

# A sustained **government effort** to foster **new energy technologies**



Photo: Air

Development of innovative, less energy-hungry and less polluting technologies, particularly in the transportation area, presents a major challenge, in terms of competitiveness, for France.

**Split as it is between national government funding and European provisions**, the French support scheme for the development of new energy technologies must avoid fragmentation of efforts.

**T**he main areas the nation's effort must address, in the field of new energy technologies (NETs), in France, it is generally agreed, should include: development of innovative, less energy-hungry technologies, in particular in transportation and construction, research on new **energy carriers**, such as **hydrogen**, or on **energy converters**, such as **fuel cells**, improved processes for **greenhouse-gas** treatment (**CO<sub>2</sub>** capture and **sequestration**), or processing of downstream, end-of-cycle products from the various pathways, together with R&D in the area of **renewable energies** of limited environmental impact (**photovoltaic** solar power, wind power, **biomass** power...).

Mastery of such technologies will be a strategic asset for sustainable development. The stakes, in terms of competitiveness, are considerable. It is to be desired that France take up a leading position as regards these key technologies, to secure a competitive advantage for its economy, and its business concerns. The country is allocating a number of financial resources to that purpose, the main source of funding, on a national level, coming from the civil research and development budget (BCRD: *budget civil de recherche et de développement*), in which the share devoted to energy has stood at around 7.5% for the past 10 years, i.e. some €570 million in 2001.

CEA provides virtually all the resources committed to the energy targets set by the civil R&D budget, the sector accounting for close to 60% of its goal-direc-

ted research effort, largely dedicated to nuclear power. Next in line is **Ademe**, its work being directed at consumption control, development of renewable energies, and environmental protection, together with **Anvar**, and the Ministries charged with research and industry.

Europe is equally involved in these issues, and curbing of greenhouse gases is included in the objectives of the **6th Framework Program (FP6)**. This has been allocated a budget of €810 M for energy, over 4 years (€640M for transportation, €250 M for the environment, marginally available for energy issues).



Jeumont

Wind-turbine bank at the Escales-Comillac site, Aude département (southern France). Wind and biomass are among the energy sources targeted by government development support.



It must be acknowledged, however, that these monies are often spread over a large number of research directions.

## Going for the technological breakthrough

The challenges, in terms of competitiveness, are such that the approach for these issues is necessarily on a European, or even global, scale. Nevertheless, fragmentation of the effort is to be avoided. An effective research and development policy, the sole means of achieving large-scale, wide-ranging results, entails, first of all, close consultation between business concerns and research organizations, and ambitious coopera-

tive programs, at a tempo and on a time scale consonant, most crucially, with short-term, concrete applications. One should go for the technological breakthrough, however this is necessarily preceded by a number of stages.

Along these lines, the French government set up, in 2003, a working group on technological breakthroughs. Comprising mainly representatives from manufacturers and laboratories (government departments also being represented), chaired by a manufacturer, this had the remit of identifying priority goals and directions for French and European research, and submit to government recommendations as to the evolution of support schemes for research and innovation, to achieve these objectives. Its report noted that adding together government funding from the various European Union member states and FP6 monies resulted in a research effort, in the area of energy, lower (by 20% probably) than what the United States and Japan are each committed to. The working group drew up a balance sheet, and arrived at proposals taking on board global requirements in terms of energy, technology, equipment and infrastructure, and government policies. It carried out a long-range forecasting exercise, setting out a longer-term French research and innovation strategy, to direct government choices on a national level, form the basis for a French initiative to impel European Union action, provide reference points for international scientific debates, and serve as an aid to businesses for their own decisions to achieve improved competitiveness. The working group put forward recommendations, combining objectives and feasibility prospects.

## NETs, a strategic education area for INSTN

New energy technologies (NETs) are one of the sixteen strategic education areas selected by CEA, following the reorientation of the syllabi at the National Nuclear Science and Technology Institute (INSTN: Institut national des sciences et techniques nucléaires), at the behest of the High Commissioner for Atomic Energy.

As a higher education institute managed by CEA (its remit is to secure revenues from the organization's expertise at the highest level, with reference to higher education and industry, be it in the form of initial training, or continuing education), INSTN has been involved for some years with NETs. As regards initial training, <sup>(1)</sup> the institute is a participant (or will be participating from 2005) in specialized master's degree courses related to NETs, for instance at Grenoble, on the hydrogen cycle, and Saclay, on materials for energy structures.

Thus, in 2005, INSTN, in association with the Petroleum and Engines School (École du pétrole et des moteurs, run by IFP), Paris-X University, and the national engineering schools in the PariTech Network (École polytechnique, École des mines, Institut national agronomique Paris-Grignon...) will offer at Saclay a master's degree on the theme of energy conservation and the environment. This new degree course will include a module from the current first-year PhD-level diploma (DESS) on The economy and energy policy (government-approved jointly via INSTN-Saclay and Paris-X University), providing students with a sound techno-economic background on renewable energies as a whole, and NETs in particular (hydrogen and fuel cells, particularly).

As regard continuing education, <sup>(2)</sup> study sessions, designed with CEA's Innovation Laboratory for New Energy Technologies and Nanomaterials (LITEN: Laboratoire d'innovations pour les technologies des énergies nouvelles et les nanomatériaux:) have already been held for the past three years, on such topics as hydrogen, fuel cells, photovoltaics, and energy storage. The main aim of these courses is to survey the state of the art, in terms of knowledge achieved, at CEA as elsewhere, with respect to these technologies, to engage the attention of researchers, industry employees, or government agency and institution personnel wishing to take part in such development.

Concurrently, another training course has been set up, in collaboration with Ademe, on decentralized electricity production in a rural environment (COOPER: Concepts et outils pour les programmes d'électrification rurale).

Finally, every year since 2002, a summer school on energy and sustainable development in the Mediterranean area is held in Tunis. Energy efficiency, and the place of renewable energies are topics comprehensively addressed on these occasions..

> Paul Maître

Institut national des sciences et techniques nucléaires  
CEA Saclay Center

## Two strong directions for R&D

Two strong thematic directions emerge, for R&D: prioritizing energy efficiency in its three major utilization sectors (transportation, residential-tertiary, and industry), through notably increased government and private-sector budgets; and, with respect to energy offer, prioritizing R&D on synthesis fuels obtained from biomass, CO<sub>2</sub> sequestration, and, as regards nuclear power, safety, waste processing, and Generation IV.

At the same time, France has set itself the aim of standing as a major partner for research programs concerned with hydrogen and fuel cells, photovoltaics, power networks and electricity storage, hydrocarbon fuel production from fossil energy, fusion power, offshore wind power, and extraction-production of fossil energies.

The issue must now be addressed, as to what the best tools are, to implement these strategic directions, and of further targeting. The national level, a prerequisite though it be, will not be adequate for an ambitious action, that will require Europe to increase quite conspicuously support for NET research. Raising this to the same level as for biotechnologies would result in a three-fold increase (€2.4 billion, as against €0.8 billion currently).

> Jean-Claude Hulot  
Ministry for Research  
Paris

(1) With respect to university education, INSTN is present in 20 specialized master's degree subjects, in collaboration with some fifteen universities.

(2) In the context of continuing education, INSTN trains 8,000 individuals every year, one third of these coming from CEA.

# 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).

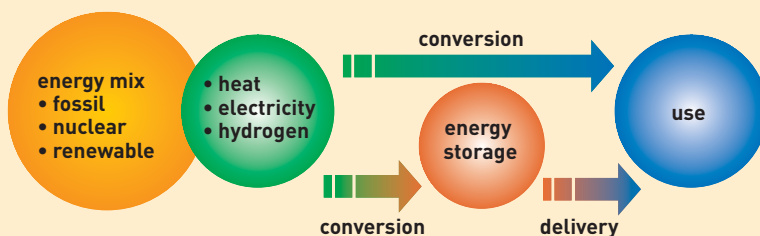


Figure 1. The energy scheme.

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.

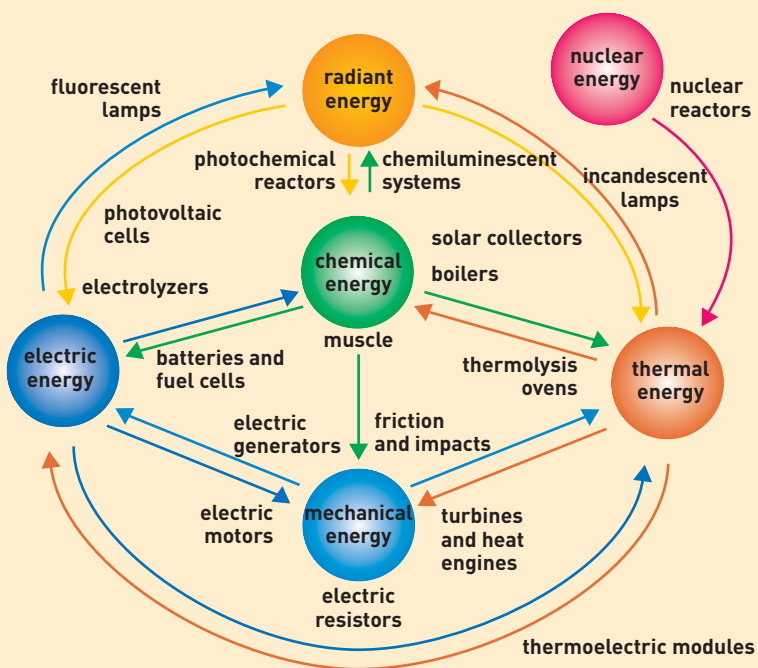
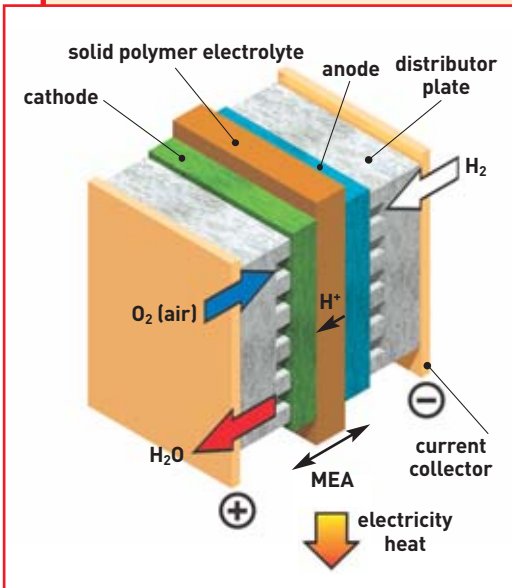


Figure 2. Conversions of the six main forms of energy, with a few examples of energy converters.

**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<sup>2</sup>. 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.

# E Storage batteries, cells and batteries: constantly improving performance

**S**torage 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, <sup>(1)</sup> 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

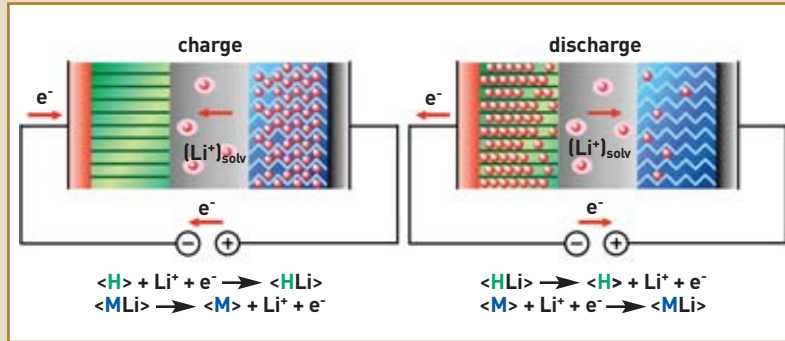
densities of 70–80 Wh/kg to be achieved. The second pathway had already been targeted by research around the late 1970s, with a view to finding electrochemical couples exhibiting better performance than the lead-acid or nickel-cadmium storage batteries used up to that point. Initial models were thus 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.

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

## Operating principle of a lithium storage battery

During use, hence during discharge of the **storage battery**, lithium released by the **negative electrode** (<H>: host intercalation material) in **ion** form ( $\text{Li}^+$ ) migrates through the ion-conducting **electrolyte** to intercalate into the **positive electrode** active material (<MLi>: lithium-insertion compound of the metal oxide type). Every  $\text{Li}^+$  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

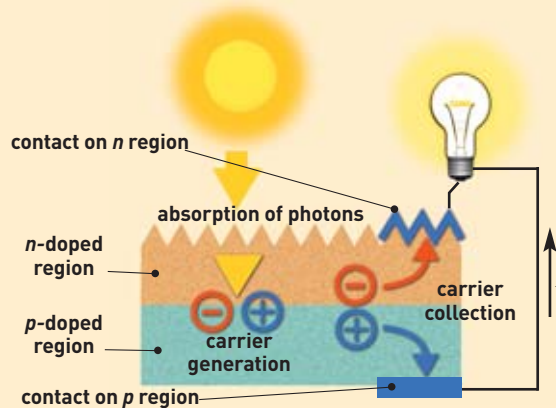
proportional both to the difference in potential between the two electrodes, and the quantity of lithium intercalating into the insertion material. It is further inversely proportional to system total mass. Now lithium is at the same time the lightest (molar atomic mass: 6.94 g), and the most highly **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.

# 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 Mendeleev 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.

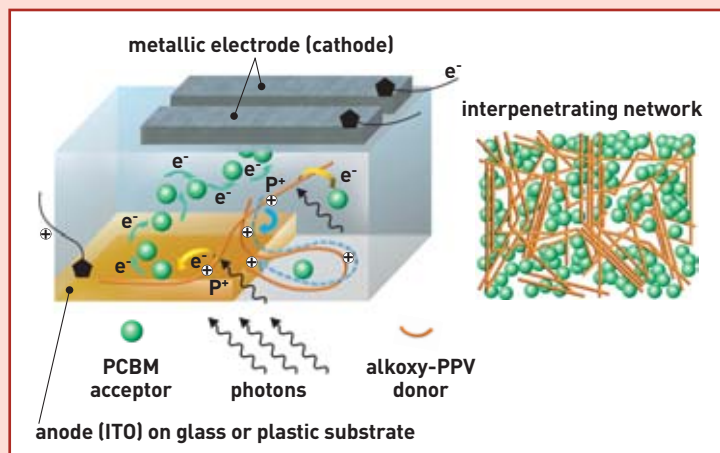


Figure from a presentation by S. Sariciffici (www.itos.at)

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