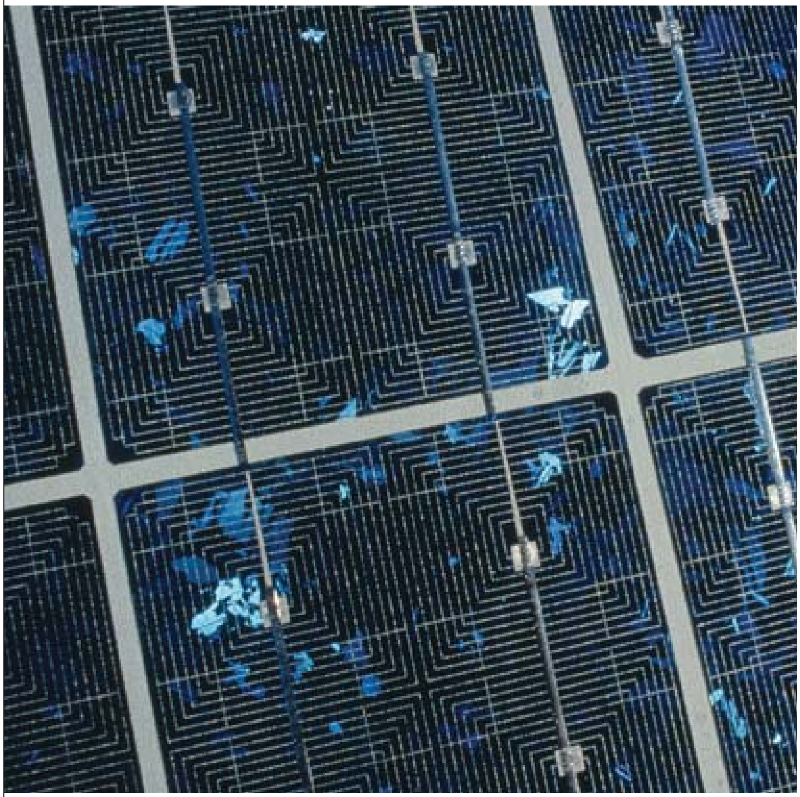
The three paths for solar energy

The three ways of making "direct" use of solar energy - the thermodynamic, thermal and photovoltaic paths - are targeted by new developments, aimed at improving their performance, and, most importantly, their economic competitiveness. CEA has been working on these pathways for some thirty years, to broaden their range of applications, and achieve cost reductions.



Coulon/CEA

Polycrystalline-silicon photovoltaic cells being tested at CEA/Cadarache.

Of the three paths for utilization of solar energy, the thermodynamic pathway had its moment in the limelight, some time back, with installations such as the Thémis power station, in France. Thermal utilization, for the direct heating of premises, or of water (swimming pools, water heaters, floor heating), remains an attractive solution, for which warranties, subsidies and technological enhancements help sustain an impetus. Direct transformation of solar radiation into electricity - **photovoltaics** - stands as the pathway most pregnant with advances, and is experiencing very rapid expansion.

Solar thermodynamic electricity

Concentrating solar radiation onto a single focus allows high temperatures to be achieved. This principle, know since Antiquity, uses either parabolic ("dish") or cylindrical-parabolic ("trough") collectors, or so-called "tower" power stations, where a multiplicity of movable heliostats concentrate the Sun's energy onto a single boiler, positioned on a tower. This allows heating of heat-transfer fluids, as a rule oil or molten salts, to temperatures ranging from 250 °C to 1,000 °C, depending on the technique implemented. These fluids go on to heat steam, which powers a turboalternator, as in a conventional thermal power station.

Prototype plants, with power outputs ranging from some tens of kilowatts (**kW**) to tens of megawatts (**MW**), have been built around the world over the past three decades. In the Pyrenees Mountains, in southern France, the Thémis power station, of 2 MW capacity, was operated in the early 1980s. The largest commercial development, however, was completed by Luz Solar International, this firm building, also in the 1980s, three cylindrical-parabolic-collector power stations, with an aggregate nominal power output of 354 **MWe**, supplying the Southern California Edison grid - which brings power to Los Angeles - with electricity during peak summer afternoon hours. These power stations stand as evidence of the relative maturity of this pathway, achieving electricity generation costs of around €0.1/**kWh**.

A potential for improvement of 20-30% may yet be anticipated, particularly through direct steam generation inside the receiver, and mirror optimization. The United States, Israel, and, in Europe, Germany and Spain (Almería solar power station) are conducting a joint research effort on these issues. Developments, combining in some cases gas turbines and solar energy, are announced in a number of countries, such as Egypt, Morocco, India, and Brazil. The concentrating solar thermodynamic pathway does, however, remain the preserve of cloud-free countries. Its future is being put in abeyance, owing to the spectacular rise of the photovoltaic pathway, simpler and more reliable as this is, even though it will remain more expensive for centralized generating capacities of a few megawatts or gigawatts (**GW**), for two to three decades yet.

Solar thermal energy

Solar thermal energy is used mainly by way of two applications: sanitary water heating, and heating of premises. As regards the former, four square meters enable the hot-water requirements of a family of four to be met, for an average outlay of €1,500-4,000. For the second application, 10-20 m^2 allow heating of an individual dwelling.

Auxiliary heating is necessary, to cater for the more climatically unfavorable periods. On average, over a year, a solar heating installation provides a rate of cover for requirements, and thus brings a saving on power bills, of some 50-70%. Depending on the types of complementary energy used, and energy substituted for, times for full return on investment range from 6 to 12 years. Such thermal collectors generate, over a year, 200-800 kWh/m^2, with efficiencies of 30-60%, depending on requirements, temperatures and type of usage. 200 kWh/m^2 correspond to intermittent use of high-temperature (over 55 °C) sanitary hot water. 800 kWh/m^2 is the figure achieved in the case of continuous, low-temperature heating. For this type of application, often referred to as "direct solar floor," the heat-transfer fluid exiting the collectors is directly piped 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 techno-economic terms.

Growth on the European market initially stood at a level of some 250,000 m^2/year in the 1980s. Introduction of new concepts, such as guaranteed solar results, and multiple sources of subsidies, induced heady growth, in France as in other countries, with surface areas sold rising by a factor 2-4, over the past five years. In the short term, the European market is estimated at several million square meters. In France, aids take the form of tax credits (40% in 2005), and regional and national grants (**Ademe**).


Coulon/CEA

Double-walled roof model, allowing natural air currents to cool a dwelling's temperature, being tested in a solar simulator at CEA/Cadarache.

Current technological developments are aimed at achieving cost reductions, through greater ease of integration and deployment into buildings. One promising path (*Face sud*, i.e. "South Face") consists in combining three functions into one and the same collector (three in one): covering, heat generation, and electricity generation. A heat-transfer circuit cools the module on its rear face, improving efficiency by 20% on average, and heats the floor. The proposed strategic orientation law for energy, in France, provides for an installation rate, by 2010, of 50,000 roofs/year complying with the *Face sud* concept. Such dwellings will generate 100% of the electric energy, and 60% of the thermal energy they consume.

Solar photovoltaic electricity


EyeWire

Tower power station built by Luz Solar International Corp., in California, one of the main commercial developments in the area of solar thermodynamic energy at the end of the 20th century.

Solar photovoltaic energy provides an attractive way of bringing down electricity distribution costs in some regions. Providing particularly high levels of availability, in most countries lying between the equator and the 45th parallel, this is an energy source of remarkable reliability, exhibiting a highly favorable energy and environmental balance (see Box D, ***How does a photovoltaic solar cell work?***).

Real advantages and definite constraints

Solar energy is a resource that is relatively well distributed, in geographical terms, thus being available in many locations. Consequently, use of **photovoltaic cells** or **modules** (see *High-tech cells for cheaper modules*) yields electricity generation "*in situ*," in immediate vicinity to utilization requirements. This is a crucial asset for solar electricity. This allows obviating the distribution costs inherent in conventional solutions, be it use of electric generators, fed by **fossil energies** (diesel oil, gasoline or gas), or the extension of a main power grid down to the point of use.

Indeed, in the former case, **fuel** availability and supply costs, down to the location involved, must be factored in, along with periodic maintenance requirements. In the latter case, the costs of extension, or increasing line capacity push up in a very major way the price per kilowatt-hour, especially if requirements are low. If on the other hand requirements are high, amortization per kilowatt-hour will be proportionately lower.

The absence of any mechanical motion or fluid circulation results in outstanding reliability for photovoltaic electricity. The most widely sold modules, **crystalline-silicon** based, are now commonly covered by a twenty-year guarantee, with substantially longer expected lifetimes. The energy balance is positive, since a photovoltaic module will yield back the energy required to make it in from one to four years' exposure to sunlight, depending on fabrication technology.

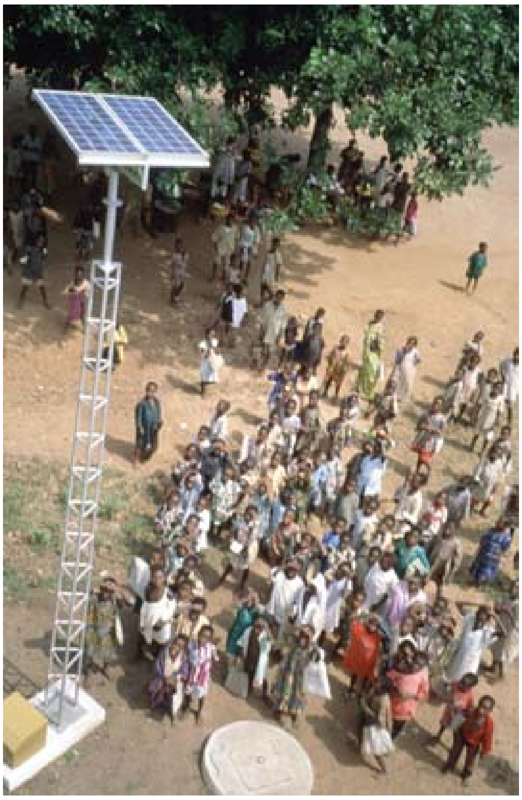
Photovoltaics are, as of now, unrivalled, as regards meeting requirements for a few kilowatt-hours per day, where there is no power grid. For instance, typical requirements in a developing country, to cover lighting, a radio-CD reader, a battery charger, and a small black-and-white television, correspond to a photovoltaic module area of 0.5 m^2. Household requirements, relating to a modern level of domestic comfort, including television, hi-fi and electric household appliances, or a pumping station for a village water distribution system, will require several kilowatt-hours per day. At all event, systems involving surface areas of the order of the square meter, or some ten square meters, will be suitable, and rarely lead to integration problems.

On the other hand, use of solar electricity still remains largely underdeveloped, as regards heavier requirements, associated to village economic activities and mechanization. This is the present challenge. Development of areas currently lacking a power grid has to be achieved not through investment in grid construction, but by setting up a stand-alone solar world, deploying specific direct-current, high-efficiency equipment.

Solar photovoltaic electricity may be used in two ways: to supply electricity to remote locations, or to inject electricity into a grid.

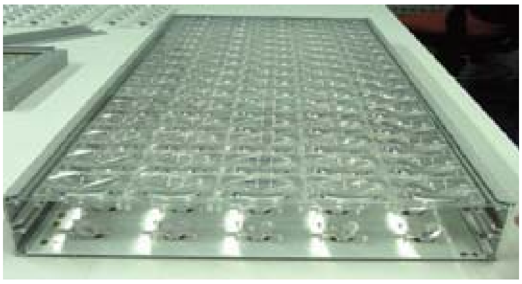
Rising power supply to remote locations

The first-mentioned application is the older, and the more widespread, if one considers the millions of systems installed worldwide. This type of application emerged as early as the 1960s, for satellites, for which photovoltaic solar modules gained widespread acceptance, mainly on grounds of weight and reliability. Initial terrestrial applications spread in the 1970s, essentially for technical purposes (power supplies for meteorological stations, or telecommunications repeater stations). The 1980s saw the successive emergence of numerous market niches, such as marine or air navigation beacons, pipeline cathodic protection, street furniture, and, most crucially, in particular through the impetus provided by CEA - the organization scoring a succession of world firsts in this respect - rural electrification, this covering, basically, such requirements as household lighting, audiovisual devices, and water pumping. Water supplies, and water treatment to make it drinkable, at remote sites, will represent, in the near future, a major market, considering the extent of the environmental issues that may be foreseen in this respect.



Michel Courillon/Ademe 1998

Two solar panels provide part of the power supply for the village of Towé, Benin.



Isofoton

One solution to bring down costs for solar photovoltaic energy is to use only a minimum number of high-efficiency cells, fitted with optical concentration systems, as this 1-**kWp** prototype, fabricated by CEA and Spanish manufacturers Isofoton.

Recent years have seen a rising number of developments being completed, for each of these sectors. Worldwide, 90% of marine navigation aids are thus equipped. In developing countries, all telecommunications stations and radio repeaters use this energy source. Completion of rural electrification programs currently involve installing systems in batches of several thousand systems. Nearly four million were in service in 2004.

The main characteristic of this first category of solar electricity applications is that they entail use of batteries, when electricity requirements are out of phase with electricity generation, in other words with the resource, i.e. the Sun (see *Storage of photovoltaic electricity*).

Increasingly rapid growth for electricity "as the Sun goes"

The second, more recent application is endowed with an even more rapid rate of growth. This involves direct transformation of the direct current delivered by photovoltaic modules into alternating current, identical to that used in low-voltage electric systems. The electricity thus generated "as the Sun goes" is either consumed locally, or injected into the grid. The economic advantage of, and current interest for, this solution arise from the fact the electricity thus generated may be sold to the power utility, at subsidized prices: €0.5/kWh in Germany, €0.15-0.30/kWh in France. In the latter country, a number of aids further complement this: tax credits of up to 40%, regional subsidies.

The usual approach takes advantage of the *distributed* nature of the resource, taking the form of "household" installations, rated at 3-5 kW, positioned on every roof. The precursors, with respect to such "solar roofs," were Japan and Germany, in the late 1980s. Currently, major programs are under way, mainly in Japan and in Northern Europe, at a pace of some 20,000 roof-mounted systems installed every month. Such "coupling" to the grid could be effected, at a later date, in centralized fashion, with photovoltaic power stations of a few megawatts capacity. Finally, if 5% of desert surfaces were to be covered with modules, it would be feasible, at some future date, to provide electricity to meet all of the planet's requirements.

Consistently falling production costs

In 2003, the market stood at an aggregate module power output of 745 MW, with an aggregate turnover, for the photovoltaics sector, of 5 billion euros. Growth is heady, and increasingly rapid, standing at 20% average annual growth, over the past ten years, and topping 37% over the past three years. In 2004, output will pass the gigawatt mark. The launch of large-scale photovoltaic-roof dissemination programs in Japan, and subsequently in Germany, has resulted in some scarcity.

Projections, drawn up on the basis of annual growth assumptions of 20% and 25%, have all been outstripped. By 2020, according to the estimate set out by the European Photovoltaic Industry Association (EPIA), the market should stand at 50 GW yearly, and 1,000 GW in 2030. To date, the major manufacturing countries, in this respect, are, in decreasing order of output: Japan (44%), the European Union (29%), and the United States (17%). The main protagonists are oil (BP, Shell, Total) or electronics (Kyocera, Sharp, Sanyo) majors. Photowatt, a company originating in France, and based in the Rhône-Alpes region, is ranked fourth in Europe, and eleventh worldwide.

Wholesale prices for modules on the international market currently stand at around €2.7/W (ex-factory, for large production batches). They have undergone, over the past twenty years, a steady evolution, evidencing halving every ten years. Future projection thus points to a price of the order of €1.5/W in 2010. For a grid-coupled photovoltaic system of a few kilowatts capacity, generation cost for the user, including cost for installation and the inverter, stands at around €4/W for roof mountings, €6/W when integrated into a roof. For a system including battery storage, prices, depending on the application, lie in the €6-10/W range.

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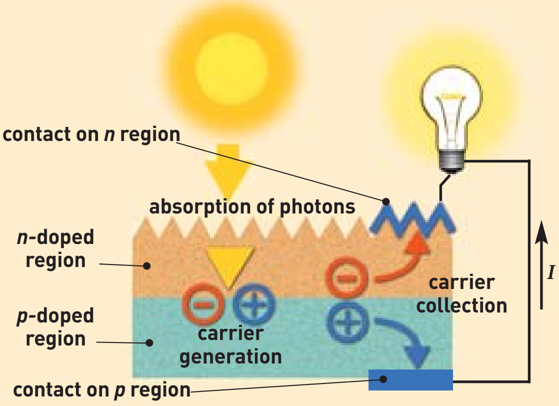
D How does a photovoltaic solar cell work?



The photovoltaic effect used in solar cells allows direct conversion of light energy from the Sun's rays into electricity, by way of the generation, and transport inside a semiconductor material, of positive and negative electric charges, through the action of light. This material features two regions, one exhibiting an excess of electrons, the other an electron deficit, respectively referred to as *n-type doped*, and *p-type doped*. When the former is brought into contact with the latter, excess electrons from the *n* material diffuse into the *p* material. The initially *n*-doped region becomes positively charged, and the initially *p*-doped region negatively charged. An electric field is thus set up between them, tending to force electrons back into the *n* region, and holes back into the *p* region. A junction (so-called *p-n* junction) has been set up. By placing metallic contacts on the *n* and *p* regions, a diode is obtained. When the junction is illuminated, photons having an energy equal to, or higher than, the width of the forbidden band, or band gap, yield their energy to the atoms, each photon causing an electron to move from the valence band to the conduction band, leaving behind it in turn a hole, also able to move around the material, thus giving rise to an electron-hole pair. Should a load be positioned at the cell's terminals, electrons from the *n* region will migrate back to the holes in the *p* region, by way of the outside connection, giving rise to a potential difference: an electric current passes (see Figure).

The effect thus involves, basically, the material's semiconducting properties, and its doping, to improve conductivity. Silicon, now used in most cells, was selected for the presence of four valence electrons in its outermost shell (column IV of the Mendeleyev periodic table). In solid silicon, each atom - termed a tetravalent atom - is bound to four neighbors, and all electrons in the outermost shell participate in the bonds. Should a silicon atom be substituted for by an atom from column V (a phosphorus atom, for instance), one of its five valence electrons is not involved in the bonds; as a result of thermal agitation, it soon moves to the conduction band, thus becoming free to move through the crystal, leaving behind it an immobile hole, bound to the doping atom. 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), carrying three valence electrons, one electron is missing, if all bonds are to be maintained, and an electron may quickly move in to fill this gap, taking up the vacant orbital, as a result of thermal agitation. A hole thus arises in the valence band, contributing to conduction, and the semiconductor is said to be a *p-type doped semiconductor*. Atoms of elements such as boron or phosphorus are thus doping agents in silicon. Photovoltaic cells are assembled into modules.

Note: In *Organic photovoltaic cells: towards an all-polymer path...*, you will find the operating principle of organic photovoltaic cells (Box, p. 122).

Operating principle of an organic photovoltaic cell

Following absorption of photons by the polymer, bound electron-hole pairs (excitons) are generated, subsequently undergoing dissociation. Owing to inherent limitations in organic materials (exciton lifetime, low charge mobility), only a small fraction of photon-generated electron-hole pairs effectively contribute to the photocurrent. One of the main ideas is to achieve volume distribution of the photogeneration sites, to enhance exciton dissociation. This approach is based on increasing junction surface area, through deployment of an interpenetrating network of the donor-acceptor (D-A) type, effecting transport of holes (P^+) to the anode (indium-tin oxide [ITO]), and of electrons (e^-) to the metallic cathode (made e.g. of aluminum [Al]). While quantum separation efficiency, for photoinduced charges in systems associating a semiconducting polymer (of PPV or polythiophene type) with a fullerene derivative (PCBM), is thus close to unity, the challenge now is to restrict recombination and trapping processes limiting charge transport and collection at the electrodes, to improve overall device efficiency, this currently still being low (less than 5%). The rise of the pathway is also heavily dependent on mastery and understanding of cell aging mechanisms, but equally on mastery of thin-film technologies, to achieve protection of the device against atmospheric oxygen and water vapor.

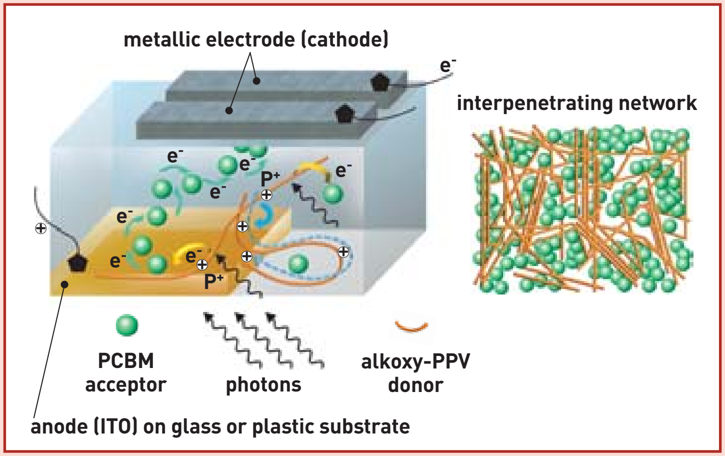


Figure from a presentation by S. Sariciftci (www.lios.at)

The blue dotted line shows the trajectory of holes inside the material.

A The many states of energy

“Nothing lost, nothing created,” as Lavoisier, the father of modern chemistry, wrote in his day. This motto, true as it is of chemical species, applies equally to energy. Indeed, energy is a multifarious entity, which may transform into highly diverse aspects. However, the **primary energies** that may be directly accessed in nature are limited in number: such are **fossil energies** (coal, oil, natural gas), **nuclear energy**, and **renewable energies** (hydro energy, **biomass** energy, solar energy, wind energy, geothermal energy, tidal energy). These primary energies are the constituents of what is known as the ***primary energy mix*** (see Figure 1).

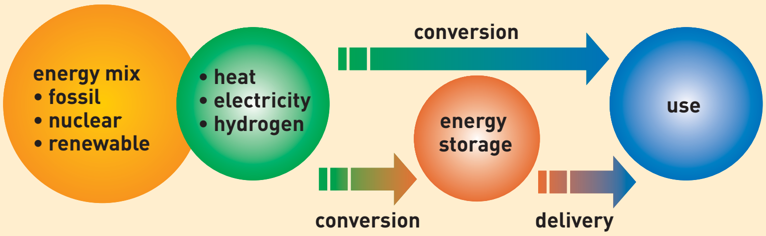


Figure 1.
The energy scheme.

For most applications, energy must be **converted** to make it compatible with the use under consideration. Of course, nature, highly ingenious as it is, devised the very first **energy converters**, namely living beings. Plants, through **photosynthesis**, effect the conversion of radiant light energy into chemical energy. The human body itself allows, in particular, the conversion of chemical energy into mechanical energy, by way of the muscular system. Subsequently, humans went on to invent large numbers of converters (see Figure 2). The first such converter, chronologically, is quite simply fire, converting chemical energy (combustion) into light, and heat. Of more recent origin, a television set carries out conversion of electricity into light energy (pictures) and mechanical energy (sounds). In fact, many energy systems involve a combination of a number of converters, as e.g. a nuclear power station, effecting as it does the conversion of nuclear energy into thermal energy (reactor), then into mechanical energy (turbine), finally through to electric energy (alternator). Unfortunately, the **second principle of thermodynamics** tells us that any energy transformation carries a cost: a more or less extensive portion of the energy involved is dissipated in the form of unusable heat (through friction in a mechanical system, for instance). In the case of a present-generation nuclear power station, the electric energy generated only amounts to one third of the nuclear energy initially contained in the fuel.

Of course, matters would be altogether too simple, however, if energy could be consumed as and when it is generated, on the very site where it is produced. In very many cases, energy-consuming sites may be far removed from the production site, production and concomitant demand, moreover, not always being matched (as with photovoltaic electricity in nighttime, for instance). Sound energy management thus requires deployment both of an **energy distribution network**, and of **energy storage** capabilities.

Energy transport is effected by means of an **energy carrier**. Currently, the two main such carriers are **electricity**, and **heat**. Tomorrow, however, a new carrier may become dominant: **hydrogen**, this being converted into electricity and heat by means of **fuel cells**.

Finally, if energy is to be available at all times, it is essential that there should be the ability to store it: to “get it in a can,” so to speak. Such **storage** may take a variety of forms. Energy may be stored in **mechanical** form (*potential energy*, in the case of the water reservoir of a hydroelectric dam, or *kinetic energy*, in the case of a flywheel), or in **thermal** (hot-water tank), **chemical** (gasoline tank, primary and **storage batteries**), or even magnetic (**superconducting** coil) form.

Energy management is thus a complex, involved craft, combining production, transformation, transport, and storage. In the current context of energy debate, it is becoming increasingly apparent that, tomorrow, energy networks will grow in size and number, in accordance with a multimodal approach (concurrent management of a number of networks combining diversified energy sources). **New energy technologies** are thus bound to play an essential part in these developments.

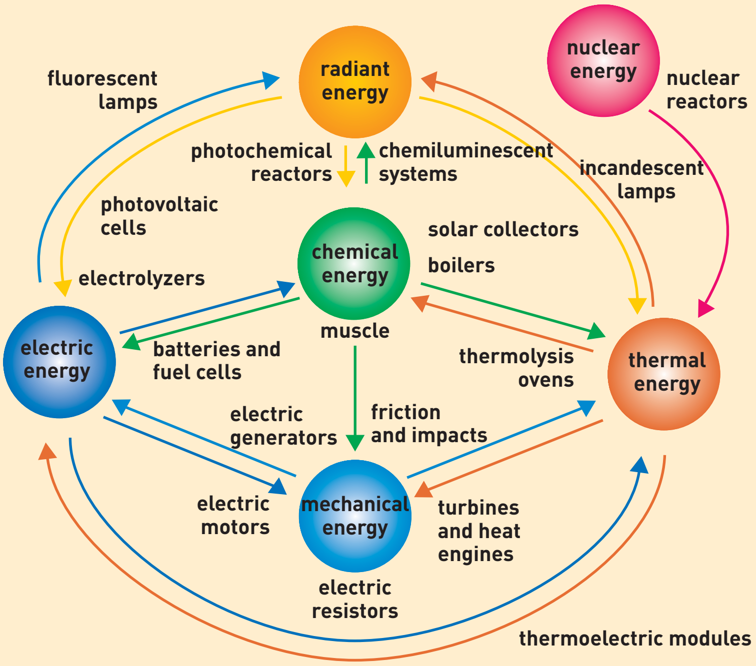
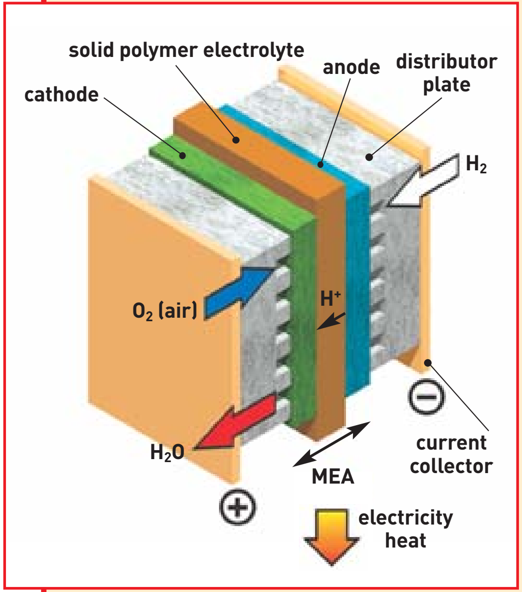


Figure 2.
Conversions of the six main forms of energy, with a few examples of energy converters.

C

How does a fuel cell work?



Operating principle of the fuel cell: the example of the proton-exchange membrane fuel cell. MEA stands for membrane-electrode assembly.

The fuel cell is based on a principle discovered quite some time ago, since it was in 1839 that Sir William Grove constructed the first electrochemical cell working with hydrogen as its fuel, thus demonstrating the ability to generate electric current through direct conversion of the fuel's chemical energy. Since the fuel cell has the special characteristic of using two gases - hydrogen H_2 and oxygen O_2 - as its electrochemical couple, the oxidation-reduction reactions occurring inside the fuel cell are particularly simple.

The reaction takes place inside a structure (the basic electrochemical cell), consisting essentially in two electrodes (the anode and cathode), separated by an electrolyte, i.e. a material that lets ions through. The electrodes employ catalysts, to activate, on the one side, the hydrogen oxidation reaction, and, on the other, the oxygen reduction reaction.

In the case of an acid-electrolyte cell (or proton exchange membrane fuel cell), the hydrogen at the anode is dissociated into protons (or hydrogen ions H^+) and electrons, in accordance with the oxidation reaction: $H_2 \rightarrow 2\ H^+ + 2\ e^-$. At the cathode, the oxygen, the electrons and the protons recombine to yield water: $2\ H^+ + 1/2\ O_2 + 2\ e^- \rightarrow H_2O$. The principle of the fuel cell is thus the converse of that of water electrolysis. The thermodynamic potential for such an electrochemical cell, consequently, stands at around 1.23 volt (V). However, in practice, the cell exhibits a voltage of about 0.6 V for current densities of 0.6-0.8 A/cm^2. The efficiency of such a fuel cell is thus equal to about 50%, the energy dissipated naturally being so dissipated in the form of heat.

Storage batteries, cells and batteries: constantly improving performance

Storage batteries – also known as accumulators, or secondary batteries – and batteries – so-called primary batteries – are electrochemical systems used to store energy. They deliver, in the form of electric energy, expressed in watt–hours (Wh), the chemical energy generated by electrochemical reactions. These reactions are set in train inside a basic cell, between two electrodes plunged in an electrolyte, when a load, an electric motor, for instance, is connected to its terminals. Storage batteries are based on reversible electrochemical systems. They are rechargeable, by contrast to (primary) batteries, which are not. The term "battery" may further be used more specifically to denote an assembly of basic cells (whether rechargeable or not).

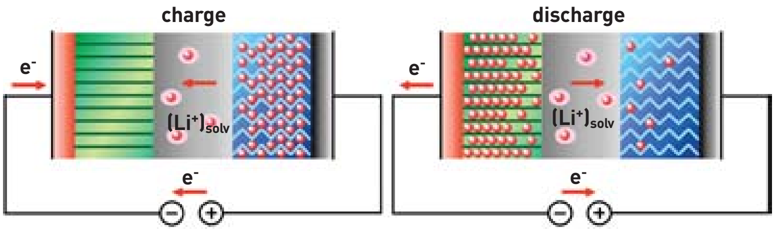
A storage battery, whichever technology is implemented, is essentially defined by three quantities. Its gravimetric (or volumetric) energy density, expressed in watt–hours per kilogram (Wh/kg) (or in watt–hours per liter [Wh/l]), corresponds to the amount of energy stored per unit mass (or per unit volume) of battery. Its gravimetric power density, expressed in watts per kilogram (W/kg), measures the amount of power (electric energy delivered per unit time) a unit mass of battery can deliver. Its cyclability, expressed as a number of cycles, (1) characterizes storage battery life, i.e. the number of times the battery can deliver an energy level higher than 80% of its nominal energy; this quantity is the one most frequently considered for portable applications.

Up to the late 1980s, the two main technologies prevalent on the market were lead–acid storage batteries (for vehicle start-up, backup power for telephone exchanges…), and nickel–cadmium storage batteries (portable tools, toys, emergency lighting…). Lead–acid technology, more widely referred to as lead–acid batteries, or lead batteries, is also denoted as lead–acid systems. Indeed, the chemical reactions employed involve lead oxide, forming the positive electrode (improperly termed the cathode), and lead from the negative electrode (anode), both plunged in a sulfuric acid solution forming the electrolyte. These reactions tend to convert the lead and lead oxide into lead sulfate, further yielding water. To recharge the battery, these reactions must be reversed, through circulation of a forced current. The disadvantages found with lead–acid technology (weight, fragility, use of a corrosive liquid) resulted in the development of alkaline storage batteries, of higher capacity (amount of energy delivered during discharge), yielding however a lower electromotive force (potential difference between the system's terminals, under open circuit conditions). Electrodes for these systems are either based on nickel and cadmium (nickel–cadmium storage batteries), or nickel oxide and zinc (nickel–zinc storage batteries), or silver oxide coupled to zinc, cadmium, or iron (silver-oxide storage batteries). All these technologies use a potassium hydroxide solution as electrolyte. Lead–acid technologies, as indeed alkaline batteries, are characterized by high reliability, however gravimetric energy densities remain low (30 Wh/kg for lead–acid, 50 Wh/kg for nickel–cadmium).

In the early 1990s, with the growth in the portable device market, two new technological pathways emerged: nickel–metal hydride storage batteries, and lithium storage batteries (see Box on *Operating principle of a lithium storage battery*). The first-mentioned pathway, involving a nickel-based positive electrode and a negative electrode – made of a hydrogen-absorbing alloy – plunged in a concentrated potassium hydroxide solution, allowed gravimetric energy densities of 70–80 Wh/kg to be achieved. The second pathway had already been targeted by research around the late 1970s, with a view to finding electrochemical couples exhibiting better performance than the lead–acid or nickel–cadmium storage batteries used up to that point. Initial models were thus designed around a metallic-lithium-based negative electrode (lithium-metal pathway). However, that technology was faced with issues arising from poor reconstitution of the lithium negative electrode, over successive charging operations. As a result, around the early 1990s, research was initiated on a new, carbon-based type of negative electrode, this serving as a lithium-insertion compound. The lithium-ion pathway was born. Japanese manufacturers soon made their mark as leaders in the field. Already in business as portable device manufacturers, they saw the energy source as numbering among the strategic components for such devices. Thus it was that Sony, not initially involved in battery manufacture, decided, in the 1980s, to devote considerable resources to advance the technology, and make it suitable for industrialization. In February 1992, Sony announced, to general stupefaction, the immediate launching of industrial production of lithium-ion storage batteries. These early storage batteries exhibited limited performance (90 Wh/kg). Since then, these batteries have seen notable improvement (from 160 Wh/kg to over 180 Wh/kg in 2004), owing, on the one hand, to the technological advances made (reduction in the unproductive fraction of battery weight and volume), and, on the other, to optimization of materials performance. Gravimetric energy densities of over 200 Wh/kg are expected around 2005.

(1) One cycle includes one charge and one discharge.

Operating principle of a lithium storage battery



$\langle H\rangle + Li^+ + e^- \longrightarrow \langle HLi\rangle$
$\langle MLi\rangle \longrightarrow \langle M\rangle + Li^+ + e^-$

$\langle HLi\rangle \longrightarrow \langle H\rangle + Li^+ + e^-$
$\langle M\rangle + Li^+ + e^- \longrightarrow \langle MLi\rangle$

During use, hence during discharge of the storage battery, lithium released by the negative electrode (<H>: host intercalation material) in ion form (Li^+) migrates through the ion-conducting electrolyte to intercalate into the positive electrode active material (<MLi>: lithium-insertion compound of the metal oxide type). Every Li^+ ion passing through the storage battery's internal circuit is exactly compensated for by an electron passing through its external circuit, thus generating a current. The gravimetric energy density yielded by these reactions is proportional both to the difference in potential between the two electrodes, and the quantity of lithium intercalating into the insertion material. It is further inversely proportional to system total mass. Now lithium is at the same time the lightest (molar atomic mass: 6.94 g), and the most highly reducing of metals: electrochemical systems using it may thus achieve voltages of 4 V, as against 1.5 V for other systems. This allows lithium batteries to deliver the highest gravimetric and volumetric energy densities (typically over 160 Wh/kg, and 400 Wh/l), 50% greater, on average, than those of conventional batteries. The operating principle of a lithium storage battery remains the same, whether a lithium-metal or carbon-based negative electrode is employed. In the latter case, the technological pathway is identified as lithium-ion, since lithium is never present in metal form in the battery, rather passing back and forth between the two lithium-insertion compounds contained in the positive and negative electrodes, at every charge or discharge of the battery.