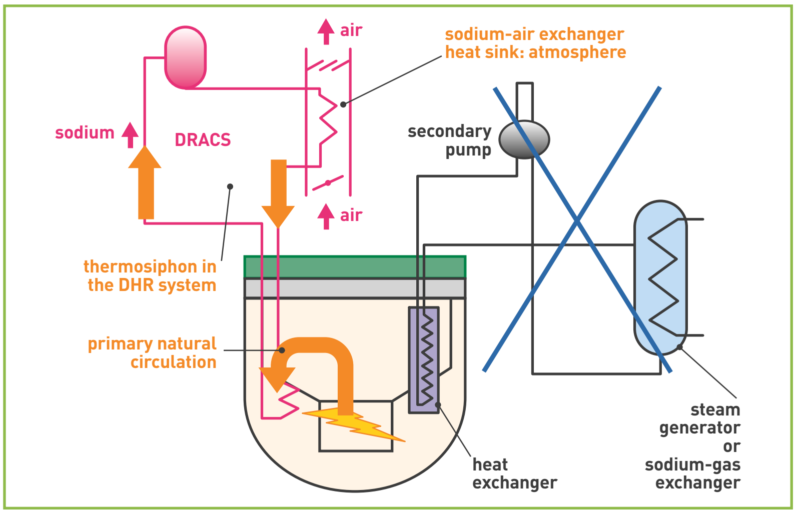


Figure 2.
Stand-alone Decay Heat Removal (DHR) of an SFR. If normal decay heat removal is lost (loss of primary pumps and secondary system, control rods dropped), and in addition to significant thermal inertia, an SFR comprises a combination of systems making stand-alone decay heat removal possible. For the first few tens of seconds, the inertia of the primary pumps is able to cool the decay heat of the assemblies, which is very high just after scram. After the primary pumps stop, natural circulation takes place in the primary system. This is reinforced by a DHR system such as DRACS (Direct Reactor Auxiliary Cooling System), which functions using passive natural circulation (thermosiphon) with air as the heat sink.

Finally, with regard to the sodium-water reaction, the aim is to produce reactors which either completely eliminate the possibility of such a reaction by using an alternative fluid (nitrogen in place of water for example), or which guarantee the absence of safety consequences should such a reaction take place, despite the lines of defense put into place (modular steam generators concept).

ASTRID, a generation IV SFR

Based on the expertise acquired with the SFRs which have operated in the past (in particular Phénix) or which are currently in operation (BN-600 in Russia), CEA is looking at a range of new technological options to develop a generation IV reactor called ASTRID (Advanced Sodium Technological Reactor for Industrial Demonstration): this technological integration prototype will demonstrate the industrial scale operating safety of generation IV sodium-cooled fast reactors.

ASTRID will comply with safety and security requirements at least equivalent to the 3rd generation of reactors, while taking account of experience feedback from the Fukushima accident as of the design stage, and will demonstrate significant progress in terms of industrial operation. ASTRID will also have radioactive waste transmutation capacity in order to continue experimentation on this subject on a significant scale.

In order to meet the generation IV goals, ASTRID will incorporate decisive innovations by comparison with previous SFRs:

---

(2) A positive void coefficient means that the reactor's reactivity increases if the sodium disappears, for example by boiling.

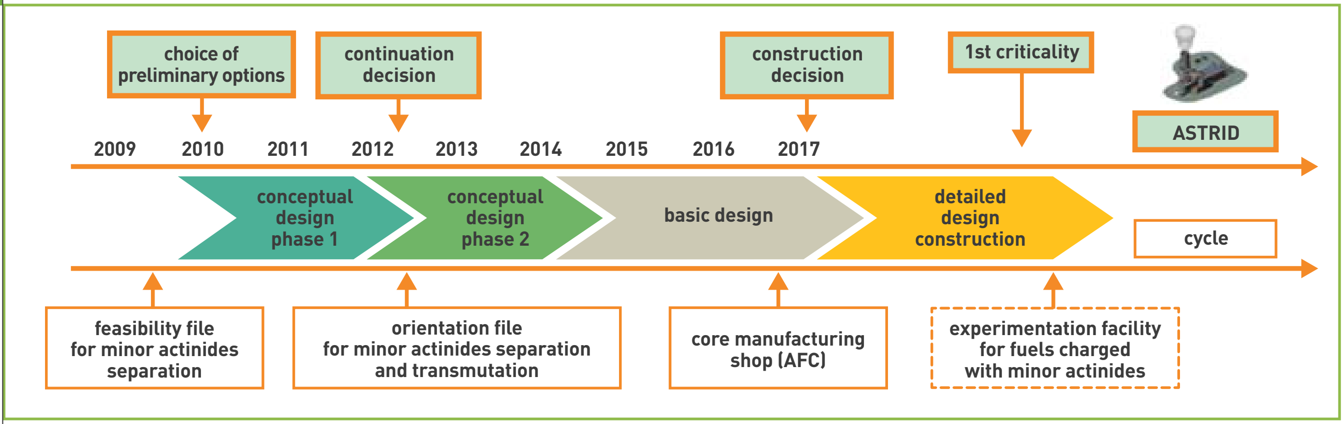
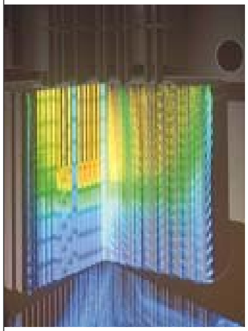


Figure 3.
The ASTRID schedule. The ASTRID program comprises the construction of the actual reactor itself, the construction of technological sodium validation loops and validation of full-scale components on these loops. It also includes setting up a core fuel fabrication shop (AFC). The detailed design and construction phase is scheduled to begin in 2018, with commissioning in about 2023.


P. Stroppa/CEA

Low void effect core (CFV) of the ASTRID reactor seen on the video wall at the Nuclear Energy Division. This innovative core design is far more robust to core loss of coolant accidents.

- an improved core with a very low, even negative void coefficient. This core, which means that the reactor exhibits favorable natural behavior in the event of a loss of coolant, is an essential step forward in the field of safety;
- the possible installation of additional safety devices in the core. For example, passive anti-reactivity insertion devices are explored (SEPIA patent), which enable a safe reactor state to be reached when there is a loss of coolant without the control rods dropping, or reinforced plate systems to rule out the risk of core compaction;
- increased core instrumentation performance: thermocouples for monitoring the temperature of the assemblies, fission chambers for detecting neutrons and fission products, ultrasound technologies for displacement measurements, acoustic detection of boiling, flow measurements, etc.;
- an energy conversion system with modular steam generators, to limit the effects of a possible sodium-water reaction, or sodium-nitrogen exchangers, to completely eliminate the presence of water in the vicinity of the sodium;
- considerable thermal inertia, natural convection and the practical elimination of total and prolonged loss of the decay heat removal systems;
- elimination of major sodium fires by bunkerization and/or inerting of the premises;
- the consideration of off-site hazards (earthquake, flooding, airplane crash, etc.) as of the design stage, with sufficient margin to rule out any cliff-edge effect, guaranteeing the reactor's ability to return to a safe state;
- a complete rethink of the reactor architecture in order to ensure increased ability to counter the risk of proliferation.

ASTRID will also include systems for reducing the length of refueling outages and increasing the burn-up and the duration of the cycle. In-service inspection, maintenance and repair are also taken into account right from the start: simplification of the reactor coolant system architecture, inspection of all the structures for which a failure would prejudice safety (accessibility of structures, inspection from the outside, carrier robots), components that are removable for repair or replacement.

With a power of 600 MWe, ASTRID will be designed for a lifetime of sixty years, equivalent to that of the EPR.

An ambitious project

The ASTRID prototype should be operational by about 2023. The first program milestone, set by the Act of 28 June 2006, was reached at the end of 2012, after the initial preliminary design (APS) phase initiated by CEA for 2010-2012. Based on the experience feedback from previous reactors and a wide-ranging R&D program, these initial studies led to the definition of innovative technical options and safety orientations. The second phase of the APS will take place from 2013 to 2014. The detailed preliminary design is scheduled for the period 2015 to 2017, with the execution studies and actual construction slated to begin at the end of that period (figure 3). At each key-step, a review of the chosen options is carried out in order to ensure compliance with the Generation IV criteria. The ASTRID design studies, including the detailed preliminary design phase, are financed by the Investing in the Future Program (PIA: Programme d'investissements d'avenir, "Nuclear industry of tomorrow" section). The PIA also covers studies for the construction of an ASTRID cores manufacturing workshop and the renovation or construction of technological facilities for qualification of full-scale components. In total, up to the end of 2017, 650 million euros are being allocated under the PIA to the ASTRID program.

For implementation of the project, CEA set up a team of industrial partners who take part in the design studies through collaboration agreements which involve the partners providing some of the funding themselves. If we count the current partnerships, more than 500 people are working on the ASTRID project, R&D and design studies, and other collaborative agreements are currently under discussion.

ASTRID is a key element in demonstrating the industrial feasibility of a generation IV reactor. It is an ambitious project which paves the way for the deployment of a fast neutron reactor technology by the 2040 time-frame.

> François Gauché
Innovation and Nuclear
Support Division (DISN)
Nuclear Energy Division
CEA Saclay Center

Fusion, an **energy source** for the future

Even if it cannot make an immediate contribution to solving the energy mix equation, magnetic confinement nuclear fusion is more than ever an avenue to be explored for the large-scale electricity generating reactors of the future. **Experimental confirmation and the continuous improvement in simulations have generated sufficient confidence to allow construction work to begin on the ITER tokamak, currently under way at Cadarache.** The results of ITER and its accompanying science and technology program will, in the second half of the century, pave the way for a demonstration reactor. The CEA is making an active contribution.

Research into magnetic confinement nuclear fusion has a social dimension with a single goal: in specified conditions of safety, to develop a source of energy based on the principle of the fusion of two light nuclei. Roughly speaking, we are talking of domesticating the energy produced in the stars, in particular in our Sun.

The benefits of fusion

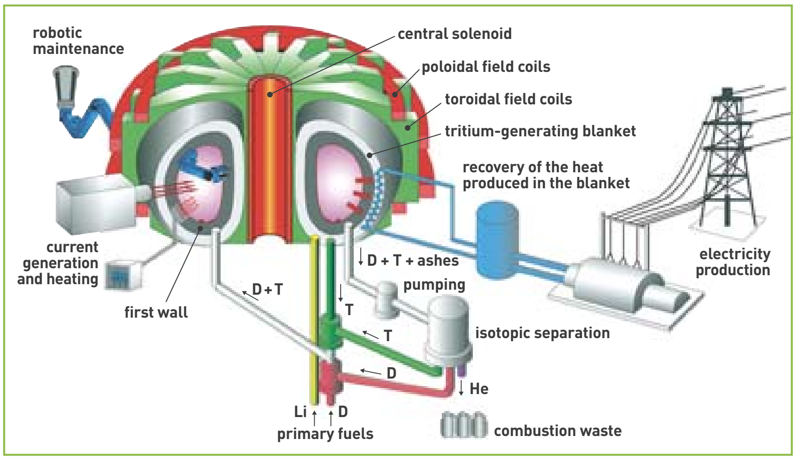
The initial motivations in the 1950s and 1960s were to be able to tap into an energy source offering the benefits of nuclear power in terms of electrical power concentration, while solving the problem of the nuclear fuel management (production and disposal of radionuclides with a long half-life). On Earth, the most accessible reaction for this type of application is to fuse a deuterium nucleus with a tritium nucleus. This reaction, which takes place in a plasma confined by a magnetic field, gives birth to a stable helium nucleus and a neutron. The potential waste from the process is thus solely linked to the activation of the structure of the reactor. Fusion also has another major advantage with respect to non-proliferation and indeed in terms of availability of raw materials. Deuterium can be found in virtually limitless quantities in our oceans. As for tritium, a radioactive isotope of hydrogen which does not occur naturally, it is created in the reactor by interaction between the neutrons created by the fusion reactions and the lithium placed in the confinement chamber blankets (figure). Lithium is particularly abundant on Earth. Finally, the benefits of fusion energy with regard to the non-production of greenhouse gases (GHG) should be pointed out. These benefits, which were brought to light somewhat belatedly, are equivalent to those of nuclear fission energy. They combine zero emissions of carbon dioxide (CO_2) during operation with the usual GHG emission levels during the construction or dismantling of a major industrial facility.

The long history of fusion

To meet the fusion challenge, it was first of all necessary to determine whether it was actually possible on Earth, on a human scale. The good news provided by the tangible and remarkable results from the scientific community at the end of the 20th century, were that it was possible. In short, the physics showed that a

P. Stroppa/CEA

The vacuum chamber of the Tore Supra tokamak. Tore Supra was installed in the CEA Cadarache Center and entered service in 1988. It is mainly devoted to studying the physics and the technologies needed to produce long-duration high-performance plasmas. It is the only European tokamak to combine superconducting components and actively cooled plasma facing components. It led to major scientific and technological advances for ITER.



CEA

Figure.
Operating principle of a magnetic confinement nuclear fusion reactor. The primary fuel, a mixture of deuterium (D) and lithium (Li), from which tritium (T) will be generated, is injected into the reactor's vacuum chamber. It is then heated by additional heating systems to a temperature of at least 150 million degrees Celsius in order to reach the plasma ignition point. Part of the energy from the helium (He) nuclei resulting from the fusion between the deuterium and the tritium is then sufficient to maintain this temperature, with the input of external energy then being used to control the reaction. The fusion energy is transferred to the blanket covering the inner surface of the vacuum chamber (plasma facing components) by the neutrons created during the fusion reaction, as well as by conduction and radiation of the plasma energy itself, and is then recovered to produce electricity. The plasma is confined, kept at a distance from the walls and stabilized by powerful superconducting magnets (poloidal field coils and toroidal field coils). The tritium, which is burned up during the course of the fusion reactions, is replaced by the tritium formed by the interaction between the neutrons and the lithium in the tritium-generating blankets.

fusion reactor was conceivable in facilities of a size comparable with those currently used for the large-scale production of electricity. This would involve units generating an electrical power of a few **GW**. This decisive step was taken at the end of the 1990s, in particular with an experimental demonstration in the European JET **tokamak** (Joint European Torus). This marked the end of the universally acclaimed, lengthy but nonetheless decisive and pioneering first phase of the history of controlled nuclear fusion, comprising two distinct periods.

Finding a solution to confine the plasma

The first period lasted two decades, from the declassification of research in 1958 to the decision to build the JET in 1980. Worldwide, it saw the exploration of numerous ways of developing a magnetic configuration, in other words an intangible box capable of confining an extremely hot plasma that no physical wall could contain. In a highly competitive atmosphere, the tokamak configuration, proposed by Russian researchers in 1968 and which was yet to be improved, was the clear winner. Although some configurations were purely and simply ruled out, other alternatives (**stellarator, inertial confinement**) were retained and are still on the drawing board.

The tokamak era

This period, which covers the next two decades, was marked by the operation of the large tokamaks, the biggest of which to date remains the JET. It was devoted to defining the performance of the tokamak configuration, in other words establishing the laws able to extrapolate the acquired results to the design of a reactor. This involved combining experimental information (construction of prototypes, measurement of design parameters, analyses and interpretations), with theoretical data (selection of physical processes governing the phenomenon, simulations, comparison with experimental results) and models reproducing the behaviors encountered. The laws are generally simple ones, with parameters fine-tuned by experience.

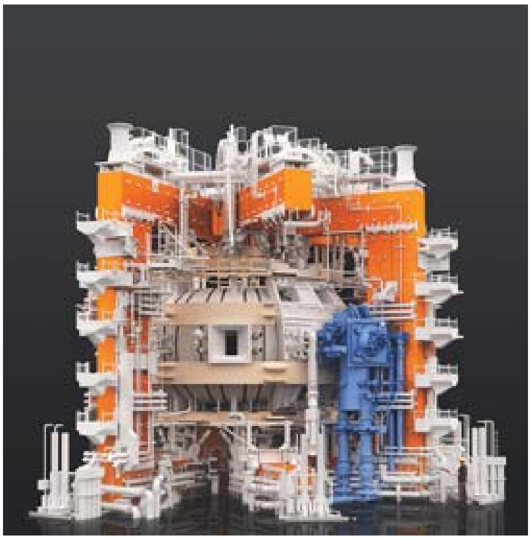
The converging conclusions of the JET experiment and the modeling process confirmed the scientific feasibility of magnetic confinement nuclear fusion and determined the minimum size required of a plasma in a tokamak that can sustain its fusion reactions. However, the JET had two major limitations. The first is linked to the size of the reactor itself which, although coming close, was unable to reach the **breakeven** point. The second lies in the design of the JET, which is unable to consolidate such a result for a period of time long enough to validate the solution for an electricity-generating reactor.

The plasma duration limitation was the subject of particular attention by the CEA, including the personnel at the Institute for Magnetic Fusion Research (IRFM) based in the Cadarache Center, with the 1988 commissioning of Tore Supra. This is the only European tokamak combining **superconducting** toroidal magnetic field coils, actively cooled plasma facing components and adequate additional power systems, enabling it to study the problems of integrating a fusion plasma in a steady-state environment.

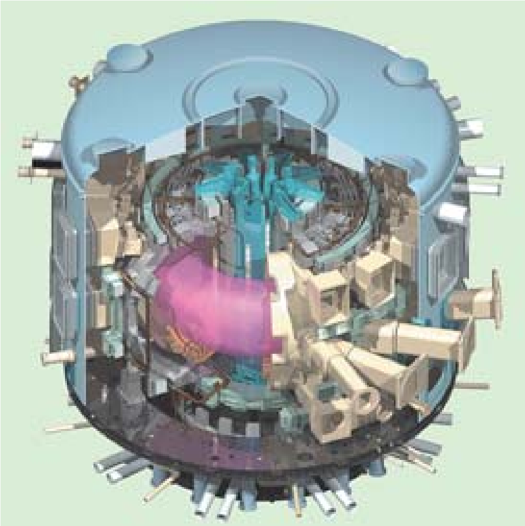
The successful operation of Tore Supra, characterized by its reliability, long duration and high injected power, which was made possible by combined advances in physics, technology and controlled real-time operation, allied with the plasma performance of the JET, led to a joint decision to build **ITER** (**International Thermonuclear Experimental Reactor**) in 2005.

ITER: ambitious scientific goals

The ITER program is supported by seven main partners, China, South Korea, United States, Europe, India, Japan and Russia, representing half the world's population. Europe, which is home to the project in France, is alone responsible for 45% of the investment. An International ITER Organization was set up to carry out the project. The CEA plays an active



EFDA-JET



ITER Organization

The JET (left) and ITER (right, exploded view; the hot plasma is shown in pink) tokamaks. Installed in the Culham Science Centre near Oxford (United Kingdom), JET produced its first plasma in 1983. With a weight of 2,800 tons, a plasma volume of 90 m^3 and a magnetic field of 3.45 teslas, JET is to date the largest of the tokamaks. Its successor, ITER, which will weigh 23,000 tons for a plasma volume of 840 m^3 and a magnetic field of 5.3 teslas, was designed to output a power of 400 MW from 40 MW input.

role in the French contribution, which combines scientific and technical developments, under the Euratom banner, with the work of preparing the site, being entrusted to the ITER France Agency.

ITER has been assigned three major scientific missions. The first concerns the production of deuterium and tritium plasmas, for which the energy released by the fusion reaction is ten times greater than the energy input needed to trigger the reaction. To achieve this, ITER was designed to generate 400 MW of energy from 40 MW of added power. These figures should be compared with the results obtained with the JET, where the power output reached 16.5 MW for about a 20 MW input. Achieving this objective will not only require confirmation that the extrapolations are correct but will also provide significant data on plasma behavior, with regard to confinement and stability.

ITER's second main mission: to produce deuterium and tritium plasmas such that the energy released by the fusion reaction makes a significant contribution to sustaining the process, in duration conditions approaching those of the operation of a reactor, in other words conditions approaching steady-state. This entails additional constraints with regard to maintaining the magnetic configuration itself, by means of adequate additional power systems.

Furthermore, ITER will be able to test conditions close to ignition, where one will be looking to minimize the total power input in order to gain a clearer picture of the conditions (temperature, density, etc.) necessary and sufficient for ensuring that fusion reactions are sustained in a future reactor.

In conjunction with these scientific missions, ITER should eventually be able to reach a conclusion concerning the technical feasibility of the process, in other words it must be determined whether magnetic confinement nuclear fusion is or is not a process that could lead to a nuclear reactor technology that differs totally from those which currently exist. This challenge is taken extremely seriously by all the players. The ITER international organization is thus entrusted with proposing a machine that will perform this task, with experimental protocols that will need to be individually validated by the French Nuclear Safety Authority (ASN: Autorité de sûreté nucléaire) before any start-up and before any introduction of the deuterium-tritium mixture into the machine.

ITER should start in the early 2020s without tritium for a period of five to seven years. Then, following an incremental ramp-up, the reactor should be able to achieve its performance targets. During these phases, all the components and physical processes will undergo constant, integrated, full-scale testing, modeling and comparison with the predictions.

Towards a new electricity generating technology

If they live up to today's expectations, the results will be able to validate magnetic confinement nuclear fusion as a process that is mature enough to initiate the next phase, that is the design of an industrial prototype, the DEMO demonstration reactor. This step will in particular have to meet the industrialization, operating lifetime and electricity production efficiency criteria of a reactor. All the ITER partners are thus starting the relevant conceptual studies and, in parallel with their contribution to the operation of ITER, are already envisaging the necessary R&D stages. The European research institutes involved are also beginning to ready themselves within the framework of the Euratom program. Even if it is probable that the first tokamak of the DEMO generation will be built in Asia, Europe is working on proposing a solution based on its scientific and industrial know-how, with its own quality requirements. The foreseeable time-scale, for such a technology, of the second half of the 21st century means that magnetic confinement nuclear fusion cannot as yet help address our need to adapt our energy mix to current environmental demands. However, maintaining a proactive and ambitious planet-wide R&D program will eventually enable us to propose a new solution for the mass-production of sustainable and environmentally responsible electricity.


ITER Organization

The ITER construction site in Cadarache (Bouches-du-Rhône *département*). The ITER tokamak is surrounded by special reinforced concrete and will rest on seismic pads arranged in a star formation. The entire site will also be equipped with sensors recording any seismic activity, no matter how small.

> **Alain Bécoulet**
Institute for Magnetic Fusion
Research (IRFM)
Physical Sciences Division
CEA Cadarache Center

FOR FURTHER INFORMATION

"L'énergie des étoiles - La fusion nucléaire contrôlée", Paul-Henri Rebut, publishing Odile Jacob, 1999, 285 pages.

"ITER, le chemin des étoiles", Robert Arnoux et Jean Jacquinot, Édisud, 2006, 190 pages.

"Nuclear Fusion: Half a century of magnetic confinement of fusion research", Cornelis M. Braams, Peter E. Stott, IoP, 2002, 327 pages.

50% of primary energy consumption in France is based on fossil energies; oil, coal and gas. These energies are present in limited quantities on our planet and are becoming increasingly costly. They also emit large amounts of greenhouse gases (GHG). Against this backdrop, the European climate plan and the French Grenelle Environment Summit set clear targets: by 2020, France must achieve a 20% reduction in its GHG emissions and meet 23% of its energy needs from renewable energies. These are targets to which CEA is devoting a significant share of its R&D work, such as that being carried out in the field of solar energy. Improving the productivity of photovoltaic technologies and thus bringing down their cost is one of the main areas on which this work is focusing. **This concerns not only the production of materials and the development of more efficient manufacturing processes, but also the development of products or systems for integrating photovoltaics into buildings.** The goal is the transfer of the progress made to the market, as rapidly as possible.

Photovoltaic solar energy

Photovoltaic technologies and centralized electricity production

Since they were first developed in the 1950s, photovoltaic technologies have made spectacular progress. With the advances expected between now and 2020, the cost per photovoltaic kWh should fall below 10 euro cents, making this electricity production method competitive.


P. Avavian/CEA

Electrical characterization of a crystalline silicon photovoltaic cell.

The **photovoltaic** effect was discovered in 1839 by the French physicist Antoine Becquerel(1) and consists in directly converting the energy radiated by the Sun into direct current electricity. Its first application was in 1956 for satellite power supplies, *via* **silicon**-based **photovoltaic cells**. These latter were developed in the Bell laboratories in the United States, during research on transistors. The first large-scale terrestrial developments took place in the 1980s, for electrical power supply to isolated sites, with professional uses such as beacons or radio-transmitters, and domestic applications such as lighting, audiovisual and pumping. Photovoltaic power plants to produce electricity for the grids began to appear as of the 1990s. They used **inverters** to convert the DC into AC, first of all in units of a few **kW** in Switzerland and Germany, and then on the **MW** scale. At present, the most powerful installations can reach 100 MW and, in the Sunbelt(2) countries, some **GW** scale projects are being announced. The reliability of the receivers or **photovoltaic solar panels** is one of the key factors in this expansion through successive niche markets: some of the technologies employed in the 1980s are still functioning today, thus demonstrating lifetimes in excess of thirty years and particularly low maintenance requirements.

A market that is becoming competitive

The technological and economic progress made over the past three decades has been particularly impressive. In the early 1980s, the **watt-peak** (**Wp**) from plants then producing a few MW per year, such as those of the RTC and Photowatt companies

---

(1) Antoine Becquerel (1788-1878): in addition to discovering the photovoltaic effect and inventing the photovoltaic cell, he also discovered the piezoelectric effect and diamagnetism. He was the grandfather of Henri Becquerel, the discoverer of **radioactivity**.

(2) Sunbelt: a group of 148 countries situated between the 35th degree of latitude North and the 35th degree of latitude South. It accounts for about 75% of the world's population and 40% of global electricity demand.


P. Avavian/CEA

Silicon crystallization oven. The silicon is heated to its melting point. As it cools, the molten silicon solidifies, forming a single, large crystal (monocrystalline silicon) or several crystals (polycrystalline silicon). The silicon ingots are cut into very fine wafers (about 200 microns thick) used to create the photovoltaic cells.

in Caen (Calvados *département*) and France-Photon in Angoulême (Charente *département*), cost 100 Francs, or 15 €/W before inflation (thus far more if we take account of inflation). Today, if we take all the technologies together, other than concentrated solar power (see *Concentration photovoltaic*, p. 38), photovoltaic modules are available for a cost price of 0.6 to 1.2 €/W. In today's prices, that is the same as dividing the cost by a factor of more than 10 in thirty years. The price of photovoltaic electricity is thus between 0.10 and 0.20 €/kWh, depending on the size of the systems and on the region(3). Based on the progress already made in the present decade, we can estimate that these prices will fall between 0.05 and 0.10 €/kWh in 2020 and that, as of 2030, photovoltaic electricity will cost less than 0.05 €/kWh virtually everywhere.

Attaining the 0.10 €/kWh barrier in areas with the most favorable sunlight conditions is in the process of opening up vast markets, not only in Southern Europe, but also in the Sunbelt countries such as Middle East and North Africa (MENA), India, China and Chile, especially those in which conventional electricity is costly (using generating sets for example). Another major advantage, unlike non-renewable energies, is that the absence of operational costs linked to any fuel means that prices are fixed primarily according to the depreciation of the initial investments over the lifetime of the receivers and associated systems (20 to 40 years for the time being). For the consumers, investing in this type of photovoltaic generator is thus a means of insuring some of their energy spending against price rises.

Three main technological sectors

The range of photovoltaic technologies is a broad one, but in reality it has changed little over the years. All the technologies marketed or currently under development were already being built or studied in the 1980s. They fall into three categories:

- *bulk silicon cells*, which is the reference technology, with the use of mono-, quasi-mono- and polycrystalline wafers from 100 to 300 microns thick;
- *thin film cells*, which are built by depositing one or more semiconducting and photosensitive films from one to a few microns thick, on a medium. They are produced from amorphous silicon, copper-indium-selenium (CIS), copper-indium-gallium-selenium (CIGS), copper-indium-gallium-sulfur-selenium (CIGSSe), or cadmium telluride (CdTe) compounds, organic molecules and dyes(4);
- *concentration cells*, based on materials such as gallium arsenide GaAs, which offer high efficiency, but which require the use of optical concentrators and trackers to follow the path of the Sun.

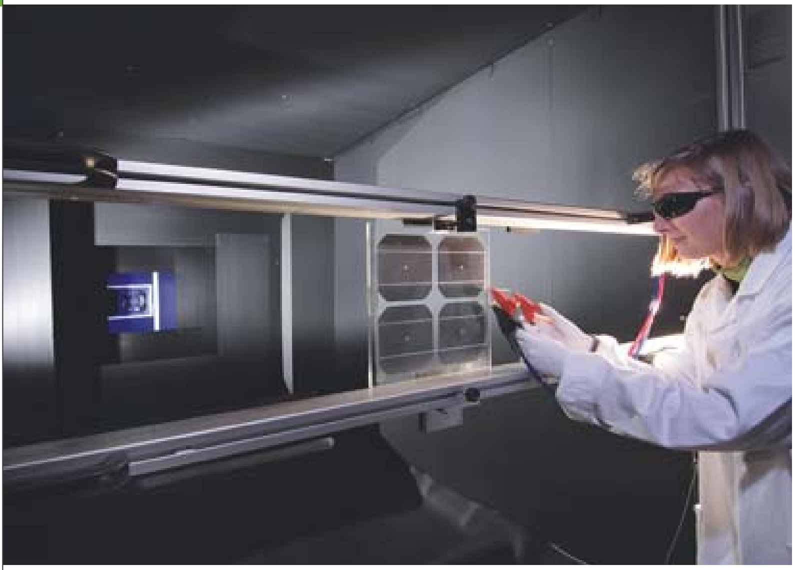
It is clear that the improvements have everywhere been regular and gradual, even if certain steps in the development of the numerous processes employed sometimes led to real technological breakthroughs. In a market enjoying considerable expansion, with annual production volumes multiplied by a factor of 1,000 (from 20 MW in 1980 to more than 20 GW in 2011), the market shares for the various technologies have on the whole remained stable, with the crystalline silicon share alone varying between 85 and 90%. Amorphous silicon was for a long time its main rival, followed by CdTe and CIGS. Organic and concentration photovoltaic systems are developing in highly specific niche markets.

(3) As a comparison, the price per kWh for domestic uses in France is € 0.099, as against € 0.128 for the European Union of 27 (Source: *Eurostat*, 2011 data).

(4) Dyed cell: cell consisting of a single-layer dyed for absorption of photons, a semiconductor for transport of electrons and an electrolyte for transport of the charge.


P. Avavian/CEA

Lamination, one of the manufacturing steps of photovoltaic modules. This operation consists in heating the modules (photovoltaic cells and encapsulating materials) while pressing them in a partial vacuum to eliminate any residual gases.



P. Avavian/CEA

Flash test performed on a photovoltaic module to determine its maximum power.

Given this vast technological range, CEA decided to focus primarily on the dominant technology, silicon, which still exhibits considerable potential for improvement, while contributing to the other two sectors, thin films, with organics and CIGS, and concentrated photovoltaic systems.

The technological challenges

Many criteria are taken into account when evaluating photovoltaic technologies: efficiency, grey energy(5) and the energy return time, ageing rate and lifetime, the presence of toxic or rare materials, recyclability, flexibility or conformability of the materials, etc. However, until now, the cost price of the rated power in €/W or of the energy produced in €/kWh for a given level of sunlight remains the determining factor. Evaluating this cost for a photovoltaic system or power plant must take account of all the other areas of expenditure beyond just the solar panels: the supports and possibly their foundations, installation work, cabling, conversion, monitoring and electricity management electronics, the transformer and the grid connection systems or the associated storage systems, depending on the applications. The cost of financing, the necessary insurance or even the complex administrative formalities in certain countries, are other significant aspects of the whole costs of photovoltaic electricity.

Pressure on cost prices is such that all the links in the value chain must be dealt with simultaneously, for all the technologies:

- the production of resource materials that are as purified as possible and at least cost. This high level of impurities management for all inputs is one of the keys to success;
- high-productivity processes for the crystallization and shaping of the materials, the production of photovoltaic cells, the encapsulation of the modules or production of thin film modules. In most of the steps, the goal is to boost productivity from m^2/min to m^2/s;
- the support structures, the installation and, in the future, the development of directly photovoltaic building envelopes (see *Decentralized electricity production: solar energy integrated into the building*, p. 36) which will facilitate installation and may even make it simply a part of the other roofing and insulation works;
- cabling, electricity conversion, electrical protection and monitoring systems.

(5) Grey energy: quantity of energy consumed during the lifecycle of a material or product, from raw material extraction up to destruction or recycling.

L. Chamussy/Sipa-CEA

Comparative test bench for the various photovoltaic technologies. The modules are being installed.

P. Avavian/CEA

Thin film photovoltaic module. In addition to its significant involvement in the silicon sector, CEA is conducting numerous studies into thin film technology.

Managing the supply of photovoltaic electricity

Making best use of this electricity, one of the characteristics of which is the variability of available power, is a major challenge. The photovoltaic solar resource is actually well-timed to meet the peak electrical consumption of daytime activity, which in France represents 10 to 20 GW depending on the season.

For the time being, the solar electricity fixed purchase price incentives do not encourage any particular form of management. However, it will eventually be possible to provide supplementary services with guaranteed energy and power by combining several of the areas on which CEA is working: power predictions 24-hours, a few hours or even a few minutes in advance, analysis of the geographical abundance and diversity which, over one or more regions, guarantees a minimum power from the solar resources, and association with electricity demand management and storage systems, to make an active contribution to balancing supply and demand on the grids. An excellent level of synergy is becoming apparent, with a view to overall optimization of the energy system, with the emergence of positive energy buildings(6) and electric vehicles.

For the entire photovoltaic sector, the aim is therefore on the one hand to work on materials and manufacturing processes and, on the other, on engineering of systems – buildings (see *Improving energy performance in the home*, p. 88), electrical transportation (see *Solar mobility*, p. 76), grids (see *Smart grids: when electrical grids become intelligent*, p. 71) – from design to operation. At the National Solar Energy Institute (**Ines: Institut national de l'énergie solaire**), CEA employs nearly 300 staff working in laboratories equipped to cover all the steps involved in production, characterization and accelerated ageing, as well as modeling tools. The work being done in partnership with industrial firms in the sector promotes direct development on full-scale components, hence the extreme reactivity of transfer of know-how and technologies and therefore repercussions in terms of rapid technical improvements and cost reductions for the market.

> Philippe Malbranche
Liten Institute (Laboratory for Innovation
in New Energy Technologies
and Nanomaterials)
Technological Research Division
CEA Grenoble (Ines Site)

Solairedirect

Les Mées photovoltaic solar array in the Alpes-de-Haute-Provence *département*. Equipped with 105,000 photovoltaic panels over 50 ha, its power output is 24 MWp. Production is 34 GWh, or the equivalent of the annual consumption of 22,342 inhabitants. This array entered service in February 2011.

EDF Médiathèque/Philippe Eranian

EDF Médiathèque/William Beaucardet

FranceWatts

Solairedirect

Examples of photovoltaic integration into buildings. At top-left, facade integration. The facade of the Société d'économie mixte de Nice (Alpes-Maritimes *département*) building is covered with photovoltaic panels. At top-right, roof integration. View of photovoltaic panels on the roof of the Geoffroy Guichard stadium in Saint-Étienne (Loire *département*).
At bottom-left, complete roof integration. The roof is covered with photovoltaic tiles. At bottom-right, integration of 12,000 m^2 of photovoltaic panels on the roof of the Rhodia Belle Étoile plant (Rhône *département*). The installation outputs a power of 2 MWp.

---

(6) Positive energy building: building which produces more energy than it consumes.

Decentralized electricity production: solar energy integrated into the building

Improving the energy efficiency of buildings – which are more than 50% dependent on fossil energies and responsible for nearly one quarter of all greenhouse gas emissions – is one of the key challenges of the Grenelle Environment Summit. It in particular involves integrating photovoltaic systems into the buildings themselves.


P. Avavian/CEA

Test benches for roof-integrated PV systems on the Incas experimental platform. The objective is to understand the electrical and thermal phenomena generated by integration of PV modules on the roof, to assess the performance of the installation and to find the means of optimizing electrical efficiency

Photovoltaic (PV) modules are able to convert solar energy into electricity. With the best technologies, the conversion efficiency levels today exceed 20%. Solar energy is abundant, but diffuse, and as the size of the photovoltaic installations can be relatively small without affecting production efficiency (a few kW), it is interesting to bring photovoltaic electricity production as close as possible to the point of consumption. Decentralized production on the roof or facade of our buildings has the advantage of using existing surfaces, while minimizing transport-related electrical losses.

Thus, according to a European study by the EPIA (European Photovoltaic Industry Association), 40% of roofs and 15% of building facades in Europe could be equipped with photovoltaic systems. In other words, it would be possible to install PV modules with a power of more than 1,500 GWp, able to produce 1,400 TWh, or about 40% of domestic electricity demand in 2020.

Diverse integration methods

In 2006, France decided to promote the development of an industrial production sector for photovoltaic panels, in particular encouraging integration into buildings. With this aim, the buyback prices by ERDF (Électricité réseau distribution France) or by the ELD (local distribution companies)(1) for the energy they produced were raised appreciably, with a bonus for integrated systems. Since then, the prices have repeatedly risen and fallen significantly. At present, there are nine different prices depending on the method of integration and the type of use of the building. This incentive led many manufacturers to design and market PV systems integrated into buildings. There are a number of methods for roof or facade integration.

Roof integration

There are three different product categories:

- *shingle type products*, for which the PV modules are integrated into supports which replace the roof shingles or the roofing support conventionally used. In this case, no specific flashing(2) is required;
- products enabling standard modules to be integrated. Two sorts of systems are proposed. On the one hand, *simplified integrated systems*, benefiting from an electricity purchase price referred to as "simplified building integration", the waterproofing seal being provided by a membrane, with a steel tray placed underneath all the modules. Removing the module in no way affects the waterproofing seal. On the other, systems for which the seal is made at the interface between two modules. In this case, the waterproofing seal is no longer guaranteed when the module is removed. The electricity produced by these *integrated systems* benefits from the highest "building integration" price;
- *PV modules integrated on membranes*.

In most cases, these products are made from flexible modules of amorphous silicon. They can be used to cover large and practically flat surfaces at least cost (hangar, logistics building, shopping mall roof, etc.).

Facade integration

Various systems can be used to integrate opaque or semi-transparent PV modules. The modules will be placed vertically on the facade, on the apron(3), on a balcony or window balustrade, in place of glazing, on a double skin(4), on a curtain wall(5), etc. Above a window, the modules could be positioned as mobile or stationary sunshades. This offers the twin advantage of a better angle for capturing sunlight while protecting the building against overheating in summer.

Areas for improvement

Photovoltaics integrated into the building offer a large number of possible combinations depending

(1) ELD: electricity provider or electricity distribution grid manager which retained prerogatives over its territory, generally municipal, when the electricity suppliers were nationalized in 1946.

(2) Flashing: element providing waterproofing between two building structures. For example, pieces of zinc between the chimney stack and the roof shingles.

(3) Apron: part of the wall (indoors or outdoors) situated between the floor and the window sill.


Ines/CEA

Example of double-skin integration of twin-sided high-efficiency PV modules. In this type of facade integration, the building's wall is doubled by a second glazed wall into which the PV modules are integrated. The space between the two walls is filled with air.

on the technology chosen (**crystalline silicon**, amorphous silicon, thin film, organic, etc., see *Photovoltaic technologies and centralized electricity production*, p. 32) and the integration system. Considerable R&D work, in particular concerning energy aspects, will be required in order to develop this solution.

Photovoltaic installations integrated into buildings are mainly connected to the grid, so it is crucial to intelligently manage these energy flows, which fluctuate considerably depending on the time and the weather. The aim is not only to ensure that production and consumption coincide as far as possible, but also to store the surplus solar energy. Hence the interest in the development of smart grids for buildings and districts (see *Smart grids: when electrical grids become intelligent*, p. 71).

Work is also under way to evaluate and guarantee photovoltaic electricity production in buildings. This implies accurately determining the output and lifetime of the installations. There are two main problems.

The first is linked to losses by shading of the PV modules. As most buildings are located in an urban environment, many objects (other buildings, posts, trees, etc.) can create shade which impairs production. New electrical architectures must therefore be proposed in order to significantly mitigate the impact of this phenomenon.

The second problem is linked to the temperature of the modules. The higher this gets, the more the efficiency drops. For technologies using crystalline silicon, a 10 °C rise in temperature leads to a drop in output of about 4%. A "solar integration in the building" platform for testing roof integrated PV systems was built on the Incas platform (Instrumentation of new solar architecture constructions) at the National Solar Energy Institute (**Ines: Institut national de l'énergie solaire**) in order to study this aspect. It consists of 10 test benches representing a heavily insulated roof element of 35 m^2. After one year of testing, it would seem that roof integrated systems on the whole offer lower performance than simplified integrated systems (figure).

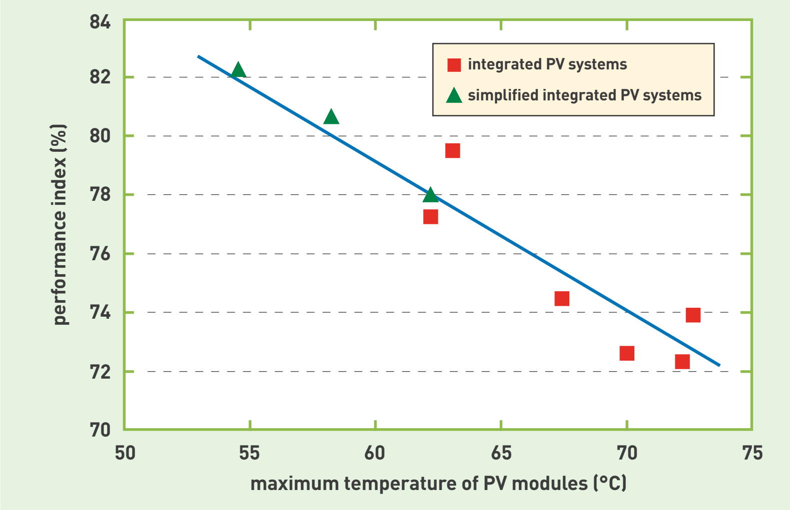


Figure.
Determination of the performance of a PV installation tested on the Incas platform.
The performance index for integrated PV systems and simplified integrated PV systems is calculated according to the maximum temperature observed on the modules during a day of bright sunshine in June 2011. A difference of more than 15 °C is apparent between the most efficient systems (simplified integrated) and the least efficient (integrated). This temperature difference, which impacts on output, is linked to less satisfactory ventilation of the rear face of the modules and to their darker color, hence their tendency to be hotter.

Furthermore, for several installations integrated into the building, such as certain facade installations or hybrid photovoltaic/thermal systems (PV/Th), a broader outlook than simple electricity production is required. This equipment will also have an impact on the building's energy as a whole. This is for instance the case with semi-transparent photovoltaic glazing, which will reduce the contribution of sunlight, thereby increasing the need for heating in the winter while reducing the need for air-conditioning in the summer, and increasing the demand for lighting. It is therefore important to develop methods for assessing not only photovoltaic production, but also the impact on consumption from heating, air-conditioning and lighting.

CEA is actively involved in developing all of these areas for improvement of PV systems integrated into buildings. Teams are also working on developing multifunction roof or facade elements which are prefabricated with PV systems, thus bringing down deployment costs and controlling quality levels. A start-up project is in fact currently being studied on this subject.

> **Benjamin Boillot**
Liten Institute (Laboratory for Innovation
in New Energy Technologies
and Nanomaterials)
Technological Research Division
CEA Grenoble (Ines Site)

(4) Double skin: second wall located outside the first wall.

(5) Curtain wall: facade wall which envelops the building without contributing to its structural stability. The photovoltaic panels are thus attached floor by floor to a fixed skeleton. This is a lightweight type of facade.

Concentration photovoltaic

With solar energy conversion efficiency levels of more than 43%, concentration photovoltaic energy, which has been developed more recently than conventional photovoltaics, is able to offer an interesting solution in regions enjoying large amounts of sunshine.

Axiosun

System of Medium Concentration PhotoVoltaic panels (MCPV) from the Axiosun company deployed in the south of France. MCPV systems use single-axis trackers, here oriented East-West. The mirrors, which concentrate the light on the CPV modules, are clearly visible. They are attached to finned heat dissipation devices to limit the temperature rise on the cells.

Of the energy production technologies based on solar photovoltaic systems, Concentration PhotoVoltaic (CPV) is one of the least well-known. However, it is rapidly entering the renewable energies circuit. The concept is based on the use of optical systems able to concentrate sunlight on photovoltaic cells with high conversion efficiency (figure).

Improving the conversion of solar energy

Research into CPV was started with a view to increasing the efficiency of solar cells. In a seminal article published in 1961(1), the American physicist William Shockley and his German colleague Hans J. Queisser established that the maximum conversion efficiency of single junction photovoltaic cells, with a light flux of 1,000 W/m^2, was about 30%. This flux constitutes the standard illumination value used to measure the performance of photovoltaic cells. It corresponds to the value of sunlight. In the same article, the two researchers laid the foundations of the CPV concept. According to their calculations, the efficiency should increase with the incident light intensity on the cell.

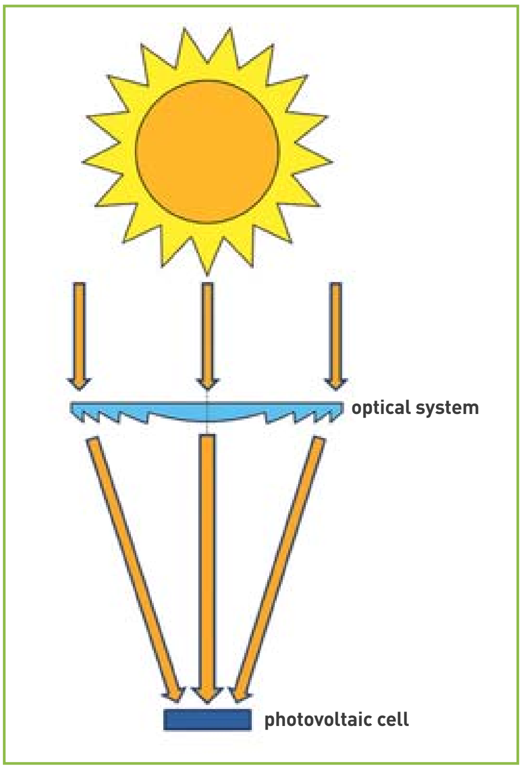


Figure.
Schematic diagram of a concentration photovoltaic system. The sunlight is concentrated on a small photovoltaic cell by means of an optical system.

---

(1) "Detailed Balance Limit of Efficiency of p-n Junction Solar Cells", William Shockley and Hans J. Queisser, *Journal of Applied Physics*, 32, issue 3, 1961, p. 510-519.

(2) X: concentration ratio of light reaching a photovoltaic cell after being concentrated by an optical system.

The accuracy of Shockley and Queisser's predictions was demonstrated in 1987 when, with the same cell, Stanford University (United States) broke two world conversion efficiency records for solar cells based on **silicon**: 20% efficiency for an illumination of 1X(2) (*i.e.* 1,000 W/m^2) and 27% efficiency for a concentration ratio of 140X, or 140 times the intensity of sunlight.

CPV technologies thus utilize the ability of photovoltaic cells to work under a more intense light flux with higher conversion efficiency levels. It is important to note that the use of optical systems implies that the CPV **modules** must be constantly turned towards the Sun. This function is handled by devices following the path of the Sun, called **trackers**, the technological complexity and accuracy of which determine the concentration ratio.

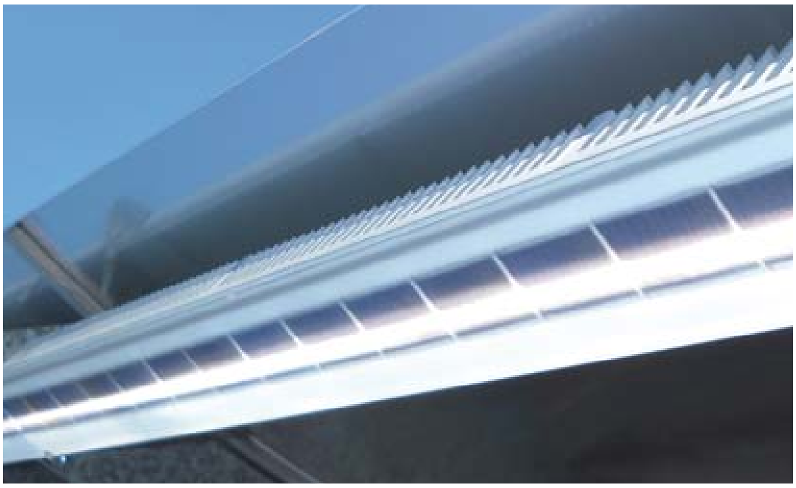
The concentration processes

The various CPV technologies available differ according to their light flux concentration ratio. They include:

- *Low Concentration PhotoVoltaic technologies* (LCPV), between 2X and 10X, generally based on conventional **photovoltaic panels** using **crystalline silicon** and assemblies of simple mirrors joined to the photovoltaic modules. The maximum concentration ratio is limited to 10X. Beyond this, the diffuse light is no longer collected by these systems. The main problem with this technology lies in the use of conventional photovoltaic panels, because few manufacturers of conventional modules will maintain their warranty if a concentrated light flux is used;
- *Medium Concentration PhotoVoltaic technologies* (MCPV), between 10X and 100X, which require special receivers. Photovoltaic conversion is still provided by high-efficiency crystalline silicon based cells. These systems require solar cells whose conversion efficiency remains high even with the concentration of the light flux and the correspondingly increased temperature. The method of concentrating the light flux is still based on mirrors. For concentration ratios in excess of 100X, trackers with a single axis of rotation are no longer sufficient;
- *High Concentration PhotoVoltaic technologies* (HCPV), which are used for concentration ratios in excess of 100X. These often rely on Fresnel lenses and cells based on III-V materials (binary, ternary, quaternary or higher materials, comprising elements of column III and column V of the periodic table). The tracker then has to be two-axis.

High efficiencies

The silicon-based cells today used in CPV can give conversion efficiency levels of 27.6%. The latest cell technologies using III-V materials for their part offer conversion efficiencies of 43.5%, levels which have been rising by 1% per year since 1999. For the industrial products, certain manufacturers are selling modules with conversion efficiency levels of about 34%, as opposed to an average of 18% for conventional silicon-based photovoltaic modules. These figures seem almost utopic, but they must be placed in the context of other aspects of CPV.



Medium Concentration PhotoVoltaic module (MCPV) from the Axiosun company. Visible are the silicon-based cells, heat dissipation devices and the incident light flux on the cells from the mirror.

Owing to the use of optical systems, CPV modules only capture direct sunlight. There is thus little if any production when clouds pass or if the sky is completely obscured. This equipment is thus intended for use in areas of intense sunlight, the Mediterranean rim for example. Moreover, the trackers comprise moving mechanical parts, which are critical to energy production. Although these components give CPV systems an energy production curve during the day that is far more interesting, they also increase the probability of a failure of CPV installations.

CPV systems, which have not yet benefited from the effect of mass production in the same way as photovoltaic systems, are more expensive than conventional installations. Their increased production rates are however offering a quicker return on investment when used in large energy production plants. These are in fact their main market. Although the number of large manufacturers can be counted on the fingers of one hand, it is nonetheless the case that nearly 700 **MW** of CPV were installed in 2012 and are operational.

At CEA, a number of cross-cutting skills are being developed around CPV. In this field of activity, the topics covered vary widely and the researchers are involved in research and development into thermal and optical aspects, **semiconductor** physics and assembly processes, as well as mechanics and energy management.

> **Mathieu Baudrit**
Liten Institute (Laboratory for Innovation
in New Energy Technologies
and Nanomaterials)
Technological Research Division
CEA Grenoble (Ines Site)

Although there may be some debate over Archimedes' use of mirrors to burn the Roman fleet attacking Syracuse, there is no doubt that the benefits of concentrating solar radiation with mirrors to produce energy have been known since ancient times. This is the principle today utilized in thermodynamic concentrated solar power plants. **Unlike photovoltaic systems which convert solar energy directly into electricity, these plants generate heat, which is then transformed into electrical energy.** The technology, which proved itself in the 1980s has, since the year 2000, enjoyed renewed interest in the face of environmental challenges (reducing greenhouse effect gases), the cost of fossil energies and their inevitable increasing scarcity. In 2012, the total installed power of thermodynamic concentrated solar power units amounted to 2 GW. According to the International Energy Agency (IEA), this power will be about 20 GW in 2020, before reaching 1,000 GW in 2050.

Concentrated solar power: the other alternative for electricity production

Concentrating the Sun's energy

Thermodynamic concentrated solar power plants are based on the use of solar radiation concentrated with a field of mirrors. This then heats up fluids to temperatures of up to 800 °C. In association with heat storage systems, they can be used not only to produce electricity round the clock, but also for heating, water desalination or the production of hydrogen.


P. Avavian/CEA

Thermal solar receiver loops in the SAED demonstrator installed on the CEA solar platform in Cadarache. The loops, which measure about 200 m in length and are installed in parallel, consist of all-welded black steel pipes.

Thermodynamic Concentrated Solar Power plants (CSPs) correspond to all the techniques designed to transform the energy radiated by the Sun, concentrated on a focal surface, into heat at high temperature. This heat is then converted into mechanical and then electrical energy (motor or turbine coupled with a current generator), by means of a thermodynamic cycle.

CSP plants generate electricity within power ranges from a few **kWe** to a few hundred **MWe**. By combining them with a heat storage system, their operation can be extended to about twelve hours. The thermal energy not converted into electricity can also be directly used for heating or put to use in the form of a source of heat for air-conditioning systems (sorption systems)(1) or for desalination (distillation).

There are four main types of CSPs depending on the nature of the reflecting surface and the way the sunlight is concentrated: plants with a **heliostat** tower and plants with parabolic troughs, with point concentration, and plants with cylindrical parabolic mirrors and Fresnel mirrors, with linear concentration (figure 1). Point solar concentration plants can be used to reach higher temperatures, but are trickier to use. At present, the cylindrical-parabolic

(1) Sorption: process whereby a substance is adsorbed or absorbed on or in another substance. It is the result of the action of molecules of gas or liquid which, when they come into contact with a liquid or a solid, adhere to its surface (adsorption) or are incorporated into its volume as a whole (absorption).

technology is the most mature. It represents the vast majority (95% of thermodynamic installed capacity) of the solar power plants in operation.

The power output determines the market

Depending on their power output, high (more than 50 MWe), medium (from 50 kWe to 50 MWe) or small (less than 50 kWe), CSP plants can be split into three main market segments (table).

High-power plants are suitable for interconnected electricity grids. They are dedicated to a basic supply, with or without hybridization (steam turbine top-up using fossil fuel). For the peak or semi-peak markets, they also offer significant storage capacity. For these high-power plants, the main challenges lie in an increase in performance (rise in operating temperature) and a reduction in investment costs for the field of solar receivers.

The medium-power plants are intended for non-interconnected grids, with the aim of achieving production closer to the point of consumption. The goals are to bring down investment and operating costs and improve operational flexibility.

The low-power plants concern isolated sites or electrical micro-grids. The aim here is very high levels of independence allied with reduced maintenance. The operating time of these plants is up to 24 hours, with very large variations in demand (0 to 100% of maximum power).

At CEA, the Liten Institute (Laboratory for Innovation in New Energy Technologies and Nanomaterials), in partnership with industry, is developing technologies targeting all these markets.

Innovative technologies

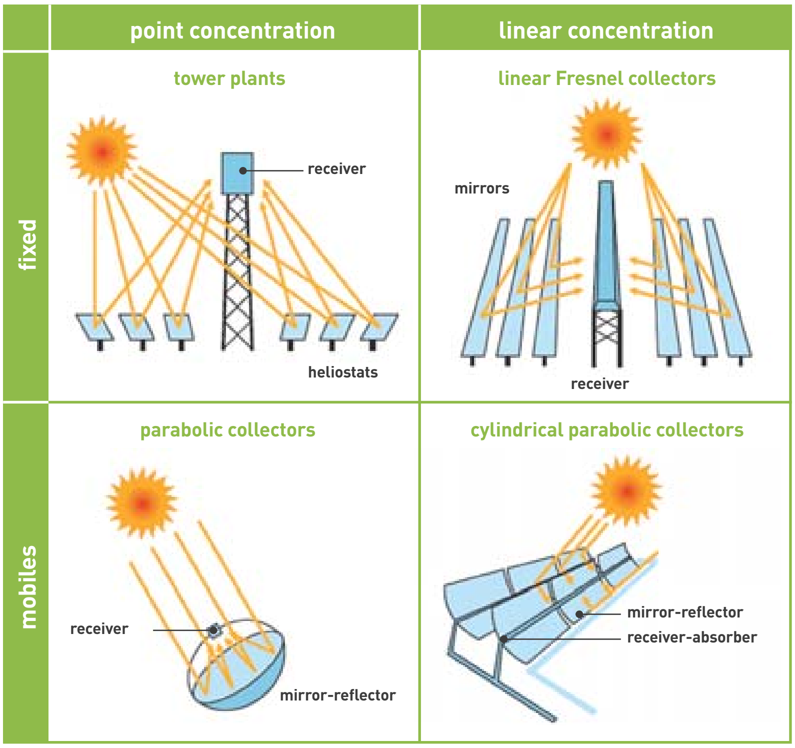
Improving the competitiveness of CSP plants entails focusing on the cost and the value per kWh.

The cost per kWh is proportional to the amount of the initial investment divided by the electricity production. To bring these costs down, either the investment must be reduced, or the quantity of energy generated must be increased. CEA has opted to pursue technological development in both areas. The Liten is thus working on developing a low-cost technology based on static receivers (SAED). It is also looking at a technology using Fresnel mirrors (ALSOLEN) operating at high temperatures (between 300 °C and 450 °C). This technology offers the advantage of attaining high efficiency levels for a manufacturing cost lower than that of the traditional cylindrical-parabolic systems.

The value per kWh is given by the availability and quality of the energy generated. Hence the work being done at the Liten on thermal storage of energy, enabling electricity production to match demand (see *The promise of thermal storage*, p. 44). This ability to modulate the power output involves far lower costs than using electrical energy storage, for example in batteries.

Low-temperature heat pipe technology

In partnership with the SAED company (*Sophia Antipolis énergie développement*), the Liten has developed a technology for fields of solar sensors. Extrapolated from domestic vacuum solar receivers, it uses original, patented heat pipes integrated into vacuum tubes. They allow effective heat transfer from the tubes to a hot water circuit. This low-temperature technology is intended for the production of industrial thermal energy (80 °C to 130 °C) at low cost. It includes a simple thermal storage function (hot water tank). Furthermore, the receivers, which use direct and diffuse solar radiation, can be installed in coastal and tropical zones. In 2011, a 200 m^2 demonstrator was deployed on the CEA's solar platform in Cadarache. It is now operational. This technological solution entered the commercial phase in 2012.



(Source: Technology Roadmap: Concentrating Solar Power, IEA-2010)

Figure 1.
The main thermodynamic concentrated solar power plant technologies.

Medium-temperature Fresnel technology

In partnership with the Alsolen company (Paris), the Liten is looking at medium-power Fresnel mirror CSPs (up to 20 MWe) (figure 2). ALSOLEN CSP plants operate with oil as the heat transfer fluid. This oil, heated to 300 °C, transfers its thermal energy to an Organic Rankine Cycle (ORC)(2) which, by actuating a turbine, generates electricity. Unlike the SAED technology, the ALSOLEN technology utilizes the direct radiation of the Sun and concentrates it 50 times on a solar receiver. Its originality in particular lies in a

Table.
Segmentation of thermodynamic concentrated solar power plants.
The market can be split into three segments according to the power of the plants.

type	low power	medium power	high power
electrical power	< 50 kWe	50 kWe – 50 MWe	50 MWe – 500 MWe
electricity grid	• micro-grids • isolated sites	• local grid	• interconnected grid
challenges	• high independence • low maintenance	• reduced investment costs • low maintenance	• high performance • reduced investment costs
target cost per kWh	0.30 €/kWh	0.15-0.25 €/kWh	0.08-0.15 €/kWh
current market	a few projects in progress	a few projects in progress	2 GWe installed to date


P. Avavian/CEA

The thermal solar receivers of the SAED demonstrator are integrated into vacuum tubes. The solar energy collected is then transferred to the heat transfer fluid (water) which circulates in the steel pipes.


Ines/CEA

Mock-up of the ALSOLEN thermodynamic concentrated solar power plant with Fresnel mirrors, installed on the Ines site. This scalable facility was designed to test various technological options.

design that maximizes manufacturing on the actual installation site, with minimal and easy maintenance, and a long service life. The associated thermal storage means that, when necessary, the operation of the solar power plant can be extended by three to six hours.

A mockup of the ALSOLEN heat production plant, comprising 100 m^2 of mirrors and a power of 50 **kWth**, was built in early 2011 at the National Solar Energy Institute (**Ines: Institut national de l'énergie solaire**). It is a unique facility and can be used for quick and simple testing of the thermal performance of various solar receivers and the optical performance of the reflectors and their Sun tracking systems. The scalable mock-up was designed to be able to evaluate various options with elements proposed by the solar industry: receiver elements, glazing, heat transfer fluid, etc. CEA and the Alsolen company thus have more rapid access to the test results, making it possible for them to select the most effective and most economical technological options for the higher power plants of the future.

A complete prototype of a representative size was built on CEA's solar platform in Cadarache at the end of the summer 2011. It has a solar field with 1,000 m^2 of mirrors, a 50 kWe ORC turbine and an air-cooler designed to remove the residual heat without the use of water. In addition, thermal storage with a rock bed of 30 m^3, offering autonomy of four to six hours was put into service in late October 2012 and initial testing has been carried out (see *The promise of thermal storage*, p. 44).

(2) Organic Rankine Cycle: the Rankine cycle is a thermodynamic cycle which describes the working of a steam engine. It includes the vaporization of the water, the expansion of the steam in a turbine or on a piston and the condensation of the steam on leaving the turbine in a condenser. In the organic Rankine cycle, the water is replaced by an organic fluid.

(3) The Prohytech platform will aim to demonstrate the industrial feasibility of large-scale hydrogen production processes.

(4) Durasol: this project comprises the deployment of a platform on several sites, both in the open and in the laboratory, to study the lifespan of three solar technologies: photovoltaic, solar thermal, and solar concentration.

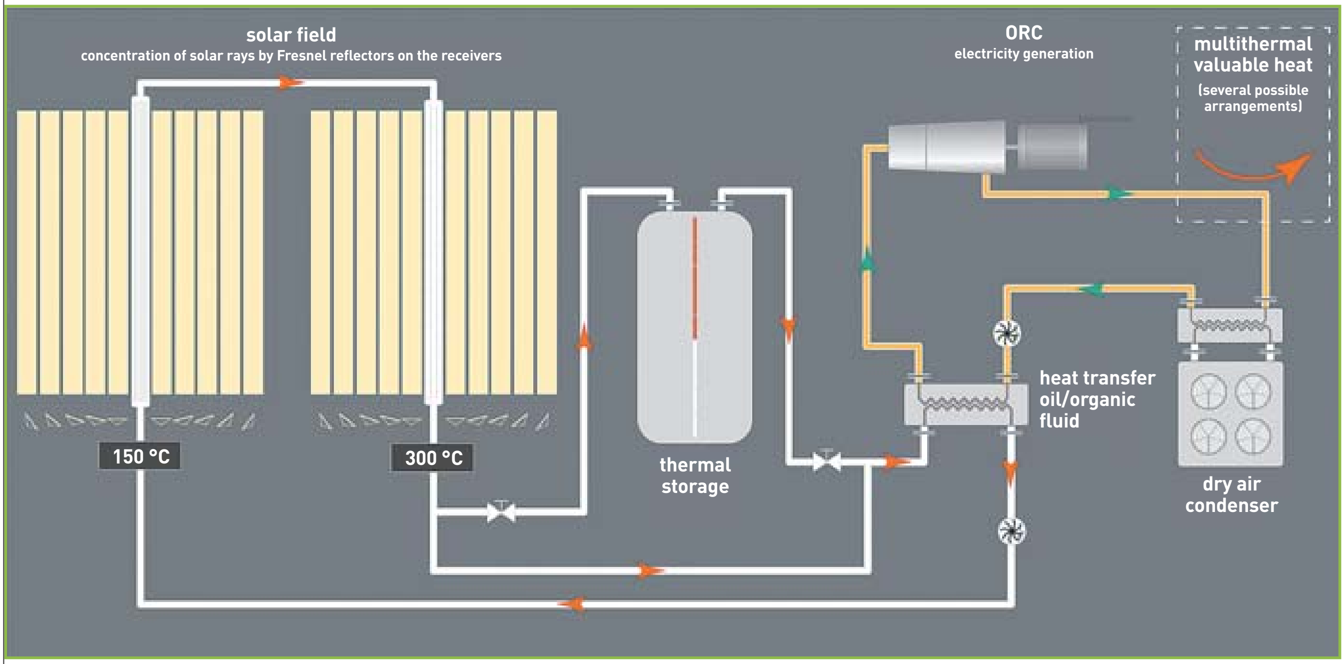


Figure 2.
General principle of a thermodynamic concentrated solar power plant, example of a plant with Fresnel mirrors and oil heat transfer fluid. The rays of the Sun are concentrated by a field of Fresnel mirrors. The heat transfer fluid (oil) which circulates in the receiver is raised to a temperature of 300 °C. It transfers its thermal energy to an Organic Rankine Cycle (ORC) which runs an electricity generator. The heat can also be stored in a reservoir integrated into the plant.


P. Avavian/CEA

Inside the Fresnel mirrors of the ALSOLEN prototype. Instead of curving the mirrors, which is a costly process, the Fresnel mirrors are very slightly angled.

The prototype will also constitute a heat source for the Prohytech(3) platform, thus demonstrating the potential of solar thermal energy for desalination, refrigeration and the production of hydrogen by electrolysis.

Tomorrow, high and very high temperatures

The race to bring down the cost per kWh is leading to constant innovation. In the case of CSPs, the heat source temperature parameter is of prime importance.

In this respect, the Liten is developing a CSP plant with high-power Fresnel mirror concentration (50 MWe and beyond) named ALSOLEN SUP. This technology, derived from ALSOLEN, will directly generate steam superheated to 450 °C and will have thermal storage capacity. The technological hurdles to be overcome concern the production of steam at high pressure and temperature, implying significant concentration factors (> 50), selective, high-performance and high-temperature treatments as well as thermal storage. A 1,500 m^2 prototype will be built and will enter service in spring 2013 on the Cadarache site.

In partnership with the CNRS' Promes laboratory (Processes, materials and solar energy – *Procédés, matériaux et énergie solaire*), the Liten is also looking at tower solar plants. An original hot air solar receiver (700-800 °C) has been developed, manufactured and successfully tested with the Odeillo large solar furnace (Pyrénées-Orientales *département*). As yet, and although the concept has been validated and looks promising, it is not industrially mature. For these projects, the Liten is employing about thirty people on developing and optimizing the CSP plant components, in particular the reflective items and their Sun tracking system, the solar receiver, its selective treatment and its thermo-hydraulic loop.


P. Avavian/CEA

ALSOLEN prototype thermodynamic concentrated solar power plant with Fresnel mirrors, installed on the CEA solar platform in Cadarache.

Cutting edge research

By means of fluid, thermal, mechanical and optical modeling, the Liten has tools enabling it to carry out the complete design of the CSP architecture and assess the solar generating capacity. It is also conducting durability studies to ensure that the CSP plants can function correctly in a difficult environment (sand, wind, ultraviolet radiation). A threefold strategy is in place. Systematic studies of failure modes are being carried out on all the subsystems of the solar power plant. These studies are then supplemented by accelerated ageing tests in the laboratory (humidity, temperature, UV radiation, sand, etc.). In this respect, the Liten's Durasol(4) project, which in early 2012 won the call for proposals for the 2nd Équipex [Excellence equipment, Investing in the Future Program (PIA: Programme d'investissements d'avenir)] will provide a first-class means of following this approach. Finally, collaboration with the MAScIR (Moroccan foundation for Advanced Science, Innovation and Research) in Rabat (Morocco) began in late 2011 with the aim of deploying and monitoring the behavior of solar field components in a real environment (for instance a desert).

These new skills, reinforced by the R&D teams working on uses of heat (thermal storage, desalination, heating, cooling, hydrogen), make the Liten a major CSP player, today in France and tomorrow internationally.

> **Patrice Tochon**[1] and **Bernard Thonon**[2]
Liten Institute (Laboratory for Innovation
in New Energy Technologies
and Nanomaterials)
Technological Research Division
[1]*CEA Grenoble Center*
[2]*CEA Grenoble (Ines Site)*

The promise of thermal storage

The storage of heat is a crucial component of a thermodynamic concentrated solar power plant, because it is a means of managing the efficiency of electricity production throughout the day and tailoring it to demand. It is also highly promising for the large-scale storage of electricity or for deriving energy from industrial waste.

Torresol Energy Investments, S.A.

The Gemasolar thermodynamic concentrated solar power plant located near Seville (Spain). Gemasolar is a tower plant using a mixture of molten salts (potassium nitrate and sodium nitrate) to store heat. 2,650 mirrors (heliostats) spread over 185 hectares follow the path of the Sun. They reflect and concentrate the Sun's rays, focusing them on a receiver located at the top of the tower, in which molten salts circulate and store the heat. The storage system comprises two large tanks (one for cold salts, the other for hot salts), which are visible at the base of the tower.

Taking a hot stone from the fireside and then putting it somewhere else where heat is needed: thermal storage is as old as man's discovery of fire. It is nonetheless a technology of the future for renewable energies. It is all the more interesting as already extensively proven technologies are today industrially available, with new possibilities for improving the compactness, efficiency and lifetime of the installations.

Physical phenomena

Storing and then restoring heat are based on three physical phenomena. The first, sensible heat, consists in using heat to increase the temperature of a solid or a liquid, which will in turn transfer its heat to a fluid. This is the role of the hot water tank coupled with thermal solar panels: it stores the heat which it then restores through sanitary hot water or a heated floor. The second physical phenomenon results from the use of storage materials which have the ability to change phases, from solid to liquid, under the effect of heat, and then from liquid to solid as they cool, hence their name Phase Change Materials (PCM). The energy per unit volume output by such a system can be high with certain particularly suitable materials, such as paraffins or salts. The last phenomenon is based on the utilization of reversible chemical reactions which, in one direction require heat (endothermic) and, in the other, release heat (exothermic). The advantage of this energy storage technique is linked not only to the energy bulk density, which can reach very high levels, but also the storage duration itself, which can be very long and even make seasonal storage possible. Heat storage is already incorporated into several thermodynamic concentrated solar power plants (CSPs), such as the Andasol cylindrical-parabolic mirrors plant in Spain, or the Solar Two tower plant in California (United States). The sensible heat storage system uses a molten salt circulating between two tanks, one in which it is stored "cold" at about 200 °C and the other in which it is stored "hot", at about 450 °C. The Gemasolar tower plant is equipped with a similar storage system. It was inaugurated in Spain in October 2011 and can produce electricity round the clock.

New developments

With the foreseeable growth in CSP plants, new heat storage systems will need to be developed, which are better suited to the temperature levels of the different technologies, which are more efficient, more compact and which require only small quantities of materials with particular safety constraints, such as molten salts.

Of these systems, heat storage from low-temperature industrial thermal discharges is one of the ways of the future. When coupled with temperature rise systems, this is a means of making deferred use of an energy which would otherwise be lost.

The large-scale storage of electricity (about a GWh) in high-temperature thermal form is also another prospect for the future. Two processes are currently being studied, Compressed Air Energy Storage (CAES) and Pumped Heat Energy Storage (PHES).

Compressed air energy storage consists in using surplus electricity to compress air, which is then stored at high-pressure (about 100 bar) in an underground cavity. This air is then expanded in a turbine to produce electricity during periods of high demand. It is essential to store the compression heat at high temperature if one is to achieve satisfactory efficiency levels. Energy storage with heat pumps was developed under the SETHER(1) project, financed by the French National Research Agency (ANR: Agence nationale de la recherche). This project is being run by the CEA's Liten Institute (Laboratory for Innovation in New Energy Technologies and Nanomaterials) in partnership with the Saipem company, which created the process. In this case, the electricity transformed into heat is stored in two chambers *via* a very high temperature heat pump thermodynamic cycle (800 °C). The heat can then be used to produce electricity *via* a conventional heat engine cycle. Thermal storage efficiency is a key factor in the size and cost of such an installation.

(1) SETHER project: French acronym for storage of electricity in thermal form at high temperature – *Stockage d'Électricité sous forme THERmique à haute température.*

Areas for research

The Liten is closely involved in the study of various technological storage solutions. The work concerns various aspects. With regard to materials, emphasis is being placed on defining their thermal physical properties, their compatibility with heat transfer fluids and the performance of tests on their resistance over time. The aspects concerning heat transfer are being studied particularly closely. Solar energy is always absorbed by a fluid, which must transfer it to a solid in order to be able to store it. The storage capacity or the response time of the system are determined by the quality of the heat exchanges. The Liten is thus working on intensifying this, by optimizing the geometrical shapes of the sensible heat systems or through concrete use of PCMs, which need to be “doped” by heat exchanger type structures in order to improve their natural heat transfer ability.

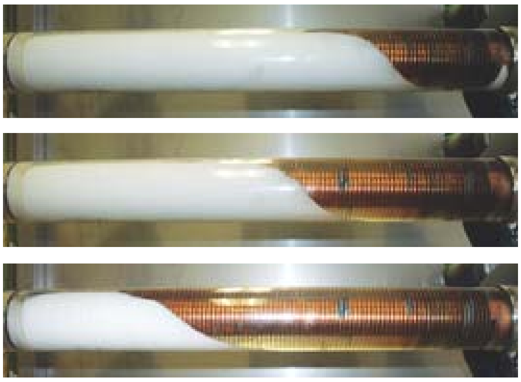
The right experimental installations

The Liten has access to unique experimental facilities devoted to studying heat storage system solutions, from simple phenomenological studies up to a semi-industrial scale test loop.

Of the phenomenological study installations, that devoted to the use of PCMs has a test section consisting of a transparent tube 4 cm in diameter and 40 cm long, with 40 temperature measurement points, to allow precise monitoring of the fusion front and validation of the simulations.

The CLAIRE test loop, which is devoted to high temperatures (in excess of 500 °C), allows the study of heat storage by sensible heat. Using air as the heat transfer fluid, it operates on a semi-industrial scale, with significant storage volumes (10 m^3) and thermal power levels (1 MW).

The STONE installation is devoted to studying thermal storage of CSPs with Fresnel mirrors, using oil as a heat transfer fluid (see *Concentrating the Sun’s energy*, p. 40). It allows detailed monitoring of the working of a rock bed by means of fine pitch instrumentation (220 temperature measurements in 3 m^3 of storage). In addition, numerical simulation of the thermal storage can visualize the progress of the heat front in this bed (figure). The simulations are validated by comparison with the temperature measurements of the STONE installation. In order to determine the orders of magnitude, it is worth specifying that the storage volume of an industrial installation should vary from a few tens to a few hundred m^3.

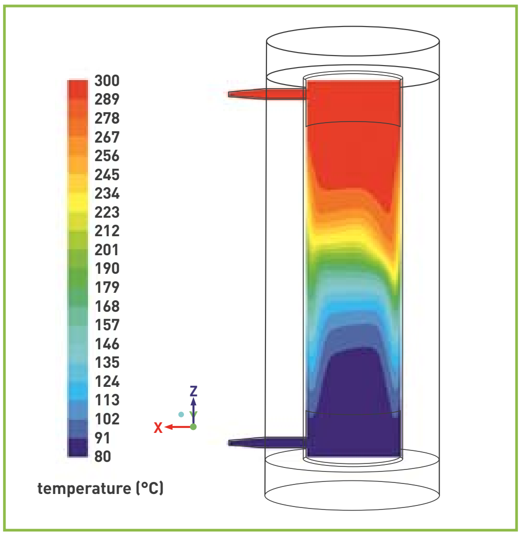


CEA

Gradual fusion of a Phase Change Material (PCM) around a tube with transverse fins.

CEA

Overview of the STONE loop (left), with rock bed type filling (right). In a thermodynamic concentrated solar power plant, the hot heat transfer fluid can be sent to the storage tank, where it transfers its heat to the rock bed, gradually heating it from top to bottom, before exiting cold. When the Sun is no longer sufficient to input the energy needed by the plant, the heat transfer fluid, injected cold at the bottom of the storage tank, heats up in contact with the rock bed and exits hot through the top. It is then used to produce electricity. As it is used, the rock bed gradually cools down from bottom to top.
The advantage of a rock bed is its extremely reasonable cost and the availability of this natural storage material.



CEA

Figure.
Simulation of the progression of the heat front in a rock bed. The heat transfer fluid (oil) gradually transfers its heat to the rock bed from top to bottom. It exits cold.

Energy conservation for deferred use will rapidly become vital for effective management of energy resources, both conventional and renewable, and thermal storage is a particularly good solution for addressing this need. The Liten has the experience and the tools needed to support this development, through the implementation of both proven and highly innovative solutions.

> **Jean-François Fourmigué**
Liten Institute (Laboratory for Innovation
in New Energy Technologies
and Nanomaterials)
Technological Research Division
CEA Grenoble Center

2nd generation biofuels: the **Syndièse** project

The production of biofuels from non-food biomass is a direct response to meeting the French and European goals for reducing greenhouse gas emissions. Backed by its work in this field, **CEA took the initiative of developing a pre-industrial pilot for the production of biodiesel, biokerosene and naphtha from the gasification of forestry residues, using a thermochemical process.** This project, which should eventually produce more than 30 million liters of biofuels annually, is the precursor for a possible French industry in this field.

Airbus SAS 2011

The Airbus A380-800 ACJ (Airbus Corporate Jetliner). The Airbus company is a stakeholder in the Biofuel Flightpath initiative launched by the European Commission to speed up the production and marketing of biofuels for air transport.

France today meets nearly 50% of its energy needs from fossil resources, as compared with more than 80% in the other countries of the world. This particular situation is primarily due (78%) to the fleet of French nuclear power plants generating electricity. Dependence on fossil fuels nonetheless remains heavy in certain sectors such as road, air and sea transport.

Rising uncertainty surrounding the price of hydrocarbons, in a delicate geopolitical context, and the expansion of national and international policies for mitigating global warming, forced the Government in 2009, following the Grenelle Environment Summit, to offer significant incentives for the development of renewable energies. In the transport sector, the Government thus undertook to achieve a 20% reduction in greenhouse gas emissions by 2020.

The European Union has also set ambitious targets in this field. Its aim is by 2020 to ensure that 10% of energies are of renewable origin. On the occasion of the 2011 Paris Air Show and in coordination with Airbus, the airlines and the biofuel producers, the European Commission launched the Biofuel Flightpath initiative. This initiative aims to speed up the production and marketing of biofuels for aircraft in Europe. The aim is, still by 2020, to achieve annual consumption of two million tons of biofuel by civil aviation, which today accounts for about 4% of fuel consumption in Europe.

Low-carbon solutions for all types of transport

Owing to rising urbanization and the concentration of populations in and around the cities, about 80% of annual fossil fuel consumption in the field of transport concerns journeys of less than 100 km per day. Vehicles with all-electric or hybrid electric motors are already operational. However, for long and medium distance journeys and, more particularly for trucks or maritime transport, which demand high power levels, diesel-FT type biofuels, produced using a Fischer-Tropsch(1) process, would appear to be a true alternative solution.

For its part, since 1 January 2012, air transport has been subject to the European ETS (European Union Emissions Trading System), a tax proportional to greenhouse gas emissions. The rise in this economic constraint, in a highly competitive and rapidly expanding sector, implies the search for alternatives to the kerosene currently used. Liquid jet fuel-FT(2) process biofuels (biokerosene) look like being a promising substitute.

Biofuels: challenges and research at CEA

The three-fold nature of the transport sector (road, sea, air) makes biofuels the focal point of research today. CEA has for several years been involved in R&D programs concerning 2nd and 3rd generation biofuels (see *Microalgae for the production of biofuels*, p. 49).

---

(1) Fischer-Tropsch (FT) process: catalytic process for producing hydrocarbons from synthesis gas (carbon monoxide CO, hydrogen H_2).

(2) Jet fuel-FT: jet fuel is a kerosene-based fuel used by turbine jet engines. Jet fuel-FT is obtained *via* a Fischer-Tropsch process.

Those of the 2nd generation are produced from the inedible parts of plants (wood, stems and non-food part of plants, green waste).

In order to avoid competing with the existing food and industrial sectors, in particular the wood industry, the organization of **biomass** supply channels is a major challenge. This organization must in particular be able to use forestry residues (remains of branches and trunks left in the forest by the forestry companies) and agricultural waste, must embrace the principles of sustainable forest management, environmental protection and biodiversity. It will have to incorporate systems designed to minimize the areas of agricultural and forestry land affected, by increasing the mass conversion efficiency of the processes transforming the biomass into fuel(3).

For the 2nd generation biofuels, two avenues are being explored: the biological route, for the production of **bioethanol**, and the thermochemical route, for **biodiesel** and jet fuel-FT.

CEA is focusing on the thermochemical option, called Biomass to Liquid (BtL), which is the principle behind its pre-industrial demonstrator called Syndièse.

The Syndièse project: four steps and a world first

The goal of the Syndièse project is, on a single site, to operate a pre-industrial demonstrator for the production of 2nd generation biofuels (BtL) in Bure-Saudron (Meuse - Haute-Marne *départements*). Using 125,000 tons of ligno-cellulosic resources(4) with 35% humidity, this facility will be able to output 30 million liters of biofuels per year, directly usable in land and air transport and for petrochemical applications. Syndièse should create about a hundred direct jobs for operation of the facility and development of the supply chain. It will entail integration on the same site of a chain of mature processes to demonstrate the industrial feasibility. The technology used in this project comprises four main steps (figure).

The first step involves pre-treatment to concentrate the forestry residues (ligno-cellulosic), in other words reduce their humidity and the size of the components. By adding oxygen and steam, at high temperature (about 1,300 to 1,400 °C) and high pressure, the pre-treated biomass breaks down into a synthesis gas (hydrogen H_2, carbon monoxide CO), called syngas.


P. Avavian/CEA

Samples of ligno-cellulosic biomass.
This renewable raw material does not compete with the existing food and industrial sectors.

This is thus a thermochemical process. The technology employed, using an entrained flow reactor, produces a gas that is rich in carbon monoxide and hydrogen, with the lowest possible level of impurities. In the next, post-treatment step, the syngas is cleaned of its impurities and enriched with hydrogen in order to double the production yield (the hydrogen is generated by **electrolysis** of water within the installation). This input of hydrogen to the process chain will be a world first.

The syngas is then transformed into long carbon chains $-(CH_2)-$ by means of a Fischer-Tropsch type **catalytic** reaction.

The last step involves cutting these chains to the lengths corresponding to diesel, jet fuel and synthetic **naphtha** by **hydrocracking**.

A CEA-Industry partnership

The German company Choren was initially the source of funding for the gasification technology processes. Following its entry into receivership in the summer of 2011, followed by its liquidation in February 2012, CEA decided – on the basis of the conclusive results of the research programs it had been running for several years in its Grenoble installations – to develop an innovative biomass gasification concept, with a major French industrial partner. The first step in the Syndièse project will thus consist in building a proof of concept pilot in Bure-Saudron. This unit will be able to process one ton of biomass per hour. Following this validation phase, the complete process chain designed to produce the biofuels, in which the funding sources

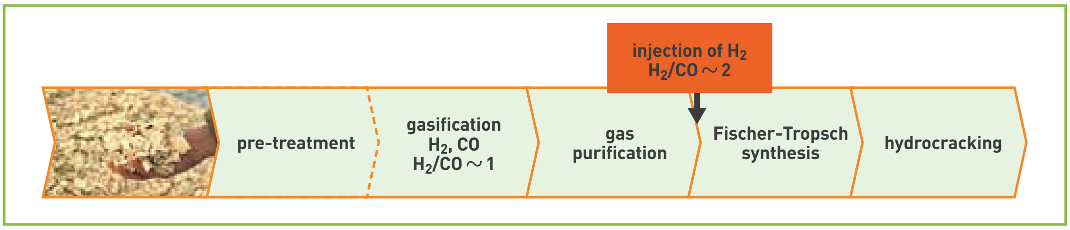
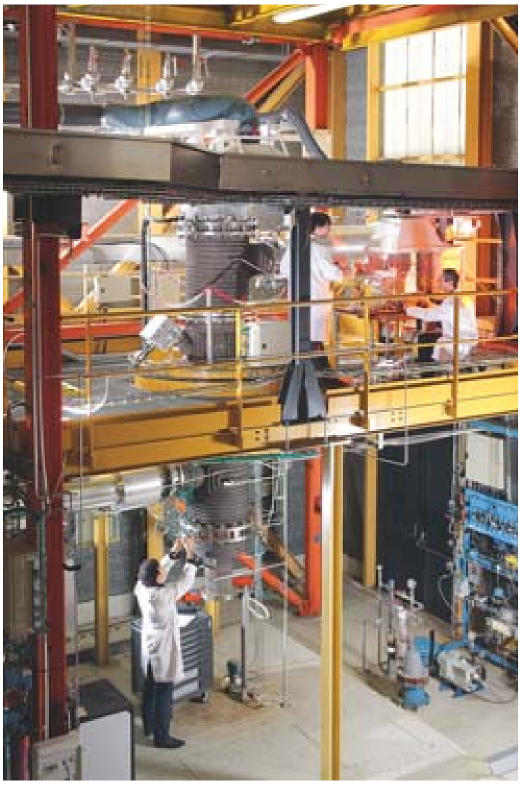


Figure.
The steps in the Syndièse project. The technology used for Syndièse comprises 4 steps: pre-treatment of forestry waste and gasification; purification of the synthesis gas obtained (hydrogen H_2, carbon monoxide CO) and enrichment with hydrogen; catalytic transformation of the syngas into long carbon chains using a Fischer-Tropsch process; production of biofuels by hydrocracking of the long chains.

---

(3) Mass yield: equivalent mass of synthesized fuel compared with the mass of dry biomass used.

(4) Ligno-cellulose: compound present in the membranes of plant cells, extremely abundant in wood and straw.


P. Avavian/CEA

PEGASE installation on the CEA center in Grenoble. PEGASE (Pure and Energetic synthetic GAS Elaboration) performs high-temperature purification of the synthesis gas resulting from the gasification of ligno-cellulosic biomass.

are Air Liquide-Lurgi, GTL.F1 and UOP for steps 2, 3 and 4 respectively, will be produced. The green light for phase 1 of the Syndièse project was given on 4 February 2013.

Ensuring sustainable management of the resource and mitigating environmental impacts

Everything is done to ensure that the construction and operation of the demonstrator will have minimal impact from the environmental and energy standpoints. The process was thus optimized and intermediate products utilized. For example, the surplus heat produced is used to dry the biomass and produce some of the electricity needed by the process. The water resulting from drying is used to generate the hydrogen that is vital to the electrolysis process, and so on.

An assessment of the impact of the Syndièse project on biodiversity was carried out. The aim was to assess the impact of the construction and operation of the site on rare or protected animal and plant species, on the loss of biotope⁽⁵⁾, on water, on protected areas nearby (sites of the Natura 2000 network), etc. Studies were carried out jointly with specialists in these fields: environmental consultants such as Sciences Environnement and Bertin Technologies, or the National Institute for Preventive Archeological Research (Inrap: *Institut national de recherches archéologiques préventives*). The results of these studies show that there is little if any impact on biodiversity.

In terms of sustainable forest management, CEA will ask the biomass suppliers for contractual proof that they are predominantly PEFC (Program for the Endorsement of Forest Certification) or FSC (Forest Stewardship Council) certified, labels which are guarantors of sustainable forest management. CEA first of all validated the local feasibility of this requirement: more than 80% of the areas considered are planted and partly exploited in compliance with these labels.

In addition, a Life Cycle Assessment⁽⁶⁾ (LCA study) was carried out by BIO Intelligence Service, an independent environmental consultant. This company is a participant in the European BioGrace project, which aims to harmonize greenhouse gas emission calculations included in the European renewable energies directive of 2009. The preliminary draft study, finalized in 2011, provided the technical data (mass and energy balance, efficiency) able to quantify the greenhouse gas footprint of all the technological components of Syndièse: drying of the woodchips, gasification, purification of the syngas, Fischer-Tropsch synthesis, hydrogen production by alkaline electrolysis, the permanent utilities requirements. The start-up and maintenance phases were also incorporated.

The conclusions of this study show that as currently envisaged, the Syndièse project will lead to a 77% reduction in greenhouse gas emissions by comparison with the diesel produced from fossil resources. This result is significantly higher than the reduction target of 60% set by the European Commission and confirms that the Syndièse project will contribute to meeting the European Union's greenhouse gas emissions reduction targets.

> **Thierry Pussieux**
Innovation and Nuclear
Support Division (DISN)
Nuclear Energy Division
CEA Saclay Center


Cnim-Architrav

Pre-industrial demonstrator project for production of 2nd generation biofuels (BtL) in Bure-Saudron (Meuse – Haute-Marne *départements*). Entrance to the Syndièse plant.

---

(5) Biotope: environment in which the physical and chemical conditions (water, light, temperature, etc.) are considered to be uniform and stable. Populated by a characteristic fauna and flora.

(6) Life cycle assessment: method for assessing the environmental impacts of products and services, from extraction or harvesting of raw materials up to disposal or recycling after use.

Microalgae for the production of **biofuels**

When compared with large-scale cereal and sugar beet crops, used to produce the first generation of biofuels, microalgae offer numerous advantages. They in particular have high yield per unit surface and can be produced on land unsuitable for conventional agriculture, thus minimizing competition with the food industry. They can naturally manufacture molecules with a high energy content. **If grown in large quantities, these micro-organisms could in the future produce the 3rd generation biofuels**. To meet this challenge, CEA is carrying out work to overcome the biological and process-related obstacles to the utilization of microalgae to produce energy.


G. Lesénéchal/CEA

Microalgae culture in photo-bioreactors instrumented for analysis of strains production capacity.

Microalgae include a very wide variety of biological organisms, ranging from cyanobacteria to photosynthetic protists, not forgetting true algae (including green algae or chlorophyceae). This biodiversity is the result of a highly complex evolutionary history, during which they evolved through a series of endosymbiotic events, with cells being incorporated into each other.

These organisms have colonized most of Earth's environments (oceans, lakes, rivers, soils, ice and deserts). Thanks to photosynthesis, they use solar energy, water and carbon dioxide (CO_2) to create biomass and are responsible for 40 to 50% of CO_2 fixing on Earth. Some species thus accumulate up to 60% of their dry mass in oils (reserve lipids consisting of triglycerides, complex compounds containing long carbon chains), which constitutes an interesting resource for the synthesis of biodiesel. However, global production of microalgae biomass, most of which is intended for the high value added compounds markets (food supplements, cosmetics, etc.) remains limited. It is thus estimated at 15,000 tons in 2011.

In the 1990s, an ambitious research program, called the Aquatic Species Program, designed to explore the potential of microalgae for the production of biodiesel, was financed in the United States. In France,


CEA

G. Lesénéchal/CEA

A. de Martino,
C. Bowler/ENS Paris

Model microalgae developed to boost progress in biology research. On the left, the cyanobacterium *Synechocystis* seen under a scanning electron microscope. It has the advantage of being easily modified by metabolic engineering to produce biofuels. Centre, *Chlamydomonas reinhardtii* which is a flagellated freshwater green microalga. On the right, the marine diatom *Phaeodactylum tricornutum*. It is polymorphous and presents three morphotypes. The diatoms are single-cell photosynthetic organisms characterized by an external silica envelope.

microalgae research began at CEA in the 1980s, in particular as part of the Association for Research into Solar Bioenergy (ARBS: *Association pour la recherche en bioénergie solaire*). Since the 2000s, there has been renewed interest in the use of microalgae to produce energy, in the form of hydrogen and biodiesel. Significant private and public investments were made in the United States and numerous companies sprang up, such as Sapphire, Solazyme, Synthetic Genomics and Aurora Fuels.

In France, several teams at CEA(1) are joining forces to take up the 3rd generation biofuels challenge. This research is supported by various projects financed by the National Research Agency ANR - Agence nationale de la recherche (Shamash, Algomics, Diesalg, DiaDomOil projects) or by the Fonds unique interministériel FUI (Salinalgue project).

The biological mechanisms involved in the accumulation of reserve lipids

When they encounter unfavorable growing conditions (limited nitrogen, stress, etc.) microalgae, like other organisms, accumulate reserve compounds such as starch or lipids (oil). The biosynthesis of triglycerides involves three main steps occurring in several cellular compartments (figure). The triglycerides are then stored in lipid bodies present in the cytoplasm as well as in the chloroplast.

The properties of the microalgal oils are determined by the characteristics of the fatty acids making up the triglycerides, in particular the length of the carbon chains and their degree of unsaturation, defined by the number of double carbon-carbon bonds. The presence of saturated fatty acids increases the viscosity of the oils. To avoid the biodiesel congealing at ambient temperature, it is beneficial either to reduce the length of the carbon chains, or to increase the number of double carbon-carbon bonds, which however has the side effect of increasing the sensitivity to oxygen. The quality of fatty acids, in terms of carbon chain length and number of double bonds is therefore an important feature determining the future utilization as a fossil oil surrogate. Intensive genetic engineering efforts have been put to optimize the composition of the oils, in order to meet the viscosity and stability criteria.


G. Lesénéchal/CEA

Banks of microalgae mutants grown in a liquid medium.

Improving the productivity of the strains

Only a few species of microalgae are currently being cultivated industrially. Their domestication thus remains a major challenge for anyone looking to use them to produce molecules of interest. This in particular involves obtaining strains which accumulate oils, without the need for a nutrient deficiency, because this seriously reduces productivity. Several strategies are used. They call on high-throughput techniques and sophisticated technological platforms (genome sequencing, global analyses of proteins or lipids), which are key advantages that can be offered by the Life Sciences Division (DSV) at CEA. This entails on the one hand searching the natural biodiversity for strains with properties of interest and, on the other, generating diversity by mutation in order to create new properties in a model species and identify the genes involved. The collection of species from the available biodiversity is in particular performed by sampling campaigns during large-scale oceanographic missions, such as

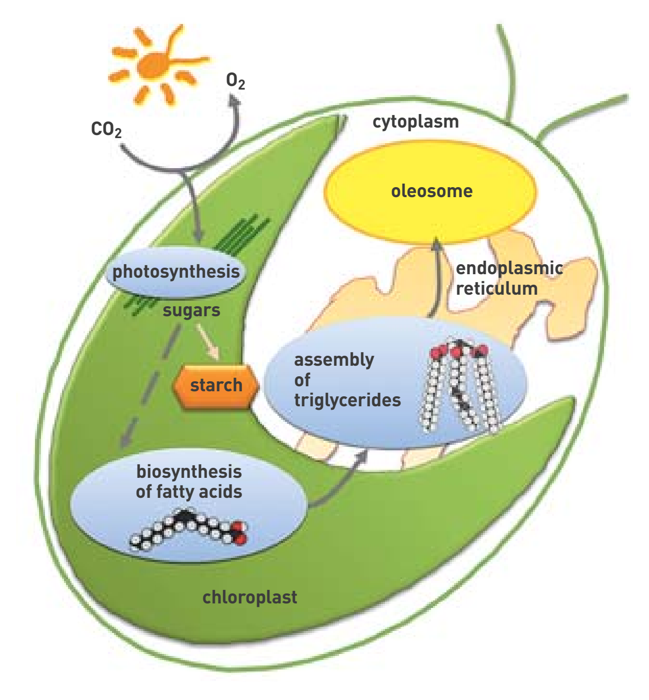


Figure.
The biosynthesis of triglycerides in microalgae. The fatty acids are first of all manufactured in the chloroplasts from sugars produced by photosynthesis. After modification, three fatty acids are combined with a glycerol molecule to form a triglyceride in the endoplasmic reticulum or in the chloroplast. The triglycerides are stored in oil bodies, lipid structures present in the cytoplasm and the chloroplasts.

(1) These are the teams from the Life Sciences Division [Institute of Environmental Biology and Biotechnology (iBEB, Cadarache Center), the Institute of Life Sciences Research and Technologies (iRTSV, Grenoble Center), the Institute of Biology and Technologies – Saclay (iBiTec-S, Saclay Center)], the Technological Research Division [Liten Institute (Laboratory for Innovation in New Energy Technologies and Nanomaterials, Grenoble Center)] and the Nuclear Energy Division (Marcoule Center).

Tara Oceans, and its extension, the Oceanomics Biotechnologies and Bioresources program, in which the DSV is associated through the work of several of its institutes.

For a given species, the direct genetic approach consists in screening collections of mutants and then identifying the gene which gives the improvement being sought. Another approach, known as the chemical genetic approach, aims to identify chemical compounds in a chemical library capable of modifying the lipid metabolism of the microalgae. These cross-cutting approaches are implemented in the DSV's laboratories.

The production of extra-cellular lipids

The transformation into biodiesel of the reserve lipids accumulated by the microalgae requires collection of the biomass and extraction of the oil, two steps which, on their own, currently account for about 70% of the production costs. The continuous secretion of lipids by the microalgae cells would be an important step forwards, liable to drastically bring down the cost of biodiesel, because the oil produced in the culture medium could be collected by simple phase separation.

The secretion of large quantities of lipids, rarely observed in microalgae, exists in all higher plants. Their epidermal cells in fact specialize in the secretion of various lipids designed to protect the plant from drying out in the Earth's atmosphere. Research designed to understand the evolution of the mechanisms of biosynthesis and of secretion of extra-cellular lipids is currently being carried out at the DSV. The finding could in the future be used to engineer microalgae to secrete lipids into the culture medium. Efforts are being focused on the family of alkanes, which can be directly used as fuels.

Biosynthesis of ethanol

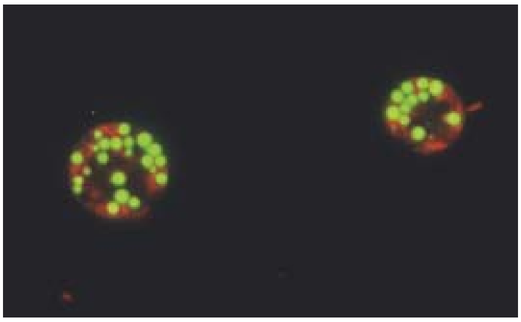
First generation bioethanol, abundantly used mixed with gasoline, is produced from sugar or cereal crops. After extraction, the simple sugars (glucose) or polymerized sugars (starch) are transformed by yeasts into bioethanol. Research carried out at CEA is looking to manufacture bioethanol directly, by coupling the photosynthetic mechanism in cyanobacteria with the production of ethanol. To do this, the enzymes allowing the biosynthesis of ethanol, such as pyruvate decarboxylase and alcohol dehydrogenase (from the yeast), are produced in the model cyanobacterium *Synechocystis*.

Development and utilization of biological models

Biological research is progressing thanks to the development of appropriate biological models. Thus the colibacillus (*Escherichia coli*) among the bacteria, thale cress (*Arabidopsis thaliana*) among the plants, or the mouse among the mammals, have become the models of choice. Various microalgae models have emerged in recent years.

- **_Synechocystis_ and cyanobacteria**

Cyanobacteria appeared 3 billion years ago and are the origin of the oxygen we breathe. These extremely simple and robust organisms are also the source, *via* endosymbiosis, of the chloroplasts in plant cells. Even if cyanobacteria do not naturally accumulate reserve lipids, they are often used as a single-cell model for the study of photosynthesis. In addition, some of them, such as *Synechocystis*, are easily modifiable by metabolic engineering to produce biofuels (alcohols, alkanes, etc.).


G. Lesénéchal/CEA

Accumulation of reserve lipids in a mutant model green alga *Chlamydomonas reinhardtii* seen under a fluorescence microscope. The lipids, stored in spherical structures called oleosomes, appear green in color.

- **_Chlamydomonas reinhardtii_ and chlorophyceae**

Chlamydomonas reinhardtii is a single-cell, freshwater green alga, often present in soils. Its genome was recently sequenced and numerous genome modification tools have been developed in this species. This alga was used as a model organism to study numerous biological processes, including photosynthesis, the function of the flagella, the photo-production of hydrogen and, more recently, the accumulation of lipids. Several other microalgae have emerged recently as study models. Thus, the genome of *Chlorella*, a species of industrial interest, has been sequenced.

- **Chromalveolata: _Phaeodactylum, Nannochloropsis_**

Numerous single-cell organisms, incorrectly referred to as microalgae – they are in fact protists – exhibit a complex cellular architecture. This is the case with diatoms, whose appearance during the course of evolution follows the inclusion of a red alga inside a non-photosynthetic cell. This association, called secondary endosymbiosis, was the origin of an extremely wide group of protists, called chromalveolata, covering creatures as diverse as marine photosynthetic species (such as the diatom *Phaeodactylum tricornutum*, whose genome has been fully sequenced), or human parasites (including *Plasmodium*, the carrier of malaria) which have been studied for more than a decade in the CEA laboratories.

Recent work has shown that the transformation of N*annochloropsis*, a microalga of industrial interest, utilized **homologous recombination**, which enables targeted modifications of the genome to be envisaged.

Cultivating, harvesting and treating biomass

Microalgae are grown in extensive open systems – generally in systems called raceways – or in intensive closed systems, photo-bioreactors, which offer higher productivity but also at higher cost. Techno-economic studies conducted at CEA show that process innovations and optimizations (growing, harvesting, extraction of compounds of interest, transformation into biofuel) are challenges faced by the sector in the same way as the biology-related improvements described previously, especially those concerning lipids productivity. The initial conclusions of an ongoing techno-economic study reveal that cultivation is a crucial step,

scenario	net energy ratio	production cost (€/L of biodiesel)	greenhouse gas emissions (kg CO_2-equivalent/100 km)	water consumption (L of water/L of biodiesel)
	average values			
reference	1.1	1.4	20.5	1,520
innovation	2.2	2.8	9.1	340
petroleum diesel	5.4(1)	0.6(2)	20.2(1)	15(3)

(1) Francesco Cherubini, Neil D. Bird, Annette COWIE, Gerfried Jungmeier, Bernhard Schlamadinger, Susanne Woess-Gallasch, "Energy- and greenhouse gas-based LCA of biofuel and bioenergy systems: Key issues, ranges and recommendations", *Resour. Conserv. Recy.* 53, 2009, p. 434-447.
(2) EIA, Gasoline and Diesel Fuel Update, April 2011. Available at: http://www.eia.gov/oog/info/gdu/gasdiesel.asp.
(3) Carey W. King, Michael E. Webber, "The Water Intensity of the Plugged-In Automotive Economy", *Environ. Sci. Technol.* 42, 2008, p. 4305-4311

Table.
Result of a techno-economic study comparing a reference scenario and an innovative scenario for the production of biodiesel. The reference scenario corresponds to the process most often encountered in the literature. It comprises the following steps: growing in a raceway (high-efficiency ponds), drying by centrifuging and gas drum dryer, extraction of the lipids by n-hexane, transesterification of the lipids and anaerobic digestion of the microalgae residues (resulting from the lipids extraction step). The innovative scenario is an optimized process consisting of the following steps: cultivation in a hybrid raceway/photo-bioreactor system, drying by filter press, wet extraction of the lipids by dimethyl-ether, hydrodeoxygenation of the lipids and anaerobic digestion of the microalgae residues. The net energy ratio is the ratio between the energy produced and the primary energy consumed.

in that it accounts for 30 to 60% of the cost of biofuel production. Numerous technological innovations are therefore expected in these cultivation systems, in order to make them more efficient and less costly. To obtain biodiesel, the lipids contained in the micro-organism must be extracted. The reference method currently used is to harvest the microalgae by centrifuging, drying them and extracting the lipids with a solvent. However, the energy consumption of these technologies, in particular for drying, is an obstacle to the large-scale development of the sector. Current research is focusing on innovative, clean technologies capable of extracting the lipids from wet microalgae (table). CEA is in particular looking at technologies based on pressurized fluids. These include: hydrothermal liquefaction, which converts a wet biomass into high-quality bio-oil with promising efficiency levels, the extraction and direct **transesterification** of lipids in a **supercritical** alcohol medium to produce biodiesel, and the extraction and fractioning of the lipids in supercritical CO_2, which enables other molecules of interest, in addition to the lipids, to be recovered, thus boosting the profitability of the technology (**nutraceutics**, molecules for the pharmaceutical and fine chemistry industries).

Once extracted, the lipids are converted into biodiesel using transesterification or hydro-treatment chemical processes which do not in principle require major R&D efforts, other than the adaptation and optimization of the existing technologies for the specific aspects of lipids obtained from microalgae.

The lipids produced by the microalgae are analyzed by high-performance liquid chromatography and mass spectrometry.

G. Lesénéchal/CEA

Meeting the economic profitability challenge

Although microalgae would appear to be a promising solution for the synthesis of 3rd generation biofuels, significant improvements are needed, in terms of the production capacity of the strains, and the cultivation, harvesting and extraction processes. Productivity will have to be significantly increased while bringing down costs, in order to be able to achieve economic profitability for energy production. It will therefore only be possible to meet the challenges of the microalgae sector by ensuring joint research by biologists and technologists. CEA, which has considerable expertise in biology and process engineering, is particularly well-positioned.

> **Fred Beisson**[1], **Yonghua Li-Beisson**[1], **Gilles Peltier**[1], **Giovanni Finazzi**[2], **Éric Maréchal**[2], **Franck Chauvat**[3], **Florian Delrue**[4], **Karine Froment**[4] and **Vincent Blet**[5]

[1]Institute of Environmental Biology
and Biotechnology (iBEB)
Life Sciences Division
CEA Cadarache Center

[2]Institute of Life Sciences Research
and Technologies (iRTSV)
Life Sciences Division
CEA Grenoble Center

[3]Institute of Biology
and Technologies – Saclay (iBiTec-S)
Life Sciences Division
CEA Saclay Center

[4]Liten Institute (Laboratory for Innovation
in New Energy Technologies
and Nanomaterials)
Technological Research Division
CEA Grenoble Center

[5]Waste Treatment and Conditioning
Research Department (DTCD)
Nuclear Energy Division
CEA Marcoule Center

Areas of R&D at CEA for developing economically and socially viable low-carbon energies

The CEA's NTE (New Energy Technologies) program focuses on "low carbon energy" including the deployment of technologies for the production of low-carbon energy carriers (electricity and heat of solar origin, hydrogen, biofuels), matching supply and demand (storage, smart grids) and certain uses of energy, in particular low-carbon transport and buildings.

The aim is to develop renewable energies and innovative energy systems, in order to make them economically and socially attractive. This implies looking at the entire product or system value chain, from design to end of life, through an umbrella approach. Whatever the technology chosen, the driving forces behind the NTE program research can be placed in five main categories, which must be dealt with systematically and simultaneously.

Eco-design

As of the design of a component (solar cell, **fuel cell**, **battery**, etc.), the materials are chosen according to a number of environmental and economic criteria. They must be abundant (security of supply, stability of costs), non-toxic and non-polluting. This is the case with the $LiFe_3PO_4$ compound (lithium iron phosphate) selected as the active material for battery **electrodes**, in order to avoid using cobalt, a highly speculative material. Studies are also under way to develop recycling processes and, whenever possible, to ensure the "reusability" of the materials. This for example entails recovering the platinum from the electrodes of fuel cells, the purified **silicon** from the silicon wafer cutting processes for **photovoltaic** systems, and so on.

Cost control

Two types of approach can reduce costs and minimize the environmental impact of the technologies. Firstly, one of the main areas for R&D to bring down production, usage and environmental impact costs is increased performance, including by increasing the lifetime and efficiency of components and systems. Whether during design or during the development of manufacturing methods, research also aims to bring down material costs (for example by using finely divided or thin film materials, or even **nano**materials, in order to minimize the quantity of material necessary), process costs (such as reducing energy costs by increasing the size of the silicon ingots) or environmental costs (aqueous rather than solvent based electrode coating techniques, etc.).

Management of usage costs

Usage costs are mainly reduced by developing smart control systems, by learning user habits and thus making the system able to anticipate: this is the case with off-peak building heating, storage of part of the photovoltaic production for subsequent use (matching supply and demand) or the storage of solar hot water. This step involves the development of sensors and software. Reduced maintenance costs, for example by on-line diagnostics and troubleshooting, is also taken into consideration.

Usages and the human-machine interface

Research is also carried out upstream to fine-tune usages or imagine new ones, for the components and systems developed, to develop the user-friendliness of the human-machine interface, to help the user with his or her choices (control systems), to ensure the interoperability of the component or system with its environment (automobile battery charging must be possible everywhere, irrespective of type or supplier). Finally – and this is a priority at CEA – numerous developments are being carried out to guarantee the dependability of these components and systems. One should mention the work being done on photovoltaic systems to detect an electric arc caused by a break in a cable connecting the solar panel to the voltage converter (in particular to avoid the risk of fire), Battery Management Systems (BMS) which protect the cells in automobile **battery packs** (for example to prevent any hazardous chemical reaction), strain gauges on hydrogen storage devices, etc.

Technical-economic and lifecycle analysis

All of this work is systematically accompanied by cost studies, by technical-economic analyses of production processes and usage conditions for components and systems (calculation of cost price of a liter of biofuel, of a **kWh** of photovoltaic electricity, of the carbon cost of the technologies, both in usage and during the manufacturing stages, and so on). The studies can also be extended to determining the economic conditions for deployment of a technology (**biomass**, photovoltaic, concentrated solar power, etc.) on a national or international scale. This work is combined with multi-criteria lifecycle analyses, including the carbon dioxide (CO_2) impact.

CEA's wide range of skills enables it to develop an integrated approach for all the technologies studied (solar, biomass, grids, mobility, buildings, etc.) ranging from the material, to the component and to the system, including fundamental, up to the research for developing pilot production lines (batteries, **cells** and **photovoltaic modules**, etc.).

> **Nicole Mermilliod**[1]
and **Hélène Burlet**[2]
[1]Head of the Cross-divisions
Program "New Energy Technologies"
[2]Liten Institute
(Laboratory for Innovation
in New Energy Technologies
and Nanomaterials)
Technological Research Division
CEA Grenoble Center

Storage of hydrogen in a TiFeMn metal hydride.

P. Avavian/CEA

II. TRANSFORMATION, STORAGE, TRANSPORT AND DISTRIBUTION

The early 21st century is a time of growing awareness of the energy problems facing our planet. This challenge is leading to significant changes in the way we approach energy, with the aim of not only diversifying the sources of this energy, but also introducing new energy carriers in order to address the needs of our new and more mobile lifestyles. For a long time, humans were sedentary, establishing themselves around directly usable energy sources. There is now a need to develop and optimize innovative technologies for the transformation, storage, transport and distribution of energy. Electricity is at the heart of this new energy mix, but its use requires a permanent and perfect balance between power demand and power supply. This problem becomes more acute with the creation of a deregulated electricity market, which encourages the growing deployment of decentralized means of production with widely varying power levels (from 3 kW to several MW) using intermittent and random energies (wind, solar, etc.).

This new paradigm for the electricity market is thus an unprecedented opportunity for the development and deployment of renewable energies, but also for the development of electricity grid management strategies. Predicting renewable energy production, programmed load-shedding and above all the storage of electricity on different time-scales (batteries for a few minutes to a few hours, hydrogen for a few hours to a few days) will contribute to the stability and security of our electricity grids. These technologies, in association with the ICTs (Information and Communication Technologies) and complex systems management algorithms, will lead to smart grids and make it possible to prevent blackouts (tens of billions of $/year), to supply isolated sites and reduce demand peaks (postponement of infrastructure investments), increase the renewable energies integration threshold (currently 30%), smooth out costs and increase the profitability of energy intensive industrial processes (taking advantage of the wide variability of prices on the EPEXSPOT market).

The energy problems today faced by islands are the forerunners of those that will be faced by the planet as a whole in the longer term. Owing to their specific energy characteristics (considerable reserves of renewable energies, primarily fossil energy mix, complex and costly access to energy, inherently more fragile and more vulnerable grid), these territories are ideal laboratories for testing the new energy storage and management technologies. CEA thus decided to join forces with the CNRS and the University of Corsica, to set up an applications branch of the National Solar Energy Institute (Ines: *Institut national de l'énergie solaire*) in Corsica, with the financial support of the Corsican authorities, the French Government and the European Union. This branch is developing three technological research platforms devoted to the management of electrical micro-grids (PAGLIA ORBA), the coupling of a hydrogen chain with a grid (MYRTE) and multimode electrical mobility (MOBIDIC).

The technological building blocks presented in this chapter are paving the way for and contributing to this new energy landscape, with the aim of more renewable energy, more energy independence, greater security of supply and growth in job-creating economic activities.

> Pierre Serre-Combe
Liten Institute (Laboratory for Innovation
in New Energy Technologies
and Nanomaterials)
Technological Research Division
CEA Grenoble Center

The development of high-performance batteries, offering improved capacity, cost and lifetime, plus guaranteed safety, is a key challenge for the deployment of efficient, non-polluting energy systems, whether mobile or stationary. Through its R&D program concerning the New Energy Technologies (NTEs), **CEA has thus become a key player in the design and implementation of innovative storage technologies** for transports (electric and hybrid vehicles), isolated site applications and applications connected to the grid, to smooth out consumption peaks and defer the need for production.

Energy in **batteries**

Batteries for electrical mobility

Since the turn of the century, CEA has been devoting a large share of its efforts to R&D work on batteries for electrical and hybrid vehicles. These activities involve numerous exchanges with industry.

Development and validation of the battery pack management system for the CEA demonstration vehicle. This vehicle was developed from an electric Citroën AX dating from the 1990s, which at the time was the lightest electric vehicle available.

P. Avavian/CEA

Road transport accounts for more than 90% of carbon dioxide (CO_2) emissions by the transport sector, 50% of that coming from private vehicles. The development of clean vehicles is thus a public policy priority. This field is being actively explored by CEA. Numerous electric and hybrid vehicle R&D programs are being proposed by its researchers, particularly at the Liten Institute (Laboratory for Innovation in New Energy Technologies and Nanomaterials). They are conducted jointly with the other public and industrial research stakeholders, in particular as part of the Research and Technology National Network on Batteries (Réseau national de recherche et technologie sur les batteries).

Battery technologies

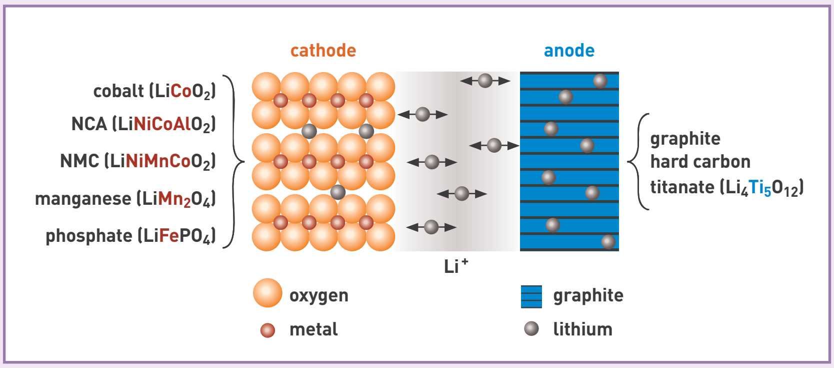
Several types of cells have been developed for the design of batteries. Lead-acid, nickel-cadmium (NiCd) and nickel-metal hydride (NiMH) cells use water-based technologies. The electrolyte consists either of sulfuric acid diluted in water, in the case of lead batteries, or potassium diluted in water for the NiCd and NiMH batteries. In addition to the main electrochemical reaction, the presence of water leads to the creation of numerous ancillary electrochemical reactions, which influence the performance and utilization of the cells. The ancillary reactions can in particular lead to self-discharge of the cells. However, these technologies do have

Lithium-ion cells

The operating principle of lithium-ion (Li-ion) cells is based on the transfer of lithium (Li^+) ions which will be inserted either into the material of the cathode (positive pole), or that of the anode (negative pole).

The choice of cathode material is a compromise between stored energy, cost and safety. The active materials are mainly mixed lithium and transition metal oxides. Initially, the main applications of Li-ion cells were laptop computers and mobile phones. Cobalt oxide provides extremely interesting specific energy (Wh/kg) and energy density (Wh/L), but it is expensive and reactive. Replacing a part of the cobalt by aluminum (NCA for Nickel-Cobalt-Aluminum - NiCoAl) or manganese (NMC for Nickel-Manganese-Cobalt - NiMnCo) is a means of optimizing the cost, safety and specific energy balance. Manganese-based technology is of considerable interest to the automobile manufacturers because the cost of the material is relatively low, and with high specific energy and energy density. However, this technology has yet to prove itself in terms of lifetime (natural ageing of the battery over a number of years) and cycling. Iron phosphate offers the best level of safety, low cost and high power, but at the expense of lower specific energy and energy density. This material is now well-positioned on the hand power tools and electric vehicles markets, primarily in the United States and China.

The materials used for the anode are essentially carbon-based (graphite, carbon fiber, etc.). The use of titanate ($Li_4Ti_5O_{12}$) offers significant gains in the potential number of cycles as well as in the power of the cell, at discharge and above all at charging. However, the voltage of the cell is about one volt less, which has a considerable impact on the specific energy and energy density.



From Martin Winter (University of Münster, Germany)

the advantage of allowing charging of a battery of cells in series, without it being necessary to add an electronic circuit in parallel with the cells. In batteries such as these, a cell which finishes charging before the others can continue to let the charge current pass through it. Conventionally, another electrochemical reaction will be initiated and will dissipate the energy received in the form of heat. The current will complete the charging of the other cells in series.

In a lithium-ion (Li-ion) cell, a single electrochemical reaction takes place, without ancillary reactions (box). The self-discharge current is extremely low, in fact virtually non-existent, which makes it possible to store energy for periods of more than a year. This is a particularly significant advantage when storing energy intended for mobile or intermittent applications, such as portable electric tools. There is thus no longer any need to recharge the battery of an electric screwdriver every time before using it. On the other hand, a current must not be run through a completely charged cell. An electronic system is required to measure the voltage at the terminals of each cell and stop the charge when the end of charge voltage is reached in one of the cells. This electronic system must also ensure that the cells are balanced, in other words allow completion of charging of the least charged cells in the series. After charging, the imbalance is very low, typically less than 1% (figure 1). The imbalance has no immediate impact on usage and the battery can be used immediately after charging. However, periodic balancing is essential to avoid the imbalance drifting and becoming amplified, charge after charge.

Electronic control

Batteries of Li-ion cells must be equipped with a Battery Management System (BMS). This monitors the voltage of all the cells, in order to stop the charge

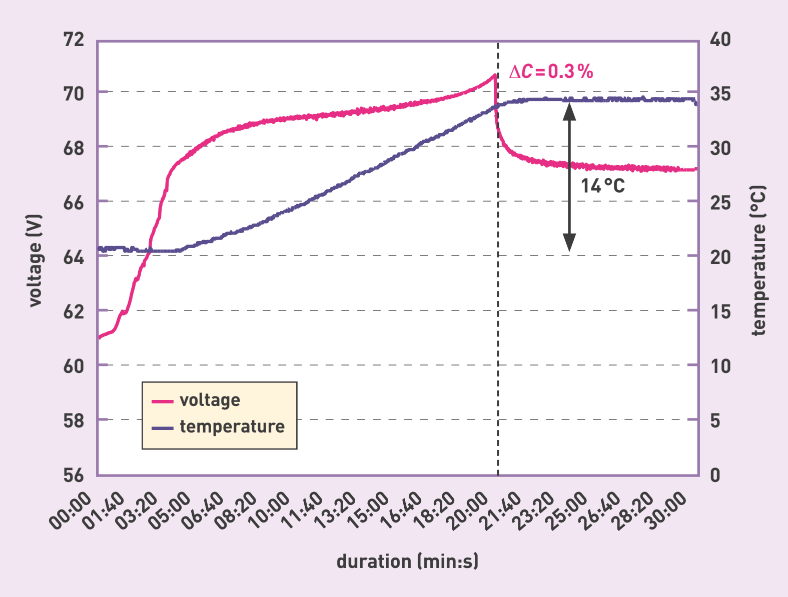
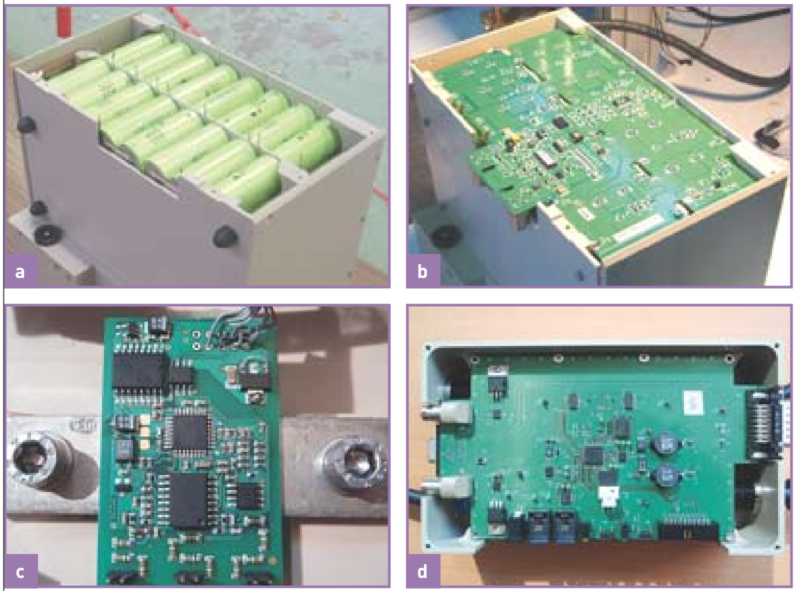


Figure 1.
Imbalance of 0.3% observed on a $LiFePO_4$ battery pack used on the CEA demonstration vehicle (a Citroën AX), after rapid charging of 20 minutes at ambient temperature.

at a high voltage threshold and stop discharge at a low voltage threshold. It also checks the temperature of the battery, calculates the remaining charge and indicates the maximum power it can output or absorb in the regeneration, braking and descent phase. Finally, the management electronics give information about battery ageing and faults and manage the voltage balancing of the cells (figure 2).

The charge status is the traditional indicator of the remaining range. At charging, the current is integrated over time in order to calculate the number of ampere·hours input into the battery. The same calculation is made while the vehicle is driving. Calculating the available charge is a means of estimating the remaining range. In the case of Li-ion cells, integrating the current over time, with readjustment at the end of charging, when maximum voltage has been reached, gives a clearer idea of the range.

The health of a battery is assessed on the basis of its drop in capacity, expressed as a percentage. Traditionally, a battery is considered to have reached the end of its life when it has lost 20 to 30% capacity. Li-ion cells must not be totally discharged as this could damage them. Assembling them to make a battery is thus an operation which involves risks of short-circuits and electrification(1). To minimize these risks, a design was chosen that uses non-hazardous voltage modules, which are connected in series as late as possible.



CEA/Liten Institute

Figure 2.
Battery pack management electronics. These packs consist of an assembly of several standard modules developed at CEA. Each module has a board measuring voltage, temperature and balancing. The data are then electrically isolated and transmitted by CAN (Controller Area Network), the standard communication network for the automobile industry. A current measurement is placed on the power current circuit. A low-value shunt resistor offers a high degree of precision over the entire measurement range, both when driving – maximum 200 amperes (A) for a battery of 400 volts (V) – and when charging – less than 10 A for the same battery in slow charge. Similarly, a board positioned on the shunt is designed to transmit the data with electrical isolation on the CAN network. The BMS CPU performs the management and calculation functions on the basis of the data received.
In picture a, an iron phosphate ($LiFePO_4$) based Li-ion cell module from a hand power tool. In picture b, balancing measurement board directly connected to the cells. In picture c, current measurement shunt. In picture d, microcontroller board comprising the monitoring, safety, balancing and status calculation (charge, energy, health, safety, maximum discharge and recharge power levels, etc.) algorithms.

Batteries and usage costs

In the 1990s, Peugeot, Citroën and Renault sold 10,000 electric vehicles, following the obligation on government administrations to use a certain percentage of electric vehicles. Production was then abandoned. The media are today focusing on the fact that electric vehicles are not being developed because of insufficient range. Although this is undeniable, this is not the main reason for this production halt. Experience feedback from these vehicles shows that the main problem was their usage cost, at the time three times higher than thermal vehicles. The energy drawn from the battery while driving only reaches 70% of that announced for an NiCd, owing to the difference between the usage conditions (discharge in one hour) and those of the manufacturers' specifications (discharge in three hours). On other vehicles, using lead-based batteries, the energy extracted was even 50% less than that specified (specification for discharge in 10 hours instead of 1 hour). The number of real utilization cycles was also far lower than that of the specifications. Instead of lasting 100,000 km, the batteries had to be replaced after three or four years and after 30,000 to 40,000 km. As for the usage cost of storing energy(2), it was about 1.5 € /kWh for the vehicles of the 1990s, while it needed to be less than 0.5 €/kWh to be competitive with the cost of energy from fuel, once the efficiency of the thermal engine was taken into account. In the calculation, the cost of electricity at the power point is ignored, as it is today far less than the usage cost of storage.

With hybrid vehicles, it is possible to achieve a competitive usage cost of storing energy by running the battery only for 5% microcycles. Thus an NiMH battery, specified for 1,000 complete charge-discharge cycles, can run 100,000 5% cycles. The usage cost is then divided by five. This is one of the advantages of hybrid vehicles with power split devices, such as the Toyota Prius: the vehicle constantly decides whether it is better to use gasoline or the electricity stored in the battery. For electric vehicles, which therefore do not have an additional energy source, the batteries are used in complete cycles. A competitive usage cost is today accessible thanks to the cost reductions achieved through volume production and the regular growth in the number of real usage cycles.

The vehicles have to be light in order to minimize the size of the battery and therefore its purchase and usage costs. A large share of today's electric vehicles are actually electrified thermal vehicles. With the increasing number of diesel vehicles, the corresponding need for sound-proofing and improved passive and active safety features means that vehicle weights have risen to 1,100-1,300 kg. Electrification leads to a final weight of about 1,500 kg and the need to include a battery of 25 to 30 kWh for a range of 160 km. The size of the vehicle and of the battery have a considerable influence on the purchase and/or leasing costs, as well as on the cost per kilometer.

(1) Electrification: passage of an electric current through the human body, leading to possible lesions and even death.

(2) Usage cost of storing energy: purchase cost of the storage (in €/kWh, where the energy is actually available for use) divided by the number of cycles in actual usage.

A far lighter vehicle and a correspondingly smaller battery are needed to ensure that electric vehicles are competitive. This would be possible provided that, rather than electrifying existing vehicles, an optimized electric car were to be designed, something that the manufacturers are now doing, or if different types of vehicles were to be proposed, such as scooters, three-wheelers, quads or the Renault Twizy(3).

Fast recharge

The power of lithium cells can be optimized by adjusting the materials of the electrodes and their thickness, as well as the aluminum and copper strips(4), to be able to carry out fast charging. This makes it possible to propose electric vehicles for local and home/work journeys, with slow charging at night for regular usage, plus the possibility of making long journeys with a succession of drive phases and fast charges.

Fast recharging of lithium cells also opens the door for new vehicles designs, as illustrated by the collaborative ElLiSup project (electric bus with lithium batteries and supercapacitors), supported by the Irisbus company.

For a bus to have a range of 150 km, with overnight charging, it must carry a battery weighing up to several tons, which is only economically competitive for a battery lifetime of ten years. Another solution is to use supercapacitors(5) designed to cover the distance between stops and to position a high-power recharging point (200 kW) at each stop. This solution is heavily penalized by the cost of the infrastructure required at each station. The ElLiSup project is looking to develop a lightweight bus, with an optimized drive train and a battery charged at the end of the line in five minutes. The infrastructure would be nothing more than a recharging terminal of 200 kW at the end of each line. The size of the battery is three times smaller than in the previous options and its purchase cost is correspondingly less. The return on investment time is brought down to three or four years. A rechargeable hybrid bus and an electric bus are being developed using this concept (see *Electric transports*, p. 84).

CEA/Liten Institute

The CEA's electric demonstrator vehicle highlighted the impact of weight on performance. By replacing the original NiCd battery pack, with its specified 12 kWh (but actually 7 to 8 kWh), with an $LiFePO_4$ battery of 10 kWh and then 13 kWh, but with only half the weight, the CEA researchers gave this vehicle a range of 130 km in actual driving conditions, good climbing performance (up to the top of the Alpe d'Huez and back) and fast recharging. The range is comparable to that of today's electric vehicles, but with a battery only half the size. Thus, an appropriate design, taking account of today's safety constraints, would make it possible to propose an electric vehicle of less than one ton, with smaller battery and lower cost. The researchers also demonstrated that thanks to rapid recharging, this vehicle could cover 780 km in a day and 1,240 km in a 24 hour period, on the roads around Grenoble (Isère *département*).

Transport electrification is today undergoing rapid development in terms of train traction and ship propulsion (electric or diesel-electric), as well as electric controls for aircraft and vehicles. The aim is to save energy while improving services. Batteries are making progress year after year, driven by the range of mobile application markets. If, in the field of microprocessors, Moore's Law states that the number of transistors on a chip doubles every two years, in the field of batteries, the capacity of the cells increases by 10% per year. The performance of batteries and fuel cells is constantly improving in terms of range, safety and lifetime. The purchase and user costs are becoming competitive. The aim is to get 400,000 electric and hybrid vehicles into circulation in France by 2015 and 2 million by 2020.

> **Daniel Chatroux**
Liten Institute (Laboratory for Innovation
in New Energy Technologies
and Nanomaterials)
Technological Research Division
CEA Grenoble Center

---

(3) The Twizy, from the car maker Renault, is a tandem twin-seater electric car. It is small (2.34 m long, 1.24 m wide and 1.45 m high), with a range of 100 km in urban cycle and can be recharged in three and a half hours. It is equipped with 6.1 kWh Li-ion batteries. Its weight, including batteries, is 450 kg.

(4) Used to collect the current.

(5) Supercapacitor: recovers kinetic energy during the braking phase and transforms it into electricity. Capable of charging and discharging very quickly, it takes the form of an ultra-fast battery.

Batteries for stationary applications

Energy storage is a crucial challenge for electricity production systems utilizing intermittent energies. The work being done at CEA is aiming to develop storage technologies making up for the weak points in the existing systems.


P. Avavian/CEA

Redox battery. By storing photovoltaic electricity, this battery can be used to regulate production and consumption on the electricity grid.

Electricity storage is essential for applications on an isolated site. Changing regulations are also tending to give it ever-greater importance in applications connected to the electricity grid, in particular in conjunction with the increasing penetration of intermittent and unavoidable sources (hard to predict and uncontrollable), such as **photovoltaic** energy and wind power, at a time when grids are becoming more flexible (smart grids). The law encouraging the self-consumption of photovoltaic energy in Germany and the calls for tenders from the French Energy Regulation Commission (**CRE: Commission de régulation de l'énergie**) for the coupling of certain high-power photovoltaic power plants and wind farms with energy storage systems in the overseas *départements* are prime examples of these changes (see *Hydrogen, a means of storing electricity*, p. 68).

Electrochemical storage

Numerous storage technologies are competing to meet a given requirement for load smoothing, grid decongestion, frequency support or backup supply. Among them, electrochemical storage, owing to its sizing flexibility, is a natural choice for low power/energy applications and, increasingly, for large-scale applications (**MW**/**MWh**).

Tackling the integration of such storage systems involves working at several levels.

In the technological development phase, attention must be focused on the electrochemistry, the formulation of materials and the development of new technologies. The Liten Institute (Laboratory for Innovation in New Energy Technologies and Nanomaterials), together with the technology manufacturers, is thus looking at all types of electrochemistry: lithium-ion (Li-ion), high temperature, lead-sulfuric acid (Pb-H_2SO_4), nickel based (NiCd, Ni-MH, Ni-Zn, etc.), lead-methanesulfonic acid (Pb-MSA) **cells**, etc.

Once the technology matures, it will need to be utilized in the best operating conditions and pertinent management indicators will have to be developed. This Battery Management System (BMS) requires not only detailed knowledge of the individual element (cell, battery) and its electrochemistry, but also how it interfaces with its environment. This work is performed with the manufacturers and with the users of the technology.

Finally, for connection to the power grid, the storage system must include a converter, which can also be responsible for part of the electrical behavior of the system.

All of this work is underpinned by characterization and modeling work to select the technologies and designs most appropriate to the application.

Liten is involved in these three levels of development, in partnership with the technology manufacturers, the electrical equipment suppliers and the final integrators. Some electrochemical technologies – Li-ion, Pb-MSA **redox** – are being fully developed at Liten. However, BMS and system level work is being carried out on the technologies present on the market, with the industrial players giving access to their individual elements: Li-ion, nickel-zinc (NiZn) cells and others based on Ni, sodium-nickel chloride (Na-$NiCl_2$) operating at high temperature, vanadium (V) type redox flow cell, etc.

Redox systems

One emblematic result of the R&D work done by the Liten concerns a **redox battery** with circulation of **electrolyte**. Owing to their inherent characteristics, these storage systems would appear to be relevant for levels of about a hundred **kW**/**kWh** and more, in particular to support distribution or transmission grids:

- decoupling possible between power and **capacity**;
- possibility of capacity extension at low cost (just needs a larger tank);
- no **self-discharge** in disconnected mode;
- stability during operation (lifetime);
- absence of memory effect(1) allowing **cycling** over the entire range of charge states;

---

(1) Memory effect: if the battery is not completely discharged, at the next charge-discharge cycle, only a fraction of the capacity is accessible. Thus, in the absence of memory effect, the battery can be charged-discharged (cycled) over its entire range of charge states, with no impact by its depth of discharge on its state of health.

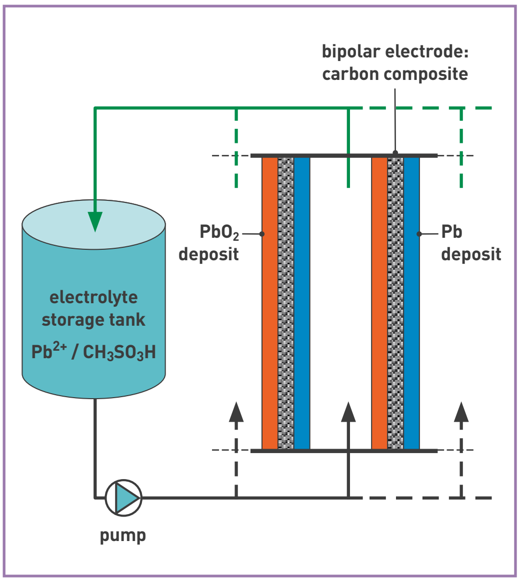


Figure 1.
Schematic of a bipolar configuration Pb-MSA redox flow battery (bipolar reactor). This type of battery, for which the lead (in the form Pb^{2+}) is in solution in the MSA, in a single tank, only requires a single pumping system. The Pb^{2+} is deposited on the electrodes in the form of Pb and lead dioxide (PbO_2) during charging.

- low sensitivity to almost total discharging.

Redox flow technologies are today reaching commercial maturity, with zinc-bromine (ZnBr) and vanadium (V) batteries. They do however have weak points in terms of durability, the complexity of the fluid system and the toxicity of the electrolytes.

Pb-MSA batteries

The Pb-MSA system developed at the Liten's Electricity Storage Laboratory (LSE: *Laboratoire de stockage de l'électricité*) uses a simpler design than the ZnBr and V redox systems. It counters their weaknesses through an original approach based on the use of lead in solution in methanesulfonic acid. This technology (figure 1) will eventually offer the following advantages:

- a single reaction compartment, hence a single electrolyte tank and a single pumping system;
- the absence of membrane, which is a means of eliminating the problems of electrolyte pollution owing to species passing through the membrane (cross-flow), and thus enabling high-power operations (which is not the case for today's technologies);
- electrodes with a large active surface and monopolar architecture, improving the reliability and leak-tightness of the system;
- eco-design upstream of the technology and the use of a non-toxic electrolyte, MSA;
- low cost, in particular thanks to the use of an electrochemical couple based on lead, with a target of less than 80 €/kWh installed (average cost for lead-acid batteries) and 0.1 € per kWh removed from storage over the lifetime.

This system has been studied by Derek Pletcher's team at Southampton University (United Kingdom) since 2004. To date, the performance achieved is 100 cycles for a unit cell with a surface of 100 cm^2, in a bipolar type configuration. Work is continuing. Numerous points still have to be improved, in particular the cyclability and the connection of the cells in series.

The operation of the Pb-MSA system is similar to conventional Pb-H_2SO_4 batteries. However, in these conventional batteries, lead accounts for most of the cost, while its utilization ratio is only about 25%: 40 to 50% of the lead is used for the current collector and the active material is only used 40-50%. On the other hand, in the Pb-MSA flow battery, up to 95% of the lead can be used because circulation of the electrolyte eliminates the diffusion restriction. Furthermore, the use of a single electrolyte considerably simplifies the design of the system. MSA also has environmental advantages. It is an organic, biodegradable acid formed during oxidation by chlorine of methanethiol (CH_3SH). This latter can be synthesized by micro-organisms, which enables future production based on biotechnologies to be envisaged.

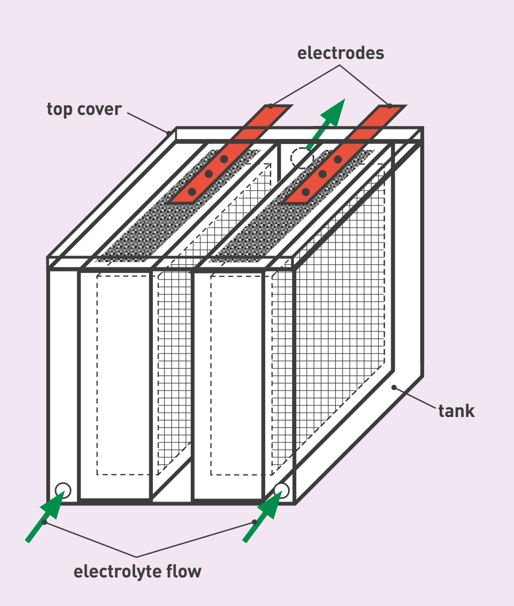
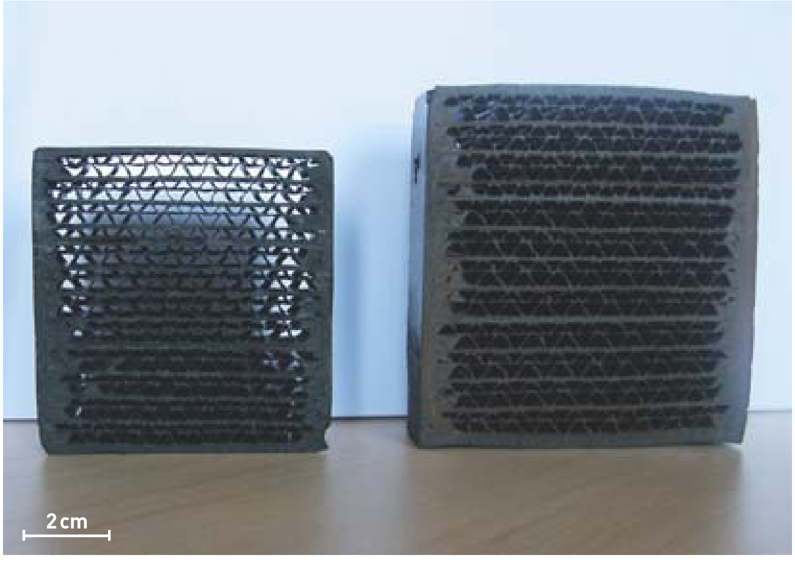


Figure 2.
Schematic of the honeycomb flow-through electrodes cell. The geometry of this cell optimizes the volume/active surface ratio for channels of diameter 1-3 mm and length 15-20 mm. Electrolyte circulation follows a cross-flow, so that the effects of the ohmic drop (internal resistance of the cell, dependent on the nature of the electrolyte, the distance between the electrodes, etc.) are offset by the Pb^{2+} concentration gradient along the channels. The high active surface leads to a very compact cell, which could provide high power with a low electrolyte flow during charging, thus limiting the risk of active material separation.



CEA

Flow-through electrode before calcination (right, composite of phenolic resin and cellulose) and after calcination (left, vitreous carbon, low-density carbonaceous material).


CEA

Prototype of a honeycomb flow-through electrodes reactor (left) from which a prototype Pb-MSA redox flow battery was built (right). Visible are the electrolyte tank, the pump (white), the reactor and the electrolyte circulation indicators (blue and black).

Honeycomb electrodes flow reactor

Derek Pletcher and his team are working on a bipolar architecture, in which the current collector supports the positive electrode (**cathode**) in one cell and the negative electrode (**anode**) in the next, acting both as the interconnection between the cells and as the wall between them. In this bipolar configuration, the lead (Pb) and lead dioxide (PbO_2) are deposited in a thin film on the surface of the electrodes, but as the cycles continue, deposits form at other locations on the reactor and generate short-circuits. To get round this problem, the flow reactor developed at the LSE

Optimizing lithium battery safety

Making **batteries** safe, in other words guaranteeing safety by understanding the phenomena involved when they are subject to external hazards. This is one of CEA's goals for optimizing lithium batteries. The lithium batteries safety program is thus testing the battery technologies developed at CEA or in collaboration with its partners. It concerns all industrial applications that use batteries (vehicle, solar power, mobile electronics, etc.). For example, the electric vehicle, which is based on R&D for new architectures and new battery chemistries, in order to improve range while bringing down costs, is the subject of work designed to optimize the safety of the devices used.

The safety goal

Testing the safety of batteries requires the design, performance and interpretation of tests for overloading this type of element in an extreme accident environment. These heavily instrumented tests require special facilities, capable of handling all formats of objects to be tested, from button cells to a vehicle's complete **battery pack**: numerous laboratories, workshops, test slabs and test benches specific to each size of object (given the specifications imposed by the standards). It must also be possible to run these tests remotely, in complete safety for the personnel and the facilities.


P. Avavian/CEA

Lithium-ion batteries developed in the Liten Institute.


CEA/DAM

Thermal test: fire caused by heating with a blowtorch. This experiment consists in overheating a cell with a blowtorch, in observing its behavior over time and in testing the usual extinguishing means (water, CO_2, etc.).

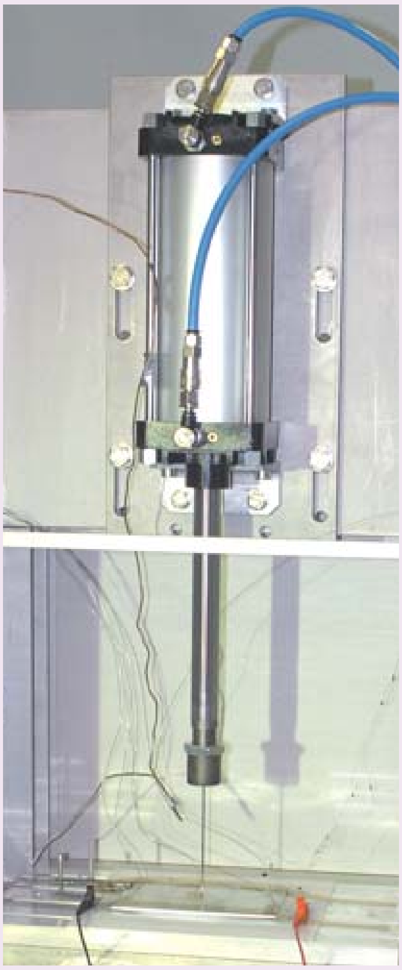
The lithium batteries safety activity is today based on CEA's material science expertise and resources, in particular energy, electrochemistry, specific test instrumentation and physical-chemical characterization. This expertise and these resources are in particular available within the Explosives Department (DXPL) [Military Applications Division (DAM), CEA Le Ripault Center] and the Electricity and Hydrogen for Transportation Division (DEHT) [Liten Institute (Laboratory for Innovation in New Energy Technologies and Nanomaterials), Technological Research Division (DRT), CEA Grenoble Center]. This primarily involves analyzing the behavior of the various technologies and architectures when subjected to thermal hazards (overheating, fire, etc.), mechanical hazards (falls, impacts, puncture, etc.) and/or electrical hazards (short-circuit, over-charging, excessive discharge, etc.). It is also possible to define specific tests at the request of external partners. These tests are based on draft standards which are still under discussion. Once the limit tests have been performed, the **cells**, modules and packs are autopsied in order to understand the physical-chemical phenomena involved. An analysis protocol was set up, from disassembly of the device in complete safety to the actual analysis itself. The *post mortem* analyses of the materials and architectures are performed in the DEHT (electrochemical, physical-chemical, etc. characterizations) and in the DXPL (mechanical, dimensional characterizations, gaseous emanations, X-rays, etc. characterizations). Particular attention is given to the nature, quantity and kinetics of the gases, fumes and flames which can be released after certain overloads. Analysis of the gases, along with the associated scientific interpretation process, is a crucial point that will only grow in importance. Special analysis resources for mapping all the molecules present during an overload test are being developed in order to assess the toxic and thermal hazards.

The purpose of the program run by CEA is not to certify industrial objects – this for example being the role of the French National Institute for Industrial Environment and Risks (**Ineris: Institut national de l'environnement industriel et des risques**) and the responsibility of the industrial firm – but to examine prototypes in an incident or accident situation, in order – on the one hand – to scientifically understand the electrochemical and physico-chemical phenomena involved during aggressive overloadings and – on the other – to optimize the technological solutions that exist or which are nearing the end of development. Once the overload tests have been completed, optimization in particular involves the development of new materials and the design of smart and is a monopolar configuration, with carbon honeycomb flow-through electrodes described in a CEA patent. Numerous electrode prototypes, obtained by calcination of a resin structure, demonstrated the feasibility of the process.

A prototype reactor was built by the LSE team according to the schematic proposed in figure 2, and then assembled in a system. The first charge-discharge tests and measurements using electrochemical impedance spectroscopy demonstrated that the electrical characteristics of the prototype battery are appropriate for solar applications that are connected to the grid and are stationary. However, the system's performance is still limited by the non-optimized geometry of the reactor and the need to improve the stoichiometry of the reaction.

> **Marion Perrin**
Liten Institute (Laboratory for Innovation
in New Energy Technologies
and Nanomaterials)
Technological Research Division
CEA Grenoble (Ines Site)

safe packagings. The Battery Materials Laboratory (LMB: *Laboratoire des matériaux pour les batteries*) at the Liten is thus using new safe chemistries, *via* the synthesis of new active materials for the positive and negative electrodes and a safe electrolyte, with the development of innovative separators. In partnership with the Leti Institute (Laboratory of Electronics and Information Technologies), the Liten is also working on new electrical architectures enabling the battery pack to be dynamically reconfigured.


CEA/DAM

Mechanical puncture test (nail test).
A cell is punctured with a metal spike which completely passes through the element.
This test simulates a battery internal short-circuit.

A battery testing platform

The DAM and the DRT are working on setting up a safety testing platform for lithium batteries in order to improve their performance in this respect. This platform, located on the Ripault site, has been operational since January 2013. It is a 300 m^2 building surrounded by a bund wall[1], comprising three independent rooms which will be used to test the different battery power ranges with the main types of loadings required: electrical, thermal, mechanical, or a combination thereof. This secure facility has a remote control station equipped with recording, control and measurement systems, plus video.

CEA will eventually be able to give an opinion on the safety of lithium technologies by applying the simulation method implemented for the DAM objects. For example, there are no performance forecasts for materials and architectures able to simulate how a battery would behave in an accident environment. For the time being, the approach is basically experimental. In the near future, it would be interesting to be able to propose a simulation method offering optimum guarantees of reliability, safety and operation based on both modeling and experimentation. This will require enhanced *post mortem* appraisal of the batteries and the modeling of physical phenomena so that the expected behavior of such objects can be modeled when subjected to accident environments.


CEA/DAM

Electrical short-circuit test. The short-circuit is created by connecting the positive and negative poles of a cell by means of a metal conductor with negligible resistance. This test simulates an external short-circuit.

> **David Descarsin**[1]
and **Johann Lejosne**[2]
[1]Explosives Department
Military Applications Division
CEA Le Ripault Center

[2]Liten Institute
(Laboratory for Innovation
in New Energy Technologies
and Nanomaterials)
Technological Research Division
CEA Grenoble Center

---

(1) Bund wall: earth dyke situated near the building to attenuate the effects of projectiles and fire on the neighborhood.

With the growth of renewable energies, which are destined to assume a key position in the energy mix, hydrogen as a carrier would appear to be a "buffer" tool, in other words one that is ideal for compensating for the intermittence of energy sources such as solar and wind power. The technologies developed for the clean production and storage of hydrogen are becoming increasingly mature and the first experiments are under way, in particular with the MYRTE platform installed in Corsica. In this demonstrator coupled to the grid, hydrogen is manufactured from electricity, stored and converted back into electricity as and when needed, in order to manage the power fluctuations of photovoltaic energy and therefore balance supply and demand. This "life size" experiment will be able to test various storage functions and develop energy management strategies. **Hydrogen is thus a pertinent alternative energy carrier capable of effectively supplementing electricity. It is more than just a carrier and can also be used as a means of storing energy, giving a whole new dimension to the hydrogen sector.**

Hydrogen, an inexhaustible **energy carrier**

Storage of hydrogen

As a storable energy carrier, hydrogen is being envisaged for two major types of applications: stationary, to make use of renewable energies, and the supply of energy on the move for on-board systems. CEA is developing various hydrogen storage solutions, whether in gaseous or solid form, meeting the compactness, light weight, safety and cost requirements. If low-pressure storage and solid storage in hydrides would seem to be the preferred options for stationary applications, several technologies are competing for transport applications.

P. Avavian/CEA

Tank for storage of hydrogen in a low-temperature TiFeMn hydride. Desorption takes place thanks to the heat provided by the fuel cell. This tank was developed by the Liten Institute/DTBH for an agricultural application with the Massey Ferguson – AGCO group. A module such as that presented can store 2 kg of hydrogen in 30 minutes at only 30 bar. The same volume capacity as a tank at 700 bar is achieved.

There are at present three main technologies for storing pure hydrogen. The aim is to obtain a compact storage system. In normal temperature and pressure conditions (STP: 1 **bar**, 20 °C), hydrogen occupies a volume of 333 L/**kWh**, as compared with 0.1 L/kWh for gasoline. It is therefore essential to find a way of making volume savings.

The first way of doing this is to *compress* the gas. This technology is recommended for automobiles. At 700 bar, hydrogen occupies a volume of 0.47 L/kWh. Another way of making it more compact is to *liquefy* it, which entails cooling it below 20.3 K (- 252.8 °C). The hydrogen then occupies a volume of 0.38 L/kWh. Finally, the third method of storage, known as "*solid storage*" consists in using a material which **absorbs** the hydrogen. The hydrogen atoms which penetrate the crystalline array of a "hydriding" material are closer together than in its gaseous or even liquid form. For example, for certain materials which absorb hydrogen, the volume occupied can be as little as 0.25 L/kWh in normal conditions. This mode of storage, which offers very good volume capacity, hence arouses interest; it exhibits however a lower mass capacity than that of all the other ways to store hydrogen, because the mass of the storage material is far higher than that of the hydrogen stored (figure 1). The Biomass and Hydrogen Technologies Department (DTBH) of CEA's Liten Institute (Laboratory for Innovation in New Energy Technologies and Nanomaterials) is working on two types of applications: stationary, to counter the intermittent nature of renewable energies, and on-board. For stationary applications, a very inexpensive system per kilogram of hydrogen stored, with high energy efficiency(1) will first of all be looked for. Current solutions are focusing on low-pressure storage or storage using hydrides. Concerning on-board systems, the volume and weight constraints are vital. Fast filling kinetics will also be sought, whereas consumption is generally more spread out over time.

Pressurized storage

The storage of hydrogen in gas form uses tanks referred to as **hyperbaric** and classified in four categories. The "type I" are all metal, the "type II" are metal with filament winding on the cylindrical part (generally fiberglass); the "type III" comprise a complete filament winding and include an internal metal liner (hydrogen barrier). The "type IV" contain a **polymer** liner (usual polyethylene or polyamide type **thermoplastic**). For storing hyperbaric hydrogen, the fibers used for the types III and IV are **carbon fibers**. This evolution was dictated by the search for lighter structures, as type I technology was unsuitable for automobile applications. This solution is however still used for stationary storage, particularly at low-pressure. In this case, low pressure is preferred in order to limit the energy cost of gas compression, which can reach 25% in the case of tanks at 700 bar. In this case, fiberglass, which is cheaper, is utilized.

At present, the only apparent solution for cars is type III or IV tanks at a rated pressure of 350 bar, with the target being 700 bar. Several dozen hydrogen cars are at present running in the United States, where "hydrogen highways" are being developed. Similar projects are appearing in Germany and Japan, where service stations are already operating. In France, legislative issues are still an obstacle to commercial hydrogen vehicles using the public highway. It is to be hoped that the standardization work undertaken by the French Association for Hydrogen and Fuel Cells (**AFHYPAC: Association française pour l'hydrogène et les piles à combustible**) will lead to the rapid emergence of hydrogen-powered cars in France.

Liquid storage

Several car makers are looking at the **cryogenic** storage of hydrogen in liquid form, as this technology today offers the best performance in terms of mass and volume. However, liquefaction demands large amounts of energy, generally corresponding to 30% of the **Net Calorific Value** (**NCV**) of the hydrogen stored. The car maker BMW has for a long time opted for this type of storage for automobiles. However, safety problems linked to the phenomenon of vaporization and the fragility of the tanks should signal the end of this method of storage for this application.

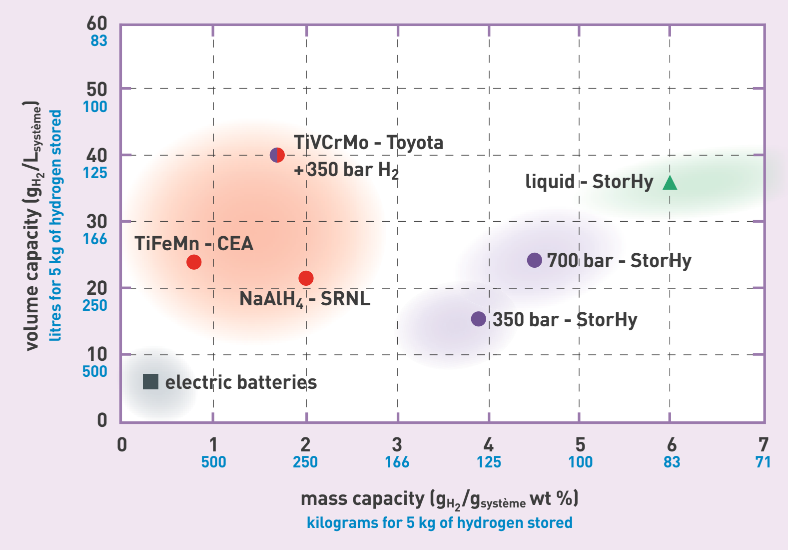


Figure 1.
Mass and volume storage capacities for the three possible storage modes with a view to automobile transport. The storage capacity in grams of hydrogen is compared with the volume and mass of the complete storage system. It is clear that hydride storage (in red), even if it leads to the least voluminous applications, offers a far lower mass capacity than the two other storage methods: pressurized gaseous state (violet) and liquid form (green). As a comparison, gasoline with an NCV of 42,700 kJ/kg and a density of 0.75 kg/L gives an energy equivalent of 36 g_{H_2}/g_{system} and 270 g_{H_2}/L_{system}. The data concerning pressurized gas and liquid storage are taken from studies performed as part of the European StorHy project and the data concerning the $NaAlH_4$ hydride come from the work done at the Savannah River National Laboratory (SRNL, United States).

Solid storage

Solid storage uses hydrides, with the term hydride encompassing a wide variety of materials. As a general rule, we talk of hydrides when a metal-hydrogen bond is formed. For these materials used to store hydrogen by absorption or **adsorption**, good reversible storage capacity(2) in conditions close to normal temperature and pressure conditions are sought. The kinetics, activation, stability during cycling (**absorption**/**desorption**) and cost characteristics, are thus very important. These materials fall into several families.

The interstitial metal hydrides

The first family comprises the metallic and intermetallic(3) hydrides in which the hydrogen positions itself in the interstices between the normal atomic positions of the crystalline structure of the material, by **metallic bonding**. Many are capable of absorbing hydrogen, some more than others, in normal temperature and pressure conditions. For example, **alkali** or **alkaline earth** metals (lithium Li, calcium Ca or magnesium Mg), the **transition metals** of the fourth or fifth columns of the periodic table (zirconium Zr, titanium Ti), or the metallic **rare earths** (lanthanum

---

(1) Energy efficiency: ratio between the energy to be supplied by the hydrogen and that needed to store it.

(2) Reversible storage capacity: this corresponds to the maximum quantity of hydrogen that the storage material can discharge (desorb) once charged, in other words once the hydrogen has been absorbed. It is often expressed as a percentage of mass of hydrogen by mass of storage material.

(3) Intermetallic: metal compound with specific crystallography and formed by the association of several metal atoms.

La, cerium Ce) create hydrides that are very stable in normal conditions. They are symbolised by an “A”. Other “B” elements constitute hydrides that are unstable in normal conditions and only stable in conditions of high pressure. These are for example most of the transition metals (chromium Cr, cobalt Co, nickel Ni or iron Fe). The combination of A and B elements often produces hydrides that are reversible in conditions close to normal. The best-known is $LaNi_5$, which forms at a hydrogen pressure of 1.8 bar at room temperature (table).

Until now, no known metal hydride combines a reversible capacity of more than 2.5% by mass in conditions close to normal.

It should be noted that hybrid pressure-hydride storage appears to be an interesting option, as shown by the results obtained with a prototype developed by Toyota (figure 1). This improves both the volume and mass capacity, the hydrogen availability, even at low temperature and the charging kinetics. There is however a slight safety penalty.

Complex hydrides

A second family comprises what is known as the complex hydrides, also called the chemical hydrides, for which the hydrogen establishes covalent or ionic bonds with the metal atoms of the storage material. This family contains hydrides based on light elements (lithium Li, boron B, sodium Na) which are able to produce hydrides with improved mass capacity. $LiBH_4$, for example, theoretically exhibits a mass capacity of 18.5%, but the extreme conditions of desorption (> 300 °C for 1 bar) and absorption (> 680 °C, > 150 bar) rule out this material for reversible storage of hydrogen. The alanates, which are the result of the combination of a complex anion $[AlH_4]^-$ or $[BH_4]^-$ with a cation of the alkali or alkaline earth class (Li, Na, Mg, Ca) pose approximately the same problem. However, recently, appropriate catalysis was able to make sodium alanate ($NaAlH_4$) regenerable in conditions close to normal. $NaAlH_4$ is for the time being the only complex hydride that is reversible in reasonable temperature and pressure conditions (table). It has only mediocre cycling resistance, the material being subject to demixing phenomena. Its high pyrophoricity, in other words its ease of spontaneous ignition in ambient air, makes it delicate to use.

hydride	reversible capacity (wt%)	desorption pressure at 25 °C (bar)	temperature for 1 bar (°C)	activation	kinetics
MgH_2 (ball milled)	5.6	~ 10^{-6}	279	–	–
MgH_2 + 5% V (mixed by ball milling)	4.9	~ 10^{-6}	279	–	++
TiFe	1.65	4.1	–8	– –	+
TiFeMn	1.65	2.6	2	+	+
$LaNi_5$	1.28	1.8	12	++	++
$LaNi_5Sn$	1.24	0.27	55	++	++
TiVCrMo	1.8	101	–76	+	+
$NaAlH_4$ (two plateaus)	5.5	0.7 0.015	33 110	++	–

Table.
A few examples of interstitial metal hydrides or complex hydrides in absorption/desorption conditions situated around normal temperature and pressure conditions.

Another way of using hydrides is hydrolysis. When sodium borohydride ($NaBH_4$) comes into contact with water, and provided that the reaction is catalyzed with a Co or Ni based catalyst (CEA patent - FR 2 892 111), hydrogen is released. However, this reaction is unfortunately not reversible, with the solution obtained having to be processed in an external system in order to return to sodium borohydride.

Adsorbent materials

Hydrogen storage can also take place by physisorption, or the adsorption of hydrogen on the surface of materials. The bonds created, of the van der Waals type, are weak bonds. The advantage lies in the fact that this phenomenon is easily reversible. However, adsorption can only occur if there is little agitation of the hydrogen, in other words for low temperatures or high pressures. The best results are obtained at the temperature of liquid nitrogen (77 K, - 196.1 °C). The capacity to a very large extent depends on the specific surface developed in the material. Materials made of nanostructures are interesting candidates. These include activated carbon, carbon nanotubes, zeolites and MOF (Metal Oxide Framework), whose structure consists of metal oxides linked by organic groups leading to the formation of tunnels with a cross-section of a few square nanometers. Some of these materials have so far shown good mass storage properties, of about 6%, but at low temperature (77 K). At ambient temperature, the best among them have trouble reaching 1% by mass. These materials also suffer from low volume capacity.

Hydride storage: a thermodynamic machine

The hydriding mechanism, which can be summarized as a phase transition between a hydrogen lean phase and a more hydrogen rich phase, is exothermic (releases heat) in the hydrogen absorption direction and endothermic (input of heat required) in the hydrogen desorption direction. For a given temperature, the reaction takes place at a constant pressure, called the equilibrium pressure. For a hydride temperature that is kept constant, if a hydrogen pressure higher than the equilibrium pressure is applied, there will be absorption. If, on the other hand, the pressure is lower, there will be desorption. Moreover, if the temperature rises, the equilibrium pressure increases.

Identifying the equilibrium pressures according to temperature is an important factor when choosing a hydride for a particular application (figure 2). These pressures are compared with a window of conditions close to normal, ranging from 10 °C to 80 °C – temperature for coupling to a fuel cell with an H^+ Proton Exchange Membrane (PEM) – and of 1 to 30 bar pressure. For example, $LaNi_5$ hydride passes through this window, while the TiVCrMo type hydride pressure is above it. This latter will therefore be reserved more for hybrid pressure-hydride storage applications, which are currently being developed. One advantage of hybriding with TiVCrMo is the availability of the hydrogen, even at low temperatures (2.5 bar at - 30 °C).

The simple existence of equilibrium curves in a domain close to normal temperature and pressure conditions does not automatically make for a good storage material. The kinetic aspects of the reaction are also very important. The hydriding reaction is not instantaneous and can last from a few seconds to a few hours.

The use of hydrides requires mastery of two particular demanding phenomena. On the one hand, the quantity of heat energy generated during the reaction is not negligible. For a type TiFe hydride, it corresponds to 12% of the energy contained in the hydrogen stored. To rapidly charge a large quantity of hydride, the heat produced must be removed. For example, to fill a TiFe tank with 1 kg of hydrogen in 15 minutes, an energy of 3.9 kWh will have to be removed in 15 minutes, or a cooling power of 15.5 kW. In addition, the volume of a hydride can increase by 10 to 30% when hydrogen is absorbed. This phenomenon is liable to create significant stresses in the tank, which increase during the hydrogen absorption/desorption cycles.

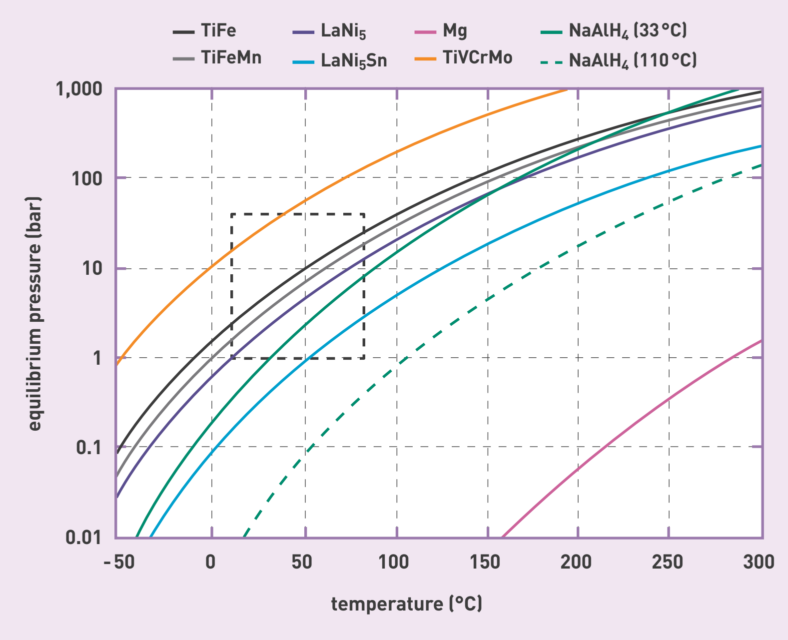


Figure 2.
Comparison of equilibrium curves for the hydrides of greatest interest for hydrogen storage around normal temperature and pressure conditions.

Hydrided tanks

For stationary applications, the DTBH is working with the McPhy Energy company on magnesium hydride (MgH_2), an attractive material owing to its high mass capacity and its abundance on Earth. The hydrogen is stored in a nano-catalyzed MgH_2 material, which improves the sorption kinetics, and compacted into pellets with graphite, which also improves the kinetics by optimizing the heat exchange process. The operation of magnesium hydride at more than 300 °C is not a problem for this type of application, especially if it becomes possible to store the hydriding energy. This is what is being done with McPhy Energy, which is developing adiabatic tanks. These conserve the hydriding energy in phase change materials and restore it during desorption.

With regard to on-board applications, even if the automobile is for the time being beyond the range of the existing hydrides, the DTBH is working on tanks for so-called heavy applications, where weight is not necessarily an obstacle, such as agricultural or maritime applications. Thus a prototype tank for 2 kg of hydrogen has been designed, built and successfully tested. Its design, which was in particular optimized from the thermal viewpoint, enabled rapid filling kinetics to be achieved, with 80% of the tank being filled in 30 minutes, for an initial target of 50% in 30 minutes.

P. Avavian/CEA

Three McPhy Energy technology hydrogen storage tanks being tested at the Liten Institute/DTBH. These tanks store hydrogen in a magnesium hydride (MgH_2). Their particularity lies in the fact that the hydriding heat is stored in a phase change material and then restored at desorption. They can each store 5 kg of hydrogen at the maximum pressure of 10 bar.

> **Olivier Gillia**
Liten Institute (Laboratory for Innovation in New Energy Technologies and Nanomaterials)
Technological Research Division
CEA Grenoble Center

Hydrogen, a means of storing electricity

The present configuration of the electricity grid, in particular on islands, exhibits limits on the integration of certain renewable energy sources such as photovoltaic or wind power. Among the new energy technologies, the stationary storage of electrical energy has been identified as one solution for countering the intermittence and unpredictability of the production of these renewable energies. It can absorb the fluctuations and/or outputs which do not meet the forecasts and thus increase the penetration of renewable energies on the grid without running the risk of destabilizing it.

s.aude@balloide-photo.com

MYRTE experimental platform (Vignola near Ajaccio, Corsica) which combines photovoltaic solar energy with a hydrogen system as energy carrier for storage of renewable energies. Its aim is to develop a control system and strategy designed to improve the management and stabilization of the Corsican electrical grid. The hydrogen produced and stored is able to manage fluctuations in the power of the intermittent renewable energies incorporated into the grid.

Studying the integration of intermittent renewable energies, associated with a means of storage on the grid, is no easy task. The architecture of the electrical systems is becoming increasingly complex, in particular when the integration of energy carriers of different types (electricity, hydrogen, heat) is being envisaged. In order to understand the interactions between these renewable energies and the rest of the electrical system, a tool capable of simulating their operation, coupled with storage solutions is being developed as part of a thesis being financed in part by the French Environment and Energy Management Agency (**Ademe: Agence de l'environnement et de la maîtrise de l'énergie**) at the Biomass and Hydrogen Technologies Department (DTBH) of CEA's Liten Institute (Laboratory for Innovation in New Energy Technologies and Nanomaterials).

The storage of electrical energy, whether through the use of **batteries** or *via* a hydrogen system, is a means of meeting a wide range of the needs of the various stakeholders on the electrical grid (economic optimization, system safety, quality of service for the end-users). A case study for an application in response to the call for bids from the French Energy Regulation Commission (**CRE: Commission de régulation de l'énergie**) illustrates the work accomplished to date. This involves the construction and operation of installations producing electricity from **photovoltaic** solar energy with a power in excess of 250 **kWp**. Here we will focus on the photovoltaic installations concerning Corsica and the overseas *départements*. The call for bids requires the integration of a means of storing the energy produced. Island electrical grids are far less robust than the interconnected European electrical grid and are therefore far more susceptible to significant variations in power input.

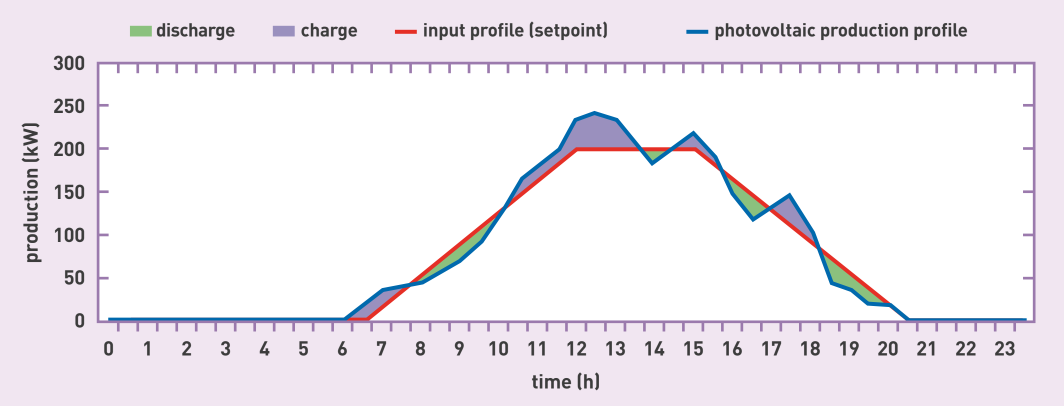


Figure 1.
Production guarantee is one of the services that can be provided by storage for an electrical grid stakeholder. Charge: the storage system fills up using the electricity not needed by the grid; discharge: the storage system empties and the electricity is sent to the grid.

Three storage architectures

The storage system has to be able to perform the "production guarantee" function (figure 1). Its role is to ensure that at all times the production input into the grid is in conformity with the trapezoidal profile announced the previous day, obeying precise rise/fall gradient criteria and steady-state production 40% below the peak power of the photovoltaic modules installed. The production guarantee is thus associated with the notion of forecasting photovoltaic production in order to manage the input of production into the electrical grid.

This work led to the selection of a photovoltaic power plant of 500 kWp, while three different storage systems were studied and compared. The first consisted only of lead-acid batteries. The second is a hydrogen system comprising an electrolyzer with H^+ Proton Exchange Membrane (PEM), storage of pressurized hydrogen (H_2) and storage of pressurized oxygen (O_2), and a PEM fuel cell. Finally, the third architecture is a hybrid of these two storage technologies (figure 2).

For the battery-based architecture, the surplus energy produced is stored in the batteries and then restored when photovoltaic production falls below the supply forecasts. Similarly, for the hydrogen system architecture, the surplus photovoltaic energy is stored *via* the electrolyzer, which converts the electricity into hydrogen and oxygen. This energy is then restored *via* a fuel cell, which reconverts the hydrogen and oxygen into electricity on the grid, to compensate for the shortfall in photovoltaic production and thus meet the announced input power level.

The performance of the two technologies was assessed on the basis of five technical indicators:

- the ratio of non-satisfaction of the load, in terms of energy and time, corresponding to the ratio between the quantity of energy not supplied and the quantity of energy demand – or the fraction of time for which the energy demand was not completely supplied;
- the ratio of non-utilization of the renewable energy source, in terms of energy and time, corresponding to the ratio between the quantity of energy not used and the energy produced by the photovoltaic field – or the fraction of time for which the energy produced is not used in full;
- the energy efficiency of the various architectures through an "architecture efficiency", defined as being the ratio between the energy input into the grid and the photovoltaic energy used.

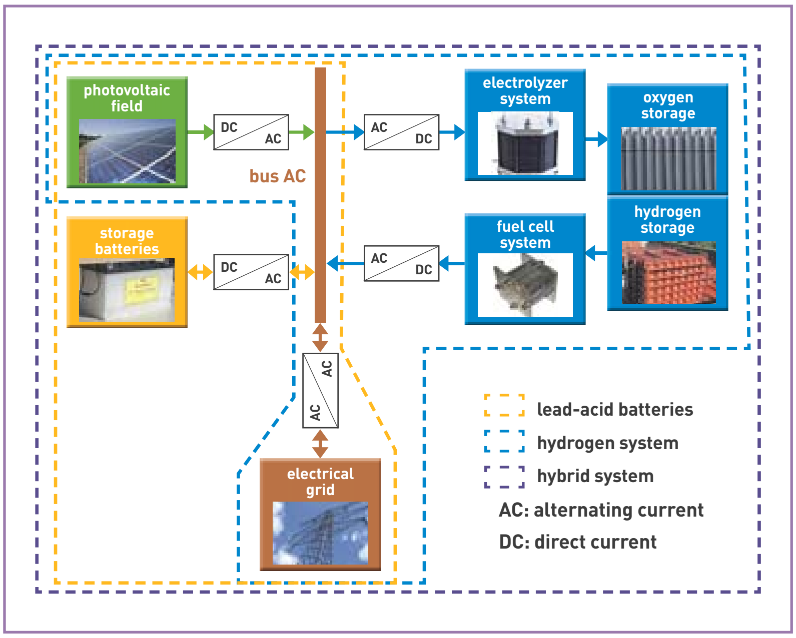


Figure 2.
The storage system architectures studied.

The tool currently under development was used to determine the value of these indicators according to the dimensioning of the systems, in other words the number of batteries and the size of the hydrogen storage.

Simulating and dimensioning energy systems

The meteorological input data used (sunlight and temperature) are those of the Carpentras weather station (Vaucluse *département*). They are obtained *via* the Baseline Surface Radiation Network (BSRN). The study covers one year of simulation (2003) based on minute by minute data. The main steps in the working approach followed comprise the formatting of the data, calculation of the anticipated photovoltaic production, creation of the proposed charge profile for the following day, in order to lead to calculation of the above-mentioned indicators. The models representing the working of the different technological building blocks used by such a system are taken from the literature and/or from public technical characteristics supplied by the manufacturers.

In the case of a storage architecture using only batteries, the results of the simulation show that about 1,800 batteries, with a capacity of 54 A·h each, are needed to reach a zero non-satisfaction ratio, in terms of time and energy (table). With regard to a storage architecture with a hydrogen system only, in this study we assume that the electrolyzer is dimensioned for maximum photovoltaic power (500 kW) and the fuel cell is dimensioned for the maximum power that

storage system	photovoltaic energy used (MWh)	non-utilization ratio (%) in energy in time	energy input (MWh)	non-satisfaction ratio (%) in energy in time	architecture efficiency (%)
batteries only (1,800 batteries)	554	0.2 0.3	465	0.0 0.0	83.9
hydrogen system only (51 kg H_2)	551	0.7 7.5	365	1.1 8.3	66.2
hybrid batteries-hydrogen system (200 batteries, 51 kg H_2)	552	0.2 0.3	367	0.0 0.0	66.4

Table.
Summary of performance of various storage architectures.


s.aude@balloide-photo.com

MYRTE experimental platform (Corsica): the fuel cell.

can be input to the grid (40% of the photovoltaic power, or 200 kW). The only room for maneuver considered here is in the mass of hydrogen stored. Its optimum value is 51 kg, or a tank volume of 21 m^3 at 25 °C and 30 bar. Analysis of the non-satisfied charge profile reveals that the charge is not satisfied for power levels less than 13 kW, corresponding to the starting threshold of the fuel cell in the case studied. In other words, the hydrogen system, as dimensioned and with the management strategy used for this case study, is not capable of supplying the lowest power levels. Similarly, small power levels cannot be absorbed by the electrolyzer system, because they are below its start-up threshold. Consequently, the calculations made would seem to show that technical improvements are required (new architectures, hydrogen-batteries hybrids, optimization of the energy management strategy) to adapt the hydrogen system to the conditions of the call for bids. It could be possible to divide the fuel cell and electrolyzer into subsystems of appropriate power, in order to minimize this drawback.

The advantage of a hybrid of the two storage systems is clear in the light of these results. It could be possible to use batteries to handle power levels below the start-up thresholds of the hydrogen system, which would then handle primary operation of the facility. With an energy management strategy designed to maintain the level of the charged batteries as often as possible and keeping the same hydrogen system as in the previous case (51 kg H_2), the addition of 200 batteries of 54 A·h is enough to meet 100% of the charge profile.

The tool thus developed is designed to dimension the storage systems for a given renewable energies production profile and a given charge profile. It enables several architectures to be compared, incorporating the technical aspects of a hydrogen system and/or lead-acid batteries, which identified the benefits of coupling the hydrogen system with batteries.

Consideration of essential factors

The next stage of the work will include the economic aspect of this case study. The investment, operation and component replacement costs will be estimated, along with the penalties imposed by the CRE when its criteria are not met. Even though a non-satisfaction ratio of about 1% in energy terms would in principle seem to be acceptable (case of the hydrogen system alone), the non-satisfaction ratio in terms of time is for its part close to 8%, which could result in the non-remuneration of a significant part of the energy input. Consideration of the economic dimension will lead to a compromise being reached, for each architecture, concerning the non-satisfaction ratio which does not excessively penalize the revenue.

Finally, these studies should be carried out over operating periods of several years (generally 20 to 25 years). In this case, it becomes essential to consider ageing mechanisms so that one can not only determine the number of replacements necessary for the various components and the corresponding costs, but also to reflect this ageing in the performance of the components and study the impact on the overall dimensioning of the system.

Projects and experiments

Through the study just presented, it would seem clear that the question of dimensioning the electricity storage, coupled with the renewable energies, is anything but simple, in particular when one envisages combining several technologies. The search for an optimum in the dimensioning and indeed the operation of the system is being carried out in a number of projects at the DTBH.

One of them, the MYRTE project (French acronym for Renewable Hydrogen Mission for Integration into the Electrical Grid), which involves the University of Corsica, the HELION company (subsidiary of Areva) and CEA, concerns the installation and operation of an experimental platform in Vignola near Ajaccio (Corsica). The platform, opened in January 2012, consists of a photovoltaic power plant, with an installed power of 560 kWp over an area of 3,700 m^2, directly connected to a storage system of 3,920 Nm^3 of hydrogen. Various energy management strategies and different storage functions will be tested by the partners, jointly with EDF-SEI (Island Energy Systems – *Systèmes énergétiques insulaires*) which will accept the energy thus reinjected into the Corsican island grid. The aim is in particular to examine the system's ability to meet the goal of load management of the peak demand from the electrical grid, with smoothing of photovoltaic power production, which consists in limiting the fluctuations and disturbances on the electrical grid.

As for the REVERSE project (French acronym for Electrical Grids: Evaluation by Simulation of the Economic and Environmental Value of Electricity Storage), financed by ANR (Agence nationale de la recherche – French National Research Agency)-Progelec (Sustainable Electricity Production and Management), which began in January 2012, its aim is to develop a systemic approach to evaluation of the technical, economic and environmental benefits of electricity storage technologies in the grids. The project is being carried out in partnership with the French Electricity Transmission System Operator RTE (Réseau de transport d'électricité), HELION, the G2Elab (Grenoble Electrical Engineering Laboratory – *Laboratoire Grenoble génie électrique*) and the LEPMI (Laboratory for Electrochemistry and Physical Chemistry of Materials and Interfaces – *Laboratoire d'électrochimie et de physicochimie des matériaux et des interfaces*).

> **Benjamin Guinot, Florent Montignac**
and **Isabelle Noirot**
Liten Institute (Laboratory for Innovation
in New Energy Technologies
and Nanomaterials)
Technological Research Division
CEA Grenoble Center

Smart grids:
when **electrical grids** become **intelligent**

The rising share of intermittent renewable energies in energy grids, the multiplication of production sites, the development of new uses such as electric vehicles... the electrical system is undergoing radical change. To deal with it, we have to adapt. **With smart grids, which incorporate functionalities derived from the new information and communication technologies, it will be possible to run everything, from production to consumption, taking account of the actions of everyone involved, and how they interact.**

The electrical grid as we know it today is highly complex. It is the result of the successive addition of different technologies and involves numerous stakeholders: grid managers (GRT), distribution network managers (GRD), producers, suppliers, consumers, etc. This complexity is also the cause of the problems encountered by the engineers when attempting to predict and mitigate large-scale failures (box 1).

A balance between production and consumption must be sought at all times, and the voltage must meet a certain quality level at all points throughout the territory. Pooling of production resources is the main advantage offered by an electrical grid. It leads to a reduction in unforeseen events (relatively speaking), in costs, down-time and so on. The production-consumption balance, the precondition for the stability of the grid, is the responsibility of the French Electricity Transmission System Operator (RTE: Réseau de transport d'électricité). This is guaranteed by production resources of several tens or hundreds of thermal and hydraulic MW. The status of the transmission grid and the production by the large power plants are monitored in real time in the various RTE dispatching centers.

The changing electrical system

Things are now changing in many ways, in terms of both consumption and production.

Consumption

The current trend is for relatively low growth in annual energy demand. We can however observe a strong increase in peak demand, with a record once again beaten during the winter of 2011: a peak of 101.7 GW as against barely 80 GW ten years ago. It is this peak electricity consumption that determines the dimensioning of the electrical system. One must be able to respond to it, even if of short duration, and the grids must be capable of carrying these power levels.

Another difficulty is looming, with the arrival of the electric vehicle. Once several millions of them are on the roads in France, if nothing is done to manage recharging, we will again see an additional few GW in peak loads, with local risks of congestion.


Guillaume Zuili/RTE

Very high voltage aerial line carrying electricity from the production centers to the consumers. Faced with the ongoing changes to the electrical grid and with a view to ensuring energy efficiency, the integration of smart technologies such as smart grids is becoming essential. They will enable electricity supply and demand to be adapted in real time.

Finally, global warming and the increasingly widespread use of air-conditioning are also leading to summertime peaks, which will pose serious problems in the PACA (Provence-Alpes-Côte d'Azur) region.

Production

Until now, this was handled by large electrical production units(1) (economies of scale) that were controllable and the status of which was known at all times. This is known as centralized production. The current trend is for the development of decentralized, renewable production. In late 2012, it already represented more than 10% of the installed power in France. And that's just the beginning! The electrical future will be "renewable" within the next few decades, for economic, resource-related, and environmental reasons. As most of these renewable energies are produced directly by water (sun, wind), the production = consumption equation needs to be read the other way round.

---

(1) Electrical production units comprise electrical generating sets and their auxiliaries. Each plant often has several of them.

Energy Pool

Control of the Energy Pool company's 1,000 MW capacity modulation unit in Chambéry (Savoie *département*). Consumption modulation is based on the new information and communication technologies implemented in the smart grids to optimize production, distribution and consumption of electricity and the adjustment of supply and demand.

A new paradigm

Little by little, the customer is king approach will be abandoned and production that adapts to consumption will give way to consumption that is more flexible and follows changes in production. This transformation is already apparent in the activities of Energy Pool(2). This company, based in the Rhône-Alpes region, "pools large consumers to take advantage of their ability to modulate their consumption at critical times for the electrical grid"(3). It runs a modulation plant with a capacity of 1,000 MW, which is a key component in a smart electrical grid. The Liten Institute (Laboratory for Innovation in New Energy Technologies and Nanomaterials), through the Solar Technologies Department located in the National Solar Energy Institute (**Ines: Institut national de l'énergie solaire**), together with Energy Pool and Schneider Electric, is running a demonstration program, the goal of which is to control 500 MW of consumption to compensate for the intermittent nature of 100 MW of renewable solar and wind production.

This consumption control, which applies to units of at least 1 MW, will then be generalized and go as far down as power levels of a few hundred and then a few tens of kW. It will eventually even become profitable for private individuals, where it will be possible to use the flexibility contributed by loads of about one kW, the main sources of flexibility being wherever the energy is stored: heating/air-conditioning of buildings (thermal storage), recharging of electric vehicles (electrochemical storage), sanitary hot water(4).

Energy and information flows: coupled networks

Managing the flows of energy is only possible if appropriate control and communication means are deployed at the same time. It is necessary to measure, communicate and/or act at each point in production or consumption in order to optimize the way that the whole system is controlled. Communication networks will thus be superposed on the energy grids. The information streams will penetrate and interconnect the electrical grids and something that already exists in the electricity transmission grid will become commonplace in the distribution networks and then in the private networks (buildings). The status of the electrical system will be known in real time and in increasing detail. The stakeholders (GRTs, GRDs, those in charge of balancing production-consumption, pooling players, etc.)

Grid stability

1

The electrical grid is the result of the addition of various equipment and technologies over a period of time, with a large number of stakeholders operating at different levels. This forms a complex system, liable to have surprising properties that the engineers have trouble in predicting. The grid can thus have a disproportionate "macroscopic" response to a local "microscopic" disturbance. American researchers(1) have in particular demonstrated that the distribution of the probability of a blackout of a certain size, measured in MWh unserved, decreases very slowly (figure). In other words, the size of the blackouts is not distributed according to a Gaussian law (bell curve), but shows significant fluctuations, with variations of almost 4 orders of magnitude. This behavior, which is typical of systems consisting of numerous interacting elements, is not yet managed in the case of electrical grids. Thus, to date, there is no sufficiently simple and realistic model for reproducing failure statistics and the response to a disruption. Moreover, with the advent of local electricity production, usually intermittent in nature, new problems are appearing. In particular, the intermittence of local production also threatens the stability of the grid. We do not yet know the precise stability conditions and this is an active field of theoretical study.

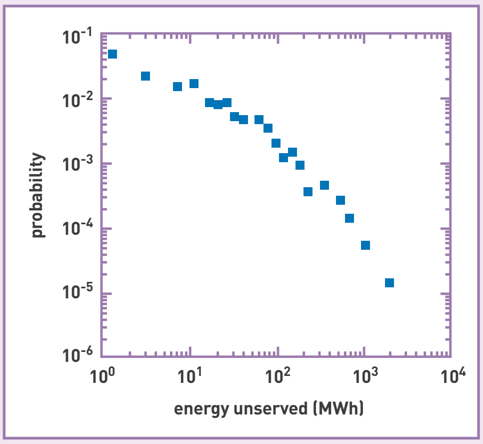


Figure.
Distribution of probability of energy unserved obtained from blackout data in the United States from 1984 to 1998(1).

(1) Ian Dobson, Benjamin A. Carreras, Vickie E. Lynch, and David E. Newman, "Complex systems analysis of series of blackouts: Cascading failure, critical points, and self-organization", *Chaos* 17, 2007, 026103.

Towards guaranteed photovoltaic energy

2

For the grid manager, responsible for balancing production and consumption at all times, unexpected problems and fluctuations in a means of production pose problems, because they require resorting to alternative means capable of compensating. The large-scale integration of electricity of solar or wind origin in small grids, for example island grids on Mayotte, Martinique or Guadeloupe, can therefore prove to be delicate and cause extra costs. There are several solutions for reducing these fluctuations:

- production forecasts for different time-frames (a few minutes to a few days) that are as accurate as possible;
- means of energy storage;
- flexibility and control of a part of consumption in line with production.

The addition to a power plant or to a group of photovoltaic plants of an intelligently controlled storage means would seem to be a realistic solution for achieving a means of operation and characteristics which, with regard to the grid manager, are similar to those of a conventional power plant:

- production plan defined the previous day for the following day;
- monitoring of the production plan;
- participation in the system services to help the grid managers ensure voltage and frequency stability;
- rapid production variations limited to a certain range of values.

This thus leads to the concept of guaranteed photovoltaic production or the regulated solar power plant (figure).

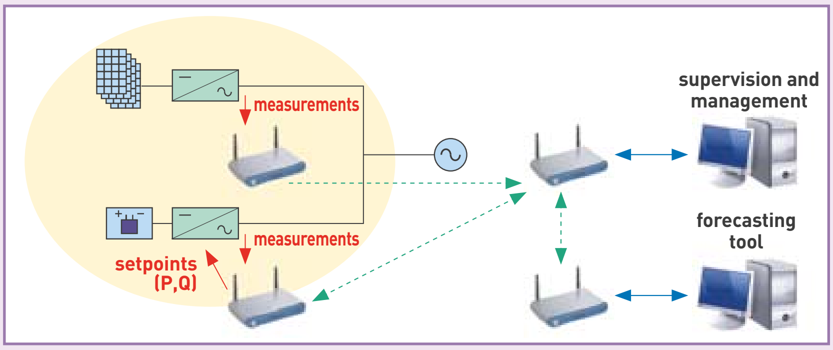


Figure.
Storage of photovoltaic energy and production forecasting. As seen from the grid, this system is comparable with any electrical power plant, with a predetermined production plan and participation in the system services. P and Q are the power setpoints. P: active power; Q: reactive power.

will be able to anticipate changes with a minimum of error and overall management will then approach the optimum.

Various strategies are being imagined concerning the distribution of intelligence, the level of pooling and the ranking of layers. Some are advocating the energy Web, others prefer a pyramid style organization or systems with multiple local agents. A wide variety of solutions can be envisaged.

This superposition of networks, that can be observed on several scales within our society, will not however be without its problems. Recent theoretical studies show that, over and above their inherent fragility, coupling two networks is liable to induce new failures. This surprising result can be explained in terms of cascading failures: a local electricity failure can lead to a breakdown of the communication network, liable in turn to lead to a malfunction at another point on the grid, and so on. There are many examples, the best illustration being that which occurred in Italy, where after the blackout(5) in 2003, the national operator had the greatest difficulty in restoring power, because the telecommunication network had ceased to function. It is therefore crucial to determine to what extent this result can be generalized and in what precise conditions coupling between networks and grids has a destabilizing effect. This problem, which applies to numerous distribution and transmission grids, goes beyond the purely electrical framework.

The first applications

Pending the advent of smart grids, R&D centers and companies are developing technological building blocks and partial solutions. This is the case with management of electric vehicle recharging, in particular from photovoltaic energy, smart buildings, which will promote energy efficiency and self-consumption of local production, the use of storage to provide services to the grids, ease congestion or ensure guaranteed renewable production (box 2). For each of these applications, tests and demonstrations of from a few tens of kW to a few MW are beginning to see the light of day.

> **Marc Barthélémy**[1] and **Xavier Le Pivert**[2]
[1]Theoretical Physics Institute (IPhT)
Physical Sciences Division
CEA Saclay Center

[2]Liten Institute (Laboratory for Innovation in New Energy Technologies and Nanomaterials)
Technological Research Division
CEA Grenoble (Ines Site)

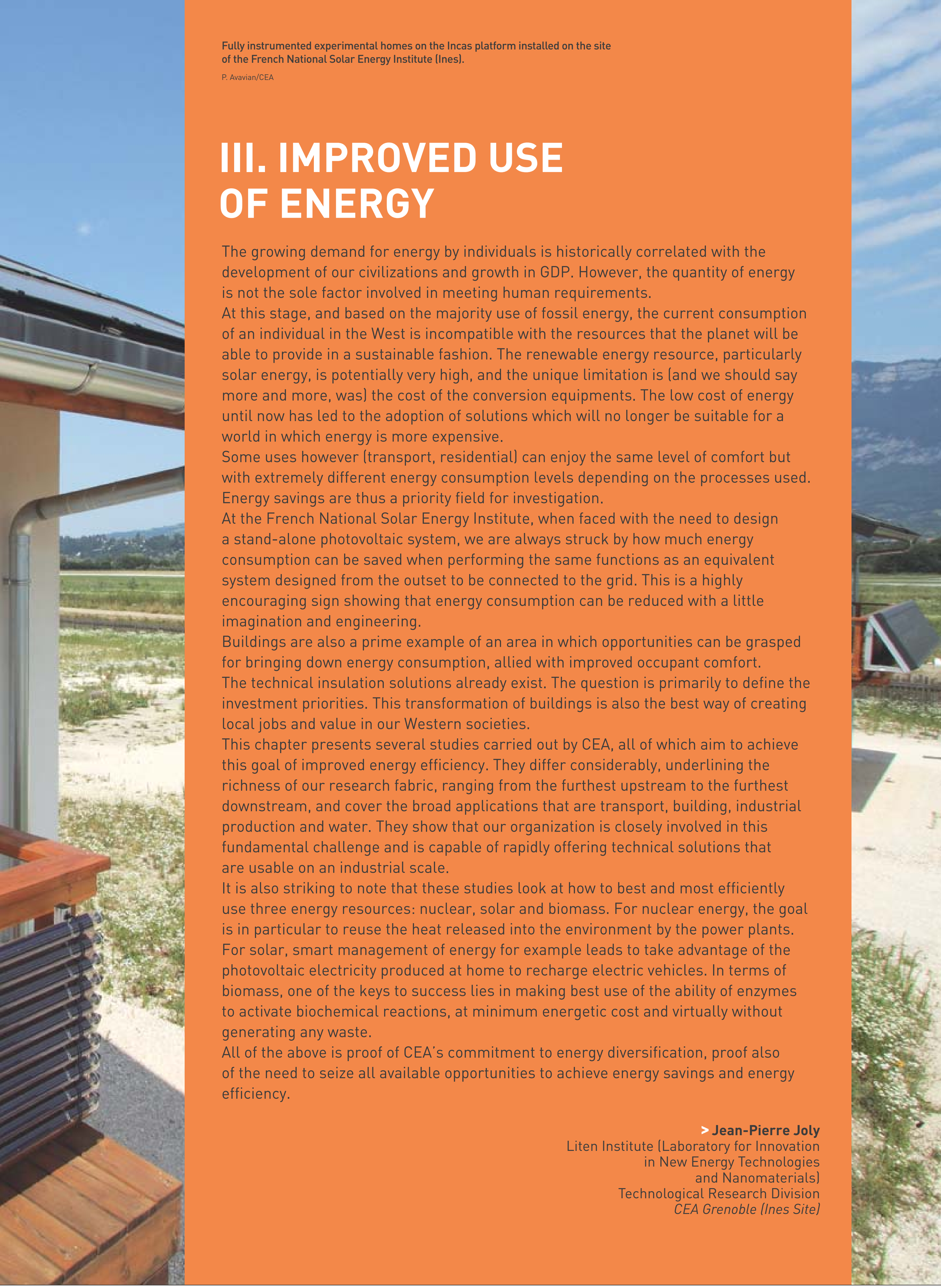
---

(2) http://www.energy-pool.eu/.

(3) This is Demand/Response or modulation of electricity consumption according to grid conditions. This electricity consumption management enables supply and demand to be adjusted. For rapid and efficient adjustment of supply and demand, the *aggregator*, who runs a large number of sites in order to benefit from a high level of flexibility, must jointly influence production and a large volume of potential load management, partial load-shedding for example, while guaranteeing limited impact.

(4) This is for example what is proposed by the French company Voltalis with the communicating BluePod module. When installed on the electrical circuit of a home or office, it can modulate the consumption over time of certain electrical devices (radiators, hot water tanks, air-conditioning units, etc.).

(5) Blackout: large-scale electricity outage.



Fully instrumented experimental homes on the Incas platform installed on the site of the French National Solar Energy Institute (Ines).

P. Avavian/CEA

III. IMPROVED USE OF ENERGY

The growing demand for energy by individuals is historically correlated with the development of our civilizations and growth in GDP. However, the quantity of energy is not the sole factor involved in meeting human requirements.

At this stage, and based on the majority use of fossil energy, the current consumption of an individual in the West is incompatible with the resources that the planet will be able to provide in a sustainable fashion. The renewable energy resource, particularly solar energy, is potentially very high, and the unique limitation is (and we should say more and more, was) the cost of the conversion equipments. The low cost of energy until now has led to the adoption of solutions which will no longer be suitable for a world in which energy is more expensive.

Some uses however (transport, residential) can enjoy the same level of comfort but with extremely different energy consumption levels depending on the processes used. Energy savings are thus a priority field for investigation.

At the French National Solar Energy Institute, when faced with the need to design a stand-alone photovoltaic system, we are always struck by how much energy consumption can be saved when performing the same functions as an equivalent system designed from the outset to be connected to the grid. This is a highly encouraging sign showing that energy consumption can be reduced with a little imagination and engineering.

Buildings are also a prime example of an area in which opportunities can be grasped for bringing down energy consumption, allied with improved occupant comfort.

The technical insulation solutions already exist. The question is primarily to define the investment priorities. This transformation of buildings is also the best way of creating local jobs and value in our Western societies.

This chapter presents several studies carried out by CEA, all of which aim to achieve this goal of improved energy efficiency. They differ considerably, underlining the richness of our research fabric, ranging from the furthest upstream to the furthest downstream, and cover the broad applications that are transport, building, industrial production and water. They show that our organization is closely involved in this fundamental challenge and is capable of rapidly offering technical solutions that are usable on an industrial scale.

It is also striking to note that these studies look at how to best and most efficiently use three energy resources: nuclear, solar and biomass. For nuclear energy, the goal is in particular to reuse the heat released into the environment by the power plants. For solar, smart management of energy for example leads to take advantage of the photovoltaic electricity produced at home to recharge electric vehicles. In terms of biomass, one of the keys to success lies in making best use of the ability of enzymes to activate biochemical reactions, at minimum energetic cost and virtually without generating any waste.

All of the above is proof of CEA's commitment to energy diversification, proof also of the need to seize all available opportunities to achieve energy savings and energy efficiency.

> **Jean-Pierre Joly**
Liten Institute (Laboratory for Innovation
in New Energy Technologies
and Nanomaterials)
Technological Research Division
CEA Grenoble (Ines Site)

Solar mobility

As the leading consumers of fossil energies in France and the cause of more than half the greenhouse gas emissions, transport and building are the prime targets for the development of renewable energies, energy technologies and energy efficiency. In order to reach the targets set by the European climate plan and the French Grenelle Environment Summit, **converging solar photovoltaic energy, buildings and transport – through the recharging of electric or hybrid vehicles – is one of the solutions designed to help achieve smart energy management.**

P. Avavian/CEA

Solar car park on the Ines site in Chambéry (Savoie *département*). The wooden sun shelter is covered with photovoltaic panels. It offers 12 parking spaces, *i.e.* a surface area of 150 m^2. The station is equipped with 12 recharging terminals.

Solar mobility first came about at CEA in 2007, on the site of the French National Solar Energy Institute (Ines: Institut national de l'énergie solaire). Its goal was to ensure local and direct use of the electricity produced by a photovoltaic (PV) system, to recharge electric vehicles or to supply the home's electrical equipment. It was a look ahead to a near future with no purchase prices and no tax credits for photovoltaic systems.

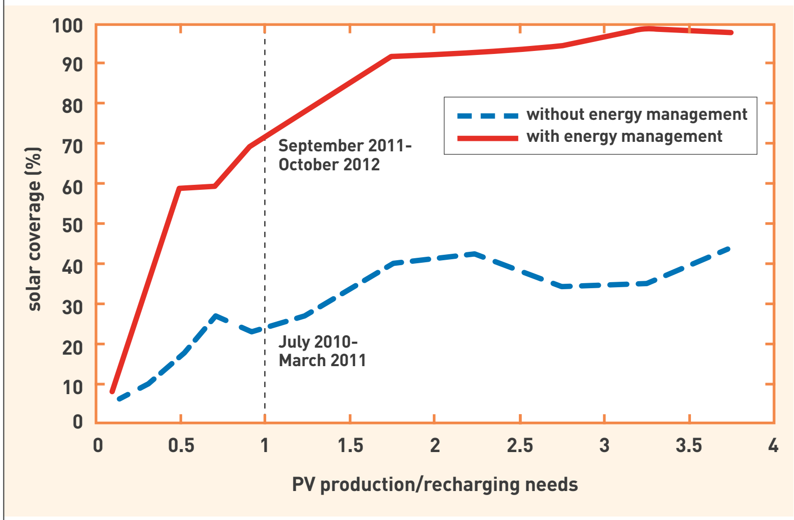


Figure 1.
Contribution of energy management to the solar coverage. Comparison between a period without management, from July 2010 to March 2011, and a period with management, from September 2011 to October 2012. For example, if the ratio over a day is equal to 1 (*i.e.* as much PV energy as recharging needs), without management, the solar coverage is 25%, whereas with management it is 73%.

Today, there is no economic incentive for the producer/consumer to opt for local self-consumption of their photovoltaic production. Everyone produces permanently when the sun shines and consumes when they need it. This is an aberration from the energy standpoint and a potential problem for the ERDF (Électricité réseau distribution France) distribution grid in electrical terms. The R&D objectives thus aim to limit the combined impacts of PV and the electric vehicle on the grid and maximize overall energy efficiency.

A few simple calculations are enough to confirm the feasibility of these objectives. They show that in 2020, 5 to 10 TWh will be supplied annually by PV systems to the grid (or an installed power of between 5 and 10 GWp) and that an equivalent power will be consumed by the 2 to 4 million electric vehicles which will then be in service, covering 12,000 km/year and 200 Wh/km.

More locally, a parking space of 12 m^2 covered with photovoltaic solar panels can generate the equivalent of 12,000 km/year, depending on the geographical location and the time of year. The average national distance for the journey from home to work is 25 km, with half of all workers covering less than 8 km. The first application is therefore quite logically focused on recharging at the workplace, where the vehicle is parked during the day, while the solar resource is present.

Photovoltaic car parks

A solar car park demonstration project, co-financed by the French Environment and Energy Management Agency (Ademe: Agence de l'environnement et de la maîtrise de l'énergie), Toyota and CEA, is under way on the CEA sites in Grenoble and at Ines. Ten rechargeable hybrid vehicles are recharged there under PV sun shelters and the users are guaranteed to have their battery fully charged. The scientific challenges in this project are clear. They are on the one hand to minimize the impact of the application on the distribution grid and to avoid consumption peaks, particularly at 8 o'clock in the morning when the employees arrive, and on the other, to maximize the quantity of electricity produced by PV directly in

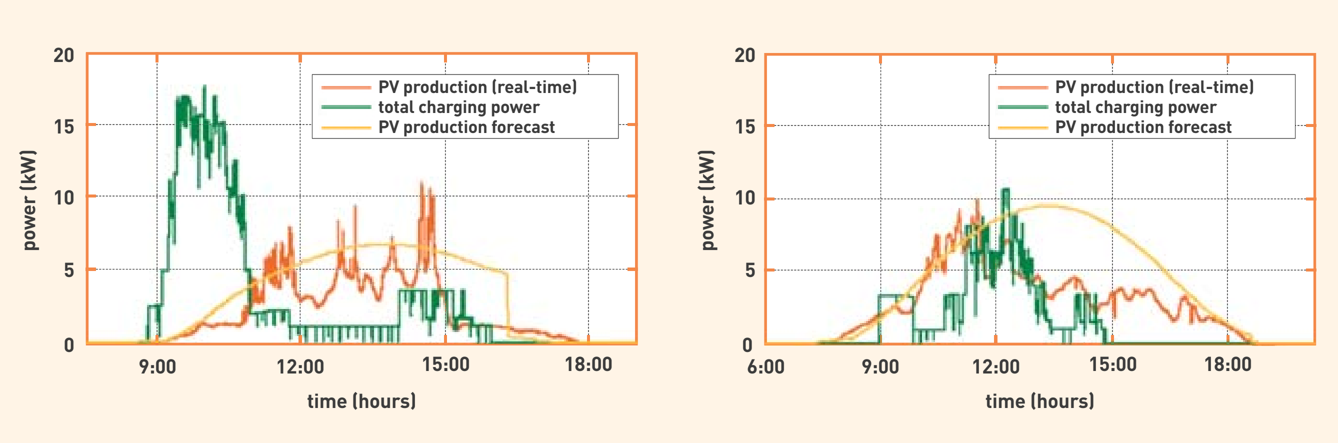


Figure 2.
On the left, production and consumption curve without energy management (solar coverage of 27%) for the day of 24 November 2010.
On the right, production and consumption curve with energy management (solar coverage of 74.5%) for the day of 15 March 2011.

the vehicles, taking account of the solar coverage, in other words the share of the vehicles' energy requirements covered by the PV installation.

Other solar car park applications are being developed. They concern car sharing in towns, where vehicles are shared by several users, and rental vehicles for the summer period in Corsica, which is of particular interest given the limited capacity of the grid and the demand for high-carbon energy. Car parks for light vehicles intended for visitors to a large industrial site or a tourism site are being studied, along with spaces for electrically assisted bicycles.

Local energy management

Energy management is one of the focal points of R&D at CEA. Solar coverage of the car parks developed for Toyota vehicles was thus significantly improved thanks to smart management taking account of the time of departure of the users, the sunshine forecasts and the charge status of the batteries. The optimization of this management increases, the higher the solar coverage (figures 1 and 2).

A second aspect concerns electrical management of a bidirectional current vehicle, that is one that can give electricity to the network during consumption peaks and recharge itself during off-peak hours. A demonstrator will be available in early 2013, in partnership with Renault, to illustrate the technical feasibility of coupling a PV system with an electric vehicle supplying energy. In the future, utilization such as this will make it possible to pool on-board storage functionalities and offer services to the network; for example, participation in the voltage plan(1) or reduction of consumption peaks. In addition to searching for optimum management, work is being done to quantify and minimize the additional ageing that could be experienced by the battery when supplying energy to the grid.

Avenues of research for tomorrow

Although solar mobility appears to be primarily a problem of local energy management, other avenues of research are being studied.

Non-intrusive diagnostic of the stationary vehicle is a function with high added value. It enables a fleet operator to plan maintenance ahead of time and thereby reduce operating costs. Several electrical signature recognition solutions have already been developed at the Liten Institute (Laboratory for Innovation in New Energy Technologies and Nanomaterials).

Another area for research concerns the design of an electronic power device maintaining the electrical infrastructure's phase balance in real time. The recharging power of the vehicles can reach 7 kW in single-phase current and create significant unbalance on the grid. This causes losses and requires oversizing of the electrotechnical installation.

Finally, on a completely different level, exploratory work has started on how to "solarize" roads by integrating solar panels into the road surface, as a possible means of supplying our electric vehicles of tomorrow.

Solar mobility illustrates one of the greatest qualities of photovoltaic electricity, that is its location as close as possible to the point of consumption (even though the energy has to be intelligently managed). It is clear that PV is the only system that allows this, thereby limiting electrical transmission losses. This is a significant advantage because these losses, due to the Joule effect, represent on average 6 to 8% of the electricity generated in France, or the equivalent of the output from two nuclear power plant reactor units.

> **Franck Barruel**
Liten Institute (Laboratory for Innovation
in New Energy Technologies
and Nanomaterials)
Technological Research Division
CEA Grenoble (Ines Site)

---

(1) Voltage plan: the grid's electrical voltage is regulated so that it is constant within a range of ± 10%.

Green chemistry, biocatalysis and biomimetics

From the very beginning, the chemical, pharmaceutical and agrochemical industries have been looking at the use of enzymes to develop efficient production processes. These enzymes catalyze chemical reactions at minimal energy cost, while generating very little waste. The hitherto unparalleled performance of these biomolecules is however linked to limited medium, temperature and pressure conditions, which restrict their use in industry. **With the growth of green chemistry, new processes are being developed, both to improve the performance of enzymatic reactions using biotechnological processes and to design artificial enzymes inspired by their natural counterparts, for instance for the production of bio-energy.**


C. Dupont/CEA


P. Avavian/CEA

On the left, automatic continuous culture systems for accelerating the evolution of strains of microbes or enzymes *in vivo* for biotechnology uses. On the right, bio-inspired photo-production of hydrogen. The hydrogen is produced from water under the action of an inorganic photocatalyst inspired by the working of hydrogenases during photosynthesis.

The benefits of chemistry are evident in all fields: food, materials of daily life, clothing, ceramics, dyes or plastics, health or energy. Industrialization has enabled it to meet many of society's needs but, owing to this industrial character, the processes and productions are the cause of pollution and are contributing to the depletion of limited resources. The development of new processes, referred to as green chemistry, has been promoted in order to reduce the undesirable effects of the chemical industry. This chemistry relies in particular on catalysis, a key technology which makes it possible to carry out chemical reactions at a lower energy cost and with improved selectivity, while leading to a significant reduction in the quantity of waste generated (solvents, unusable by-products).

The powerness of catalysts

A catalyst is a small molecule, a macromolecule or a solid material which interacts temporarily and highly selectively with one or more chemical species in a reaction, lowering the activation energy of this reaction. It can orient the reaction towards a majority product with good efficiency, under relatively moderate conditions. In addition, following the reaction, the catalyst returns to its initial state, so that it can contribute to the transformation of a large number (ideally infinite) of molecules in succession. A very small quantity of catalyst is thus required. This explains why the chemical industry has for the past fifty years been looking to introduce catalysis into the synthesis processes employed. The search for new and ever more selective and robust catalysts is one of the most widely developed approaches in the chemical industry and therefore 80% of the products manufactured are the result of a step carried out *via* a catalytic process. But where are these new catalysts to be found? Those with the highest performance are probably to be found in nature: enzymes. In an aqueous medium, at low energy cost and under generally moderate temperature and pH conditions, these proteins catalyze thousands of highly chemoselective, regioselective and stereoselective reactions, without generating toxic by-products. Some are used as catalysts in industrial or domestic synthesis or biodegradation processes. The researchers are also trying to imitate/mimick them, either by producing artificial proteins capable of catalyzing the original reactions, or by designing assemblies of molecules derived from synthesis chemistry and able to reproduce the reactions performed by the enzymes in biological systems. Several CEA laboratories are directly involved in these various biocatalytical or bio-inspired alternatives.

Enzymes, biocatalysis and synthesis chemistry

In practice, there are two main ways of taking advantage of the properties of enzymes.

Historically, the first was to use living organisms directly to effect the chemical transformations being sought, in order to obtain a product of interest (figure 1). This is the greenest way, which in particular and at minimal energy cost, makes it possible to perform a series of reactions *in vivo*, using biomass as the raw material. There is thus at present a considerable upsurge in interest in these processes. Yeasts and bacteria from natural environments were the first micro-organisms used to catalyze one or more reaction steps in the process to produce a chemical compound. Their efficiency was subsequently improved using genetic methods and then by genetic engineering. Today, genes derived from biodiversity, coding complete biosynthesis chains, sometimes completely unprecedented, are being introduced into micro-organisms (figure 1). The introduction of these exogenous biosynthetic solutions is sometimes poorly tolerated by the host cells, even as far as compromising their viability. To help these cells to readapt they can in certain cases be left to evolve in automatic culture systems, which enable to alternate the growth conditions (see the left-hand illustration, p. 78). Efficiency is also improved by optimizing the chemical regulation and balances within the cells.

The second solution involves using the enzymes themselves, in solution or immobilized. The range of known enzymes usable for industrial applications however remains limited and their quality (effectiveness, robustness, etc.) is often inadequate. In addition to improving their properties using controlled gene evolution methods, which can be implemented by means of the automatic culture systems mentioned before, it is possible to explore enzyme biodiversity to discover new biocatalysts. The databases of DNA sequences are full of genes coding unknown functions, in particular unknown biocatalytic activities. The Genoscope of the Genome Institute (IG) has undertaken to exploit these extensive collections and look for genes coding new activities. This work is beginning with the search for candidate genes using bio-informatic methods. These candidates are then screened using large-scale tests on non-physiological compounds, to detect enzymes liable to catalyze a new transformation, using the proximity phenomenon, whereby a given enzyme can catalyze a chemical reaction on different but chemically similar compounds.

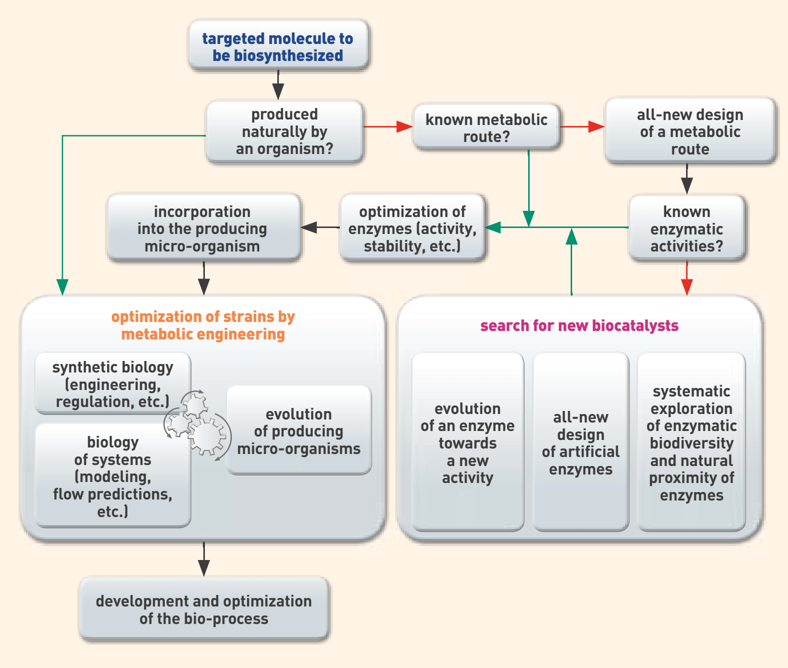
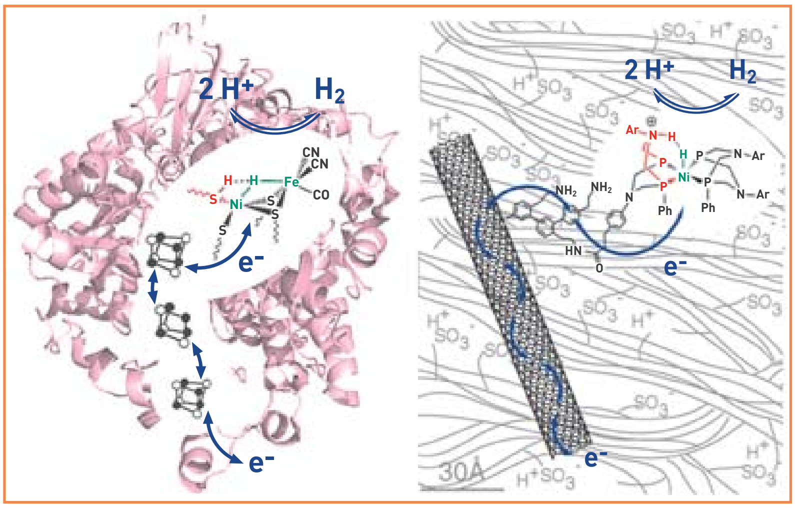


Figure 1.
Strategy used for the production of a molecule by a micro-organism. The green arrows indicate the action taken in the event of a positive answer to the question posed, unlike the red arrows, which lead to another alternative.

Biocatalysis and bio-energy

Biotechnologies for energy are enjoying large-scale development. Hydrogenases(1) are of particular interest for the production or utilization of hydrogen. They adsorb spontaneously on certain carbon electrodes, covering them with a film of protein and offering remarkable catalysis of the production of hydrogen or its oxidation, that is as good as platinum under certain conditions. Crystallography reveals that their active site is a binuclear cluster(2) (figure 2) where two metal atoms of nickel (Ni) and/or iron (Fe) are connected by atoms of sulfur (S), belonging either to cysteine(3) residues of the protein chain – case of nickel-iron (NiFe) hydrogenases – or consisting of a small dithiomethylamine ligand – case of iron-iron (FeFe) hydrogenases. The iron atoms are also coordinated by carbon monoxide (CO) and cyanide (CN^-) ligands. Basic sites, such as certain terminal thiolate ligands of the active site of the NiFe hydrogenases or the amine function of the dithiomethylamine ligand of the FeFe hydrogenases, play a crucial role by facilitating the protonation or deprotonation(4) reactions during the catalytic cycle.

The crystallographic structure of the hydrogenases also shows the presence of a chain of iron-sulfur clusters, less than 15 Å apart. This enables the electrons to circulate between the active site and the surface of the protein, where they are taken or from which they are extracted by the physiological partners of the hydrogenases(5), in particular the reductases. The teams from the Institute of Structural Biology (IBS: Institut de biologie structurale) highlighted a preferential pathway within the protein for the transfer of protons and for the circulation of gases. Consequently, the hydrogenases are actually small hydrogen factories with optimized logistics.



CEA/DSV

Figure 2.
On the left, a schematic representation of the structure of a NiFe hydrogenase. The cysteine residues (〰 S), ligands of the metallic centers, are symbolized by their sulfur atom. The terminal cysteine, acting as a base in the catalytic mechanism, appears in red. The interaction between the hydride ligand (H^-) coordinated with the active site (in green) and a proton carried by this basic site is represented by a dotted line. The two-way blue arrows show the electron exchanges between the iron-sulfur centers of the hydrogenase and the catalyst.
On the right, a schematic representation of the structure and reactivity of the material obtained by grafting the bio-inspired nickel-(bis)diphosphine catalyst onto carbon nanotubes inserted into a film of Nafion®. The amine functions of the diphosphine ligand are shown in red. The interaction between the hydride ligand (H^-) carried by the nickel atom (in green) and a proton carried by an amine function is represented by dotted lines. The two-way blue arrows show the electron exchanges between the nanotubes and the catalyst.

Bio-inspired chemistry and artificial enzymes

Enzymes are fragile biomolecules, which usually only develop its activity in water, under relatively

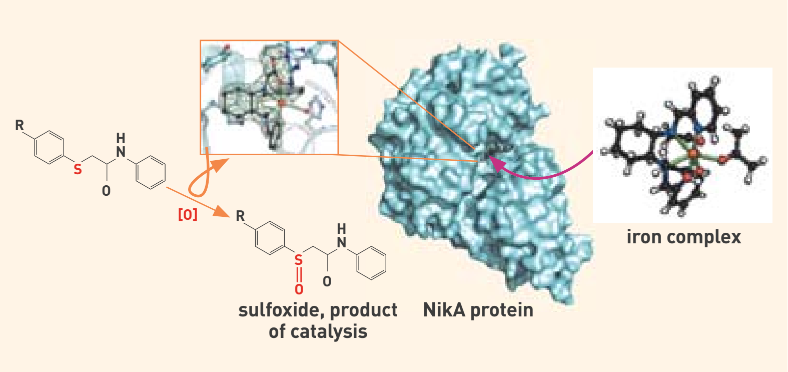
(1) Hydrogenases: enzymes which can either produce hydrogen from the H^+ protons of water and electrons, or oxidize it.

(2) Cluster: aggregate of several atoms.

(3) Cysteine: natural α-amino acid possessing a thiol group (–SH).

(4) Protonation/deprotonation: chemical reaction during which an H^+ proton is added to/removed from a molecule.

(5) In biological systems, oxidation (loss of one or more electrons) and reduction (gain of one or more electrons) reactions are catalyzed by oxidases and reductases respectively.



The introduction of an iron complex into the hydrophobic pocket of NikA, a nickel transport protein, allows its activation for catalysis of transfer of an atom of oxygen, to form a sulfoxide. The product of the catalysis is a potential analogue of omeprazole, an inhibitor of the proton pump in the mucous membranes of the human stomach. The position of the chemical catalyst is identified by crystallography of the proteins.

limited temperature, pH and ionic strength conditions, and which require physiological partners. One solution is to mimic the enzymatic working to produce catalysts referred to as bio-inspired. Thanks to a molecular level understanding of the structure of the active site of an enzyme, the chemist can either make a faithful synthetic copy (biomimetic model), or invent new catalysts based on its operating mechanism, or its interactions with its biological partners (bio-inspired model). This approach allows the use of chemical elements or combinations of atoms that nature has neither explored, owing to bio-availability, nor selected, for example owing to their toxicity during evolution. Such catalysts exhibit numerous advantages. They are easy to synthesize and relatively inexpensive to produce on a large scale, because they generally contain no noble metal or rare metal and can, unlike the enzymes on which they are based, be used in numerous solvents and throughout a broad range of temperatures and pressures. They are also less sensitive to oxidation by the oxygen in the air.

The design of artificial hydrogenases

Nickel (bis)diphosphine complexes are an example of catalysts bio-inspired by the structure of the active site of the hydrogenases. They combine the structural elements taken from the active sites of the two types of hydrogenases: the nickel ion of the NiFe hydrogenases and an amine function, this time incorporated into a diphosphine ligand rather than in the dithiolate cofactor of the FeFe hydrogenases. One of these complexes was chosen by a team from the Laboratory of Chemistry and Biology of Metals of the Institute of Life Sciences Research and Technologies (iRTSV), in collaboration with a team from Iramis (Saclay Institute of Matter and Radiation/Physical Sciences Division), to develop the first material without noble metal capable of catalyzing, in the same way as platinum, both the production of hydrogen from water (for use in electrolyzers) and its oxidation (for use in fuel cells). By grafting the bio-inspired catalyst onto carbon nanotubes and incorporating this assembly into a Nafion®(6) matrix, it was possible to optimize the logistics of the supply to the catalytic site of protons and electrons, exactly in the same way as it was organized within the hydrogenases (figure 2).

Artificial metallo-enzymes

Controlling the immediate environment of the site on which catalysis takes place is vital to optimizing its activity. This can be done using an original approach consisting in creating hybrid objects based on inserting an inorganic catalyst into a protein. We then talk of artificial metallo-enzymes. The activity of the artificial enzyme is controlled by the nature of the synthetic component while its selectivity depends on the protein structure, which makes it possible both to obtain original catalysis (unidentified reactions *via* biocatalysis) in moderate conditions and promote the selectivity of the targeted reaction. It is thus possible to control the stability of the protein formed and manage production costs. Recent results obtained by the Laboratory of Chemistry and Biology of Metals at the iRTSV show the potential of artificial metallo-enzymes in aromatic hydroxylation(7) or sulfide oxidation reactions. Together with the Metalloprotein group at the IBS, a new type of effective thioether (R S R') oxidases(5) was produced, using supramolecular bonds to fix a bio-inspired iron-based catalyst in a nickel transport protein, NikA (figure 3). The iron complex is only active if inserted into the protein, thus demonstrating the synergy between the two partners forming the hybrid. Another more fundamental aspect led to the development of a new technique for dissecting a catalytic mechanism for aromatic hydroxylation by combining the crystallography of proteins and bio-inspired catalysis.

Biological processes, alternatives to industrial processes

Owing to the energy crisis and environmental constraints, our society will have to propose alternatives to a large number of existing industrial practices. Many of these alternatives will be based on the development of completely or partially biological processes, or which are directly inspired by the solutions employed by nature itself. Several laboratories in the Life Sciences Division are already actively and successfully exploring these various avenues. CEA is thus contributing to the development of energy alternatives and sustainable biotechnological processes.

> **Vincent Artero**[1], **Véronique de Berardinis**[2], **Stéphane Ménage**[1] and **Jean Weissenbach**[2]
[1]Institute of Life Sciences Research and Technologies (iRTSV)
Life Sciences Division
CEA Grenoble Center

[2]Genome Institute (IG)/Genoscope
Life Sciences Division
Évry

---

(6) Nafion®: fluorinated polymer exchanging H^+ protons.

(7) Aromatic hydroxylation: replacement of a hydrogen atom by a hydroxyl group (OH) in an aromatic molecule such as benzene.

Nanosciences and **nanotechnologies** working for **energy**

Nanosciences and nanotechnologies are major sources of innovation for all the energy-related challenges: production and storage of energy, energy conversion and energy savings. They are also opening up avenues for progress in terms of economizing raw materials, in particular by replacing or making less use of rare materials. **CEA has extensive expertise in this field and it is using it to meet all of these goals, with the aim of contributing to the scientific breakthroughs required to meet the challenges of renewable energy production and energy savings.**

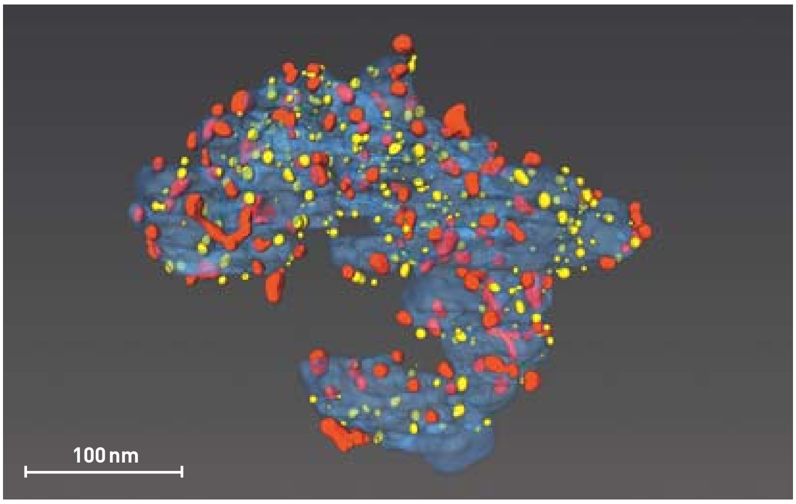
CEA's nanoscience and nanotechnology skills are based on advanced nano-manufacturing, self-organization of matter, characterization and numerical simulation techniques. Often, in order to speed up the innovation process in a context of fierce international competition, the work performed closely involves upstream research teams and technological research teams.

Producing electrical energy

Photovoltaic solar energy is certainly one area in which the benefits of controlling matter at the nanometric scale are most apparent. A description of the processes involved will show why. After the creation of the exciton (electron-hole pair) at absorption of an incoming photon within a semiconductor material, generation of the electric current relies on the separation of the charges under the influence of the electrical field of a p-n junction: the electron goes to an n doped semiconductor and the hole to a p doped semiconductor. The efficiency of the photovoltaic cell depends to a large extent on the effectiveness of this separation. Defects in the materials are all opportunities for recombination of the charges produced, so it is important to minimize the transport distances of the electrons and holes.

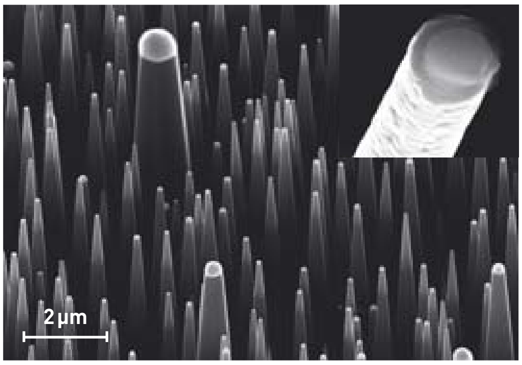
In the case of semiconductor-based solar energy, and over and above the conventional thin-film structure, this research is exploring highly innovative alternatives such as structures based on semiconducting nanowires, which offer the prospect of comparable efficiency, with considerable material savings. These solutions rely on advanced expertise in nano-manufacturing processes in order to produce the desired heterostructures (figure 1).

In the case of organic photovoltaic energy, the same constraints require the close mixing of two organic semiconducting type n and p phases and the reduction to a few nanometers of the distances between interfaces, in order to optimize the dissociation of the initial exciton and the transport of the photo-generated charges. This objective is mobilizing the skills of the chemists, both for the synthesis of higher-performance organic n or p materials, and for the nano-structuring of the material when mixing polymers (figure 2). On the basis of such or similar organic systems, the best efficiency levels today being obtained at CEA are around 10%.



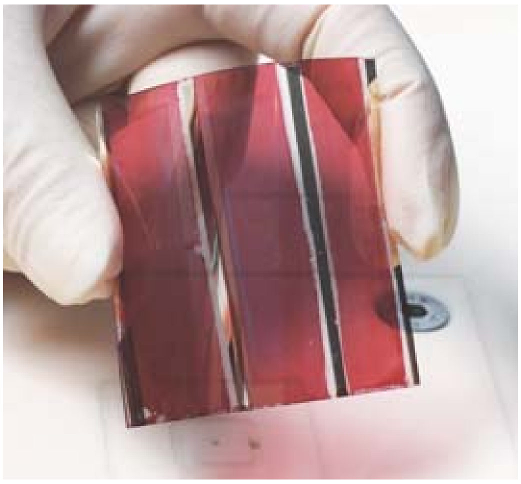
CEA

Platinum is a highly effective catalyst in a fuel cell, but also a rare and costly metal which needs to be economized. In order to reduce its quantity and optimize the operation of the fuel cell, it is used in the form of nanoparticles which are dispersed in porous nanometric scale support materials, often carbon based (carbon black). The platinum nanoparticles distributed over the carbon black, here of the cathode, after 2,000 hours of fuel cell operation, are clearly visible on this image obtained with a transmission electron microscope (tomography) on the nano-characterization platform (PFNC) at MINATEC. It can be seen that the largest ones (> 10 nm, artificially colored in red) are located on the surface of the carbon black, while the smallest ones (< 3 nm, colored in green) are located inside.



CEA

Figure 1.
Silicon nanowires produced by CVD (Chemical Vapor Deposition) growth at the Inac (CEA Grenoble). The insert shows a radial SiGe-Si (silicon germanium-silicon) hetero-junction in another nanowire. The two images were obtained with an electron microscope. Geometries such as these are one of the avenues of research for future generations of photovoltaic cells, in which the active material is finely nanostructured in order to combine performance and economize material.



P. Avavian/CEA

Figure 2.
Flexible organic photovoltaic cell manufactured at the Liten (CEA Grenoble, Ines site). The active material of such cells consists of organic semiconducting polymers. The work of the chemists concerns the synthesis of appropriate molecules for effectively absorbing visible spectrum light and the production of a mixture of polymers with a nanostructure controlled to optimize the transport of electrons and holes to the electrodes.

Storing energy

Batteries are a key component of any transition to a more environmentally-friendly economy: electric cars, matching supply to demand through the storage of the energy produced by intermittent sources (photovoltaic, wind), etc.

In this field, nanomaterials are a major source of progress, as illustrated by the case of lithium-ion (Li-ion) batteries, one of the most efficient and widely used technologies (see *Energy in batteries*, p. 56).

These batteries are based on the reversible exchange of the lithium ion, *via* an electrolytic liquid, between a positive electrode (insertion of the Li^+ ion, typically in a compound such as iron phosphate, $FePO_4$) and a negative electrode (insertion of the lithium atom). The capacity of the battery depends directly on the quantity of lithium that can be reversibly stored by each of the electrodes. Silicon, which is able to form a phase particularly rich in lithium ($Li_{15}Si_4$), would thus appear to be a highly promising insertion material. However, the insertion of such quantities of lithium leads to considerable swelling of the silicon, by a factor of more than 3. This swelling leads to fragmentation of the material during battery charge-discharge cycles. Faced with this difficulty, the nano-structuring of silicon provides a solution: the fracturing phenomenon is far more limited for nanoparticles, which are more able to withstand the swelling stresses, than for a bulk material. On subjects such as these, the CEA's teams, here those from the Saclay Institute of Matter and Radiation of the Physical Sciences Division (Iramis/DSM) and the Liten Institute (Laboratory for Innovation in New Energy Technologies and Nanomaterials) of the Technological Research Division (DRT), are active, from synthesis of the nanomaterials (figure 3) up to the production of technological devices allowing performance assessment and paving the way for industrial transfer.

Recently, a team from the Institute for Nanosciences and Cryogenics (Inac/DSM), in collaboration with the Institut des Matériaux Jean Rouxel (Nantes, Loire-Atlantique *département*), for the first time studied the performance of silicon nanowire electrodes for supercapacitors. Supercapacitors are devices similar to batteries, and enable a far higher power density to be delivered, although with a far lower stored energy density. In this case, electrodes consisting of silicon nanowires offer a current density 7 times higher than that of a flat silicon surface, while maintaining excellent resistance to repeated charge-discharge cycles.

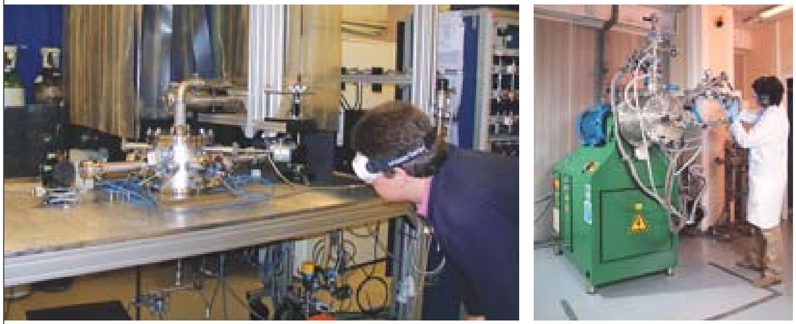
Converting energy

Given the intermittent nature of renewable energy production, the storage of energy in other forms, which do not emit greenhouse gases, is a major challenge. Hydrogen is a particularly effective carrier, the combustion of which is non-polluting. Fuel cells using ion exchange membranes are a relatively mature technology, but one that demands the use of significant quantities of platinum. The CEA teams are working on improving the available technologies, in particular economizing the use of platinum, and on new, disruptive solutions.

In the first area, significant progress has been made in recent years, with a considerable reduction in the quantity of platinum used. It is therefore important to have highly sophisticated characterization techniques able to identify the structure of the catalytic layers, in particular the size distribution and breakdown of the particles of catalyst. To do this, on the PFNC(1) nano-characterization platform at MINATEC, the Inac and Liten teams are for example using the technique of electronic tomography. It is thus possible to see a three-dimensional distribution of the catalysts on their supporting carbon and to monitor its evolution at various steps in the life of the device (see the illustration p. 81).

Energy saving

Energy savings are a final but key issue. The contribution of nanotechnologies in this field is already an important one. In the case of lighting, for instance,



CEA

P. Avavian/CEA

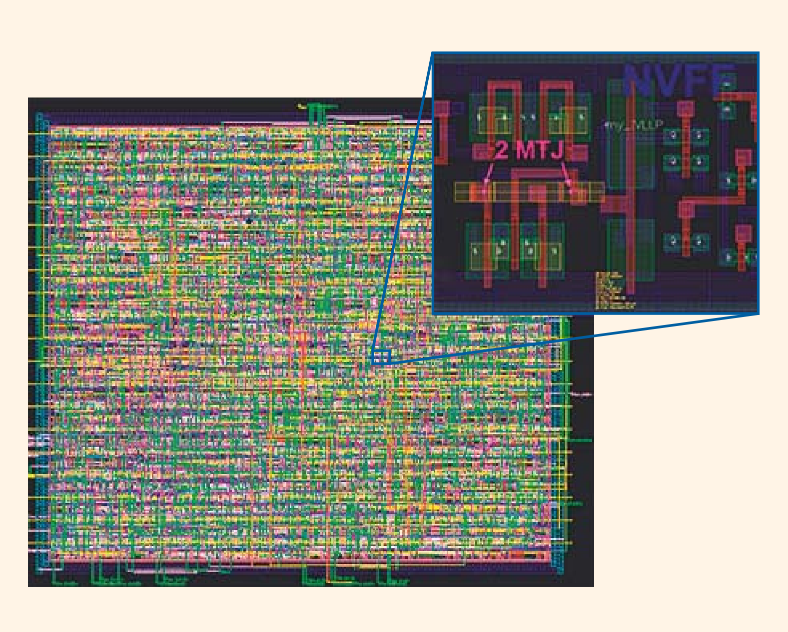
Figure 3.
Synthesis of nanomaterials. On the left, an installation for the production of nanoparticles by laser pyrolysis (Iramis, CEA Saclay). The nanoparticles are produced during the interaction between an infrared laser beam and a flow of reagents formed from gas or liquid precursors. This research installation can manufacture 60 g of silicon nanoparticles per hour. On similar materials (silicon carbide, SiC), higher production rates, of about one kg per hour, are being obtained on a pilot developed within the Department of Materials for Nuclear Energy of the Nuclear Energy Division (DMN/DEN). The silicon nanoparticles are then associated with other materials to make battery electrodes. On the right, confined unloading of a high-energy, semi-industrial crusher containing nanostructured powders, on the Nanomil platform (Nanostructured materials by milling) at the Liten (CEA Grenoble). Nanomil is dedicated to industrial transfer (synthesis of nanostructured materials for Li-ion batteries).

(1) In order to deal with the most advanced characterization needs of its programs (requiring high level of expertise and considerable investment costs), CEA has brought together teams from the Inac, Leti (Laboratory of Electronics and Information Technologies), and Liten Institutes within the PFNC. Fundamental and technological research are carried out on the same tools, ensuring rapid transition of the methodological developments made upstream to technological applications. Other platform characterization techniques are contributing to research for energy, such as surface spectroscopy, X-ray diffraction, ion beam analyses or nuclear magnetic resonance.

light-emitting diodes can produce light with high efficiency from quantum wells or dots. They are extensively used in applications for the general public. The aim of the HelioDEL start-up, created in 2011 on the basis of work done at CEA Grenoble, is thus to develop gallium nitride (GaN) nanowire diodes on a silicon substrate.

In another field, innovation lies in the components and the architecture of the integrated circuits derived from microelectronics. The processors in computers, mobile phones and numerous other devices are an important source of energy consumption, which is far from negligible when considered nationwide. Moreover, the consumption by integrated circuits limits battery life and thus restricts the uses of mobile devices (telephones, game consoles, etc.).

MRAM(2) type memories, on which the Spintec laboratory (Spintronics and Component Technologies)(3) at CEA Grenoble has innovated extensively, combine very low consumption, high cyclability(4), high writing speed, immunity to ionizing radiation and, above all, non-volatility. The performance and the advantages of hybrid electronic components (CMOS(5)-MRAM) are being studied with a view to determining the possible reduction in consumption by comparison with conventional silicon microelectronic technologies (CMOS-SRAM(6) and DRAM(7)). To do this, research is combining a study of the physics of basic MRAM type components and work on the design of future CMOS-MRAM architectures (figure 4). By more closely combining logic functions and memories in the architecture of the circuits, it is for example possible to create reprogrammable circuits with functions optimized for a given calculation, and to produce normally-off electronics, in other words in which the various parts of a processor are only powered for the time they need to perform the calculation.



CEA

Figure 4.
Drawing of masks for a complete digital filter, designed with conventional microelectronic tools. The close-up shows a synchronous flip-flop with a non-volatile memory (NVFF). The non-volatility comes from the addition of two magnetic tunnel junctions (MTJ) manufactured in a complementary step above the CMOS components, thus at very little extra cost in terms of surface consumed.
Based on the calculations made, and when compared with conventional architectures, the consumption gains for this type of hybrid circuit, incorporating silicon electronics and MRAM type elements, are estimated to be by a factor of 10!

A priority field for energy

The considerable potential of the progress achieved through nanosciences and nanotechnologies for energy technologies has been identified by all the leading international stakeholders. It is thus among the leading priorities of the National Nanotechnology Initiative in the United States, to which the DoE (US Department of Energy) is now the leading contributor agency, and the priorities of the 2015 Action Plan for nanotechnologies published in 2011 by the Federal Government in Germany.

Based on the progress already achieved, the contribution of nanotechnologies to fields as diverse as solar photovoltaics, heat recovery (thermo-electricity), energy storage in batteries, supercapacitors or fuel cells, is now a reality. With its academic and industrial partners, CEA is combining its expertise in nanosciences and nanotechnologies with its know-how in industrial systems for the new energy technologies. It thus aims to address the two key challenges for these technologies: improved performance and sustainable technological development, allowing widespread dissemination of the technologies while limiting the utilization of non-renewable resources (rare materials, etc.).

> Yves Samson
Director of the Program
"Nanosciences"
CEA Saclay Center

(2) MRAM: Magnetic Random-Access Memory. This non-volatile memory is based on the use of magnetic tunnel junctions. It combines inherent non-volatility, high immunity to radiation, high reading and writing speed, high density and low consumption. It is therefore identified by the microelectronics roadmap as one of the most promising technologies for at least a part of the memories in logical applications.

(3) The Spintec laboratory (CEA-CNRS-Université Joseph Fourier-Grenoble INP) and the Leti, in collaboration with the Montpellier Laboratory of Informatics, Robotics, and Microelectronics (Hérault *département*) and the Orsay Institute of Fundamental Electronics (Essonne *département*), have developed a range of software tools to assess the potential gains that could be obtained by adding magnetic tunnel junctions to integrated circuits, in particular to processors. These tools led to the design of the circuit shown in figure 4. They are being made available to several national and international partners.

(4) Cyclability: ability of a component to pass repeatedly from state 0 to state 1 without degradation. The parts of the memory of a computer close to the processor, which are activated a large number of times, require very high cyclability (10^{14}).

(5) CMOS: Complementary Metal Oxide Semiconductor. Integrated circuit technology based on the use of complementary MOS type transistors (a p type stage and an n type stage). Because of its advantages (speed, reliability and low consumption), it is used in virtually all the purely logical applications.

(6) SRAM: Static Random-Access Memory. This is a CMOS and therefore volatile memory which is extremely fast but not very dense (6 transistors per memory cell). It is used in applications requiring high speed, for a relatively small quantity of data, for example in processor cache memories.

(7) DRAM: Dynamic Random-Access Memory. This memory consists of a capacitor and an access transistor. The information is stored in the capacitor in the form of an electric charge. It must be regularly refreshed because the capacitor spontaneously discharges over a period of time. This memory with average speed, but very high density, is typically used as the main memory in computers.

Electric transports

Hybrid vehicles and rechargeable hybrids, self-service battery-powered cars in a growing number of cities, towns building electric tramways and adopting hydrogen buses, as well as electric boats, cars and aircraft that will soon be equipped with fuel cell systems... **Electric power is today enjoying real development and reaching all modes of transport**. This deployment has been made possible by the progress achieved in the design of electric batteries. Its future is based in particular on the implementation of appropriate infrastructures, the economic competitiveness of electric mobility, the continuation of R&D work in this field, particularly in terms of battery life, and adapting the users to this type of transport.


CEA

Recharging an Irisbus rechargeable hybrid bus at the CEA Grenoble fast recharge station.

Mobility of the future can be summarized in three words: clean, safe and connected. Given the diversity of the means of transport and the types of journey, there is no single magic solution. Thermal vehicles will continue to represent a significant share of the fleet for many years to come. However, electric vehicles will have a key role to play in the new context. Electrical mobility, in all its forms, is a way of meeting environmental and energy challenges and the population's justified demand for mobility that is both cheaper and more practical, in particular in the emerging countries. Nonetheless, numerous challenges will still have to be met, such as implementing new economic models, creating a new environmentally friendly industrial chain, taking account of the end-of-life vehicle as of the design stage (production, utilization and recycling), adaptation of infrastructures and user adoption of new travel habits.

A difficult start

The electrification of automobiles is not a new idea. The first electric motors and the first rechargeable cells date back to the mid-19th century. As for the first vehicles, they date from the end of the same century, including the famous "*La Jamais contente*", which reached a speed of 106 km/h in 1899 and covered a 307 km journey without recharging in 1901. However, after a promising beginning in the early 20th century, electric motors gave way to the internal combustion engine. The rapid improvement in the performance and reliability of these engines, falling fuel costs, the range offered, the practicality of usage, with the growth of the necessary infrastructures (roads and service-stations), combined with the arrival of an electric starter, sounded the death-knell for electric traction and its heavy and expensive lead batteries with their limited range.

During the 1990s, the Battery Electric Vehicle (BEV), generally equipped with nickel-cadmium (NiCd) batteries, made a fresh attempt to break into the market, especially in France. This was not a success either and only 10,000 vehicles found their way onto the roads. The cost, lifetime and risk insurance of the batteries, plus their limited range, meant that this was not what the users wanted.

At the same time, the car manufacturers developed a range of thermal/electric hybrid vehicles (HEVs: Hybrid Electric Vehicles). This technology is ideally suited to diversified automobile usage. In town, low-speed and highly variable driving takes advantage of the high efficiency (about 90%) of the electric motor. The batteries, generally nickel-metal hydride (NiMH) and with limited range (a few kilometers), are recharged by the thermal engine set to its maximum efficiency. On inter-city and highway journeys, the thermal engine takes over and offers long range, using liquid fuel.

The Toyota Prius, the hybrid vehicle pioneer, was launched in 1997 and more than 4 million vehicles have now been sold. Even if hybrid vehicle penetration is still low by comparison with the automobile fleet as a whole, it is clear that the process is now under way and many manufacturers are now including at least one vehicle of this type in their range.

Electric vehicles: an emerging market

The development of lithium batteries (see *Batteries for electrical mobility*, p. 56), with improved specific energy and energy density, able to accept numerous, rapid charge-discharge cycles and with longer lifetimes, led the car manufacturers, as of 2010, to make a third attempt to deploy electric vehicles. The models proposed offer a range of 70 to 150 km, far in excess of the average distance travelled daily by a driver. Their advantage is clear for urban usage or local rural uses. Although still very low (0.5%

of the French automobile market in Q1 2013), the number of registrations is rising: in 2012, it was more than twice the figure reached in 2011. Of the most significant deployments is the Bluecar from Autolib', the Parisian self-service car-share system, the Ion and the *C-Zéro*, as well as Kangoo type utility vehicles, 15,000 of which have been ordered by the Government's centralized buying department for about twenty public and private enterprises. New electric vehicles appeared in the second half of 2012 and beginning of 2013, notably with the high-profile entry of the Zoé. However sales of electric vehicles could really take off with small urban vehicles or quads, offering an interesting compromise between safety, handling and easy parking in an urban environment, when compared with cars and scooters.

Rechargeable hybrids and hydrogen-fueled vehicles

In order to meet the need to reduce polluting emissions, especially in towns and cities, while maintaining a range of several hundred kilometers, hybrid vehicles are evolving, with the appearance of rechargeable hybrid vehicles (PHEVs: Plug-in Hybrid Electric Vehicles). With an architecture comparable to conventional hybrids, these vehicles offer greater range in electric mode, from 15 to 60 km, thanks to the use of a larger capacity lithium battery and the possibility of recharging it from a power socket. The first vehicles on sale are the Chevrolet Volt in the United States, the Opel Ampera and the Toyota Prius Rechargeable in Europe.

An additional step forwards in the search for a clean car with long range was made with the arrival of vehicles with a fuel cell (FCEVs: Fuel Cell Electric Vehicles). Significant progress has been made in fuel cell technology in recent years, both in terms of performance and lifetime, and in integration – utilization of standard chassis for systems of 90 kW –, range – the Toyota FCHV-adv (Fuel Cell Hybrid Vehicle-advanced) covered 760 km without emitting any carbon dioxide (CO_2), better than gasoline! – and cost – 80% reduction since 2002 leading to a total cost of ownership[1] by 2025 comparable with that of a thermal or battery vehicle, see *The competitiveness of electric travel*, p. 87. Feedback from hundreds of demonstrators, with more than 15 million kilometers covered and more than 90,000 recharges, has reassured car manufacturers such as Toyota, Hyundai, Honda, General Motors, Daimler, Nissan and Ford who have announced respectively the commercial launch of this type of vehicle for 2015 and 2017. A lower-power fuel cell (5 to 40 kW) is also included as a means of extending range in these vehicles, especially utility vehicles.

The other challenge to be met for the FCEVs is the development of a hydrogen (H_2) infrastructure. Several hundred H_2 stations have already been deployed worldwide and there are increasing numbers of initiatives for creating hydrogen highways in North America, in Scandinavia, in the United Kingdom, in Germany, a country which aims to install 500 to 1,000 stations by the year 2020 and recently in France (figure).

All forms of transport are concerned

Electrification is not restricted to cars. It is applicable to all modes of transport and all types of vehicles. Therefore, numerous special vehicles, such as airport or urban cleaning vehicles, forklift trucks and so on have for several years now been fitted with electric motors. What is new is the introduction of fuel cell systems when more range or continuous operation are required. This is in particular the case with forklift trucks: more than 3,000 units were sold with financial incentives and then, over the past two years, without incentives, to logistics centers such as those of Coca-Cola or US Postal. The feedback from their operation is highly positive both in terms of productivity and

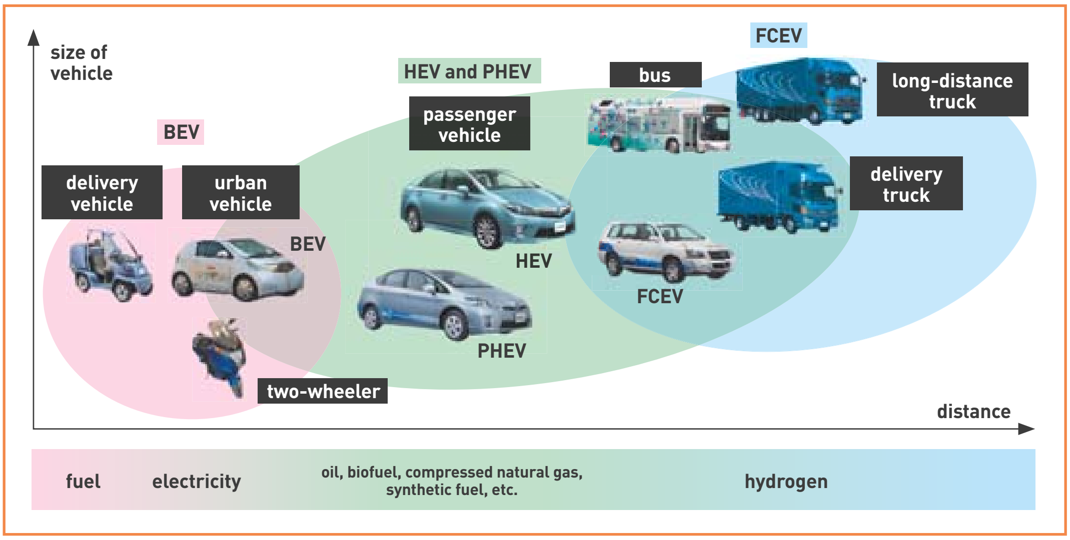


Figure.
Complementary range of electric motor types for land transport according to usage. It is able to deal with the diversity of types of journey and the expectations of the users: Battery Electric Vehicles (BEVs) for short journeys, Hybrid thermal/Electric Vehicles (HEVs) and Plug-in Hybrid Electric Vehicles (PHEVs) for mixed urban/medium-distance usage and Fuel Cell Electric Vehicles (FCEVs) for medium/long distances, without CO_2 emissions.

---

(1) The Total Cost of Ownership (TCO) represents all the expenditure involved in the possession of a vehicle: purchase, maintenance, repairs, fuel consumption.


CEA

The *Zéro CO₂* yacht sailing off the coast of Ajaccio. It is 12 m long and equipped with a lithium battery and a 25 kW fuel cell system which supplies the boat's auxiliary motor. The on-board needs are met by renewable energies (solar, wind, hydraulic).

return on investment. This augurs well for large-scale deployment in the coming years.

The aeronautical world is also involved and is looking at electrification of its fleet. Even if the electricity on-board aircraft is currently produced by turbines and electricity generators running on **fossil** fuel, fuel cell systems have been tested as Auxiliary Power Units (APU), for example Michelin's 20 kW system assessed on an A320. The aircraft manufacturers (Airbus, Boeing) are aiming for initial commercial flights equipped with fuel cells to supply non-essential applications before 2020.

The maritime market is following the same trend. The supply of electric boats is constantly on the rise, in particular for tourism. The batteries used at present utilize lead. The cost of lithium batteries, which is still too high, is a major obstacle to their introduction. In the same way as for cars, an increase in range entails the addition of fuel cell systems, either as an APU, or as the main motor. On this subject, using its *Zéro CO₂* sailing boat equipped with a hybrid lithium battery/fuel cell electric motor, CEA recently demonstrated the feasibility and the benefits of these new technologies.

Fleets of less polluting buses

Reducing pollution from land transport also involves increasing the cleanness of public transport. New ranges of buses have been developed: battery electric buses, hybrid thermal buses, hydrogen buses. About twenty fuel cell buses have been in service in Vancouver (Canada) since the 2010 Winter Olympic Games and similar buses were deployed for the 2012 Summer Olympic Games in London (United Kingdom).

The electric bus today accounts for a tiny fraction of the French fleet (200 trolleybuses(2) out of a fleet of 20,000 buses). Those running at the moment have higher operating costs than **diesel** or gas buses, owing to frequent replacement of the batteries. Trolleybuses also require costly overhead wire systems which are often felt to be unsightly. Today's battery bus suffers from a lack of range, combined with energy storage mass and volume that are too high, thus reducing its passenger carrying capacity. These drawbacks tend to detract from the advantages: comfort, silence, performance, very low CO_2 emissions and an energy price per kilometer that is three times lower than that of diesel.

The problem of electric or rechargeable hybrid buses is linked to the size of the battery. There are two possible options: batteries capable of operating for the length of a shift, or a smaller battery that can be partially recharged rapidly at the terminus. This latter solution is currently being experimented at CEA under the AMI (call for expressions of interest) project from the French Environment and Energy Management Agency (**Ademe: Agence de l'environnement et de la maîtrise de l'énergie**) being run by Irisbus company (ElLiSup project, see *Batteries for electrical mobility*, p. 56). The deployment of these buses depends on the development of the best technical and economic solution for a high-power (200 kW) fast recharge terminal with adjustable voltage in order to be able to adapt to the level required for each bus in service (300 V, 600 V, etc.) and minimize the impact on the grid. Depending on the length of the lines and the distance between network nodes, electric buses recharged in the terminus have a lifetime cost that is equivalent to that of diesel. Rechargeable hybrid buses would see their diesel consumption drop by 40 to 50% instead of 15 to 25% for non-rechargeable hybrids. The results obtained in 2012 are highly promising and several towns have already shown an interest.

Today's technologies offer a complementary range of electric drive systems (battery, hybrid, fuel cell) and a level of maturity able to handle the diversity of the types of journey and modes of transport, the expectations of the users and the needed energy transition towards a sustainable mobility.

> **Laurent Antoni**
Liten Institute (Laboratory for Innovation in New Energy Technologies and Nanomaterials)
Technological Research Division
CEA Grenoble Center

---

(2) The trolleybus is a bus powered by an electric motor supplied by two overhead contact lines (catenaries).

The competitiveness of electric travel

For environmental and strategic reasons, the transport propulsion methods have been becoming more diverse in recent years: use of synthetic fuels in internal combustion engines, vehicles running on natural gas, electrification of the automobile fleet, whether for rechargeable hybrid vehicles, or for all-electric battery vehicles (BEVs - Battery Electric Vehicles) and/or using a fuel cell (FCEVs - Fuel Cell Electric Vehicles)... So today, how competitive are these different systems?

An overall technical-economic analysis of mobility must take account not only of the data concerning the key technological components of the different power trains, both present and future (internal combustion engines, electric motors), but also the population's actual mobility needs, in particular owing to the still insufficient range of the BEVs. A report from the CGDD(1) clearly states that a motor with limited range can meet most of the needs of the private light vehicle fleet in France: for an average distance travelled of 15,500 km/year, more than 90% of daily journeys are over a distance of less than 100 km, in other words the typical range of the electric vehicles that will be on the market in the near future. The remaining 10% however represent 37% of the total kilometers covered, which still leaves a large share for modes of transport offering high range (conventional and fuel cell vehicles).

Battery electric vehicles

When electric mobility can replace all or part of conventional oil-based mobility, the competitiveness of the "electric fuel" taken from the grid is real, in any case given the current price of this energy in France *via* a domestic contract (for example night-time recharging of battery or rechargeable hybrid vehicles), provided that there is no levying of an equivalent of the domestic energy products consumption tax (TICPE). However, an economic analysis of Total Cost of Ownership (TCO: purchase, maintenance, repairs and fuel consumption), for example over a period of ten years and taking account of the differences in investment costs, shows that, if one excludes the subsidies as provided today, electric travel is not profitable if battery costs remain high, for example around 300 €/kWh (figure 1), the average value envisaged for 2020 by a European study(2). It would also appear that there is no point in attempting to achieve high ranges, in particular for annual journey distances of less than 30,000 km: the frequency of long daily journeys does not warrant over-investment in storage capacity.

Fuel cell electric vehicles

In this case, the journey breakdown has no impact on the competitiveness of travel in a hydrogen (H_2) vehicle by comparison with conventional vehicles. Several hundred kilometers could be travelled without stopping, for virtually identical recharging durations. However, the price of the fuel cells, generally expressed in €/kW, has a considerable influence on the profitability thresholds of hydrogen at the pump, thus confirming the value of research in this field. As shown in figure 2, when talking in terms of TCO, a 70 kW fuel cell vehicle, costing 40 €/kW(2) and consuming 1 kg of H_2/100 km (current value of the vehicle in question) would be competitive with a similar conventional vehicle consuming 5.6 L/100 km, if the fuel prices at the pump are of about 6.8 €/kg of H_2 and 1.75 €/L respectively. The DoE (US Department of Energy) is already envisaging a target cost of 30 $/kW (about 20 €/kW), for mass production in the medium term(3). This would make hydrogen fuel competitive up to 8 €/kg. A target that would seem to be perfectly feasible.

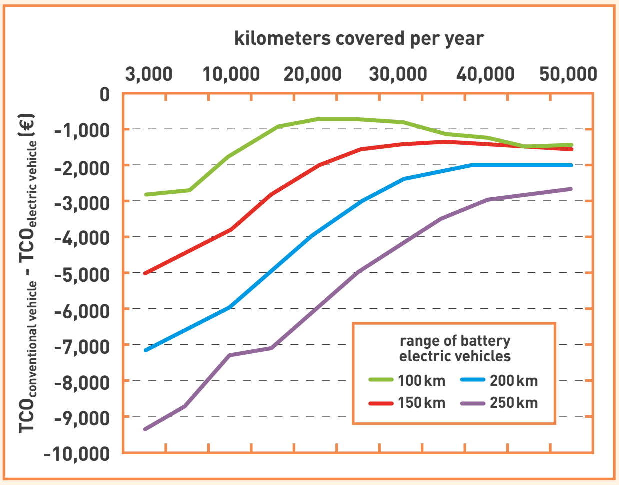


Figure 1.
Differences in Total Cost of Ownership (TCO) for conventional and battery electric vehicles (variable range, battery price = 300 €/kWh), for 10 years of use (discount rate of 5%).

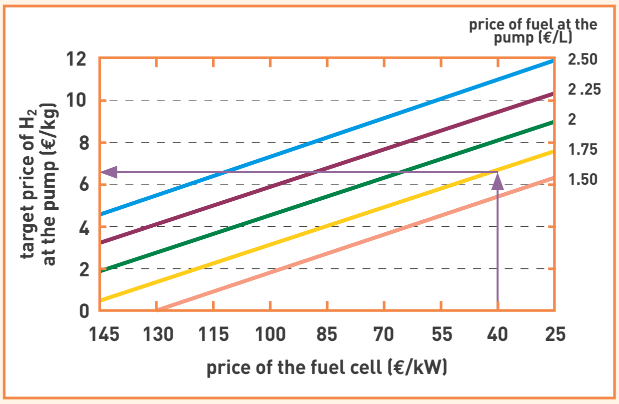


Figure 2.
Target prices for hydrogen at the pump versus fuel cell costs (cell of 70 kW, 15,000 km/year, over 10 years, discount rate of 5%).

> **Alain Le Duigou, Yuan Guan**
and **Aimen Smatti**
Institute for Techno-Economics
of Energy Systems (I-tésé)
Nuclear Energy Division
CEA Saclay Center

(1) Stéphanie DEPOORTER and Pierre-Marie ASSIMON, "*Les véhicules électriques en perspective. Analyse coûts-avantages et demande potentielle*", May 2011, Commissariat général au développement durable (CGDD). Can be downloaded from:
http://www.developpement-durable.gouv.fr/Les-vehicules-electriques-en.html.

(2) "*A portfolio of power-trains for Europe: a fact-based analysis. The role of Battery Electric Vehicles, Plug-in Hybrids and Fuel Cell Electric Vehicles*", McKinsey & Company, November 2010. Can be downloaded from:
http://www.fch-ju.eu/sites/default/files/documents/Power_trains_for_Europe.pdf.

(3) 2011 Annual Merit Review Proceedings, US Department of Energy. Can be downloaded from:
http://www.hydrogen.energy.gov/annual_review11_fuelcells.html.

Improving **energy performance** in the **home**

Constructing buildings that consume less energy, without reducing the comfort of the occupants and with no negative impact on individual energy bills is one of the key issues of French energy policy. It is also one of the strategic areas for development at CEA. **Every day its researchers work on new innovations, that are tested on demonstration platforms providing the interface between R&D and real-world performance.** The goal is energy optimization of buildings, from design to management of all components, for both new-build and renovation work.


P. Avavian/CEA

P. Rifflard/CEA

The Incas platform located at the Ines. It comprises four fully-instrumented experimental houses, the associated PASSYS cells (cell visible at bottom-left) and several benches for testing roof-integration of photovoltaic systems. The PASSYS cells can be used to develop and characterize innovative components of envelopes and of HVAC (Heating, Ventilation and Air-Conditioning) systems. This research tool offers the scientists a means of understanding the behavior of new construction methods.

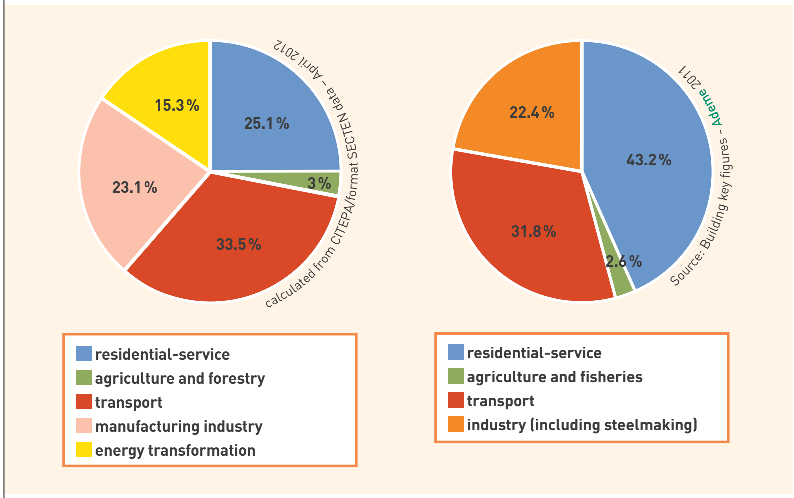


Figure 1.
On the left, breakdown by activity sector of greenhouse gas emissions in metropolitan France in 2010. The emissions from the residential-service sector depend on climatic conditions. Mild temperatures enable heating consumption to be reduced, and therefore the greenhouse gas emissions as well. 2010 was particularly cold.
On the right, final energy consumption in France per sector in 2010. The residential-service sector accounts for more than a quarter of greenhouse gas emissions. It is also that which consumes most energy.

In France and Europe, the construction sector is today the activity that is most hungry for energy and that emits the most greenhouse gases (figure 1). More particularly, the housing sector in France comprises numerous sources of heat loss(1) which need to be renovated and classified using the energy label, now well-known to the public owing to its widespread adoption in the household appliances sector.

The home is destined to undergo a major revolution, both in its design – for new buildings (low consumption buildings or positive energy buildings) which constitute less than 3% of the total inventory – and for renovation (the main share of the future market). Whether because of global warming and rising energy costs, which will weigh heavily on user bills, or the rising complexity of equipment within the home (**home automation**, security, multimedia, assistance for the elderly, etc.), buildings must adapt … and soon!

A strategic area for CEA

More than 400 CEA researchers are directly or indirectly working on energy improvement in buildings. In this field they have an ideal opportunity to experiment with and demonstrate the numerous technical building blocks produced in their research laboratories. For example, this includes energy components and systems (generation, storage of electrical or thermal energy) for electricity production, heating in winter, or cooling in summer; devices for collecting, measuring and transmitting all information of use for improving energy performance, closely linked to what the users want; the design of solutions (software, human-machine interface, etc.) able to interpret the information from the sensors and display it without error in a format that is comprehensible to a wide audience.

The innovations applied to the housing sector were initiated within the Energy in Building Laboratory (LEB) of the Liten Institute (Laboratory for Innovation in New Energy Technologies and Nanomaterials), created in 2005 at the French National Solar Energy Institute (**Ines: Institut**

---

(1) The French housing sector comprises 31 million homes (17 million individual houses and 14 million collective residential units), two-thirds of which were built before the first Thermal Regulations in 1974. Heating accounts for more than 70% of energy consumed.

national de l'énergie solaire). Since then, they have expanded to include several other topics: integration into the home of solar, **photovoltaic** then thermal, energy (technical and socio-economic performance target); thermal performance studies of the building envelope and its construction techniques; diagnostics of good operation and good usage of new and refurbished housing; improvement in the quality of the interior environment and the air. The importance of this last aspect will increase for homes with a degree of insulation making it essential to install atmosphere renewal systems to ensure energy performance and above all public health.

For all the researchers at the Technological Research Division (DRT), but also the building profession and academic stakeholders, the LEB is an exceptional experimental proving ground, owing to its systemic nature, enabling it to test any component (production of heat, cold, energy, storage, etc.) in association with other products, while keeping sight of the overall performance goal.

Platforms for testing housing

Tools for upstream modeling, characterization, simulation, full-scale testing of solutions on real constructions: CEA's technology platforms such as the Liten Institute's Incas platform (Instrumentation of new solar architecture constructions) at Ines, or the @Home platform in the Leti Institute (Laboratory of Electronics and Information Technologies) in Grenoble, are complementary facilities for testing innovative construction systems or components that dialogue with each other.

The Incas platform

This platform is dedicated to the development of positive energy housing, in other words which produce more energy than they consume in the course of a year. To date, it consists of four experimental houses – two designed with techniques based on concrete, one with a wooden frame – of about 80 m^2 on two floors – and the fourth in monowall bricks. These houses are geometrical in shape and laid out identically in order to facilitate the comparison of resources. They are equipped with **photovoltaic** and thermal **solar panels** and fitted with instruments which simulate the daily lives of the inhabitants (shower, opening/closing of shutters, etc.).

The platform also includes rotating PASSYS **adiabatic** cells, which can be used to experiment with different natural lighting conditions and assess the thermal performance of the interchangeable facade elements. It also comprises several roofs for testing the integration of photovoltaic systems into buildings (see *Decentralized electricity production: solar energy integrated into the building*, p. 36).

The LEB's expertise is supplemented by other CEA skills, for example from the systems laboratories(2) at Ines or the DRT, in several areas concerning individual housing:

- energy utilization systems (electrical/thermal/air-conditioning);
- electrical and thermal storage;
- automation, monitoring, energy management systems;
- diagnostic and predictive maintenance;
- software;
- systems for the production of photovoltaic and thermal energy;
- industrialization, prefabrication, industrial production;
- labels and certification.


P. Avavian/CEA

Installing sensors in one of the experimental houses on the Incas platform.

Collective housing and eco-districts are also the subject of work which, among other things, concerns interactions between buildings, heat networks, thermal smart grids, as well as the production and storage of electrical and thermal energy at the level of a district. All these R&D activities overlap what is being done at the Liten and involve the two other institutes of the DRT, the Leti and the List (Laboratory of Integrated Systems and Technologies).

The @Home platform

This platform was designed by the Leti [Solutions and Systems Integration Division (DSIS) and Architecture, IC Design and Embedded Software Division (DACLE)] to manage the complexity and heterogeneous nature of "smart systems" for housing. It takes the technological building blocks from Leti and its partners, with the aim of meeting three challenges: simplified deployment of the sensor systems themselves (temperature, humidity, brightness, carbon dioxide (CO_2), etc.); management of their interoperability and processing of their data in order to trigger actuators (lighting panels, roller blinds, etc.); optimization of their consumption and the energy autonomy of sensors and actuators. For this, the techniques developed must meet zero cabling and zero maintenance constraints.

Setting up this platform required the implementation or development of communicating systems of sensors and actuators, either from Leti or off-the-shelf, compatible with the target fields (energy, health and wellbeing, security) and criteria, along with the design of a middleware(3) and a graphic interface for Smartphone.

CEA/Leti - G. Cottet

A Homes sensor. Developed by Schneider Electric and CEA/Leti, the Homes sensors operate in a network and provide wireless communication to monitor comfort parameter settings (temperature, brightness, humidity and CO_2). The Homes sensors are simple to install, compact, powered by a solar cell, energy independent and require no maintenance.

---

(2) Solar Systems Laboratory (L2S)/Electricity Storage Laboratory (LSE)/Thermal Systems Design Laboratory (LETH).

(3) Middleware: third-party software used to create a data exchange network between different IT applications.

CEA/Leti - G. Cottet

On the left, a graphic interface on Smartphone and on the right, a graphic interface on PC, developed for the @Home platform. The platform is multimodal: different types of interaction are possible.

There is a wide variety of sensor and actuator types and methods of communication, a variety which will inevitably be found in the home. This is due to the diversity of connection methods. Connection can be by wires – this is the case with the present **formaldehyde** sensors from the ETHERA(4) company – or by radio transmission. These latter are of three types:

- Leti proprietary **RF** links(5) to address application constraints: network of vibration sensors, multi-sensor system (brightness, temperature, accelerometer, magnetometer);
- ZigBee RF link(6): system of presence sensors, **light-emitting diode** (LED) ceiling light, LED screens, smart plug;
- ZigBee Green Power RF link(6): system of Homes(7) sensors (temperature, CO$_2$, humidity and brightness) developed in partnership with Schneider Electric.

Apart from the absence of cabling for elements communicating by RF link, these devices are characterized by their energy autonomy and thus an absence of maintenance for the Homes sensors systems, by the low consumption of the other devices and, finally, by their compactness and ease of installation.

The middleware and the graphic interface for Smartphone meet the criteria concerning the absence of configuration or administration and interoperability management. They give access to heterogeneous data from different sensors and to control of actuators (off-the-shelf and resulting from R&D), the incorporation of other data, in particular from the Web, the coordination of devices according to predetermined scenarios and dynamic management of the network of sensors and actuators.

The architecture of the @Home platform makes it possible to easily add new devices, communication protocols and scenarios. Over and above platform extension, the plan is to deploy it in realistic conditions, to identify the sensor and actuator requirements and associated usages, during national and European projects.

Thermal flows and assessment of a building's energy efficiency

This project, which is the fruit of collaboration between the Liten [Solar Technologies Department (DTS) and Department of Nanomaterials Technologies (DTNM)] and the Leti [Multimode Sensor Systems Laboratory (LSCM)/DSIS], aims to adapt thermal flowmeters to the constraints of the building and to utilize the measurement of heat flows in the energy diagnostic of the constructions.

Temperature measurement is widely used in the housing sector. However, while this temperature is the consequence/result of thermal exchanges and flows, understanding the **convective** transfer coefficients of the walls remains highly limited, despite considerable efforts made in recent years by the Scientific Community. Thanks to heat flow measurements, it will be possible to reduce the uncertainties concerning wall exchanges, to work on the cause of temperature changes and thus anticipate them. Furthermore, a building is a permanently changing system and a steady-state situation does not exist, owing to daily and seasonal shifts. A combined understanding of heat flows and temperatures means that exhaustive knowledge of the building's construction will not be necessary and it will be easier to more accurately predict its future behavior.

Thermal flow measurements will also broaden our understanding of the behavior of walls with high **thermal inertia** or of solar input through glazed surfaces. The efficiency of thermal inertia is not simply limited to a material's ability to conserve temperature. It is also linked to the ability of this material to store and then restore energy, which is directly linked to its **conductivity**. Understanding exchanges through walls will also allow the development of models for determining their time constants(8) and thus the damping(9) and peak shift(10), thereby opening the door to the possible definition of a time constant for an entire construction, at the design stage. Controlling this parameter will lead to the construction of energy independent buildings with heating being by managing the stored and restored solar inputs and regulation then being by air renewal.

Improved energy control in buildings

By optimizing the control of the thermal systems in buildings, it is possible not only to save energy, but also to reduce its operating costs. The Intelligence, Models and Learning Laboratory (Lima) at the List has developed a software able to meet this two-fold challenge.

In housing, heating, cooling and the production of hot water are the responsibility of different equipment. Their operation is often complex and inter-dependent, particularly when new energy sources or new systems are added, such as solar sensors or heat pumps. In order to address this problem, the List has developed a software which is able to control these various devices (figure 2). When installed in the home, this software optimizes overall energy consumption, operating costs and the

---

(4) On this subject, see *Clefs CEA* No. 60, Summer 2011, p. 70.

(5) When a standard communication protocol does not meet the requirements of the target application, the Leti designs and develops proprietary protocols. This is the case with the network of vibration sensors which requires accurate synchronization of the various nodes and high data rates.

(6) ZigBee: short-range wireless communication technology. ZigBee Green Power has broadened the scope of ZigBee by offering technology for devices operating with energy recovery techniques. The energy from outside sources (solar, wind, vibration, chemical, kinetic, etc.) is recovered and then converted into electricity. This is used to supply small devices, which therefore no longer require a battery.

(7) From the name of the European program "Habitat and building Optimized for Management of Energy and Services", run by Schneider Electric and in which CEA is a stakeholder.

environmental impact. When coupled with thermal simulation software, it provides a useful tool for designing a control system.

The software uses modeling of the building in the form of a multi-agent system, with distributed optimization techniques. Optimization takes account of various criteria: energy resources (electrical, solar, wind, gas, etc.), the price and availability of which can fluctuate over time, exogenous data (weather information) to predict free energy inputs, or inhabitant occupancy forecasts. By considering all these factors, system optimization ensures the comfort of the occupants while permitting energy savings and thus reduced costs (figure 3). The approach is also designed to be totally usable with different buildings, with the aim of addressing the industrial problems involved in developing control systems.

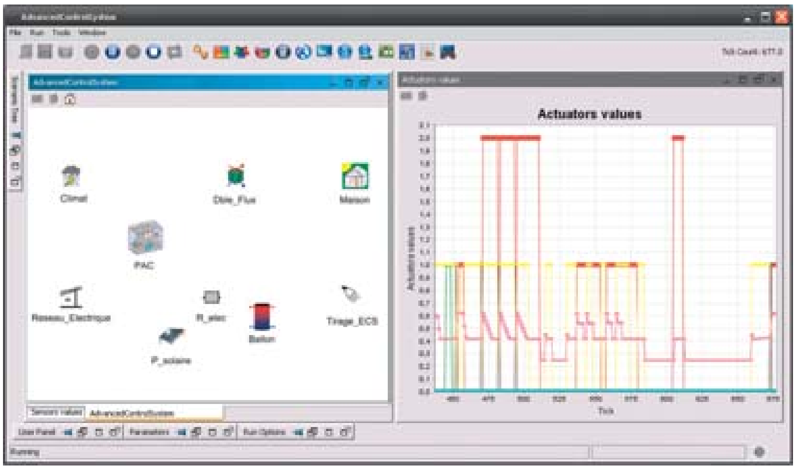
The software was produced in close collaboration with the Thermal Systems Design Laboratory (LETH) at the Ines, and is undergoing testing in real physical environments. During its validation by simulation, it was possible to achieve immediate improvements in heating comfort of more than 40% over the year, with only very slight repercussions on operating and integration costs. In the light of these results, some firms have already expressed an interest. The List is already working on extending it for adaptation to future developments in energy systems, in particular to take account of exogenous forecasts in order to fine-tune control scheduling. So what are the next steps? Incorporating smart electricity grid and heat network issues so that based on the work done on the equipment and then on isolated buildings, it will become possible to make the transition to an entire district.

Future prospects

The challenges to be met concern several aspects. Pushing integration of construction systems to the extreme in the factory, with optimal quality of finishing, will allow rapid assembly while minimizing any complications on the construction site (for example the thirty-story towers built in China in just two weeks).

The design of a building that is not only energy independent, but which also consumes less water and recycle most of its waste (Autonomous Building Concept® from Bouygues Construction) as well as whole housing estates sharing the production, storage and consumption of their energy mixes *via* smart electrical and thermal grids, are also among the goals set.

Finally, it is important to bring down construction and operating costs for the new generations of buildings, through the emergence of new economic models, in the same way as the picture was changed through the use of a battery for electric vehicles.



CEA/List

Figure 2.
The control software developed by the List. On the left, the various devices controlled by the software (heat pump PAC, electrical resistors R_elec, hot water tank, sanitary hot water demand Tirage_ECS, etc.), the energy resources (solar panels, etc.). On the right, a representation versus time of the values given to the system actuators (on, off, etc.).

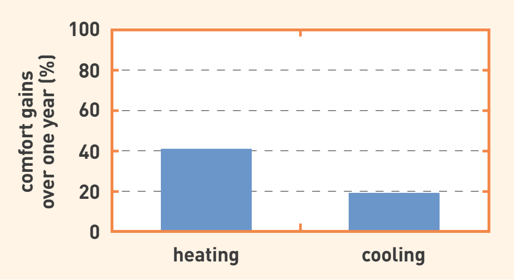


Figure 3.
Total comfort gains over one year resulting from the control software developed by the List.

> **Jean-Louis Six**[1], **Stéphanie Riché**[2] and **Frédéric Suard**[3]
[1] Liten Institute (Laboratory for Innovation in New Energy Technologies and Nanomaterials)
Technological Research Division
CEA Grenoble (Ines Site)

[2] Leti Institute (Laboratory of Electronics and Information Technologies)
Technological Research Division
CEA Grenoble Center

[3] List Institute (Laboratory of Integrated Systems and Technologies)
Technological Research Division
CEA Saclay Center


CEA

Prototype of a multi-function device performing heating, cooling, ventilation and sanitary hot water production functions. This prototype stands about 2 meters high and contains a wide range of instrumentation. It was used to validate the control algorithm. It was built as part of the AMMPERe project (Multi-function Device dedicated to Passive Homes and using Renewable Energies – *Appareil Multifonctions dédié aux Maisons Passives et utilisant les Énergies Renouvelables*) run by CEA/Ines, Groupe Atlantic and the Cetiat (Technical Center for the Air Flow and Thermal Industries).

---

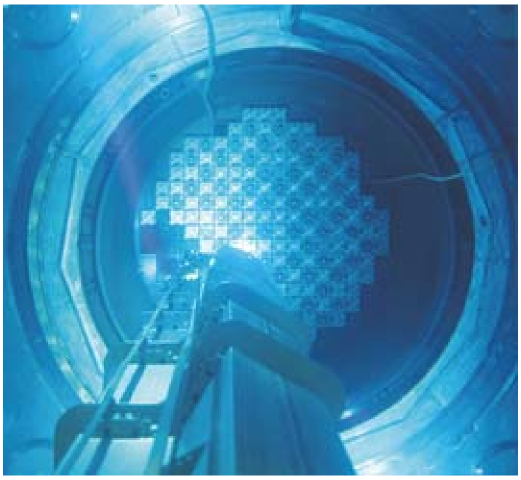
(8) Time constant: a material's response time to a sudden change in external temperature.

(9) Damping: absorption by a wall of a part of the thermal variations. It can attenuate the effect of heat waves or spells of extreme cold.

(10) Peak shift: offset in time between the temperature peaks outside and inside a building.

Using **nuclear heat** for **non-electric applications**

Whereas a large part of the primary energy consumed worldwide is in the form of heat, that generated by nuclear reactors is primarily used to produce electricity. Yet **nuclear heat offers a range of opportunities, whether in the fields of district heating, or water desalination, or synthesis of liquid fuels and hydrogen, as well as for industrial applications.** With a production not relying on fossil energies and which emits no greenhouse gases, the future looks promising.



Areva/C. Pauquet

Core of a nuclear reactor. In addition to being primarily used today to generate electricity, the heat produced by fission in the reactor core could meet a large percentage of the thermal energy needs, without having to resort to limited fossil fuel resources and without emitting greenhouse gases.

In France, nuclear energy is almost exclusively utilized to generate electricity. However, numerous other applications of this energy, taking directly advantage of the heat released by fission in the reactor core, could be envisaged. They fall into three temperature ranges, associated with three types of reactors.

Desalination Division/Bhabha Atomic Research Centre (BARC)

Set of reverse osmosis modules (right) in the nuclear desalination demonstration plant in Kalpakkam, India. The plan comprises a second system based on multi-flash evaporation. These installations, with a production capacity of 6.3 million liters of freshwater per day, are coupled to two Pressurized Heavy-Water Reactors (PHWRs) with a power of 170 MWe each.

The use of low-temperature heat (below 250 °C) could be envisaged with today's Light-Water Reactors. Two major applications are today implemented around the world: district heating and seawater desalination.

Medium temperature heat (between 200 °C and 500 °C) is required to generate the industrial steam needed for petrochemical processes such as hydrocarbon cracking or the extraction of oil sands(1). For these applications, the operating temperature range of Fast Reactors (FRs) would be ideal.

Finally, high-temperature reactors (operating above 500 °C), or even very high temperature reactors (above 800 °C) are required to produce synthetic fuels or hydrogen (H_2).

Water desalination

Freshwater is vital for humans, whether for drinking or for hygiene. In some countries, the supply of freshwater is a matter of survival and an increasing number of places around the world are suffering from water scarcity. The situation is liable to get even worse owing to the combined effect of growing populations, depletion of aquifers and climate change. One means of mitigating this shortage of freshwater lies in the desalination of seawater or brackish water.

The decade 2000-2010 saw a staggering increase in the number of desalination plants around the world (+ 160%), with more than 14,000 plants in operation, generating a total of 70 million cubic meter of freshwater per day. There is strong indication that this growth will accelerate even faster in the future.

The technologies employed are based, on the one hand, on water evaporation, using the multi-flash system(2) or distillation with or without vapor compression, and on the other, on reverse osmosis(3) filtration. Distillation requires both heat and electricity, whereas membrane separation only requires electricity.

Hydrocarbon cracking

An oil refinery uses industrial heat for its distillation processes and for hydrocarbon cracking. To do this, a significant fraction (between 6% and 12%) of the fuel produced is burned in a cogeneration unit in order to provide large quantities of water vapor at a temperature of around 350 °C. Furthermore, a fraction of the methane extracted is reused to synthesize the hydrogen needed for desulfurization of the refined liquid fuels. The significant own energy needs of the refinery could be almost entirely delivered using a dedicated nuclear reactor. For example, a single 600 MWe FR would be able to fulfill all the electricity, heat and hydrogen needs of the Total Petrochemicals France plant in Gonfreville-l'Orcher, Normandy. This would enable the plant owner not only to generate over one million extra ton of fuel per year but, at the same time, reduce the annual carbon dioxide (CO_2) emissions by 4 million tons.

Extraction of heavy oils

Some regions of the world contain very large reserves of oil sands. For example, the potential of the bitumen reserves in Alberta (Canada) is evaluated at 1,700 billion barrels(4), or the equivalent of 50 years of the world's consumption. Unfortunately, these heavy hydrocarbons are highly viscous and difficult to extract. One possible technique is to inject steam heated to 300 °C, at high pressure, into wells drilled into the soil, to liquefy the bitumen and make it extractable. This *in situ* extraction enables the bitumen and the sand to be separated in the same tank. As large quantities of water are required, a significant percentage of the extracted oil must be burned to obtain the quantity of steam necessary. In the end, the overall energy efficiency is relatively poor – it can be lower than 50% – and the environmental consequences are disastrous: the extraction of a single barrel of oil generates more than 80 kg of greenhouse gas (GHG). Here again, the use of nuclear heat would significantly improve extraction efficiency, with no GHG emissions.

District heating

District heating is one of the most promising outlets for industrial nuclear energy. It could become a reality simply by using the existing reactors in service.


Total

Total Petrochemicals France refinery and petrochemical plant in Gonfreville-l'Orcher (Normandy). The energy requirements (electricity, heat and hydrogen) needed to operate the site's installations could be covered by a single FR of 600 MWe.

For a long time, the geographical distance between the production site, the nuclear power plant, and the users, who are concentrated in the cities, was an obstacle to the development of this application. However, urban district heating networks have gradually become more widespread. In addition, improvements in heat piping technology means that heat can now be transported over very long distances, more than 100 km, with thermal losses of less than 2%. This really paves the way for large-scale nuclear cogeneration. For example, the Finns recently proposed supplying the city of Helsinki with electricity and heat by building a new nuclear power plant on the Loviisa site, 80 km from the capital.


CPCU

Pipes for heat transport on the cogeneration site of the *Compagnie parisienne de chauffage urbain* (CPCU) district heating plant at Vitry-sur-Seine (Val-de-Marne *département*). The site produces both electricity (125 MWe) and steam (400 tons per hour), *via* a turbine running on natural gas.

Hydrogen production

Hydrogen can be produced industrially by means of three processes: methane reforming(5), electrolysis of water or using thermochemical cycles. Other techniques exist or are currently under study, such as the biosynthesis of hydrogen from algae grown in bioreactors.

The most widely used (96%) and least expensive method is without doubt the reduction of steam at high temperature by a hydrocarbon – in this case methane – in the presence of a catalyst. Water electrolysis has the advantage of avoiding CO_2 emissions,

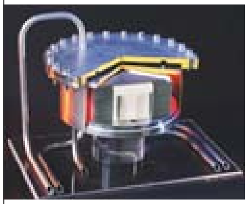
(1) Oil sands: mixture of bitumen, sand, clay and water.

(2) Multi-flash system: in this process, low-temperature heat (70 °C at entry into the plant) is used to heat water. This is then input into a sub-atmospheric pressure chamber in which immediate vaporization occurs (flash). The boiling point temperature of water decreases with the pressure. The steam is recovered in a condenser. The remaining water then passes through a 2nd chamber, at lower pressure. A second flash takes place, followed by further condensation, with passage through a 3rd chamber at even lower pressure, and so on in 7 to 10, or even more, consecutive chambers.

(3) Reverse osmosis: separation process consisting in forcing pressurized water through a semi-permeable membrane, which retains the salt and other impurities.

(4) Barrel: a barrel of oil is equivalent to 159 liters.

(5) Reforming: chemical cracking of a hydrocarbon or alcohol molecule to transform it into its major components. Methane reforming releases hydrogen and carbon monoxide.



P. Avavian/CEA

High-temperature electrolyzer for hydrogen production. The use of nuclear heat in the water electrolysis process would improve its energy efficiency and reduce its cost.

but it is achieved at the expense of a lower energy efficiency and a higher cost. Depending on the process, the total energy efficiency may vary between 30% and 65%. The performance of all of these processes can be enhanced upon the injection of heat delivered by a nuclear reactor, making a better final use of the carbon atoms and a reduction in CO_2 emissions.

When the hydrogen synthesized in this way is used as an energy carrier in **fuel cells** to supply electricity, the complete cycle is exactly equivalent to an electrical storage. However, in addition to the low efficiency and high cost of its production, the technological problems inherent in the storage of hydrogen (it is a gas, therefore with low density), its transport and its distribution, for the time being anyway, seriously compromise this energy conversion on a large scale.

Synthesis of biofuels

The gasification of carbonaceous substances (coal, gas, **biomass**) generates a synthetic gas (called Syngas), a mixture of carbon monoxide (CO) and hydrogen, which can be in turn used to produce liquid fuel by chemical **catalysis** (Fischer-Tropsch process). The generic term XTL (Coal To Liquid, Gas To Liquid or Biomass To Liquid) refers to those techniques used to manufacture synthetic fuels. The term biofuel is used when the initial organic compound is not **fossil**.

There are two tracks for agro-fuels derived from agricultural biomass: alcohol, which leads to the synthesis of **bioethanol** by fermentation of sugars from sugar or cereal crops (sugar cane, corn, wheat, etc.), and oil, which provides **biodiesel** by **transesterification** of the lipids from oleaginous plants (sunflower, rape-seed, oil palm, etc.). The transformation of the lignin and the **cellulose** found in plants (wood, straw, forestry waste) into either alcohol or synthetic gas prevents the conflicting issue of land use for energy instead of food production.

Nuclear energy could make a dual contribution to the production of biofuels. On the one hand, the heat from a high-temperature reactor could help with the pyrolysis or gasification reactions without having to burn hydrocarbons, thus reducing CO_2 emissions. On the other, the injection of additional hydrogen into the Syngas triggers a reverse reaction to that of water-gas shift(6) (Reverse Water-Gas Shift). By compensating for the hydrogen shortage in organic synthesis gas, we obtain the proper H_2/CO ratio (~ 2) in line with the final fuel molecule looked for.

Common but less advertised applications

In addition to heat, many other non-electric applications of nuclear energy are already commonly utilized by the public, without them being really aware of the fact. For example, we could mention the benefits of **radioisotope** production for medical uses, whether for diagnostic (imaging) or treatment (oncology) purposes, naval propulsion (and maybe space propulsion at some time in the future) or radioisotope thermoelectric generators, used as main energy sources for satellites into deep space far from the Solar system. Furthermore, thanks to the sensitivity of **radioactivity** detection techniques, radioactive elements are being increasingly widely used as **tracers** in numerous industrial and environmental applications. They are used to detect leaks, study the ageing of materials by erosion or by corrosion, check welds, determine the nature of soils or the configuration of fields/reserves. Tracing with **radionuclides** is also a technique being used in hydrogeology to monitor run-off and infiltration of surface water, the dynamics of air masses, or marine currents.

Nuclear cogeneration, an option for the future

Nuclear reactors today produce a significant share (75%) of the electricity generated in France and are already making a significant contribution to the reduction of GHG emissions. At the same time, large quantities of unused heat are dispersed and wasted into the environment. For a better energy management, it seems to be technically possible to recover some of this heat for non-electrical uses, thus making maximum use of the primary energy supplied by fission. In the future, nuclear cogeneration will naturally assume an increasingly important role.

> **Henri Safa**
Scientific Division
Nuclear Energy Division
CEA Saclay Center

P. Avavian/CEA

High Temperature Fluidized Bed (HTFB), for the production of synthesis gas from biomass, located in the CEA Grenoble Center. An input of nuclear heat would help with gasification without consuming hydrocarbons.

---

(6) Reaction of water-gas shift: chemical reaction leading to the synthesis of carbon dioxide and hydrogen from carbon monoxide and water.

Institutions and organizations: who does what?

Act of 30 December 1991: also called the "Bataille Act", from the name of the author of the accompanying parliamentary report, this Act has set the framework, for 15 years, in France, for research work on the management of long-lived high or intermediate level radioactive waste, conducted along three directions (partitioning-transmutation, disposal and storage).

Act of 28 June 2006: the Act setting out the program for sustainable management of radioactive materials and waste in France. It organizes continued research on the management of long-lived high or intermediate level radioactive waste, setting the following milestones: after an evaluation of the industrial prospects for the partitioning-transmutation pathways in 2012, deployment of a prototype facility to be commissioned before the end of 2020, selection of a reversible deep geological disposal site to be put into operation by 2025 and, no later than 2015, creation of new storage facilities.

Ademe (Agence de l'environnement et de la maîtrise de l'énergie): the French Environment and Energy Management Agency is funding research carried out in other organizations and technical developments in the regions. As a public-sector establishment of industrial and commercial character, it is primarily involved in research and forward-looking studies, expert appraisal and consulting, as well as information and promotion.

AFHYPAC (Association française pour l'hydrogène et les piles à combustible): French Association for Hydrogen and Fuel Cells, whose goal is to promote hydrogen-related technologies, from hydrogen production to its utilization, and fuel cell-related technologies.

Ancre (Alliance nationale de coordination de la recherche pour l'énergie): the French National Alliance for Energy Research Coordination was created on 17th July 2009, with the aim of boosting the efficiency of French research in the energy field, by promoting partnerships and synergy between public and private players in the sector. In addition to its four founding members, CEA, **CNRS**, IFPEN (*IFP Énergies nouvelles*) and CPU (*Conférence des présidents d'université*), Ancre is a forum for all French public research organizations concerned by energy-related issues.

Andra (Agence nationale pour la gestion des déchets radioactifs): the French National Radioactive Waste Management Agency was created in 1979 and became a public-sector establishment of industrial and commercial character under the terms of the **Act of 30 December 1991**. Its role is the long-term management of the radioactive waste produced in France, for which it makes its expertise and its know-how available to the French Government for identifying, implementing and guaranteeing safe management solutions for all French radioactive waste, in order to protect present and future generations from the risk posed by this waste.

ANR (Agence nationale de la recherche): the French National Research Agency is a public-sector establishment of administrative character (created in 2005 in the form of a public interest grouping) tasked with financing research projects selected on the basis of scientific quality and economic pertinence criteria.

Areva: a French industrial group created in 2001 through the merger of CEA-Industrie, Cogema and Framatome. Its role is to manage all industrial and commercial activities, in particular in the nuclear, renewable energies, electricity transmission and distribution fields. Its subsidiaries include **Areva NP** (Nuclear Power) – formerly Framatome ANP – the world leader in the design and construction of nuclear reactors, the supply of fuel and maintenance and modernization services; **Areva TA** – formerly Technicatome – specializing in research reactors and nuclear propulsion systems; **Areva NC** (Nuclear Cycle) – formerly Cogema – which covers all the services linked to the fuel cycle.

ASN (Autorité de sûreté nucléaire): the French Nuclear Safety Authority is an independent administrative authority responsible for technical and regulatory control of nuclear safety and radioprotection in France. It performs this task in the name of the French Government to protect the public, workers, patients and the environment from the risks linked to civil nuclear activities, and contributes to information of the public.

ASND (Autorité de sûreté nucléaire de défense): the French Nuclear Safety Authority for Defense is tasked with technical and regulatory control of nuclear safety and radioprotection in France in the fields of defense-related nuclear facilities and activities.

Climate and Energy Package: a European Union (EU) action plan presented in January 2008 by the **European Commission** and adopted in December 2008, aiming to implement a common energy policy and combat climate change. It set three targets to be met by the EU, by 2020 (3 x 20): 20% reduction in greenhouse gas emissions by comparison with the 1990 levels, 20% improvement in energy efficiency and a 20% renewable energies share in energy consumption.

CNRS (Centre national de la recherche scientifique): the French National Center for Scientific Research is a public-sector establishment of scientific and technological character, carrying out its activity in all fields of research (34,000 personnel, including 25,500 permanent staff).

CRE (Commission de régulation de l'énergie): the French Energy Regulation Commission is an independent administrative authority created on the occasion of deregulation of the energy markets. Under the terms of the Act of 10 February 2000 on the modernization and development of the public electricity service, it is tasked with ensuring the correct functioning of the electricity and natural gas markets in France, to the benefit of the end-consumer and consistently with energy policy goals.

DoE (US Department of Energy): American ministry of energy. Its mission is to ensure America's security and prosperity by addressing its energy, environmental and nuclear challenges through transformative science and technology solutions.

EDF: as the leading energy group built around *Électricité de France*, EDF is present in all segments of the electric power industry, from production to trading and grids, as well as in the natural gas industry. With a network of European subsidiaries and companies established worldwide, EDF provides energy and services for 37.7 million customers around the world.

ENSREG (European Nuclear Safety Regulators Group): created in 2007 at the initiative of the **European Commission**, ENSREG is an independent authoritative expert body, composed of senior officials from national regulatory or nuclear safety authorities from all 27 member States in the European Union. The fundamental principle of its work is that there should be continuous improvement in nuclear safety. It also aims to develop a common understanding among European nuclear safety regulators concerning the safety of nuclear facilities, and spent fuel and radioactive waste management.

EPIA (European Photovoltaic Industry Association): a European socio-professional organization for promoting the photovoltaic industry. Its headquarters are in Brussels (Belgium).

ERDF (Électricité réseau distribution France): as a wholly-owned subsidiary of **EDF**, ERDF is tasked with managing the public electricity distribution grid covering 95% of continental French territory. It is responsible for the operation, maintenance and development of nearly 1.3 million km of grid.

Euratom: European atomic energy community created in 1957 by the treaty of the same name. Its role is to contribute to the development of nuclear activities for peaceful purposes and to perform control of these activities in the member States of the European Union.

European Commission: this executive body of the European Union manages the implementation of the regulations and directives adopted by the **Council**, may call on the Court of Justice and has a monopoly on legislative initiatives. It enjoys extensive powers for running common policies, including in the field of research and technology, where its main instrument is the Framework Program for Research and Technological Development (PCRD).

European Council: summit of the heads of State or Government of the 27 member countries of the European Union. The European Council defines orientations and general policy priorities for the European Union. It meets at least twice every six months.

Foundation on Economic Trends (FOET): a non-profit organization created in 1977 by the Americans Jeremy Rifkin and Ted Howard, which is active in both national and international public policy issues related to the environment, the economy, and climate change. The FOET examines emerging trends in science and technology, and their likely impacts on the environment, the economy, culture and society.

FUI (Fonds unique interministériel): the French Single Interministerial Fund finances collaborative R&D projects run by the competitiveness clusters. Its role is to support applied research projects involving the development of products or services liable to reach the market in the short or medium term.

Generation IV International Forum (GIF): an intergovernmental association launched in 2000 at the initiative of the DoE. Its 13 members to date (Argentina, Brazil, Canada, China, Euratom, France, Japan, Russia, South Africa, South Korea, Switzerland, United Kingdom, United States) are carrying out research on a new generation of nuclear systems affording improved qualities in terms of economics, safety, waste minimization and proliferation resistance.

Genoscope: created in 1997, the Genoscope – the National Sequencing Center (*Centre national de séquençage*) – has formed since 2007, together with the National Genotyping Center (CNG: *Centre national de génotypage*), the Genome Institute in the Évry Genopole (Essonne *département*), linked to the CEA Life Sciences Division. The role of this major infrastructure is the large-scale sequencing and analysis of genetic information of various organisms of scientific, medical or economic interest. It is a key player in the sequencing of the human genome and is today focusing on environmental genomics.

Grenelle Environment Summit: a number of meetings which took place in France from July to September 2007, involving the State, the local authorities, NGOs, employers and employees, in order to define a roadmap for ecology and sustainable development and planning. They were followed by a public consultation phase from late September to mid-October. The undertakings made at the Grenelle Environment Summit are enshrined in the Grenelle 1 Act of 3 August 2009 and the Grenelle 2 Act of 12 July 2010.

IAEA (International Atomic Energy Agency): an intergovernmental agency which, under the aegis of the United Nations, works towards the peaceful use of nuclear power and compliance with the Non-Proliferation Treaty.

IBS (Institut de biologie structurale): the Institute of Structural Biology is a joint CEA/Life Sciences Division-CNRS-University Joseph Fourier Grenoble 1 research unit; its role is to develop research into the structural and functional biology of biological macromolecules, in particular proteins.

ICSM (Institut de chimie séparative de Marcoule): the Marcoule Institute for Separative Chemistry is a joint research unit involving CEA (Nuclear Energy Division and Physical Sciences Division)-CNRS-University of Montpellier 2-ENSCM (Montpellier National School of Chemistry – *École nationale supérieure de chimie de Montpellier*). The ICSM conducts nanometric-scale studies of interfaces in extreme conditions, in order to understand the mechanisms underpinning separation phenomena in complex fluids and nuclear materials, with a view to sustainable development. Its goal is the emergence of innovative processes and materials in the field of separative chemistry, particularly for the fuel cycle of the generation IV nuclear reactors.

IEA (International Energy Agency): an independent agency of the OECD which works for the production of clean, safe and accessible energy for its 28 member countries as well as for non-member countries.

Ineris (Institut national de l'environnement industriel et des risques): the French National Institute for Industrial Environment and Risks was created in 1990 and is a public-sector establishment of industrial and commercial character under the control of the Ministry of Ecology, Sustainable Development and Energy. Its focus is the prevention of the risks that economic activities pose for health, for the safety of individuals and property, and for the environment.

Ines (Institut national de l'énergie solaire): the French National Solar Energy Institute includes teams from the CEA, CNRS, University of Savoie and CSTB (French Scientific and Technical Center for Building). This center of reference in the field of solar energy, set up with the backing of the Savoie General Council and the Rhône-Alpes Regional Council, is located at Savoie Technolac on the shores of Lake Bourget (Savoie *département*).

Institut des Matériaux Jean Rouxel: this CNRS-University of Nantes joint unit is active in the production, physical properties characterization and modeling of materials. It brings together chemists, physicists and specialists in plasmas and thin films.

ITER (International Thermonuclear Experimental Reactor): the aim of this very large-scale scientific experiment is, as of 2026, to demonstrate the scientific and technological feasibility of magnetic confinement fusion energy. ITER, which is currently under construction, is situated next to the CEA Cadarache Center (Bouches-du-Rhône *département*). During its operational phase, this tokamak will test the fundamental technologies needed to move onto the next stage: a demonstration fusion reactor capable of producing energy for commercial purposes.

MAScIR (Moroccan foundation for Advanced Science, Innovation and Research): a Moroccan public institution whose mission is to promote R&D in the fields of environment, energy, health and valorization of Moroccan natural resources.

MINATEC: based in Grenoble, MINATEC is the first European campus for innovation in the micro and nanotechnologies. Through a policy of dynamic collaborative work, it comprises 2,400 researchers, 1,200 students, and 600 business and technology transfer experts, occupying 20 hectares and enjoying access to exceptional infrastructures.

OECD (Organization for Economic Cooperation and Development): the aim of this organization, which comprises 34 of the most industrialized nations, is to promote policies to achieve the greatest possible growth of the economy, of employment and of living standards in the member countries, while maintaining financial stability and thus contributing to the development of the world's economy and trade on a multilateral basis.

Programme d'investissements d'avenir (PIA): the Investing in the Future Program is financed by the major national loan launched on the financial markets in 2010 and is worth 35 billion Euros. It aims to modernize and boost the competitiveness of France, by promoting investment and innovation in five priority sectors: higher education and training, research, industrial sectors and SMEs, sustainable development and the digital sector.

Réseau national de recherche et technologie sur les batteries: the Research and Technology National Network on Batteries was created in 2010 and combines public research – CEA, CNRS, universities, IFPEN (*IFP Énergies nouvelles*), Ineris, Inrets which has now become IFSTTAR (French Institute of Science and Technology for Transport, Development and Networks) – and industry. It is built around an upstream research center, coordinated by the CNRS, whose role is to explore new battery concepts and high-performance materials, along with a technological research center, run by CEA, which tests and validates these new concepts.

Rosatom: set up in 2004, the Russian Federal Atomic Energy Agency became, in late 2007, the State Atomic Energy Corporation "Rosatom". Its role is to implement Government policy, provide integrated control over the use of atomic energy, ensure stable operation of civil and defense nuclear facilities, take care of nuclear and radiation safety. It is also responsible for fulfilling the international commitments of Russia on the peaceful use of atomic energy and non-proliferation.

RTE (Réseau de transport d'électricité): the French Electricity Transmission System Operator is a wholly-owned subsidiary of EDF and is the manager of the French electricity transmission grid. The role of this public service company is to operate, maintain and develop the high and very high voltage grid.

Glossary

A

actinides: natural and/or artificial radioelements with an atomic number between 89 (actinium) and 103 (lawrencium); major actinides: heavy nuclei of uranium and plutonium present or formed in nuclear fuel; minor actinides: heavy nuclei formed in relatively small quantities in a reactor through successive neutron captures by fuel nuclei. These are primarily neptunium, americium and curium.

activation: the process whereby certain initially stable nuclides, in particular within the structural materials of reactors and fuel elements, are made radioactive through bombardment by neutrons (neutronic activation) or other particles.

activity: the number of disintegrations per unit of time within a radionuclide or a mixture of radionuclides, expressed in becquerels (Bq). High-level activity can reach several billion becquerels per gram.

adiabatic: refers to transformations which take place with no heat exchange with the outside.

adsorption: binding of atoms or of a vapor or liquid phase to the surface of a solid medium.

algorithm: the sequence of logical mathematical operations necessary to perform a calculation.

alkali metals: the metals belonging to the IA group (column 1) of the periodic table of elements (lithium, sodium, potassium, rubidium, cesium and francium).

alkaline earth metals: the metals belonging to the IIA group (column 2) of the periodic table of elements (beryllium, magnesium, calcium, strontium, barium and radium).

alkanes: saturated hydrocarbons of formula C_nH_{2n+2} for the non-cyclic versions (linear or ramified) and C_nH_{2n} for the cyclic versions. n-hexane is a non-cyclic alkane of formula C_6H_{14}.

amino acid: an organic molecule that is the basis of proteins containing an amine group (NH_2) and a carboxyl group (COOH). In an α-amino acid, the amine group and the carboxyl group are bound to the same carbon atom.

anaerobic: which develops or functions in the total absence of oxygen.

angström (Å): 1 Å = 10^{-10} meter.

assembly (fuel): an array of fuel elements loaded together into a nuclear reactor.

atomic number: the number of protons in the nucleus of an element.

B

bacterium: a living microorganism, generally single-cell, without a nucleus (prokaryote) and multiplying rapidly, typically measuring between 0.2 and 2 micrometers.

bar: unit of pressure; 1 bar = 10^5 pascals (legal unit Pa).

battery: an assembly of cells. The assemblies of cells can also be called modules, when the unit voltage is within the SELV range (Safety Extra-Low Voltage < 50 V). The battery packs installed in electric vehicles consist of an assembly of modules.

becquerel (Bq): a unit, named after French physicist Henri Becquerel, of measurement of nuclear activity (1 Bq = 1 atomic nucleus disintegration per second).

biodiesel: diesel obtained from plant biomass (oleaginous crop plants [1st generation], forestry residues, agricultural waste [2nd generation], microalgae [3rd generation]).

bioethanol: ethanol obtained from sugar crops (beetroot, sugar cane, etc.) or cereals (wheat, corn, etc.) [1st generation bioethanol], from forestry residues and agricultural waste [2nd generation bioethanol], from microalgae or cyanobacteria [3rd generation bioethanol].

biokerosene: kerosene obtained from biomass.

biomass: the mass of living matter, more than 99% vegetable, present on the surface of the Earth.

bitumen: an organic matter that is either natural or produced by distillation of petroleum oil, consisting of a mixture of hydrocarbons, highly viscous and even sometimes solid at ambient temperature, black in color. It is used in the composition of asphalt.

Boiling Water Reactor (BWR): a type of nuclear reactor in which water boils directly inside the core.

breakeven (point): a point of energy equilibrium of a plasma, where the power produced by the fusion reactions within the plasma is equal to the power input to maintain the configuration and heat the plasma.

breeder: a nuclear reactor which, from fertile material, produces more fissile material than it consumes.

burn-up fraction: the ratio, normally expressed as a percentage, of the number of atomic nuclei of an element or set of given elements, which disappear by fission, to the number of nuclei initially present in the fuel. It is then expressed in at.%. It is commonly used to assess *specific burn-up, i.e.* the quantity of thermal energy per unit mass of fuel obtained in the reactor from fuel loading to discharge (*mass burn-up*); it is then expressed in megawatt·days per ton (MW·d/t) or in gigawatt·days per ton (GW·d/t).

C

capacity (of a battery): quantity of electricity stored: charge stored. It is expressed in ampere·hours (A·h).

carbon fiber: a material consisting of extremely fine fibers (from 5 to 15 microns in diameter), primarily made up of carbon atoms. These are agglomerated into microscopic crystals aligned more or less parallel to the longitudinal axis of the fiber, making it very strong. Several thousand fibers are wound together to form a thread, which can be used as-is or woven.

catalysis: a process involving a substance (the catalyst) capable of accelerating a chemical reaction. In principle, the catalyst is not consumed and is restored at the end of the reaction.

cathode (of a television set): in a cathode ray tube, the cathode is the electrode which, when heated, emits electrons. These are then accelerated by the electrical field between this cathode and the anode. They strike the screen onto which a light-emitting layer is deposited and which reacts to the impacts from the electrons, thus creating a dot of light.

cell (photovoltaic): the basic unit for direct conversion of light energy from the Sun's rays into electricity, *via* the production and transport in a semiconducting material of positive and negative electrical charges.

cell: a device for storing electrical energy in chemical form. It is based on a reversible electrochemical system, in other words, it is rechargeable.

cellulose: the main component plant cell walls. It is a linear polymer of formula $(C_6H_{10}O_5)_n$ consisting of glucose units.

chain reaction: a sequence of nuclear fissions during which the neutrons released cause further fissions, which in turn generate new neutrons causing further fissions, and so on.

cliff-edge effect: in terms of nuclear safety, designates the sudden change in the behavior of a facility, which can be generated by only a slight change in an envisaged accident scenario, the consequences of which are then made significantly worse.

closed cycle (fuel): the cycle is said to be "closed" when the spent fuel is reprocessed for recycling, otherwise it is "once through" or "open".

cogeneration: the use of thermal energy from a boiler (for example a nuclear reactor) for several applications, such as simultaneous production of electricity and heat.

complex: an edifice consisting of a central metal ion to which other ions or molecules, called ligands, then bind.

conditioning (of radioactive waste): the ensemble of successive operations that must be carried out in order to turn waste into a stable, safe form, allowing its subsequent management, whether it be by way of storage, transmutation or disposal. These operations may include, in particular, compaction, encapsulation, melting, vitrification and containerization.

convection: movements generated in a fluid owing to differences in density and temperature at various locations. Natural convection is the automatic transport of heat by this circulation, while forced convection involves mechanisms, such as pumps.

conversion efficiency (of a photovoltaic cell): the ratio between the electrical energy produced by a photovoltaic cell and the light energy received on the corresponding surface.

coolant: a fluid (gas or liquid) used to extract the heat produced by fission processes in a nuclear reactor.

coordination: bonds established by an ion with electron-donor atoms. The *coordination number* is the number of bonds an ion is capable of making with such atoms.

covalent bond: a bond established when two atoms, in order to saturate their last orbit, share one or more electron pairs. Covalent bonds are generally the strongest and most stable.

cracking: a modification of the molecular structure of a hydrocarbon under the effect of heat, pressure and sometimes a catalyst.

cryogenics: literally "producing cold"; by extension "related to low temperatures" (the boiling point of cryogenic liquids is lower than – 150 °C).

current density: in a battery or in a supercapacitor, current output per unit surface of electrode (A/cm^2).

CVD (Chemical Vapor Deposition): a method for preparation of layers (with a thickness that can vary from a few tens of nanometers to about a hundred micrometers) by vapor phase deposition formed by a chemical reaction from a gaseous medium of different composition.

cyanobacteria (from the Greek *kuanos*, dark blue): bacteria capable of transforming light energy by oxygen-based photosynthesis (in the same way as plants). Cyanobacteria today live more or less everywhere, in the oceans, in freshwater and also on land.

cyclability: expressed as a number of cycles, it characterizes the number of times that an electrochemical generator can restore a charge higher than a defined threshold (generally 80% of the initial capacity). It depends to a large extent on the type of loadings and the positioning of this threshold.

cycle (of a battery): corresponds to the succession of a charge and a discharge.

cycling: alternating charge and discharge.

D

decay heat: the heat given off by a nuclear reactor that has been shut down or by a fuel assembly. It is mainly produced by residual fissions, the disintegration of actinides and fission and activation products contained in the fuel and the structural materials. At the moment of shutdown (dropping of the control rods), its level is of a few tens of percent of the *nominal power* and it then decreases very quickly.

demixing: a phenomenon involving the micro-separation of phases of different compositions in a mixture or an alloy, when a compound in solution in the mixture exceeds its solubility limit.

deuterium (D): one of the two "heavy" isotopes of hydrogen. Its nucleus comprises one proton and one neutron.

diesel: a colorless to yellow liquid fuel produced by refining oil. It is practically insoluble in water and its auto-ignition temperature is up to 220 °C.

dimethyl-ether (DME): a chemical compound of formula $CH_3–O–CH_3$ occurring in liquid state at 20 °C at a pressure of 5.3 bar.

discount rate (of a project): an economic rate, in part comparable to an interest rate, which reflects the value of time – and sometimes includes the risk – for an economic evaluation of a project taking place over several years. Typically, public rates are about 5% and private rates about 10% in European countries (these rates are presented here exclusive of inflation: they are thus referred to as "real" rates, as opposed to "nominal" rates).

disposal (of radioactive waste): the operation consisting in placing radioactive waste in a facility specifically engineered to hold it on a possibly final basis. This term also refers to the facility in which the waste is placed (disposal repository), with no plans for subsequent recovery. Recovery would however remain possible in a reversible disposal facility (see also storage). The deep geological disposal of radioactive waste involves disposal of these substances in an underground facility specially designed for this purpose.

DNA: DeoxyriboNucleic Acid, carrying genetic information within the living cell.

E

electrical charge (of a battery): the quantity of electricity that a battery can carry during its utilization. It is measured in ampere·hours (A·h).

electrochemical impedance spectroscopy: its principle is based on the application of a small sine voltage (disturbance) superposed over the rated voltage and on the analysis of the amplitude and phase shift of the response current. It provides information about the reactional mechanisms taking place at the electrode/electrolyte interface.

electrode: a conducting element which uses an electric field to emit, capture or guide electrons or ions. When placed in a medium (electrolyte, etc.), electrodes can be divided into cathodes and anodes depending on whether they supply electrons to the external medium or receive them. The anode is where an electrochemical oxidation reaction occurs, while the cathode is where an electrochemical reduction reaction takes place. In a disposable battery or a rechargeable cell, there is a positive electrode and a negative electrode.

electrolysis: the use of electric current passing through an electrolyte placed between two electrodes to perform a chemical reaction. In the specific case of electrolysis of water, the electric current breaks the water down into oxygen and hydrogen, given off at the two electrodes.

electrolyte: a liquid or solid medium allowing the conduction of the electric current *via* the displacement of the ions it contains.

electrolyzer: an electrochemical device used to perform electrolysis, for example that of water, through the use of an electric current which breaks the water down into oxygen and hydrogen.

electron tomography: an imaging technique used to obtain a 3D representation of an object. If specific, high-performance electron microscopes are used, resolution of a few nanometers is possible.

energy output (by a cell): expressed in watt-hours (Wh), it corresponds to the product of the current (in amperes A) by the voltage (in volts V) integrated over the discharge duration (in hours h).

enriched uranium: uranium in which the isotope 235 content has been raised from its naturally low level (0.71% by mass) to, for example, 3.5% in fuel intended for use in a pressurized water reactor.

enrichment: the process designed to increase the content of one of the isotopes of an element.

entropy: a quantity, expressed in joules per kelvin, the change in which is equal to the heat input to a system by a reversible process and at a constant temperature, divided by this temperature. Entropy measures the degree of disorder of a system.

enzyme: a molecule used to lower the activation energy of a reaction and to accelerate up to several million times the chemical reactions of the metabolism taking place in the cellular or extra-cellular environment, without modifying the resulting equilibrium; these proteins are the catalysts of the living world.

EPR: a third generation pressurized water reactor (PWR) concept, developed by Areva NP and designed to offer optimal safety, durability, performance and competitiveness.

ethanol: an alcohol of chemical formula C_2H_5OH derived from ethane (C_2H_6), a gaseous hydrocarbon.

F

Fast Neutron Reactor (FNR): a nuclear reactor without moderator in which most of the fissions are caused by neutrons with energy levels of the same order of magnitude as that they have when produced by fission.

fast neutrons: neutrons released during fission, traveling at very high speed (20,000 km/s). Their energy is about 2 MeV.

fertile: refers to a nuclide whose nucleus can be directly or indirectly transformed into a fissile nucleus by neutron capture.

fissile: refers to a nuclide whose nucleus is liable to undergo fission through neutron absorption. Strictly speaking, it is not the nucleus referred to as fissile that undergoes fission, but the nucleus formed following a neutron capture.

fission: the splitting of a heavy nucleus, generally into two fragments, accompanied by the emission of neutrons, radiation and a significant release of heat.

fission products: nuclides generated either directly by nuclear fission, or indirectly by the disintegration of fragments of the fission. They may be gaseous (fission gases) or solid (volatile or otherwise).

formaldehyde: of chemical formula CH_2O, it takes the form of a gas at ambient temperature. It is highly soluble in water (the solution is called formol). It is present in numerous products such as paints, wallpaper, detergents, glues, softeners, adhesives, forest fires, tobacco smoke. It is even produced in small quantities by the human body. It is classified as "carcinogenic to humans", and is the cause of nasopharyngeal cancers.

fossil: a hydrocarbon fuel, such as coal, oil or natural gas, extracted from fields formed by the accumulation and transformation of organic matter. Also refers to the energies derived from it.

fuel (nuclear): a fissile material which, by means of an appropriate geometry, enables a chain reaction to be sustained within the core of a reactor; spent fuel: fuel which is no longer able to sustain the nuclear reaction and is removed from the reactor.

fuel cell: a cell in which electricity is produced by the oxidation on an electrode of a reducing fuel (for example hydrogen) coupled with the reduction on the other electrode of an oxidant, such as oxygen. Conventional cells (H_2/O_2) are supplied with hydrogen and produce water.

G

gene: a sequence of DNA on a chromosome constituting a unit of hereditary information which allows the creation of a phenotypic character (apparent character of an individual) *via* the production of one or more proteins.

generation IV nuclear reactors: a new generation of nuclear energy systems currently being investigated on an international basis, and affording, at the same time, improved qualities in terms of economics, safety, waste minimization and proliferation resistance, compared to the reactors now in service, or under construction. Six reactor lines, most of them involving a closed fuel cycle and using fast neutrons, have been selected for further in-depth study, these lines differing in terms of the coolant used: sodium, lead, supercritical water, gas (helium) or molten salts.

genome: all the genetic material of a living organism.

H

half-life (radioactive): the time after which one half of the radioactive atoms initially present in a sample of the radioactive nuclide has disappeared through natural radioactive disintegration.

heliostat: a flat and mobile mirror. It follows the path of the Sun and concentrates its rays towards a single point.

higher plants: photosynthetic organisms characterized by the existence of roots and the presence of vessels through which the sap circulates. They in particular include seed plants, flowering plants, ferns, etc.

home automation: a field of research defined by a range of electronics, information and telecommunication technologies used in service and residential buildings. The purpose of these technologies is to improve the life of the occupants of a house by increasing comfort and making it easier to manage energy consumption in the building.

homologous recombination: genetic recombination between two identical sequences situated on two different DNA molecules, or which are distant from each other on the same molecule.

hybrid vehicle: a vehicle which associates several energy generation modes. The currently preferred formula (series hybridization) combines an internal combustion engine and a battery supplying an electric drive train; the first, which operates at constant speed and thus at optimum efficiency, recharges the battery which absorbs the current peaks and recovers braking energy. There is also a "2 motor" version, one electric and one thermal, which can provide drive power either separately or together. They "share" the maximum power while each operating in their optimum conditions, as well as being able to recover braking energy. Another formula is to associate a battery and a fuel cell.

hydrocarbon: a molecule consisting only of carbon and hydrogen.

hydrocracking: a process which consists in breaking a complex organic molecule (for example a long carbon chain) into smaller molecules (diesel, kerosene, naphtha) under the effect of heat, of pressure and by injecting hydrogen to "hydrogenate" the unsaturated molecules. This operation is carried out in the presence of a catalyst.

hydrolysis: the breakdown of a chemical species (molecule or ion) by water. For example, the breakdown of an aqueous solution of sodium borohydride produces hydrogen according to the following reaction: $NaBH_4 + 2\ H_2O \rightarrow NaBO_2 + 4\ H_2$.

hydrometallurgical (processes): in the reprocessing of spent fuels, the hydrometallurgical path involves its dissolution in an acid medium and the use of liquid-liquid extraction processes.

hydrophobic: which repels water.

hyperbaric (storage): at a pressure far higher than atmospheric pressure.

I

ignition: self-sustaining of the temperature of the plasma within a thermonuclear fusion machine at a sufficient level for the reactions to continue without interruption.

inertial confinement fusion: this process is based on the use of powerful lasers to compress and heat microballs containing a deuterium-tritium mixture, thus placing them in the density and temperature conditions needed to start and sustain thermonuclear fusion reactions.

inverter: used to transform the direct current produced by photovoltaic panels or by other devices into alternating current to supply loads or so that it can be input into the electrical grid.

ionic bond: a bond characterized by the *transfer* of electrons from one atom to another, but without *sharing* as in a covalent bond.

ionic strength: the sum of the concentrations of all the ionic species present in a solution.

irradiation cycle (in-reactor): the time interval over which a nuclear reactor is operated, between two successive loadings (whether partial or otherwise) with nuclear fuel.

isotopes: forms of a given chemical element, the nuclei of which have an identical number of protons (as well as an identical number of electrons orbiting the nucleus) but a different number of neutrons.

J

Joule effect: the release of heat due to the resistance exhibited by a conductor to the passage of an electric current.

K

kerosene: a mixture of hydrocarbons containing alkanes ($C_nH_{2n}+_2$) of chemical formula ranging from $C_{10}H_{22}$ to $C_{14}H_{30}$. It is mainly used to produce aviation fuel.

L

lanthanides: the family of elements with an atomic number between 57 (lanthanum) and 71 (lutetium).

ligand: an organic molecule which can be fixed by a coordination bond to an ion within a coordination complex.

Light-Emitting Diode (LED): an opto-electronic component capable of emitting light when an electric current passes through it: the emission of a photon is linked to the recombination of an electron and a hole in a semiconductor. The associated basic process is the opposite of that at work in a photovoltaic cell.

Light-Water Reactors (LWRs): a family of nuclear reactors in which ordinary water acts as the coolant and the moderator. The LWR family includes Pressurized Water Reactors (PWRs) and Boiling Water Reactors (BWRs).

M

magnetic confinement fusion: see tokamak.

magnetic tunnel junction: a nanostructure consisting of two thin magnetic films separated by a tunnel barrier (a thin film of oxide). Its electrical resistance depends on the relative directions of the magnetization of the two thin films. The use of these elements in a synchronous flip-flop makes it non-volatile: the magnetization of the thin films remains even when there is no further electrical power supply. It is then possible to cut the power to the circuit when it is inactive, without losing the information.

mass or **volume power densities:** energy per unit of time (power) that can be output by the unit of mass (W/kg) or volume (W/L) of a cell or a supercapacitor.

metabolism: the set of molecular and energetic transformations which continuously take place in the cell or living organism.

metallic bond: a chemical bond allowing the cohesion of the atoms of a metal. It concerns a very large number of atoms (typically several million) which share free electrons ensuring electrical conduction within a metal object.

methane: as a hydrocarbon of general formula CH_4, methane is the main component of natural gas and of biogas resulting from the fermentation of animal or vegetable organic matter. It is given off naturally in wet zones with little oxygenation such as marshes and flooded land. It also forms in the stomachs of ruminants.

micro: prefix μ for one millionth (10^{-6}). 1 micrometer (μm) or micron = 10^{-6} meter.

module or **panel (photovoltaic):** an electric generator of direct current, consisting of an assembly of electrically interconnected photovoltaic cells.

Mtoe: million tons oil equivalent. 1 toe = 42 billion joules or 11,630 kWh.

mutation (genetic): a transmissible alteration of the genetic message by modification of a sequence of DNA nucleotides.

N

nano: prefix n for one billionth (10^{-9}); 1 nanometer (nm) = 10^{-9} meter.

naphtha: a transparent liquid resulting from the distillation of oil. Depending on the distillation temperature range, light naphtha or heavy naphtha is produced. One of the uses of light naphtha is as a basis in the composition of gasolines. Synthetic naphtha can be obtained from forestry waste and agricultural residues.

Net Calorific Value (NCV): the amount of heat given off by the complete combustion, at constant pressure, of a normal cubic meter of gas, the water yielded being in the form of steam. The energy of the steam is not recovered.

noble metals: historically, precious metals that are unaltered by air or water (silver, gold, platinum), used in jewel-making. This term now applies to other metals which are scarce in the Earth's crust and which are thus also costly (palladium, rhodium, iridium, osmium and ruthenium).

normal cubic meter: 1 normal cubic meter (Nm^3) of gas is a cubic meter taken at 0 °C at a pressure of 101,325 Pa (1 atmosphere).

nuclear glass: a mineral matrix used for confinement of high-activity nuclear waste. Glass exhibits the structure of a frozen liquid, in other words a short-range order and an absence of intermediate-range order, which enables it to accommodate most of the fission products and minor actinides resulting from the reprocessing of spent fuels.

nucleotide: a basic unit of nucleic acids (DNA and RiboNucleic Acid RNA), consisting of a *purine base* (adenine, guanine for example) or a *pyrimidine base* (cytosine, thymine for example), a sugar and one or more phosphate groups.

nuclide: a nuclear species characterized by its number of protons Z (atomic number), its number of neutrons N and its mass number A, equal to the sum of the number of protons and the number of neutrons ($A = Z + N$).

nutraceutic: an active substance present in the natural state in a food and which has a beneficial effect on health.

O

oxidation: a reaction during which an atom or an ion loses electrons. The most common is that in which a compound combines with one or more oxygen atoms, thus forming an oxide; **oxidant:** which causes an atom or an ion to lose electrons.

P

panel (photovoltaic): see module.

passive (systems): systems based on natural forces such as convection and gravity, which make the safety of an installation theoretically less dependent on active systems (pumps, motors, etc.).

peak power (of a photovoltaic module): the maximum electrical power output by a photovoltaic module for "standard" sunshine of 1,000 W/m^2 and a temperature of 25 °C.

pH: a measurement of the concentration in hydrogen ions in a liquid. In pure water, below 7 it is acid and above 7 it is basic (or alkaline).

Phénix: an experimental reactor, in the sodium-cooled fast neutron reactor line. Located at Marcoule (Gard *département*), this reactor diverged for the first time in 1973 and was shut down on 1st February 2010. It has made it possible, amongst other achievements, to gain knowledge as to the irradiation behavior of materials being considered for the reactors of the future.

phenol: a cyclic molecule of basic formula C_6H_6O and carrying a hydroxyl –OH function.

phenolic resin: obtained by polycondensation of formaldehyde and phenol.

photocatalysis: the catalysis of chemical reactions under the effect of light.

photosynthesis: the process whereby plants, algae and certain bacteria use solar energy to synthesize organic molecules. Plants, algae and cyanobacteria use carbon dioxide and water to do this, while giving off oxygen (O_2).

photovoltaic: the effect whereby light energy is directly transformed into electrical energy in a semiconductor.

plasma: the state of matter heated to a temperature such that most, or all atoms are ionized (the electrons are separated from the nuclei).

plenum: a chamber (or a receiver) filled with a fluid. A sodium plenum positioned above the core of a reactor is a volume of sodium which, when voided at a time of hypothetical coolant boiling, allows to reduce the reactivity.

plutonium: chemical element of atomic number 94 and symbol Pu possessing isotopes, ranging from ^{232}Pu to ^{247}Pu. Five of them are important for the nuclear industry: from ^{238}Pu to ^{242}Pu, especially ^{239}Pu, a fissile element, generated inside reactors from uranium 238.

p-n junction: see single junction.

polymerization: the progressive addition of molecules of *monomers* to each other by covalent bonds, forming a polymer, a macromolecule with high molecular weight, repeating the same pattern.

Pressurized Heavy-Water Reactor (PHWR): a nuclear reactor which uses natural uranium as the fuel and heavy-water (D_2O) as the coolant. The heavy-water is kept under pressure up to its boiling point, which enables its temperature to be increased so that it can remove more heat from the core of the reactor.

Pressurized Water Reactor (PWR): a nuclear reactor in which the heat is transferred from the core to the heat exchanger, by the water kept at high pressure in the primary circuit, in order to prevent its boiling.

proliferation: the uncontrolled dissemination of nuclear technologies or materials for military purposes.

protein: the main macromolecular component of cells, formed by the DNA coded chaining of amino acids.

protists: these comprise the eukaryotes (organisms whose genetic material is contained in a nucleus) other than plants, fungi or animals. Some belong to the plant kingdom and carry out photosynthesis (algae), while others belong to the animal kingdom. Many protists have flagella or cilia enabling them to move around.

Q

quantum dot: a nanometric scale component in which each electron has no degrees of freedom, constrained by a semiconductor with a broader forbidden band.

quantum well: a region of nanometric thickness in which each electron can only move (ideally) in two dimensions in space. A quantum well can be obtained by stacking thin films of semiconductors with different forbidden bands.

R

radioactive decay: the reduction, over a period of time, of the activity of a radioactive substance by radioactive disintegration of its constituent nuclei.

radioactive disintegration: the process whereby a nucleus or a particle breaks up into several fragments (particles and nuclei, constituting the *disintegration products*, photons) in order to reach a lower-energy state that is thus more stable. The characteristics of this transformation only depend on the state of the original nucleus (of the particle) and not on the process which produced it.

radioactive waste: a radioactive substance for which no subsequent use is planned or envisaged. Ultimate radioactive waste is radioactive waste that can no longer be reprocessed in the technical and economic conditions prevailing at the time, in particular through extraction of its reusable part or by reducing its polluting or hazardous nature.

radioactivity: the ability of a nuclide to spontaneously transform into another nuclide, with the emission of radiation (particles, X-rays, gamma rays, etc.), or be the location of spontaneous fission accompanied by the emission of particles and gamma rays.

radioelement: an element in which all the isotopes are radioactive.

Radio Frequency (RF): frequency situated in the 9 kHz-3,000 GHz band.

radioisotope: a radioactive isotope of an element.

radionuclide: an unstable nuclide of an element which decays or disintegrates spontaneously while emitting radiation.

rare earths: a family of elements chiefly comprising the lanthanides as well as yttrium (39) and scandium (21).

reactivity: the deviation, relative to unity, of the ratio of the number of neutrons produced by fission, over the number of neutrons which disappeared, within a nuclear reactor.

rechargeable hybrid vehicle: with an architecture comparable to a conventional hybrid vehicle, it exhibits increased range in electric mode thanks to the incorporation of a battery with higher capacity and the possibility of recharging from a power outlet.

recycling: the recovery of reusable materials after a production process. In a nuclear reactor, the reuse of fissile materials (generated plutonium, residual uranium 235, etc.) resulting from a previous cycle, after reprocessing of the spent fuel.

redox (for reduction/oxidation): a redox reaction is a chemical reaction during which a transfer of electrons takes place. The chemical species which captures the electrons is called the oxidant and that which releases them, the reductant.

reduction: a reaction during which an atom or an ion gains electrons released by a reductant.

reprocessing (of spent fuel): the selective sorting of substances contained in the spent fuels, in order to extract those that are recoverable and recyclable (uranium and plutonium), or possibly amenable to transmutation, while conditioning the ultimate waste.

S

selectivity (chemo-, regio- and stereo-): a reaction is *chemoselective* if it leads to the preferential attack of a functional group within a molecule from among other groups. A reaction is *regioselective* if it leads to the preferential attack of a part of a functional group which comprises several reactive parts. A reaction is *stereoselective* if it leads preferentially, or even exclusively, to one of the possible stereoisomers (compounds with the same semi-developed formula but which differ in the spatial arrangement of their atoms).

self-discharge (of a cell): the self-discharge rate of a **cell** corresponds to the average relative loss of stored charge, without any utilization, per month and for a given temperature, generally 20 °C.

semiconductor: a material in which the band of occupied electronic states (**valence band**) is separated from the band of unoccupied states (**conduction band**) by a relatively narrow **forbidden energy band** (**gap**). Such a material is an electrical insulator at absolute zero, but becomes moderately conducting when its temperature is high enough to excite electrons in the valence band towards the conduction band. A semiconductor may be of **n type** (with electrons as the majority of charge carriers) or of **p type** (holes as majority charge carriers), depending on the **doping agents** used.

sequence: the order in which the constituent elements are concatenated in biological **polymers** (**DNA**, RiboNucleic Acid RNA, **proteins**). **Sequencing** is the determination of that order.

shale gas: a gas of natural origin, resulting from the breakdown of the clay, rich in organic matter, in clay shale. It is trapped in porous rock and to exploit it, the structure of the rock must be fractured, by hydraulic fracturing. This technique consists in causing a very large number of micro-cracks in the rock, by injecting water at high pressure, which enables the gas to move to a well, where it can be recovered on the surface.

silicon: the most common **semiconductor**, extensively used in microelectronics and also in the fabrication of **photovoltaic cells**. It exists in the non-crystalline state (**amorphous silicon**) and in the **crystalline** state (c-Si), a designation which comprises the various crystalline forms (microcrystalline µc-Si, monocrystalline sc-Si, multicrystalline mc-Si and polycrystalline pc-Si).

single junction or **with p-n junction (photovoltaic cells):** a zone of a material in which the doping varies suddenly, switching from p to n. In the case of **silicon cells**, **n doped** silicon (a very small percentage of the silicon atoms has been replaced by an electron donor, such as phosphorous or arsenic) is associated with **p doped** silicon (silicon atoms have been replaced by an electron acceptor, such as boron or gallium). In a **photovoltaic cell**, the electric field of the p-n junction separates the electron-hole pairs created by light.

sodium: an **alkali metal** used in liquid state as a **coolant** in **fast neutron reactors** because of its "transparency" to neutrons, its good heat transport properties and its excellent compatibility with steels.

solid absorption/desorption: exchange processes occurring between a gaseous phase and a solid phase, leading to the setting up/breaking of bonds between the molecules or atoms forming the gas and the substrate. The molecules or atoms of gas penetrate the material.

specific energy or **energy density:** these correspond to the quantity of energy stored per unit mass (**Wh/kg**) or volume (**Wh/L**) respectively, in a **cell** or a supercapacitor.

specific surface area: the actual surface area of an object (taking account of its roughness for example) as opposed to its apparent surface area.

spectrum (neutronic): the energy distribution of the population of neutrons present in the core of a reactor.

stellarator: a device similar to a **tokamak**, but in which the **plasma** is entirely confined by the helical magnetic field created by the complex arrangement of coils around the torus.

stoichiometry: the study of the proportions according to which, in a chemical reaction, reactants combine and products are formed.

storage (of radioactive waste): an operation consisting in placing **radioactive waste**, temporarily, in a specially designed facility, either on the surface or at shallow depth, pending its recovery. This term also refers to the facility inside which waste is placed pending subsequent recovery (see also **disposal**).

superconductor: a metal or an alloy in which resistivity (ability of the material to oppose the circulation of an electric current) suddenly drops to a near-zero value, at a so-called *critical* temperature (**superconductivity**).

supercritical (fluid): a fluid which, when placed in temperature and pressure conditions higher than their critical values, exhibits a **viscosity** close to that of a gas, a density close to that of a liquid and high diffusivity. Its solvent capacity evolves with the pressure and temperature conditions. Fluids most commonly used: **carbon dioxide** (**CO_2**) owing to its low critical temperature (31 °C) and **water** (H_2O) owing to its high **oxidizing** capacity.

Superphénix: this prototype **sodium**-cooled **fast neutron** reactor, located in Creys-Malville (Isère *département*), is currently being dismantled. It reached full power in 1986 and was shut down in 1998. The core comprised 364 **assemblies**, each consisting of 271 fuel pins containing a stack of **U**-**Pu**-O_2 mixed oxide fuel pellets.

supramolecular bonds: non-**covalent** or weak interactions between atoms within a molecule or between molecules within the same structure.

synchronous flip-flops: memorization devices distributed in an integrated circuit, flip-flops are used to synchronize the circuit with a clock and contain all the active data of the calculation at a given moment. They typically consist of two SRAM cells (Static Random-Access Memory, a volatile, very fast and low density memory) and are volatile (requiring an electrical power supply to retain the information).

T

thermal conductivity: characterizes the ability of a material to conduct heat.

thermal inertia: the resistance of a material to a change in its temperature. This depends on its ability to store and restore heat in its structure.

thermal neutrons: also called slow (or thermalized) neutrons, neutrons in thermal equilibrium with the matter within which they travel, at a speed of about 2 to 3 km/s. Their energy stands at less than 1 eV.

thermonuclear fusion: a reaction whereby small atomic nuclei combine at high temperature to form larger nuclei having a mass lower than the sum of the masses of the initial nuclei, the difference being converted into energy following Einstein's law of equivalence $E = mc^2$. The most widely studied reaction is the fusion of **deuterium** and **tritium**, which forms a nucleus of helium and emits a highly energetic neutron.

thermoplastic (material): a material which softens when heated above a certain temperature and which, below this temperature, returns to a hard state, without suffering any damage, even repeatedly. This is the case with metals, glass and certain **polymers**.

tokamak: the acronym for *Toroidalnaya Kamera Magnitinimy Katushkami* (toroidal vacuum chamber and magnetic coil) or the association of three Russian words *Tok* (current), *Kamera* (chamber) and *Mak* (magnetic) defining torus shaped machines which are used to study thermonuclear fusion by magnetic confinement in which the fusion plasma is confined by magnetic fields.

tracer: an organism, element or substance, whether natural or artificial, used to study physical, chemical or biological processes in the medium in which it is placed. The tracer can in particular be isotopic and/or radioactive.

tracker: a device which enables the photovoltaic panels in solar power plants or in concentration photovoltaic cells to follow the path of the Sun, thus optimizing their energy efficiency. The one-axis tracker follows the Sun from East to West as the day progresses. The two-axis tracker also takes account of the Sun's elevation according to the season.

transesterification: a reaction during which the R' group of an ester (the ester function is formed of a carbon atom bound to an H or R group, to an oxygen atom by a double bond and to an O—R' group) is exchanged with the R'' group of an R''OH alcohol.

transition metals: a family of 38 elements with atomic numbers 21 to 30, 39 to 48, 72 to 80 and 104 to 112, including titanium, manganese, iron, cobalt, nickel, chromium, platinum, etc.

transmutation: the transformation of one nuclide into another, by means of a nuclear reaction. The transmutation envisaged for the management of radioactive waste aims to transform a nuclide with a long half-life into one with a shorter half-life or into a stable nuclide.

tritium (T): a radioactive isotope of hydrogen with a short half-life. Its nucleus consists of one proton and two neutrons.

true algae: these are the result of the inclusion of an ancestral cyanobacterium inside a primitive eukaryote cell (primary endosymbiosis). These algae, whose genetic material is contained in a nucleus (eukaryotes), include red algae, the glaucocystophytes and green algae. Some of them have flagella which enable them to move around. Certain green algae are the origin of plants on Earth.

U

uranium: chemical element of atomic number 92 and symbol U, which exists in the natural state (natural uranium) in the form of a mixture of three isotopes: ^{238}U fertile (99.28%), ^{235}U fissile (0.71%) and ^{234}U (traces).

V

van der Waals bond: a low-intensity electrical interaction between atoms, molecules, or between a molecule and a crystal.

viscosity: the degree of resistance to flow exhibited by a fluid.

vitrification: the operation consisting in incorporating radioactive waste into glass, to ensure conditioning in a stable form, as packages amenable to storage or disposal.

void coefficient: a coefficient reflecting the variation in the multiplication factor (for a given interval of time, the ratio between the number of neutrons produced by fission and the number of neutrons which disappear) of a reactor, when the coolant forms more voids (such as bubbles) than normal. If this coefficient is positive, the surplus will lead to an increase in reactivity and power. If negative, this effect will tend to shut down the reactor. The unit of the void coefficient is the dollar or pcm.

W

watt (W): a unit of power, corresponding to the consumption or production of one joule per second. Main multiples: kilowatt (1 kW = 10^3 watts), megawatt (1 MW = 10^6 watts), gigawatt (1 GW = 10^9 watts) and terawatt (1 TW = 10^{12} watts); watt-hour (Wh): the amount of energy consumed or delivered by a system, corresponding to 1 W power for 1 hour. Thermal power is expressed in Wth and its multiples, electrical power in We and its multiples.

watt-peak (Wp): a unit of measurement of the maximum electrical power that can be output by a photovoltaic installation in standard conditions (1,000 W/m^2, 25 °C).

Y

yeast: a microscopic single-cell fungus, representative of living cells possessing a nucleus and used in this respect as a model by biologists. Yeasts are also used in the agro-industry (production of bread, beer, wine).

DE LA RECHERCHE À L'INDUSTRIE

cea

www.cea.fr