THE THREE WAYS TO EXPLOIT SOLAR ENERGY

The three ways to exploit solar energy "directly" are undergoing further developments in order to improve their performances and, above all, their economic viability. The oldest way is the use of thermal collectors, for direct heating of premises or water circuits. It is an attractive solution that has been promoted by guarantees, subsidies and technological improvements. Another one, based on thermodynamic, was developed some years ago with installations in France such as the Odeillo solar furnace or the Thémis 2 MW power plant, and is now used on a larger scale in California. The direct transformation of sunlight into electricity, i.e. photovoltaic power, constitutes the potentially most promising way forward. For some ten years, the CEA *has been working (box, p. 26) on developing its advantages and minimizing constraints.*

CEA/Coulon

Photovoltaic cells made of polycrystalline silicon tested at the CEA by the Genec in Cadarache (Bouches-du-Rhône).

Thermodynamic solar electricity

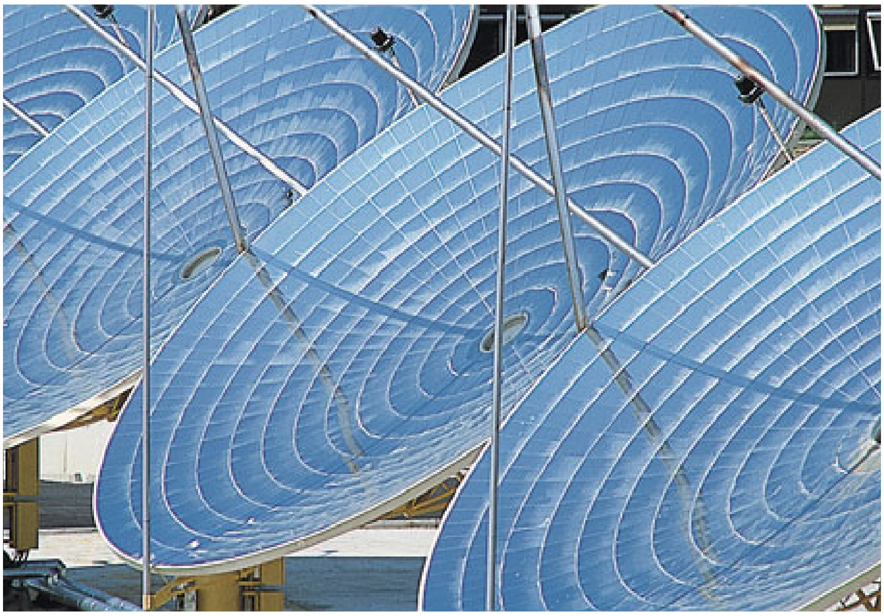
Focusing the sun rays on a single point or on a line can produce high temperatures. This principle of concentration, known since antiquity, uses parabolic collectors, cylindrical-parabolic collectors, or "solar thermal-electric" power plants, for which a multitude of multi-directional heliostats focus the sun's energy on a single boiler located at the top of a tower. This enables the heating of heat-transfer fluids, generally oil or molten salts, in a temperature range running from 250 to 800 °C, depending on the techniques used. These heat-transfer fluids then heat the steam, which drives a turbo-alternator, as in standard thermal power plants.

Prototype units from around a few dozen kilowatts (kW) up to a dozen megawatts (MW) have been built throughout the world over the past two decades. In the Pyrenees, the Thémis power plant, with a power output of 2 MW, was put into operation at the beginning of the 1980's. The largest commercial development was nonetheless accomplished by the Luz Corp. company, which, in the same decade, built three power plants with cylindrical-parabolic collectors amounting to a total power rating of 354 MWe, supplying the Southern California Edison network – which feeds Los Angeles – with peak period electricity during summer afternoons. In spite of the constructor's bankruptcy ten years ago, these power plants have been operating non-stop and their productivity has improved. They now confirm the relative maturity of this way of producing power, with the cost-price of electricity at around 0.1 Euro per kWh.

A potential improvement of 20 to 30% is possible, especially if the steam is directly produced in the collectors and the mirrors are optimised. The United States, Israel and, in Europe, Germany and Spain, are conducting joint research on these topics. In the framework of financing facilities made available by the Global Environment Facility, new plants are to be built within the next two to three years in several countries including Egypt, India and Brazil.

Thermal solar energy

Thermal solar energy is used mainly in two applications: heating of domestic hot



B. Charlon/GAMMA

Multi-directional mirrors on the Thémis solar power plant site, an example of the implementation of thermodynamic solar electricity.

Genec at the age of ten

The Genec (Cadarache research group for new energies), founded in 1991 under the name "Groupement énergétique de Cadarache" (Cadarache energy group), is responsible for research and technological development in the field of the rational use of photovoltaic solar energy and thermal energy. As a result of cooperation between the CEA and the Ademe (Agency for the environment and energy control), the Genec has acquired extensive experience in laboratory testing and work on real sunshine, as well as in technical assistance for photovoltaic electrification programs, especially in developing countries.

The Genec users association brings together industrialists, cooperating organizations and the Genec group for the purpose of optimising work and information and creating partnerships.

water and heating of premises. For these applications, the glazed collectors used ensure efficiency of around 50% at the required temperatures. Four square meters are sufficient to satisfy the hot water needs of a family of four, with an average investment of 3 000 Euro, and ten to twenty square meters are enough to heat a single-family house.

An auxiliary heating system is necessary for cold weather periods and, on a yearly average, a solar heating system covers around 50 to 60% of a family's needs, thus providing the same amount of savings. Depending on the types of substitute back-up energy, return on investment is between 6 and 12 years.

Every year such thermal collectors produce from 200 to 800 kWh per m^2, depending on the needs and methods of use. The lowest values correspond to intermittent uses of domestic hot water at high temperatures (more than 55 °C), with the highest values being obtained in the case of continuous low-temperature heating. For this type of application, often called "direct solar floor", the heat-transfer fluid from the collectors is injected directly into building floors at a temperature of 25 to 30 °C. On the one hand, this design produces fairly comfortable housing-units and, on the other hand, it offers one of the best ways to achieve technical and economic profitability.

The development of the European market was relatively slow, at around 250 000 m^2 per year in the 1980's, due to numerous counter-references caused by the lack of training available for installers. But the introduction of new concepts, such as solar performance guarantees, along with the activity of the German, Austrian and Dutch markets during the 1990's, brought about substantial growth, with an increase in two and four-fold factor increase in surface-areas sold over the last five years compared with the previous decade. In the short term, the European annual market is estimated at several million square meters. In France, the recent national program, Helios 2006, is intended to further increase distribution of these products by providing users with financial incentives.

Current technological developments are intended to lower costs, by means of improved integration and implementation in the structural frame of buildings.

Photovoltaic solar electricity

Real advantages and genuine constraints

Photovoltaic solar energy is an interesting way to reduce electricity distribution costs in certain regions. Readily available in most countries located between the equator and the 45th parallels, it is a remarkably reliable energy source that has a completely positive energy balance and environmental report card (box C, ***How does a photovoltaic solar cell work?***).

As a resource, solar energy is relatively well distributed geographically and is thus available in numerous places. Henceforth, solar cells or photovoltaic modules can be used to produce electricity *on the spot*, i.e. where the needs are actually located. This is the essential advantage of solar electricity: it means none of the distribution costs inherent in conventional solutions, whether this involves the use of generating sets supplied by **fossil energies** (diesel, petrol or gas), or the extension of a main electricity power line up to the point of use.

In fact, in the first case, it is necessary to take account of the availability and supply cost of the fuel up to the site in question, as well as routine maintenance. In the second case, the costs of extending or reinforcing a line considerably increases the price of a kWh, especially if energy needs are low. If they are high, the depreciation on each kWh will be reduced proportionally.

The absence of any mechanical movement or flow of fluids ensures photovoltaic electricity with an exceptionally high level of reliability: the most widely-sold models, based on **silicon crystalline**, are now currently backed up by guarantees of around twenty years and even longer service-lives. The energy balance is positive, since a photovoltaic module returns the energy necessary for its production in two to four years of exposure to the sun, depending on its manufacturing technology.

The main factor limiting the feasibility of a photovoltaic system is the amount of energy required, which must be in line with the resource's possibilities. To give a few orders of magnitude, lighting needs amounting to a few hours a day will require a daily "output capacity" of several dozen Wh, which corresponds to a surface of photovoltaic modules well under one per square meter. Domestic needs associated with a modern level of comfort, including television, hi-fi and household appliances, or pumping facilities for the distribution of village water, will require several kWh, or even, in some cases, around ten kWh per day. In all these scenarios, installations of around one square meter or ten square meters do the job, and they rarely cause integration difficulties.

On the other hand, the use of solar electricity is rarely cost-effective for higher needs, when these are located in one place only: this energy source is not appropriate for high-energy intensities.

Photovoltaic solar electricity can be used in two ways: to supply electricity to isolated sites or to inject electricity into an electricity power supply system.

Increase in the supply of isolated sites

The first application is the oldest and most widespread with regard to the millions of systems installed throughout the world. This type of application began in the 1960's for satellites, in which photovoltaic solar modules clearly dominated most other solutions, mainly owing to questions of weight and reliability.

The first ground-based applications came into widespread use in the 1970's, mainly for professional requirements (the power supply of weather stations or telecommunication relays). In the 1980's, numerous market gaps appeared, one after the other: maritime and air beaconing and lighting systems, the cathodic protection of pipelines or pylons, urban furniture and, above all, rural electrification, which mainly covers needs such as interior lighting, audiovisual equipment and water pumping. In the near future, the supply of water to isolated sites and its subsequent treatment in order to render it drinkable, will represent a very substantial market, since considerable environmental difficulties are foreseeable in this field.

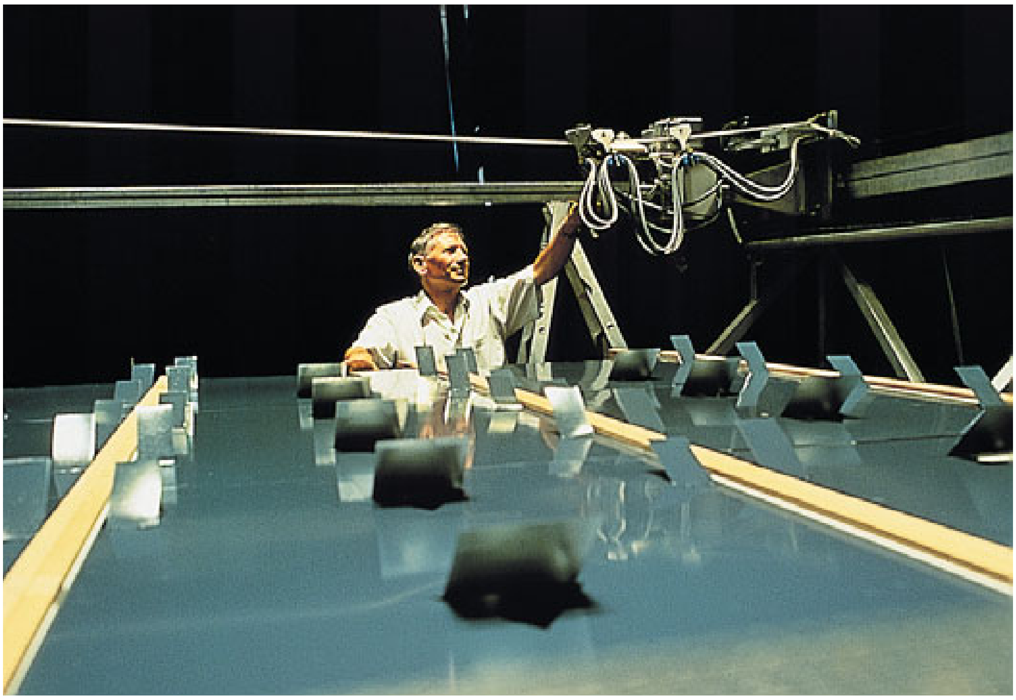
The most recent years have seen an increase in the number of facilities built in each of these sectors. In France, 9% of sea buoys are equipped this way. In developing countries, all telecommunication stations or microwave stations use this energy source. Rural electrification programs are now carried out in blocks of several thousand systems.

The main characteristic of this initial category for the application of solar electricity is that it requires the use of **batteries** when electricity needs are not in phase with production, that is, the resource, or, put otherwise, the sun (box F, ***Storage batteries, cells and batteries: steadily improving performance***).

Accelerated growth for electricity, "as the sun shines"

The second, more recent application and thus, for the time being, one which is less well-developed, is experiencing an even higher growth rate. It is based on the idea of transforming the direct current from the photovoltaic modules directly into alternating current, identical to the current which is used in low-voltage electricity power supply systems. The electricity which is thus generated "as the sun shines" is either consumed *in situ*, or injected into the network. The cost-related advantage and the current enthusiasm for this solution result from the fact that electricity generated in this way can be sold to electricity distribution companies.

Such electricity can be "hooked up" to the grid following a centralised layout with photovoltaic power plants of a few megawatts: power plants were built this way in the United States in the mid-1980's. The complementary approach uses the *distributed* characteristic of the resource and is limited to "domestic" facilities, that is, facilities of around a few kilowatts. The precursors in the field of "solar roofs" were Switzerland and Germany at the end of the 1980's. Several operations or demonstration programs, whereby modules are installed on building façades or in roofs, were carried out during the 1990's. At present large programs are under way, mainly in Japan and northern Europe, and are advancing at a rate of a thousand roof-mounted systems per month.


CEA/Coulon

Test on the CEA/Cadarache solar simulator of double-wall roof model permitting natural air currents (created in this case by blades) to lower the temperature in a housing-unit.

CEA/GENEC

Lamp posts with individual photovoltaic cell power supply in Antibes (Alpes-Maritimes).

Cost-prices consistently dropping

In 1999, the market amounted to a volume of 200 MW of electric power modules, and a total turnover for the photovoltaic sector of over 1.5 billion Euro. Growth is high, with 18% per year on average over the past ten years, and gathering speed: up 27% over the past five years, and up 34% per year over the past three years. New large-scale distribution programs of photovoltaic roofs in Japan, and subsequently in Germany, are at the origin of this upswing.

Forecasts for the year 2010, based on growth estimates of 20 and 25% per year, show an annual market of 1 500 and 2 300 MW, respectively. For the year 2020, according to the same estimates, the market should be between 9 and 21 GW. At present, the main producing countries are, in order of importance, Japan, the United States and Europe, with respective market shares of 40, 30 and 20%. The main parties working in this area are the major petroleum industrial or electronic groups: BP Amoco, Siemens, Kyocera, Sharp and Sanyo. Photowatt, a company of French origin with facilities in the Rhône-Alpes, is number one on a European scale, and number seven worldwide.

The selling price of modules on the international market is currently around 3.35 Euro per watt (price, ex-works in mass-production runs). Prices and sales volumes over twenty years show a steady progression, corresponding to price cuts of fifty percent every ten years. The forecast for the future is a price of around 1.5 Euro per watt in the year 2010. For a photovoltaic system of a few KW, hooked up to the grid, the cost-price for the user, including installation and power inverter, is about twice the price of the module ex-works, i.e. a little more than 6 Euro per watt. For a system equipped with battery storage, prices vary between 9 and 12 Euro per watt, depending on the applications.

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Photovoltaic solar modules: from crystalline silicon to thin film

Photovoltaic solar cells presently use silicon as a raw material, as do most microelectronic components. After having used the manufacturing scraps from the microelectronics sector, today solar cell production is beginning to follow its own specifications and adopt new methods, such as thin film, or even the use of plastic materials. The CEA is working on several of these new technologies.

From ingot to wafer

A photovoltaic cell has the ability to directly convert solar rays into electricity (box C, ***How does a photovoltaic solar cell work?***). From an electronic standpoint, it is a **diode**. The most widely used **semiconductor** material for its manufacture is **crystalline silicon**: the width of its bandgap allows a high conversion efficiency, its technology is well mastered, and it is very abundant. Presently, over 80% of solar cells are made with crystalline silicon. **Amorphous silicon** represents only about 10% of the market, since cells manufactured with this material have conversion efficiencies that are half that of crystalline silicon cells. The portion of other materials (CdTe, CIS, etc.) remains very low.

Photovoltaic cells are manufactured from very fine silicon wafers (thickness from 200-350 µm, with a surface area ranging from 10 × 10 cm^2 to 15 × 15 cm^2), cut from **monocrystalline** or **multicrystalline** silicon ingots. The Czochralski or CZ process is used to manufacture monocrystalline ingots. A seed, which itself is monocrystalline, is immersed at the surface of a bath of slightly overheated silicon in a silicon crucible, and pulled at a constant speed. Solidification takes place and reproduces the seed's crystalline pattern. If the pulling conditions are properly controlled, this operation produces a monocrystalline silicon cylindrical ingot of with no defects. This process allows the production of cells with excellent conversion efficiencies (16 to 17% in production), but remains fairly expensive.

The process used to manufacture multicrystalline ingots involves silicon melting in silicon crucibles. This method consists in slowly cooling liquid silicon in a given direction in order to achieve a solidification structure that is uniformly oriented in this direction. It yields an ingot with fairly large grains (1 cm) that can be cut into cells having a good efficiency (14%). It is a slow but inexpensive process.

The silicon obtained must be very pure, since the presence of impurities, even slight, will reduce the cells' efficiency: the impurity concentrations tolerated range from 0.1 to a few dozen ppm (parts per million) and are even of the order of a few dozen ppb (parts per billion) for some impurities. Once solidified, the crystalline silicon blocks obtained are cut into ingots and then wafers. Wafer cutting is performed with a wire saw, a long process that consumes a lot of material: the saw makes a cut approximately 200 µm wide, and almost half the silicon is lost.

CEA/Coulon

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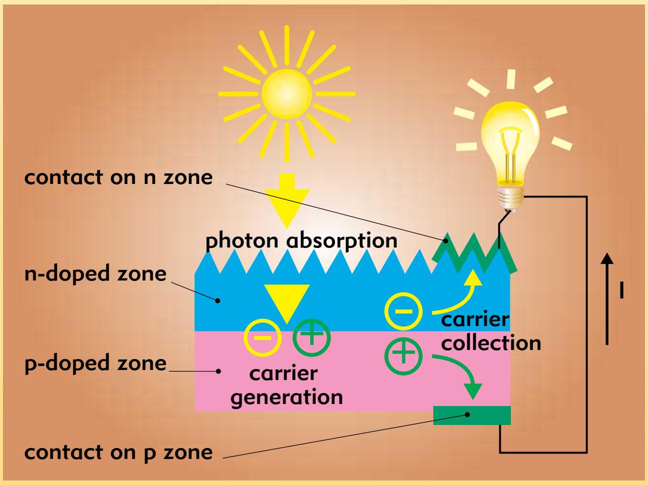
From a silica stone to a silicon block.

Cells and modules

Overall, silicon wafer manufacture represents 40% of the price of a module. This module fulfils several functions: the connection of the cells to each other in order to supply the desired voltage (usually a series of 36 cells for a 12 V output), and protection of the cells from environmental stress (erosion, humidity, hail, salt, UVs, etc.). In order to reduce costs, savings must be sought at all stages: silicon purification, C

How does a photovoltaic cell work?

Silicon was chosen for the manufacture of photovoltaic solar cells because of its electronic properties, characterized by the presence of four electrons on its peripheral layer (column IV in Mendeleiev's table). In solid silicon, each atom is bonded to four neighbors, and all the electrons in the peripheral layer help the bonding process. If a silicon atom is replaced by an atom from column V (phosphorous for example), one of the electrons no longer participates in the bonds, and can therefore move around in the network. There is conduction by one electron, and the **semiconductor** is considered of the *n-doped type*. If on the contrary a silicon atom is replaced by an atom from column III (boron for example), an electron is then missing to make all the bonds, and an electron can come to fill this hole. This is called hole conduction, and the semiconductor is considered of the *p-doped type*. Atoms such as boron or phosphorous are silicon **dopants**.



When a type n semiconductor is placed into contact with a type p semiconductor, the excess electrons in the n material diffuse in the p material. The zone that was initially n-doped becomes positively charged, and the zone that was initially p-doped becomes negatively charged. An electrical field is therefore created between the n and p zones, which tends to push the electrons into the n zone, and a balance is established. A *junction* has been created, and by adding metal contacts onto the n and p zones, one then creates a **diode**.

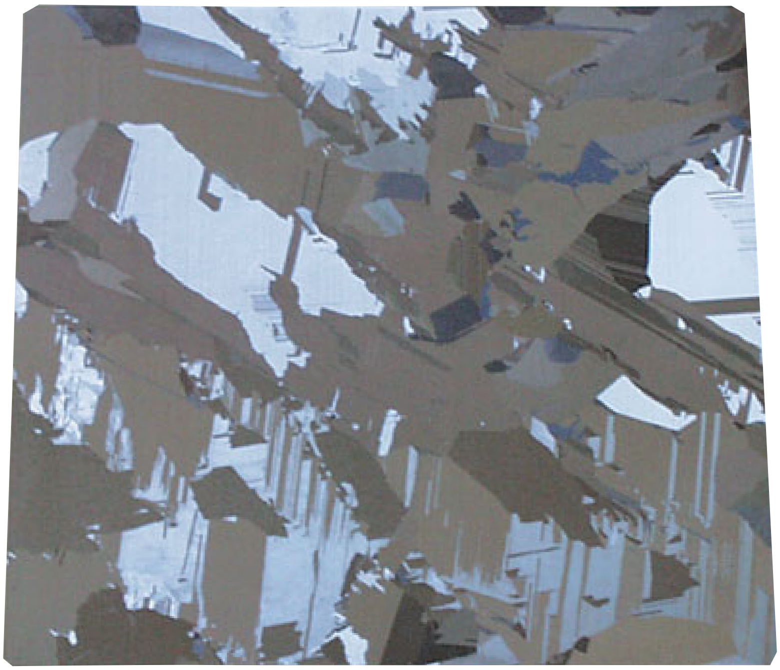
When this diode is irradiated, the photons are absorbed by the material, and each photon gives birth to an electron and a hole (this is called an **electron-hole pair**). The junction of the diode separates the electrons from the holes, creating a voltage between the n and p contacts, and a current circulates if a resistor is placed between the diode contacts (figure).

ingot manufacture and wafer cutting. One attractive solution consists in producing ribbons of silicon, which eliminates wafer cutting. However, this technique, extensively developed over the past twenty years, has not been able to establish itself, in particular due to the inferior quality of silicon obtained.

For a cell to work several functions are required: maximum absorption of light over the entire solar spectrum, efficient collection of the **carriers** (electrons and holes) generated by the photons, and the establishment of an electrical connection with the exterior circuit. The first step of its manufacture is therefore a chemical attack on the surface, to clean it and make it rougher, and therefore less reflective. The junction is then formed by diffusion of **dopants** (the wafers used are generally p-doped but phosphorous is introduced by diffusion in order to n-dope the silicon to a depth of about a micrometer), and an anti-reflective coating is deposited. The metal grids used to collect the current, very narrow to avoid creating any shadowing effect, are then applied by screen printing. An annealing operation then allows the creation of the electrical contact between the silicon and the collecting grids. The conversion efficiencies of these cells range from 14 to 17%, depending on the type of material used (multi- or monocrystalline) and the cell manufacturing process. An aluminium ribbon designed to make the interconnections between cells is then welded onto the grids. Then the cells are individually tested, sorted according to conversion efficiency, and assembled into modules. The irradiated surface of the cells is bonded to a plate of tempered glass which ensures mechanical protection. The back of the cells is protected with a sheet of glass or plastic. These bonding operations are performed with a **polymer** which ensures protection from humidity.

Crystalline silicon cells assembled into modules on the CEA/Cadarache experimental site.

J.-F. Mutzig



PHOTOWATT INTERNATIONAL

100 mm multi-crystalline silicon cell.

The technological obstacles

Up until now, the volumes of silicon used in the photovoltaics industry were low (3000 metric tons per year, i.e. about 10% of the silicon consumed in the microelectronics sector), and the silicon came from scraps (ingot tops and tails, polycrystalline silicon) from the microelectronics sector, which supplied a silicon with a purity of a few ppb, higher than that required for photovoltaic cells. However, the growth forecasted for the photovoltaics sector now makes it necessary to find an autonomous source that could supply silicon at a low cost with a level of purity suited to its needs. Among the possible alternatives to the use of microelectronic scraps, the **fluidized bed** process using metallurgical silicon as a basic material appears the most promising. It would allow the production of silicon of satisfactory quality at an accessible cost. The German chemical group Bayer is presently studying the industrialization of this process.

Today's ingot manufacturing process is slow. The industry is moving towards methods involving continuous casting in a cold crucible, whereby the melted silicon is introduced, confined by an electromagnetic field, and solidified without any contact with the walls. This makes it possible to continuously obtain large-sized ingots (35×35 cm^2 in section and 3 m long) with a crystalline structure compatible with photovoltaic applications. This type of process has several advantages in comparison with conventional processes: the electromagnetic confinement prevents contamination from the crucible, productivity is multiplied by 10, and the ingot's homogeneity allows production of cells with a very targeted conversion efficiency, so that cell sorting is no longer necessary.

Concentration cells

In a concentration system, a small-sized cell is placed in the focal spot of an optical system (figure 1). The surface area of the silicon cell is thus divided by the concentration factor, which can be as high as 300. The cell can be made of very good quality silicon with microelectronic technologies, which authorizes higher conversion efficiencies (above 20%) than those of cells used without concentration (15%). However, the system must be placed on an orientable support in order to track the sun. The cost of the system is then essentially determined by the optical system, which can be made of plastic and therefore remains fairly cheap, the assembly, and the tracking system. The low concentration systems (less than 50) use cylindrical optical systems that require the sun be tracked according to one axis, and the high concentration systems (over 100) use a system with two axes. This approach is particularly well-suited to electricity generation in mini power stations, and should allow to reduce the cost of the generated energy. In order to improve these concentration systems, researchers are trying of course to increase the cells' efficiency, but also to develop optical systems with shorter focal distances in order to reduce panel thickness and therefore the space required.

Future prospects: thin film modules

The scientific and technological obstacles

The low consumption of raw material and the direct production of the material using conventional deposition techniques on a low-cost support material such as glass,

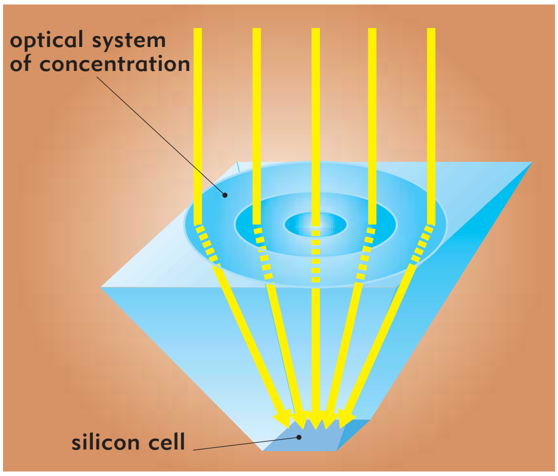


Figure 1. Schematic diagram of a concentration cell.

steel or polymer, without requiring any other costly shaping stages such as sawing, make the thin film technology a particularly attractive solution for photovoltaic cells (see box). Crystalline silicon, due to its **electronic band** structure, is not naturally the best-suited semiconductor material for thin film photovoltaic conversion. Indeed, the absorption depths for the portion of the solar spectrum located in the close infrared range are high, and can be measured in dozens of microns. Nevertheless thin film monocrystalline silicon cells have their advantages, as we will see below.

In order to achieve a *thin film* cell, it is preferable to use semiconductors with a **direct electronic bandgap** (rather than indirect like silicon) and with a value suited to the solar spectrum (of the order of 1.5 eV). With such materials, the entire solar spectrum can be absorbed in a thickness of about one micrometer. Moreover, the shallow absorption depth makes the cell fairly tolerant of defects acting as recombination centers for the **charge carriers** (electrons and holes).

Numerous research efforts have therefore been carried out on a fairly large number of materials over the past forty years, in order to achieve thin film photovoltaic cells with good conversion efficiency at a low cost. Historically, two materials have been especially studied and tested in industrialization: amorphous silicon and cadmium telluride (CdTe), both deposited on glass. In spite of the research efforts, the maximum efficiency of this type of cell remains unfortunately limited for significant cell sizes. This is due to the difficulty in achieving this type of material with a low defect density and thus good electronic properties. Moreover, amorphous silicon suffers from an aging effect linked to the instability of the hydrogen in its structure, and the presence of cadmium, a heavy metal with a toxicity comparable to that of mercury, makes the CdTe fairly inappropriate for consumer applications. Recently, remarkable progress was made with another type of material, **chalcopyrites**, such as the reference materials copper indium di-selenide ($CuInSe_2$) called CIS. This path of research has therefore rapidly become the reference in *thin film* research.

But other possibilities have not yet been explored, and efforts are being made in many other directions: manufacture of silicon material with very small grains leading to a modification of the electronic band structure (so-called "micro-crystalline" silicon), multi-junction cells based on amorphous silicon-germanium alloys, and cells based on organic semiconductor materials.

One of the most important aspects of *thin film* research is also linked to the possibility of applying these films directly to a flexible material which could then be applied to a construction material. This poses another challenge: to find support polymers that resist humidity and thus prevent any corrosion or deterioration of the semiconductor material and electrical connections.

The field of research on these thin film materials remains fairly wide open. The entire range of possible materials has not been studied in detail. Numerous efforts will still be necessary in order to achieve an application that combines minimum cost with maximum efficiency. Finally, the elementary physical mechanisms that control the initial efficiencies and the deterioration factors are still poorly understood in all of the thin film materials studied, whatever their maturity.

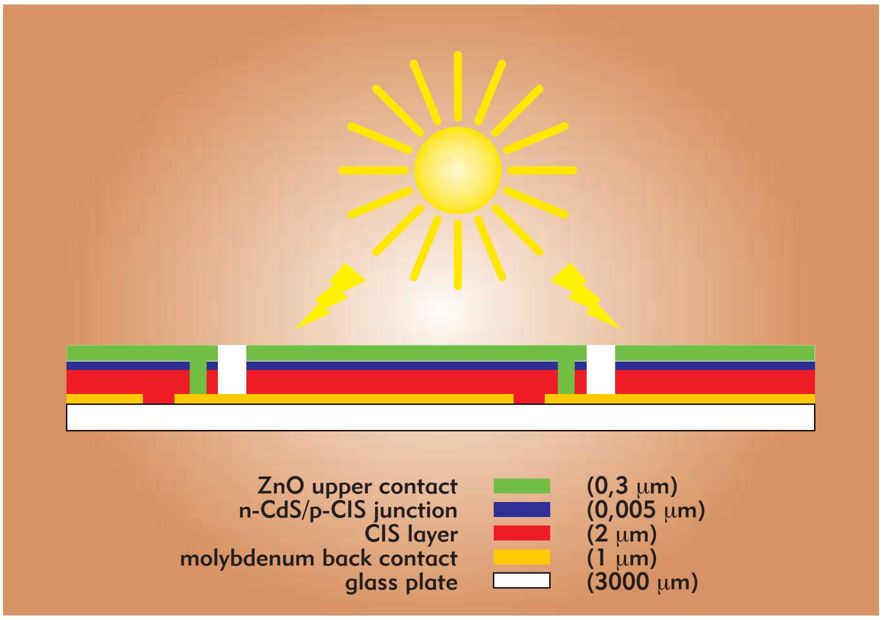


Figure 2. Schematic diagram of the stacking of a CIS (copper indium di-selenide) photovoltaic cell and of the electrical interconnection between two cells in series. The thickness of the different layers is indicated in parentheses.

Technologies currently being developed or industrialized

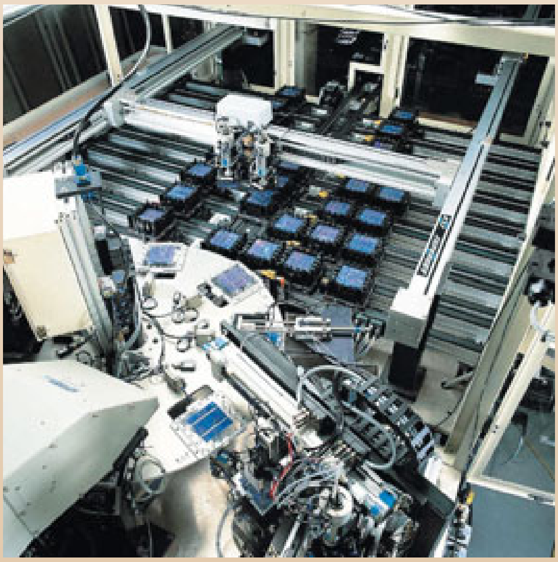
In the past few years, while the conversion efficiencies of solar cells based on thin films of $CdTe$ have stagnated at around 16% in the laboratory, constant progress has been achieved with CIS semiconductor material. An efficiency value of 18.8%, a record for thin films, was achieved in the laboratory with a cell of small size. For modules measuring 30 × 30 cm^2, performances of 12.8% have already been achieved. Moreover, fundamental research has shown that this material has the quality of remaining very stable under irradiation, as well as the ability to auto-regenerate. This auto-regeneration can be explained by the chalcopyrite structure of this material, which is not completely ordered, and by the fact that numerous defects such as the lack of atoms, or foreign atoms (sodium, iron, gold, etc.) are present, and that the copper atoms it contains are relatively mobile. These results have stimulated renewed interest in this field of research, especially in Germany.

The stacking structure of a CIS cell (figure 2) includes a glass support and a molybdenum electrode deposited by **cathode sputtering**. The junction between the cadmium sulfide (CdS) of the n type and the CIS of the p type is obtained by depositing a 50-nanometer film of CdS in a chemical bath (*CBD-Chemical Bath Deposition*) on the CIS. The upper contact consists of a transparent zinc oxide (ZnO) electrode doped with aluminium. Several deposition techniques have been used to obtain the CIS film (vacuum evaporation, **selenization** of the metallic precursors, cathode sputtering or spraying, electrodeposition). The best performances have been achieved with the technique based on co-evaporation of the elements. The cell's final surface is then encapsulated in a layer of polymer and a protective glass plate.

The main industrial actors in this field are Siemens Solar (Germany, USA), Wurth Solar (Germany) and Matsushita (Japan). In France, no industrialist has yet entered this field, whereas in the research sector, the electrochemistry laboratory of the ENSCP (National school of chemistry in Paris) has been working on this material for several years, with international renown. EDF, Saint-Gobain Recherche and the ENSCP are participating in a project that would allow the development in France of an original type of CIS thin film based on electrodeposition.

Photowatt-CEA: intensified cooperation

The working partnership established between Photowatt International, the leading European vertically integrated manufacturer of photovoltaic wafers, cells and modules, the CEA/Cadarache and the Leti in Grenoble should be increasing in the coming years, in the areas of module integration in the building sector and the development of new photovoltaic cell manufacturing processes. Photowatt is pursuing its strategy of growth in a rapidly expanding international market. Having progressed from an annual production capacity of 5 MW in 1997 to 18 MW today, Photowatt International also proposes an expanded product range, with two sizes of wafers and cells, and a line of modules generating from 10 to over 100 **peak watts**. This has allowed the company to broaden its geographical presence: Photowatt is now equally present in Europe (the "grid-connected" market, particularly in Germany), America (thanks in particular to its American parent company Matrix Solar Technologies, a subsidiary itself of the Canadian company Automation Tooling Systems), and the Asian-Pacific area (Japan is the largest market in the world). The objective is to rank among the top five international manufacturers. Photowatt attaches particular importance to the development of new technologies and new manufacturing processes. With the participation of Ademe, the company devotes approximately 15% of its turnover to technology research and development. Its main objectives in the short and medium terms are: 1) a continuous casting furnace for silicon in a cold crucible, making ingot manufacture ten times faster than the technique presently used, with a reduction by a factor of 2 of the added value, and 2) the development of an innovative cell manufacturing process allowing a significant increase in the conversion efficiency. Other projects for the longer term involve silicon refining and the development of ultra-thin cells (100-150 µm).



PHOTOWATT INTERNATIONAL

Manufacturing multicrystalline silicon cells at the Photowatt International plant in Bourgoin-Jallieu (Isère).

Thin film monocrystalline silicon cells

Even if, as we have seen, silicon requires thicknesses greater than 10 microns to achieve sufficient conversion efficiency, a very attractive solution to manufacture photovoltaic cells at a low cost consists in taking a film a few dozen microns thick from a monocrystalline silicon wafer and applying it to a low cost support, such as glass or ceramic.

This would make it possible to use only the amount of silicon that is strictly necessary for the cell to work, and avoid losses linked to wire sawing, while still preserving a material and technology that have proven to be especially reliable. Several processes are currently being studied in laboratories in Japan, Germany, Australia and France. They all have in common the weakening of the silicon in depth in order to be able to detach the surface film located above this fragile zone and apply it to a large-sized, low-cost support (figure 3). An additional advantage: the performance of the technological stages on the cells is done at the scale of a large

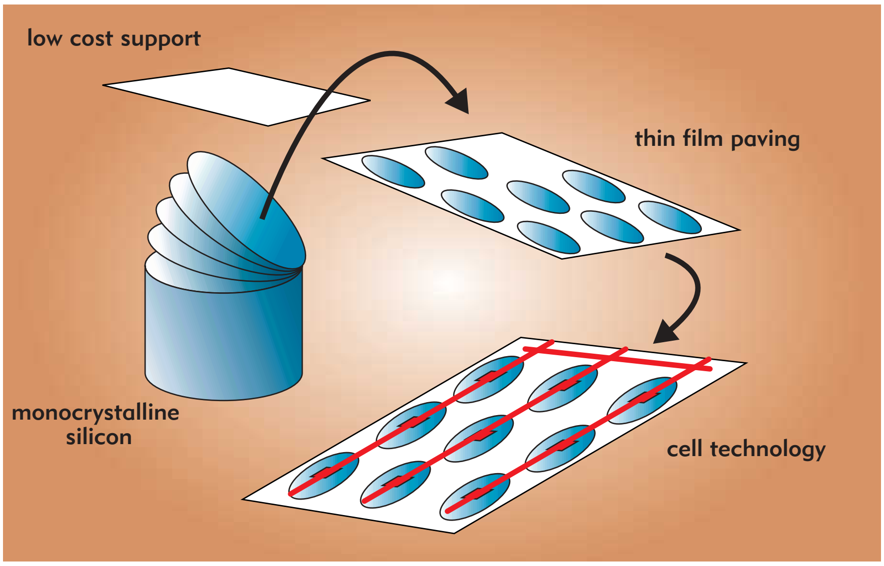


Figure 3. Schematic diagram of the transfer of a thin film and its application to a large size, low cost support, with performance of the technological stages of cell manufacture at the scale of the module.

surface module and no longer for each silicon wafer, which allows significant reduction of the cost per unit of surface area. The CEA/Leti (Electronics and information technology laboratory), which has been a pioneer in developing this type of approach for microelectronic applications, proposes to study its application to photovoltaic cells in the framework of a contract with Ademe, and in collaboration with the INSA engineering school in Lyon.

Organic cells: moving towards total polymer composition

Research and development on solar cells based on organic materials or **polymers** is motivated by the advantages that these materials present: low cost, unlimited raw material, simple implementation, low temperature technologies, large surface areas, flexible systems, etc. Moreover, this solution would make it possible to process the substrate (mechanical support), the active material where the photovoltaic conversion takes place, and the encapsulation, all with a single technology.

Today organic photovoltaic cells exist that have a conversion efficiency higher than 10%. They are based on the so-called Grätzel technology which consists in a junction between an organic polymer and a liquid **electrolyte**.

The photovoltaic generation is located in the polymer and the electrolyte ensures the charge transfer and the voltage (electromotive force) *via* its junction with the polymer. This type of cell is being developed in Switzerland by Solaronix for low power applications, and in Germany by the INAP (*Institut für Angewandte Photovoltaik*) for high power applications. The presence of liquid electrolyte is one of the major drawbacks of this technology, due to its lack of stability over time (evaporation) and limited range of operating temperatures.

Researchers are therefore now focussing on a total polymer solution. In this field, the best performance achieved to date is a conversion efficiency of 3.6%. The number of laboratories working in the field, at a stage that is still relatively upstream, remains fairly limited, but several publications, patents and lectures illustrate the emergence of this subject of research which could enter the development phase around the year 2010. The CEA/Leti has acquired significant experience in this area by working on the first European contract on the subject, and has proposed an original way to improve the collection performances of the charge carriers in this type of structure. A national project bringing together the Leti, several university laboratories and the TotalFinaElf group is presently being organized to develop polymer photovoltaic cells for energy generation applications. In a first phase, this project will constitute an upstream research activity.

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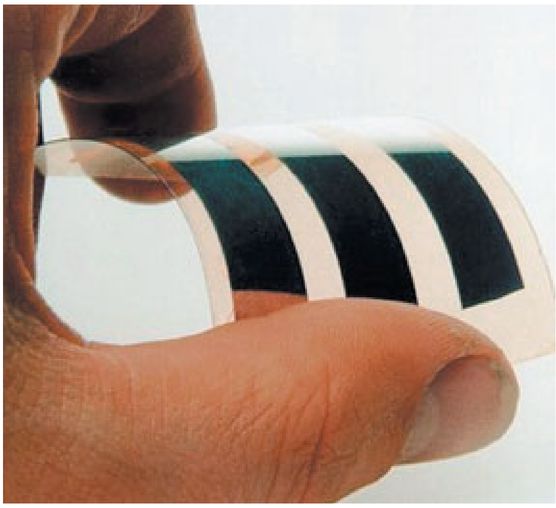


Flexible photovoltaic cell developed at the University of Linz (Austria).

JKU Linz

Photovoltaic systems

Beyond the module that holds the cells exposed to the sun, the exploitation of photovoltaic electricity uses "systems" whose future development requires research efforts, on each component, to improve their economy and reliability. This is especially true for the essential link that is storage, as the main constraint weighing on the industry is the need to store electricity between periods of sunshine. The CEA is attempting, among other things, to model the operation of photovoltaic systems by integrating the evolutions of the storage characteristics over time.

The interface between the user and the resource

The photovoltaic system is the interface between the user and the resource, it processes the energy captured by the photovoltaic modules according to the types of applications. In addition to an association of photovoltaic modules, an inverter converts the direct current into alternating current for use on an electric grid. The user may then either use the energy that he has produced or re-inject it into the electric grid if, for example, the operator's purchasing conditions are appealing to him. The inverter may set off a pump in the case of a sunshine direct coupled pumping system daytime, water is then forced back into a reservoir sized according to the requirements of the village and released on demand.

If it's necessary to store the electrical energy produced, a storage bank is introduced. This bank will be managed *via* a regulator: it charges when the sunshine allows it and supplies the user as required. This type of storage allows, on one hand, to compensate for the day-night alternation as well as for several consecutive days of bad weather conditions, and on the other hand, to meet power requirements that are substantially above those that the photovoltaic generator may supply instantly.

Hybrid solutions

This type of architecture becomes more complex for more important applications: in order to avoid the setting-up of a sizeable and therefore costly storage bank, an auxiliary generator such as a Diesel generator may be selected. It will then be a photovoltaic system said to be "hybrid", meaning that it associates a photovoltaic generator with an energy source, conventional or not. If the weather conditions are favorable, the association of several renewable sources (photovoltaic, wind power or micro-hydraulic) may even be considered.

Ph. Malbranche

Installation destined to meet the electricity and water requirements of a holiday camp in Alice Springs in the Australian outback. It associates photovoltaic modules, a battery bank, a Diesel generator, a boring pump, a desalination unit and a fresh water tank.

The research and development directions for all of these systems aim mainly at lowering the electricity production costs. This decrease is obtained by playing on the cost/performance ratio of each component making up the system, but also on the more general factors of system management and architecture.

In the order of importance of initial investment costs for a hybrid photovoltaic system, for example, the photovoltaic generator represents on average 35%, the battery bank 20%, the other components 20%, the additional energy sources (Diesel generator) 10%, the logistics and the installation 15%. The integration of O&M (Operation and maintenance), intervention and replacement of equipment (the storage bank for example) disrupts the "life cycle" costs breakdown: the battery bank then represents 50%, the photovoltaic generator 20%, the additional energy sources 15%, the other components 10%, and the logistics and installation 5%.

Research on photovoltaic modules has direct effects on the cost of the systems in terms of increasing the performance and **conversion efficiency** of the cells (more power at a constant price), but also in terms of reducing the production costs by wor-

A second home in the center of Finland supplied with electricity by a photovoltaic system delivering approximately 5.6 kWh per day in summer. The roof-top modules also ensure the functions of roofing and insulation.

Neste Oy NAPS

king on the manufacturing processes (photovoltaic module less expensive at equal power, see *Photovoltaic solar modules: from crystalline silicon to thin film*). It is reasonable today to estimate that a gain margin exists that would allow a 30% reduction in the cost of a complete system. The two other most important research directions should not be neglected. In the storage bank, the potential gain is estimated at 50% if, for example, it is possible to double the lifetime of the battery. For the other components, the goal is to minimize the conversion losses: the "solar" inverters are much more efficient than standard inverters. Their efficiency reaches 95% at their rated power with a very low self-consumption, while the efficiency of Uninteruptible Power Supply inverters is barely 80% with a far higher self-consumption. The price varies as a result.

Increasing reliability, energy management and new architectures

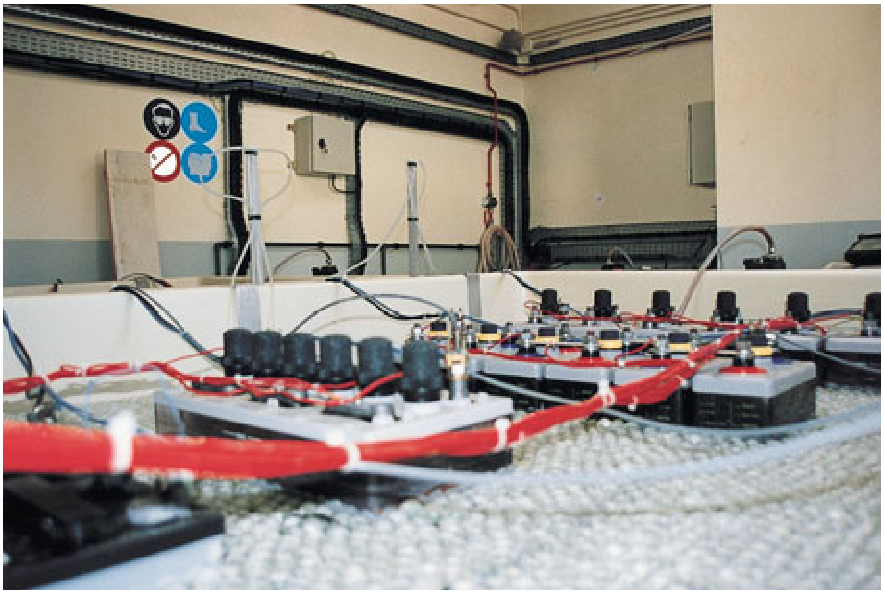
In the case of complete systems, the main technological levers that guide research actions fall essentially into three categories. The first concerns the reliability of the systems. In the short and long term, it's one of the most effective means of action: it concerns, for example, reducing the frequency of maintenance in isolated sites or conferring services lives on all of the components that are as long as those of the photovoltaic modules. This requires a better knowledge of the reliability of the system and the installation of monitoring and user assistance devices, but also a certain standardization of the components and an increasingly important quality assurance and normative approach. One part of the studies undertaken by the Cadarache Group for new energies (Genec) aims at the elaboration of international standards for system testing.

The second lever is the management of energy flows: in the medium term this solution seems the most promising. It consists in optimizing the use of the energy flows from all of the components, by attempting to have the photovoltaic modules producing as near as possible to their maximum power, by having better knowledge of battery management strategy, by optimizing the association of energy sources in order to favor the use of renewable energies, all while corresponding to an economic optimum. The implementation of "predictive" management methods, meaning that they forecast the future state of the resources or the system, currently makes up one of the important directions for the studies undertaken at Genec.

The third lever acts on the overall architecture of the system: it's certainly the most innovative point that will develop products whose architecture will be very different from the first systems. This trend is very obvious for "grid-connection" type applications. Increasingly diversified products are being developed to allow a more simple and modular integration into buildings: roof tiles, slate or "solar" roofing, semi-transparent façade or roof windows and even multifunctional components simultaneously ensuring several functions, such as the mechanical rigidity of the building, insulation, solar protection, capture of thermal energy and generation of photovoltaic electricity. But this is also the case for the other applications where the technical answers will allow the final product to better meet the requirements, or even to find new applications.

If the improvements to the complete systems are mainly linked to the technological innovation process, the gains forecasted in the field of electrochemical storage – like the photovoltaic conversion examined earlier – are in the field of competence of upstream research.

Batteries undergoing accelerated testing at Genec, CEA/Cadarache.



CEA/GENEC

The storage of the electricity of photovoltaic origin

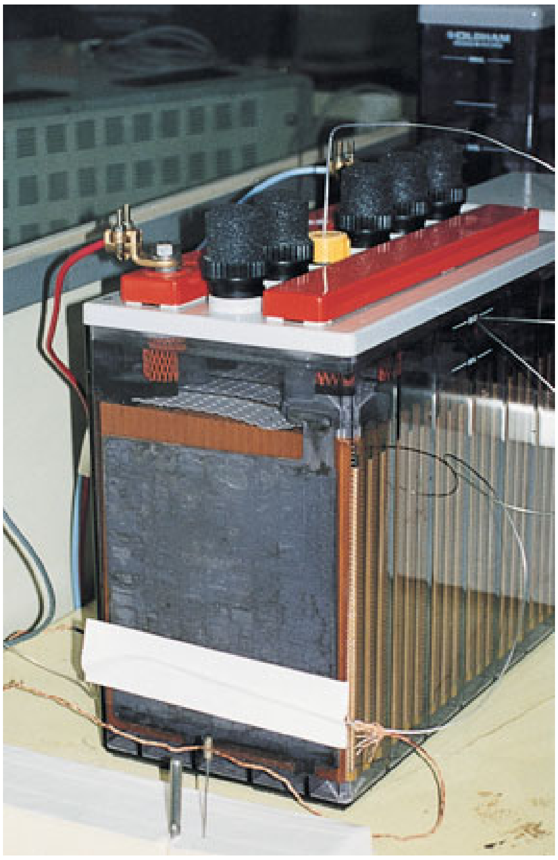
Stand-alone photovoltaic generators require electric storage to ensure a uninterrupted energy supply regardless of the meteorology. According to the applications, this supply will be ensured, for example, for two to three days for certain small domestic systems and for approximately two weeks for professional applications, such as lighthouses and maritime buoys.

Different types of batteries

The different types of applications require different types of **batteries** to guarantee the service provided to the end-user. From among these technologies, the lead acid battery, despite having been around for over one hundred years, currently, and for many years to come, offers the best answer in terms of price and service lifetime. Certain sites where the operating or climatic constraints are particularly severe may be equipped with nickel-cadmium batteries, but their prohibitive cost prevents the generalization of their use. The new pairs (lithium-ion, lithium hydride metal) present interesting solutions for low capacity portable applications, but they are also too expensive (box F, ***Storage batteries, cells and batteries: steadily improving performance***).

Experiments are being performed in certain northern countries (Germany, Finland) to use **fuel cells** as a generator associated with conventional storage. In this case, the storage is ensured by hydrogen reserves produced by the electrolyzers supplied from the photovoltaic generators. This type of interseasonal storage does not self-discharge. If the prices were sufficiently competitive to compensate for the current low efficiency of this technology, it would resolve the problems at our latitudes due to the variation in electric production between summer and winter.

The stand-alone systems will use starter type flat-plate lead acid batteries for the installations with peak installed capacity approaching one hundred watts. The most important installations will be equipped with tubular batteries more adapted to a daily cycle, but with a cost per kilowatt-hour 1.5 to 2 times higher. This type of battery equips installations from several hundred watts to several kilowatts peak and all the professional applications for reliability and safety reasons (television and telecommunication relay stations and maritime lighthouses). The sealed lead acid battery is essentially used in restrictive environments that only allow very infrequent maintenance, such as for the equipment in maritime buoys and in confined installations.



Tests on a prototype battery at Genec.

CEA/GENEC

Storage in a photovoltaic system contributes a non-negligible amount to the total operating cost due to its successive replacements during the service lifetime of a system. Indeed, according to the technology and use of lead acid batteries, their service lifetime may vary from 2 to 15 years. In addition, the total storage cost does not follow the same decrease as the one obtained on the other components of a photovoltaic system. One of the current objectives is to double the service lifetime of low-priced batteries with a design close to that of starter batteries and to prolong to 20 years the service lifetime of positive tubular stationary industrial batteries. In order to do this, industry level research is aimed at the design of new products that are more adapted to the constraints of photovoltaic applications.

Better management of battery lifetime

A second work direction concerns the improvement of battery management systems: this concerns conserving them while making them work in less constraining states of charge. These improvements require a better knowledge of the degradations observed on-site. The work currently taking place at Genec, within the scope of the contracts with the Ademe, EDF, the European Commission and industries, allows the identification and the study of the relevant parameters that are at the origin of the degradation mechanisms.

The degradations observed on batteries returning from the field are essentially hard sulfation, the loss of active matter cohesion and, to a lesser extent, the corrosion of the grids. To successfully complete these works, the laboratory is equipped with charge-discharge cycling, electrochemical study and optical and chemical characterization means. The knowledge acquired will allow the modeling of these mechanisms and their integration into adaptive management algorithms that will evolve according to the constraints actually sustained by the battery subject to its specific operating conditions. The battery will then be managed according to its own state, its own behaviour and no longer according to parameters pre-established during its installation, which will strongly contribute to the improvement of the service provided to the end-user and, in the long run, of the storage service lifetime.

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