Solar energy: a major potential to be realized

CEA/Coulon

Outside trial installation of polycrystalline-silicon solar panels, run by Genec at CEA's Cadarache Center (Bouches-du-Rhône département, southern France).

As a raw material coming "free," albeit yielding a form of energy relatively costly to collect and utilize, solar energy, despite its inherent limitations, shows huge potential, which technological advances are seeking to develop further still, particularly as regards photovoltaic solutions.

Solar energy is a resource that is relatively well distributed, geographically speaking. Its theoretical potential, which is huge, amounts to several thousand times current global energy consumption. From the equator to regions situated at latitudes 45° north and south, this potential is significant the year round. Further out, seasonality becomes more pronounced, and, while the resource remains abundant in summertime, auxiliary solutions are required during the winter.

Solar thermal energy: a large scope for growth

The first way of getting value out of solar energy consists in using it for thermal applications, i.e. to heat sanitary water, or premises. For such utilization, glazed collectors are most commonly used: they generate the required greenhouse effect, letting the rays of sunlight through the glass, while precluding too rapid heat dissipation. Efficiencies achieved are of the order of 50%, at the looked-for temperatures. Four square meters enable the hot-water requirements of a family of four to be met, for an average cost of €3,500, and 10-20 m^2 allow heating of an individual dwelling. Auxiliary heating is necessary, to cater for the more climatically unfavorable periods, and, on average, a solar heating installation brings, over a year, a rate of cover for requirements of the order of 50-60%, and a consequent saving on bills.

Such thermal collectors generate, over a year, 200-800 kWh per square meter, according to requirements and usage. The lower values correspond to intermittent use of domestic hot water at high temperature (above 55 °C), the higher values being achieved in the case of continuous low-temperature heating. For this type of application, often referred to as "direct solar floor" heating, the heat-transfer fluid exiting the collector is injected directly into the building's floor, at a temperature of 25-30 °C. This design brings, on the one hand, high domestic comfort, and, on the other, one of the best efficiencies, in technical-economic terms. Growth of the European market was relatively stagnant during the 1980s, due to numerous counter-testimonials, linked to inadequate training of installation operators. However, the introduction of new designs, together with guaranteed solar results and strong activity on the German, Austrian and Danish markets in the 1990s, were conducive to a noticeable takeoff. Per capita installed equipment rate thus stands at 264 m^2 and 203 m^2 per thousand, respectively, in Greece and Austria. Germany and Denmark follow, with 51 m^2 and 44 m^2 respectively. France comes tenth, with 4 m^2, well behind the present European average of 26 m^2 per thousand inhabitants. The Plan Soleil (Sun Program), launched three years ago, has led to sales picking up, particularly in mainland France.

To give an idea of the prospects being looked to, the goal set by the European Commission in its White Paper on Energy for the Future pointed to a total installed capacity of 100 million square meters in Europe by 2010. At the same time, ESTIF (the European Solar Thermal Industry Federation) evaluates the potential, in Europe, at 3-4 m^2 per capita, i.e. 100 times the present average. Such an installed rate would account for 6% of the European Union's final energy consumption.

The scope for growth is thus important, and solutions making for easy, economical integration of systems into old buildings as well as new ones have yet to be developed.

Solar thermodynamic electricity: a degree of maturity

When solar radiation is concentrated by means of an optical concentrator, high temperatures can be achieved. This principle, known since Antiquity, uses parabolic or cylindrical-parabolic collectors, or so-called "tower" power stations, where a multiplicity of movable heliostats reflect solar energy onto a single boiler, mounted on a tower. This allows heating of heat-transfer fluids to temperatures ranging from 250 °C to 800 °C. These fluids go on to heat steam, which powers a turboalternator, as in conventional power stations.

Prototype units, with capacities ranging from a few tens of kilowatts to about 10 megawatts, have been built, the world over, over the past two decades. In the Pyrenees Mountains, in the south of France, the Thémis power station was operated at the beginning of the 1980s. The largest commercial development, however, was completed by Luz Solar International, this firm building during the 1980s three cylindrical-parabolic-collector power stations, with a total combined electric power capacity of 354 MWe, supplying the grid in the area close to Los Angeles with high-value electricity, mainly during peak summer afternoon hours.


Eyewire Inc.

One of the three cylindrical-parabolic-collector solar thermodynamic facilities constructed in the 1980s by Luz Solar in California.

Despite the constructor filing for bankruptcy ten years ago, these power stations have remained in operation, and their productivity has kept rising; they are evidence of the maturity of this technology, with electricity generation costs of around 10-12 cents per kilowatt-hour.

A potential for improvement of 20-30% may yet be anticipated, particularly through direct steam generation inside the receiver, and optimized mirrors and selective coatings. On the European scene, Germany and Spain are carrying out a joint research effort on these issues, and an initial 50?MW unit is at the design stage, to be sited in Almeria province (Spain).

In the context of the financial facilities on offer through the World Environment Fund, programs are under consideration in a number of countries, such as Egypt, India and Brazil.

Solar photovoltaic electricity: the race to efficiency

Another way to get value out of solar energy consists in using direct conversion of light into electricity. This is the "**photovoltaic**" **effect**, taking place in specific materials known as **semiconductors**, whereby every **photon** of incident light enables one electron to be set in motion, thus generating an electric current (see Box F, *How is solar energy turned into electricity?*). The most commonly used material is **silicon**, which is found in abundance throughout the planet, employed to fabricate solar cells, which are then assembled into solar **modules** or **panels**.

Efficiencies commonly achieved for this conversion range from 10% to 20%, depending on whether amorphous, multicrystalline or monocrystalline silicon is used. The product involved should be specified, however: a laboratory-constructed cell, using high-purity silicon and sophisticated processes, may achieve an efficiency of 25%, close to the theoretical limit of 33% for a single-junction cell. Its manufacturing cost will then be such as to restrict utilization to specific market niches, e.g. electric cars intended as entrants in the famous Darwin-Adelaide Australian Solar Challenge.

In industrial mass-production, average efficiency, i.e. taking into account all sampling fluctuations, for crystalline silicon will be lower, usually in the 14-16% range. On the other hand, manufacturing cost will be lower, meaning the cost of the energy generated will be more attractive - and this is the criterion, rather than any other, relevant to the consumer.

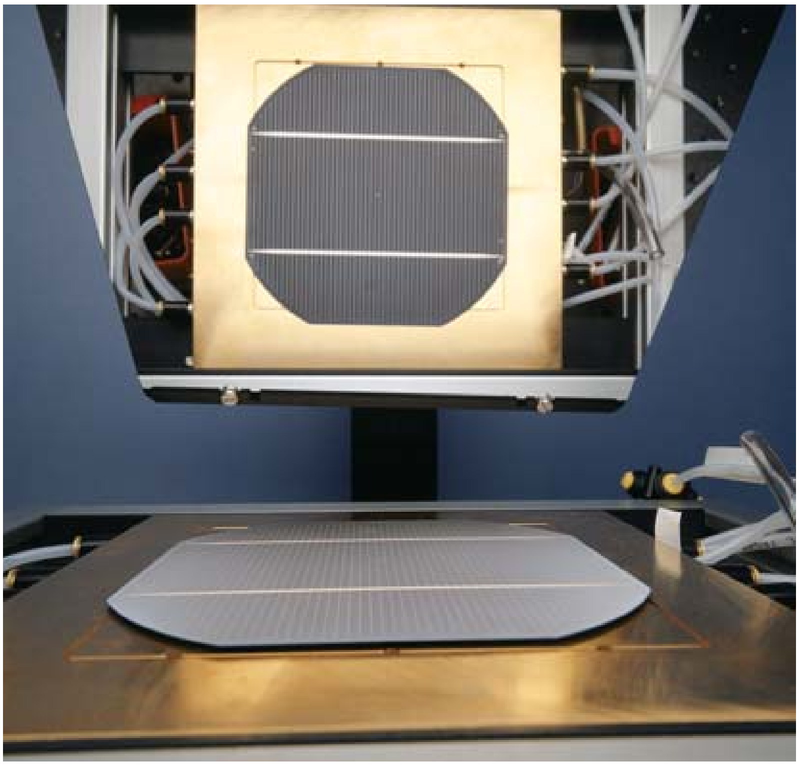
"Solar photovoltaic" electricity, as a whole, finds two distinct kinds of use, serving either for electricity supply at isolated sites, or injection of electricity into an electric power grid. The first application is the older, and the most widespread, if one considers the millions of systems installed worldwide. This started as early as the 1960s, for satellites, where solar photovoltaic modules won general acceptance, over most other alternatives, on grounds of weight and reliability.

Initial terrestrial applications spread in the 1970s and 1980s, mainly for industrial purposes (meteorological stations, telecommunications repeater stations, air navigation and marine beacons, cathodic protection), then for applications related to rural electrification, such as domestic lighting, audiovisual equipment and water pumping.

Recent years have seen a rise in the number of installations put into operation, with annual growth topping 20% for the past 20 years; in France, 90% of marine navigation aids are thus equipped, and in developing countries most telecommunications stations and radio repeaters use this energy source. Completion of rural electrification programs currently involves installing systems in batches of several thousand or tens of thousands.

The main characteristic of this first category of solar photovoltaic electricity applications is that they entail provision of batteries, when electricity requirements are out of phase with the solar resource.

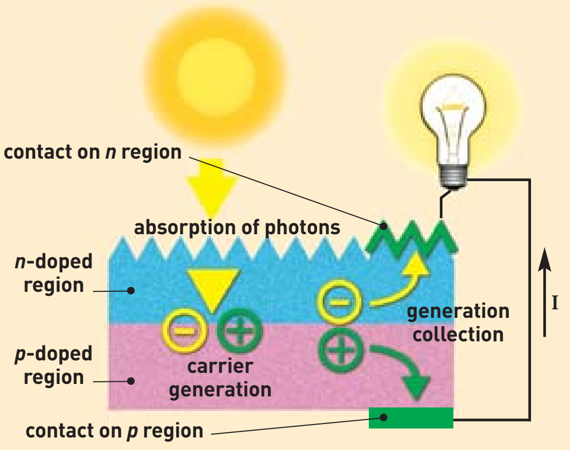
The relevant potential market is massive, bearing in mind the two billion denizens with no access to electricity. The main assets of solar energy, as regards this market, are its outstanding reliability - the most widely sold modules, crystalline-silicon-based, are now commonly subject to a twenty-year guarantee, with longer still expected lifetimes - and the absence of the distribution costs attached to conventional-technology solutions, whether it be use of electric generators powered by fossil energies (Diesel fuel oil, gasoline or natural



A. Gonin/CEA

Monocrystalline-silicon photovoltaic cells on a spectral-response measurement bench at CEA's Grenoble Center (eastern France). After silkscreen metallization and annealing, cells are tested by monitoring electric-current output for every wavelength in the solar spectrum range.

F How is solar energy turned into electricity?

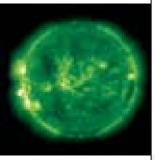


The photovoltaic effect used in solar cells (which are further assembled into modules, then into panels) for the direct conversion of the rays of sunlight into electricity involves the generation and transport of positive and negative electric charges through the action of light in a semiconducting material.

Silicon was selected for its electronic properties, characterized by presence of four electrons in its outermost shell (column IV of the Mendeleyev periodic table). In solid silicon, each atom is bound to four neighbors, and all the electrons in the outermost shell participate in the bonds. If a silicon atom is substituted for by an atom from column V (a phosphorus atom, for instance), one of the electrons is not involved in the bonds; it is thus free to move through the lattice. There is electron conduction, and the semiconductor is designated as an n-*type doped semiconductor*. If, on the other hand, a silicon atom is substituted for by an atom from column III (boron, for instance), one electron is missing if all bonds are to be maintained , and an electron can move in to fill this gap. One then speaks of hole conduction, and the semiconductor is said to be a *p*-type doped semiconductor. Atoms of elements such as boron or phosphorus are doping agents in silicon.

When an *n*-type semiconductor is brought into contact with a *p*-type semiconductor, the excess electrons from the *n* material diffuse into the p material. The initially *n*-doped region becomes positively charged, while the initially *p*-doped region takes on a negative charge. An electric field is thus set up between the *n* and *p* regions, tending to force electrons back into the *n* region, and equilibrium arises. A junction has been set up, and, if metallic contacts are placed onto the n and p regions, a diode is obtained.

When this diode is illuminated, photons are absorbed by the material, and every photon gives rise to an electron and a hole (this is termed an electron-hole pair). The diode junction keeps apart the electrons and the holes, giving rise to a potential difference between the *n* and *p* contacts, and a current passes, if a resistance is inserted between the diode contacts (see Figure).



A. Gonin/CEA

Front side, showing the contact grid and anti-reflective coating, of multicrystalline-silicon cells manufactured by Photowatt.

gas) or the extension of a main power grid to the point of use, with low returns when requirements are low. The second application is more recent, however it shows an even headier growth rate, at 30-40% per annum. This involves direct transformation of direct current from photovoltaic modules into alternating current. The electricity thus generated "straight from the Sun" is either used locally, or injected into the grid, depending on the optimization being sought. The economic advantage and current interest for this application arise from the fact the power may be sold to an electricity distribution utility, which, in some cases, may offer attractive purchase rates, to foster emergence of this technology.

Such "coupling" to the grid may be carried out in centralized fashion, with photovoltaic power stations of several megawatts capacity, such as those completed in the United States in the mid?1980s, The most common approach, currently, relies on the "distributed" character of the resource, taking the form of "domestic" developments, of a few kilowatts, known as "solar roofs": the pioneers, in this respect, were Switzerland and Germany, in the late 1980s. A number of demonstration operations or programs were completed during the 1990s, establishing the feasibility of individual dwellings fitted with 30-40 m^2 of photovoltaic collectors, which turn out to be self-supporting, taking the overall yearly balance, with summertime overproduction compensating winter underproduction. Presently, major programs are underway, mainly in Japan and Germany, these two countries having installed some 100,000 systems each, with aggregate capacities of 450 MW and 300 MW respectively. Japan is looking to 4.8 GW by 2010, and 40 GW by 2020 through such applications.

Taking all applications together, EPIA (the European Photovoltaic Industry Association) has set out a scenario which appears conservative, compared to the Japanese ambitions, leading to a global yearly market of 54 GW by 2020, and showing the potential for creation of 2.3 million jobs worldwide.

While by that time, even with such growth figures, the share of solar photovoltaic electricity will remain less than 1% of global consumption, its long-term potential, in other words some decades further on, is much greater, as shown by a survey by IEA (International Energy Agency): use of 40% of surfaces covered by existing buildings will lead, according to the country considered, to generating 20-60% of present electricity consumption, with no extra groundspace required. As regards France, which was not covered by the survey, interpolation between the figures for Spain, Italy and Germany would point to availability of 200 TWh, i.e. 40% of present-day electricity consumption.

Roberto Petronio/Total

Solar panels installed by Total in Morocco, as part of a rural electrification program.


ESA

Artist's impression of the European Envisat satellite in orbit.
Use of solar photovoltaic modules for satellites started as early as the 1960s, gaining general acceptance in this sector on grounds of weight and reliability.

The stakes are thus anything but marginal, justifying a proactive development policy. Presently, as for solar thermal energy, per capita installed equipment rate, in France, is 10 times lower than in Germany, and 15 times lower than in Japan.

Market growth goes hand in hand with price reductions. Wholesale prices for modules on the world market currently stand at around €3 per watt. Consideration of prices and sales volumes over the past twenty years shows a steady fall in prices, corresponding to a halving of prices every ten years. Future projection thus points to a price of the order of €1.6 per watt in 2010.

For a grid-connected photovoltaic system of a few kilowatts capacity, generation cost to the user, including costs for installation and the inverter, stands at about double the module price ex-factory, i.e. around 5-6 per watt.

Another component conducive to such price reduction, research remains essential to develop the technological solutions that will allow such large-scale dissemination. As regards basic materials, the spread of options being investigated ranges from today's silicon (whether crystalline or amorphous) to other candidates, allowing fabrication of thin, possibly flexible films, such as CIS (copper-indium diselenide), or even organic semiconductors, polymer-plastics based. A number of laboratories are even embarking on investigation of new concepts, which may yield higher efficiencies: three- or four-junction tandem cells are already approaching 40% efficiency. Further out, preliminary work has shown that innovative devices, involving a metallic intermediate band to utilize low-energy photons, or so-called "hot-carrier" or "quantum-well" designs could achieve theoretical efficiencies of the order of 80%.

As for systems, research thrust should bear on electricity storage, which accounts for a substantial part of overall costs, energy conversion, and management of these energy systems: the aim being to provide the user with a user-friendly interface, presenting operational scenarios based on predictive analysis of production and consumption, and generating alert signals in case of malfunction.

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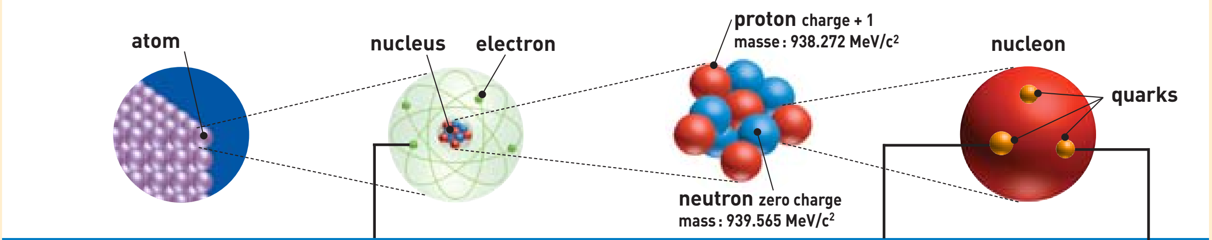
FOR FURTHER INFORMATION:

CEA's efforts in the field of solar energy will be covered in a forthcoming issue of Clefs CEA, to be devoted to the new energy technologies.

C

Elementary particles and fundamental interactions

Neutrinos are the stealthiest particles in the **standard model of particle physics**, the theoretical framework describing all known **elementary particles** and the **fundamental interactions** they mediate (see Table).
The basic constituents of matter, **fermions**, are partitioned into two main categories: **leptons**, which do not respond to **strong interaction**, and **quarks**, which are subject to all of the interactions. The six quarks form three pairs (up/down, charmed/strange, beauty/top). In the lepton category, the **charged leptons** (**electron** e^-, **muon** μ, **tau** τ) are involved in the **electromagnetic interaction** and the **weak interaction**, while **neutral leptons** (**electron neutrino** ν_e, **muon neutrino** $\nu\mu$, **tau neutrino** ν_τ) are only subject to weak interaction. In the standard model, neutrinos have zero mass, however experiments have shown they do have some mass, though very small, the exact value of which is as yet unknown. Involvement



		leptons able to move freely		**quarks** held captive in larger particles, they are not observed separately	
Fermions Common matter is made up of particles from this group.	first family	**electron** Responsible for electricity and chemical reactions. Charge: – 1. mass: 0.511 MeV/c^2	**electron neutrino** Has no electric charge, and interacts very seldom with the ambient medium.	**down** Electric charge: – 1/3. The proton holds one, the neutron two. mass: 5 – 8,5 MeV/c^2	**up** Electric charge: + 2/3. The proton holds two, the neutron one. mass: 1,5 – 4,5 MeV/c^2
Most of these particles were around just after the Big Bang. Presently only to be found in cosmic rays, and around accelerators.	second family	**muon** A more massive companion to the electron. mass: 105,658 MeV/c^2	**muon neutrino** Properties similar to those of the electron neutrino.	**strange** A heavier companion to "up." mass: 80 – 155 MeV/c^2	**charmed** A heavier companion to "down." mass: 1 000 – 1 400 MeV/c^2
	third family	**tau** Heavier still. mass: 1 777 MeV/c^2	**tau neutrino** Properties similar to those of the electron neutrino.	**beauty** Heavier still. mass: 4 000 – 4 500 MeV/c^2	**top** Heaviest in the family (observed in 1985): 180 times the proton mass. mass: 174 300 ± 5 100 MeV/c^2
Vector Bosons Fundamental particles carrying out transmission of all natural forces.		**photon** Elementary grain of light, vector for the electromagnetic force.	**gluon** Bearer of the strong force between quarks.	**$W^\pm$, Z^0** W^+ W^- Z^0 Bearers of the weak force, responsible for some forms of radioactive decay.	
Higgs Boson?		Responsible for "electroweak symmetry breaking."			

Tableau.
Constituants élémentaires.

of the various elementary constituents in the fundamental interactions is governed by their quantum numbers, or interaction charges (electric charge, color charge [1]...). To every constituent of matter is associated its **antiparticle**, a particle having the same mass and opposite charges. The **gravitational force**, which is not included in the standard model, acts on all fermions in proportion to their mass.
The table of elementary constituents of matter manifests another classification – independently from their involvement in fundamental interactions – into three generations, or families. From one family to the next, charged quarks and leptons having the same charges only differ by their mass. The electron, up quark and down quark, which all belong to the first family, are the lightest massive particles. They are stable particles, and the constituents of common matter. For instance, the **proton** is made up of two up quarks and one down quark; the **neutron**, of two down quarks and one up quark. Particles in the other two families are unstable, and rapidly decay into stable first-generation particles. This is why all the stable matter in the Universe is made up from constituents from the first family.
According to quantum mechanics, for an interaction to take place, at least one elementary particle, a **boson**, must be emitted, absorbed or exchanged. The **photon** is the vector for the electromagnetic interaction, the **W^+**, **W^-** and **Z^0** mediate the weak interaction, and **gluons** act as messengers for the strong interaction.
Quarks and charged leptons exchange photons, but conserve their electric charge after the exchange, the photon having no electric charge. Since the photon's mass is zero, the electromagnetic interaction's range is infinite. Having no electric charge, neutrinos are the only elementary fermions that are not subject to electromagnetic interaction.
In the electroweak theory (a unification of the weak and electromagnetic interactions), the weak interaction has two aspects: charged-current weak interaction, for which the interaction vectors are the W^+ and W^-; and neutral-current weak interaction, for which the mediator is Z^0. These two forms of weak interaction are active between all elementary fermions (quarks, charged leptons and neutrinos). The mass of these bosons being very large (80,000 MeV/c^2 for $W^\pm$, 91,180 MeV/c^2 for Z^0), the range of the weak interaction is tiny – of the order of 10^{-18} m. Since $W^\pm$ bosons have a nonzero electric charge, fermions exchanging such bosons undergo a change in electric charge, as of nature (flavor). Conversely, since the Z^0 boson has no electric charge, fermions exchanging one undergo no change in nature. In effect, neutral-current weak interaction is somewhat akin to exchanging a photon. As a general rule, if two fermions are able to exchange a photon, they can also exchange a Z^0. On the other hand, a neutrino has the ability to exchange a Z^0 with another particle, though not a photon.
Only those quarks that have a color charge exchange gluons, these in turn being bearers of a color charge. Thus, when a gluon exchange takes place between quarks, the latter exchange their respective colors. Gluons have zero mass, however, since they do bear a color charge, they are able to interact. The range of the strong interaction is consequently very restricted – of the order of 10^{-15} m.
The graviton, the vector for gravitational interaction, has not so far been observed.
Theory predicts that another fundamental interaction mechanism exists, responsible for the mass of elementary particles, for which the messenger is the Higgs boson, which remains as yet undiscovered. This boson makes it possible to assign a mass to elementary fermions of zero mass that interact with it.

fundamental interaction	**messenger**	**actions**
gravitational	graviton?	responsible for the mutual attraction of any two masses and for the law of falling bodies
electromagnetic	photon	responsible for the attraction between electrons and atomic nuclei, hence for the cohesion of atoms and molecules
weak	W^+, W^-, Z^0	the root cause of **thermonuclear fusion** inside the Sun, ensuring its longevity. β^- and β^+ radioactivity, and reactions involving neutrinos are weak interactions
strong	gluons	ensures the cohesion of the atomic nucleus

Table.
Fundamental interaction and elementary constituents.

[1] Color charge: a quantum number that determines whether a particle is involved in strong interaction. The color charge can take on three values: "red," "green," or "blue" – such colors bearing no relation to visible colors. Every quark bears one of the three color charges, every antiquark one of the three anticolor charges. Gluons bear double color–anticolor charges (eight possible combinations).