

Energy efficiency in housing

While energy consumption in the residential-tertiary sector has seen a steep rise, the potential for energy savings remains considerable in this sector. Improved energy efficiency involves development of high-performance technologies, with preference being given to systems enabling value-added use of renewable energies, and development of high-efficiency devices.

The challenge of energy efficiency in housing is of particular importance, owing to heavy consumption in this sector, and the steeply rising trend this has evidenced, over the past 20 years. This concerns equally residential and tertiary-sector buildings, and, due to the low renewal rate of the housing stock, in France, older buildings (whether single-household or collective), these remaining a priority target for a policy fostering improved energy efficiency for the sector. On the other hand, new buildings stand as the area where the more up-to-date energy technologies may most easily, and effectively, be installed.

Improved energy efficiency in buildings may be targeted by strong incentives, through regulatory provisions, as implemented since 1975, and further foreshadowed in the French Energy White Paper, this aspect being due to form an integral part of the forthcoming Energy Act.

Diverse and original technologies

Technologies allowing better energy efficiency in housing are of highly diverse kinds. For the *building envelope*, insulating qualities for walls and roofs, as for windows can be enhanced, in particular by use of active techniques, such as electrochromic glazing. Such glazing consists of panes bearing a thin film having the specific ability to become tinted, thus restricting light transmission, when a voltage is applied.

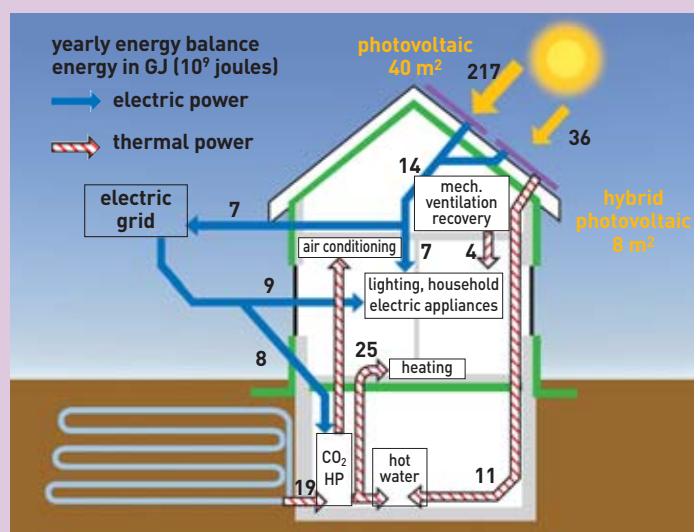


Added-value use of renewable energies favors improved building energy efficiency indicators in housing. Part of the domestic water for these apartments in a social housing block in Montreuil (Seine-Saint-Denis *département*, Paris Region) is heated by 220 m² of solar photovoltaic collector panels installed on the roof.

An instance of very-low-energy-consumption housing

1

The Figure at right shows a dwelling making value-added use of two **renewable energies**: solar energy, by way of hybrid thermal (photovoltaic-thermal) and photovoltaic collectors, positioned on the south-facing roof slope; and *geothermal energy*, by way of buried heat collectors, coupled to a reversible heat pump (HP). The latter functions with CO₂, a very-low **greenhouse-effect** refrigerant fluid, compared to current refrigerants, of HFC-134a type, for which the greenhouse contribution per unit mass is 1,300 times greater than that from CO₂. In this instance of housing, for which yearly energy fluxes have been evaluated according to the various energy sources and energy converters, as well as according to main uses, electric power is reinjected into the grid. The entire energy requirements for heating, domestic hot water and electric appliances are covered, for an energy efficiency indicator lower than 20 kWh/m²/year.





"Active" heat storage

2

Air temperature in a room is a determining factor for a feeling of comfort. However, realities are more involved. The feeling of wellbeing also arises from the thermal balance between energy radiated by the human body, and energy received from the environment. This feeling of comfort is thus governed by heat exchanges, occurring essentially through radiation and **convection**, between the human body and the environment.

Thus, wall temperature for the premises is also involved in the sensation of heat. If the walls are at a temperature lower than 18 °C, the human body experiences an unpleasant sensation, as it dissipates a large amount of thermal energy by radiation. This is typically the case, in winter, for poorly insulated buildings. For an outside temperature of - 10 °C, inside surfaces on the walls of such a building barely reach 17 °C, and, as a result, ambient temperature must be "boosted" to 23 °C, for "subjective" temperature to stand at 20 °C. Moreover, the thermal differential prevailing between the air and walls favors processes of **natural convection**, to which the human body is peculiarly sensitive.

Many factors involved in comfort are now vouchsafed by recent housing, insofar as this complies with regulations. Cold walls are a thing of the past, as a result of insulation, windows are airtight, mechanical ventilation allows, to a certain extent, control of humidity, and floor heating ensures mild heat, through both convection and radiation. One parameter, however, does remain very poorly controlled, namely wall temperature. Thus, it would be feasible to improve substantially indoor comfort by regulating wall temperature. One original technique involves use of thermal energy storage inside the walls. For that purpose, phase-change materials are included in the walls. Their presence allows surface temperature to be stabilized, at a value close to that of the room.



Paraffin wax granules: a phase-change material with a fusion temperature of 26 °C.

Likewise, preference is given to *devices enabling value-added use of **renewable energies***, such as:

- *active solar thermal collectors*, for production of domestic hot water (DHW) or as an auxiliary heating source, or even for air conditioning or environmental cooling;
- *photovoltaic collectors*, for electric power supply, as an adjunct to supply from the grid, or even, in some cases, to cover the entire power requirements of a building, by means of a set of storage batteries;
- *geothermal collectors*, buried superficially or deep in the ground, in vertical wells, associated to a heat pump enabling the heat available to rise in temperature, providing value-added use for energy readily available at low temperature (see [Box 1](#));
- *wood-fired boilers*, providing value-added use for **biomass**, a renewable resource;
- in the longer term, *fuel cells* may form a so-called "polygeneration" system, yielding, along with electric energy, the heat and cold required for dwelling comfort (see [Box on The GECOPAC Program](#)).

Technologies being developed to improve energy efficiency in buildings equally concern *electricity storage* (see [Chapter III](#)) or *heat storage systems*. As regards the latter, daily storage systems (see [Box 2](#)) involve water, or, in order to save on storage volume, phase-change materials.

Further, *efficient heat and cold emission and recovery systems*, such as solar floors or cooling ceilings, allow the temperature of heat sources to be limited, thus resulting in improved efficiency of heat- or cold-generating thermodynamic cycles.

Achieving successful architectural integration

This ensemble of technologies may not win acceptance on the market, unless the many constraints involved in building design and use are clearly taken on board. Aside from the economic constraint, which obviously is a major one, calling for "smart," "high-performance"

couplings of such technologies, and standing as an incentive to optimized building energy system architecture, two important points should be noted. On the one hand, architectural integration of the elements involved, in particular for solar collectors - these as a rule involving large areas - is essential, if acceptance is to be more readily gained for such technologies among the public at large. Many developments have been completed in Northern Europe, and original developments are under way in France (see [Box 3](#)). And, on the other hand, comfort and air quality are ever stronger requirements for the environment, be it in residential or tertiary-sector buildings. Indeed, temperature, humidity, and **CO₂** and pollutant levels must be controlled to best effect.

At the same time, operating costs for the building's energy system may not be brought under control, and maintenance of the installation be carried out in optimum fashion, unless system monitoring and management devices are developed. Such devices will also be required to provide the user with a clear presentation of energy system performance.

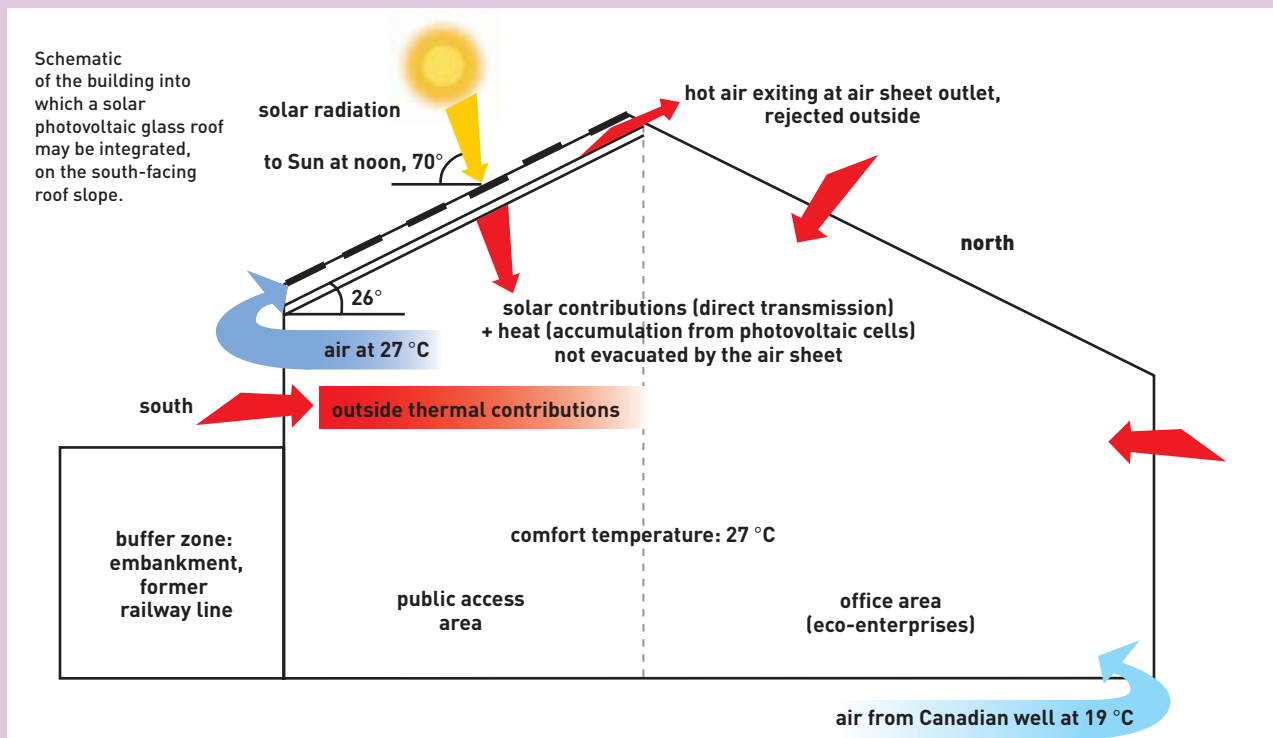
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Integration of a photovoltaic glass roof into a building during renovation

3

French company Solarte, acting in partnership with CEA's Innovation Laboratory for New Energy Technologies and Nanomaterials (CEA/LITEN: Laboratoire d'innovation pour les technologies des énergies nouvelles et les nanomatériaux) and Anglade Structure Bois, have firmed up a contract with Ademe, under the aegis of the "Preparing construction for the 2010 timeframe" ("Préparer le bâtiment à l'horizon 2010") Program, for a research project concerning "Large-scale rooftop integration of photovoltaics in an older building located in the Pyrénées-Orientales [département]." This project involves design of a solar **photovoltaic** glass roof, cooled by a sheet of ventilated air. This original concept makes it possible, aside from electricity generation from the **photovoltaic cells**, to benefit both from a lighting contribution through the transparent surface of the photovoltaic roof, and a thermal contribution, through heating of the air sheet.

The aim of this research project is to arrive at a construction end product featuring the appropriate physical characteristics to provide an optimum heat and lighting management service.



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).

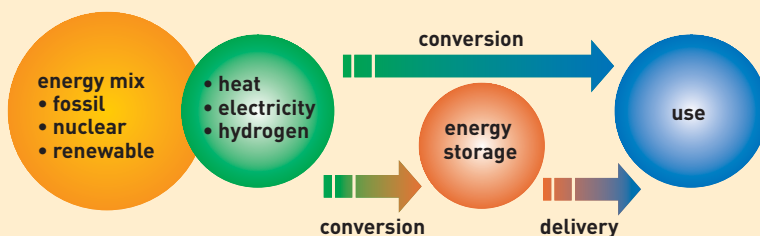


Figure 1. The energy scheme.

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.

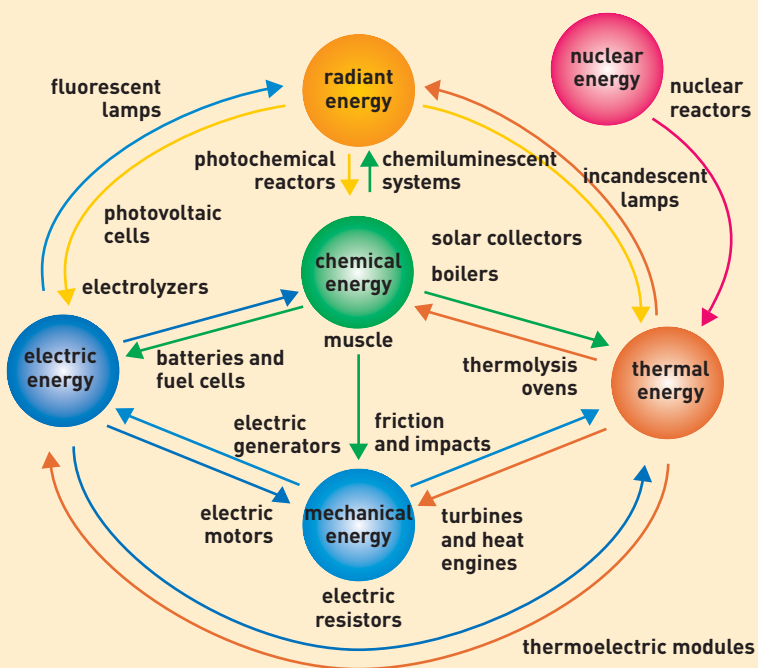
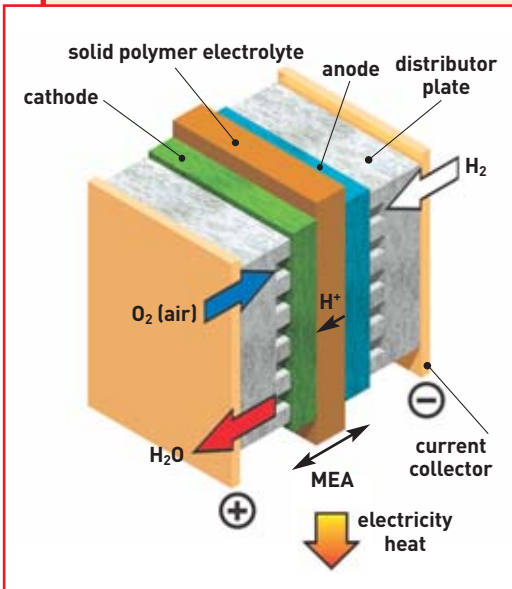


Figure 2. Conversions of the six main forms of energy, with a few examples of energy converters.

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/cm². 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

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.

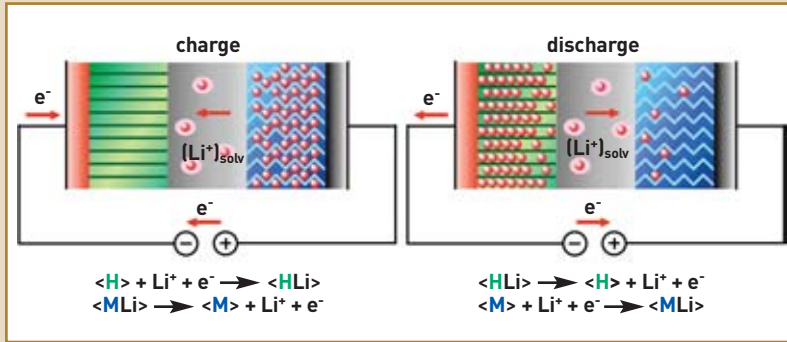
I (1) One cycle includes one charge and one discharge.

Operating principle of a lithium storage battery

1

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.

B The greenhouse effect and CO₂

The Sun's energy reaching the ground warms the Earth, and transforms into **infrared radiation**. Just like the panes of a greenhouse – hence the name given to this mechanism – some of the gases present in the atmosphere trap part of this radiation, tending to warm the planet. Thus, in terms of power, the Earth receives, on average, slightly less than 240 **watts/m²**. Without the **greenhouse effect**, mean temperature on Earth would stand at $-18\text{ }^{\circ}\text{C}$, and very little water would be present in liquid form. This effect thus has a beneficial influence, since it allows our planet to experience a mean temperature of $15\text{ }^{\circ}\text{C}$.

However, from the beginning of the industrial era, i.e. for more than a hundred years, humans have been releasing into the atmosphere gases (**carbon dioxide**, **methane**, **nitrogen oxides**, etc.) that artificially augment the greenhouse effect. Since 1750, this increase, with respect to “well-mixed” gases, has amounted to 2.43 W/m^2 . Contributing as it does an “additional radiative forcing” of 1.46 W/m^2 , carbon dioxide (CO₂) accounts for more than half of this “additional greenhouse effect,” well ahead of methane (0.48 W/m^2), **halocarbons** [chlorofluorocarbons [CFCs], hydrochlorofluorocarbons [HCFCs], and hydrofluorocarbons [HFCs]), accounting for 0.34 W/m^2 , and nitrogen dioxide (0.15 W/m^2). Further, the **ozone** in the troposphere exhibits a *positive* radiative forcing of 0.35 W/m^2 (however, it is estimated that depletion of the stratospheric ozone layer observed between 1979 and 2000 has resulted in a *negative* radiative forcing, of 0.15 W/m^2).

This addition to the natural greenhouse effect (155 W/m^2) is small, correspon-

ding to an increase of about 1%. Nevertheless, it is practically certain that this has contributed to the rise in mean temperature, for our planet, of about $0.5\text{ }^{\circ}\text{C}$, observed over the 20th century (see Figure 1). If nothing is done to curb these emissions, carbon dioxide concentration in the atmosphere (see Figure 2) could double by 2100. From current world consumption ⁽¹⁾ of **fossil** fuels (7,700 Mtoe), the mass of CO₂ currently produced may easily be computed: 20 billion tonnes per year!

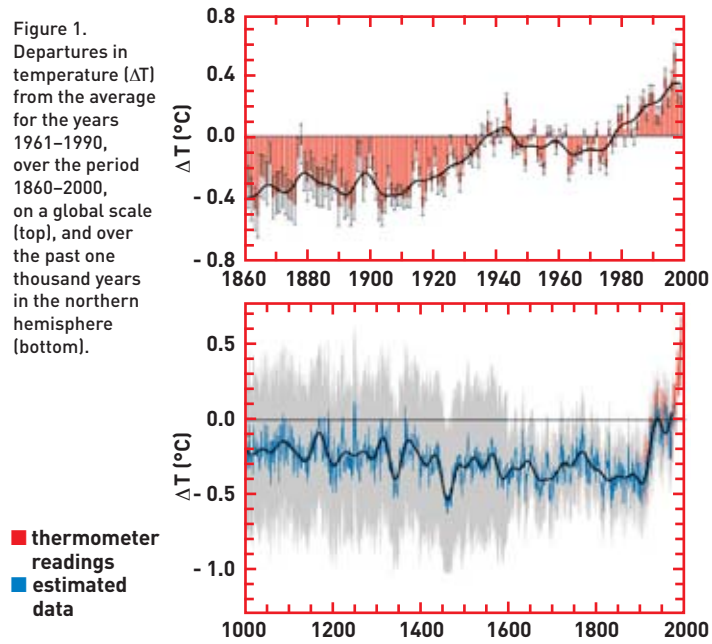
This could result in a substantial increase in the greenhouse effect, causing, through nonlinear amplifying effects,

(1) European Community, Directorate General for Energy (DG XVII), “Conventional Wisdom” scenario (*European Energy to 2020: A scenario approach*, 1996).

profound alterations in climate. Most models predict that doubling the present carbon dioxide concentration would result, by the end of the 21st century, in a rise in temperature of some $2\text{--}3\text{ }^{\circ}\text{C}$. Some models even yield a bracket of $1.5\text{--}4.5\text{ }^{\circ}\text{C}$, meaning dramatic consequences could be foreseen for the environment, such as a substantially rising sea level.

Such figures may seem small, entailing only minor consequences for the climate; that, however, is not the case. To understand this point, one should bear in mind that during the “little ice age,” from 1450 to 1880, mean temperature only fell, in France, by $1\text{ }^{\circ}\text{C}$, on average. Some 6,000–8,000 years ago, as Western Europe experienced a war-

Figure 1. Departures in temperature (ΔT) from the average for the years 1961–1990, over the period 1860–2000, on a global scale (top), and over the past one thousand years in the northern hemisphere (bottom).



B The greenhouse effect and CO₂

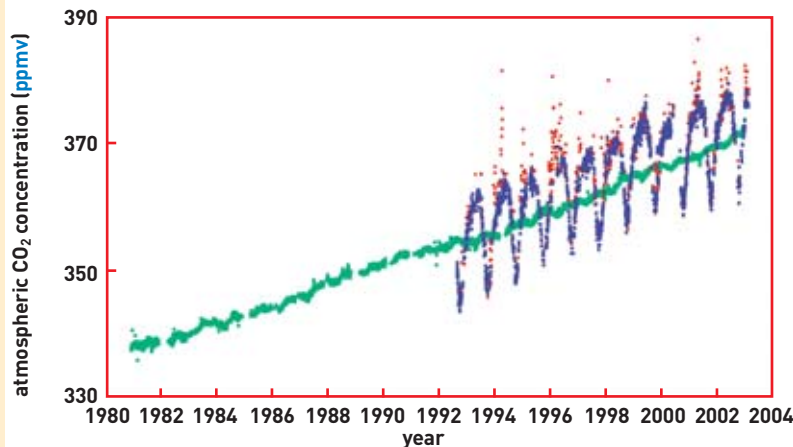


Figure 2.

Evolution of atmospheric CO₂ concentration since 1980, as measured on a daily basis by the automatic stations of the Climate and Environmental Science Laboratory (LSCE: Laboratoire des sciences du climat et de l'environnement), since 1981 on Amsterdam Island (Indian Ocean), and since 1992 at Mace Head, on the western coast of Ireland.

Readings on Amsterdam Island (shown in green), well away from any direct perturbation of human origin, essentially evidence the constant rise in concentration. The Mace Head site basically measures oceanic atmosphere (under normal conditions, westerly winds: blue). When wind conditions are reversed, the site receives a continental atmosphere, showing a strong excess in CO₂ (red plots), compared to oceanic atmosphere. Over the mean rise in CO₂ concentration is superimposed a marked seasonal modulation, due to plant vegetative cycle (chlorophyll photosynthesis), plants being CO₂ emitters in winter, and CO₂ absorbers in summer.

mer spell, with a mean temperature 2–3 °C higher than it is today, the Sahara was not a desert, but a region of abundant rainfalls. It is not so much the rise in temperature that gives cause for concern, as its rapid variation (in the course of one century). The large variations previously observed in nature all occurred over much longer timescales, for those at least of a global character. Thus, the last glaciation lasted 100,000 years, and the corresponding deglaciation took 10,000 years. The rapid variation we are currently experiencing may induce major, unexpected perturbations in the climate and the ecosystem, which will not always have time to adapt.

From Rio to Kyoto: the major conferences on the global environment

The evolution of the global environment has led to major conferences being organized, starting in the closing decade of the 20th century.

At the Earth Summit, held in **Rio de Janeiro** (June 1992), the **United Nations Framework** Convention on Climate Change was signed, this setting the goal of a stabilization of **greenhouse gas** emissions (this convention came into force on 21 March 1994).

At the Kyoto Conference (December 1997), the protocol was signed providing for a global reduction in emissions of such

gases, by an average 5.2% in the period 2008–2012, compared to 1990 levels, for **OECD** countries and Eastern European countries (including Russia). Reduction targets for the **European Union** and France are set at 8% and 0% respectively. The ways and means to meet these targets were debated, unsuccessfully, in November 2000 at **The Hague**. Subsequent conferences, held in **Marrakech** (2001), **Johannesburg** (Earth Summit held in August–September 2002), **New Delhi** (October 2002), **Moscow** (September–October 2003), and **Milan** (December 2003) had still not enabled, by 2004, this **Kyoto Protocol** to be brought into force, until Russia finally decided to ratify the document, at last allowing this enforcement in February 2005.

Under the impetus provided by the United Nations Environment Program (**UNEP**), the issues raised by substances that deplete the ozone layer in the atmosphere were addressed in **Vienna** (1985), and most importantly in **Montreal** (1987), where the protocol was signed, imposing a reduction in production and use

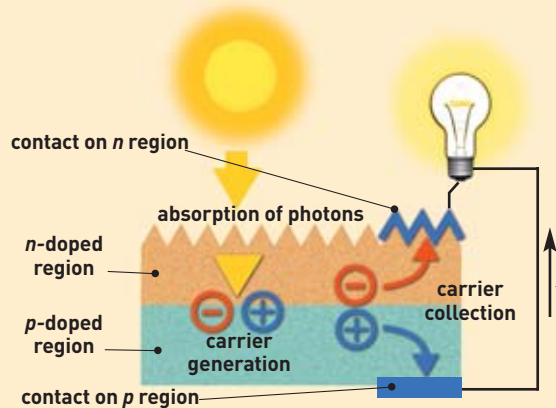


The Mace Head monitoring station, Ireland.

of chlorofluorocarbons (CFCs). This protocol was specified by amendments adopted in **London** (1990), imposing a ban on CFCs from 1 January 2000, and extending controls to other compounds (including HCFCs), **Copenhagen** (1992), **Montreal** (1997), and **Beijing** (1999).

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.

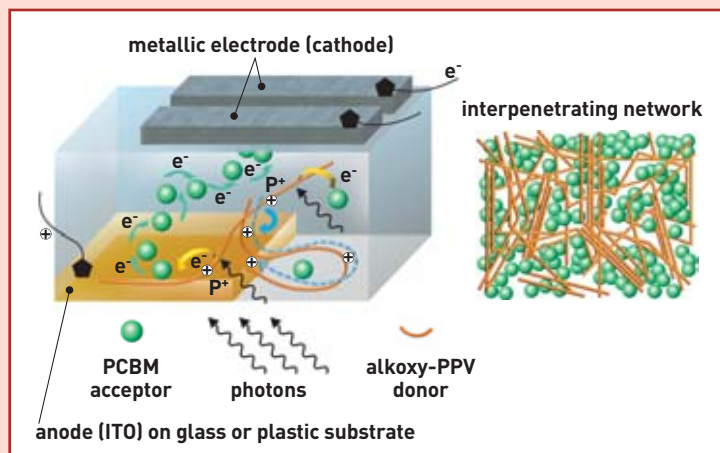


Figure from a presentation by S. Sariciffici (www.itos.at)

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

The GECOPAC Program

The GECOPAC (Génération d'énergie combinée par pile à combustible: Combined Energy Generation by Fuel Cell) Program, bringing together the French Centre Region, CEA, the Orléans-Tours *académie* (educational district), and industrial partners Dalkia and SNECMA Moteurs, aims at development of the first French prototype complete **cogeneration** system to comprise an SOFC fuel cell. The cell is to be designed, developed, and constructed by CEA. Rated at 5-kW power, the system will be fed from the **natural gas** grid, being coupled to the electricity system of the premises where it is installed, a high school selected by the *académie* rectorate. The GECOPAC Program will comprise a cell core, a **fuel** processing unit, developed by société N-GHY, a power-conversion, monitoring and control unit, developed by Ainelec, together with the modules required for system internal and external heat management. Program partners will build, initially, a 1-kW scale model, featuring the same subsystems as the future prototype. An initial overall assessment will be carried out on completion of 6 months' trials, to decide on construction launch and bringing into operation of the 5-kW prototype.

As a focus for research and development, the GECOPAC Program will channel technical and funding support, in particular as regards the cell core at CEA. It will further afford the possibility of a first operational feedback for a complete cogeneration system, this being of interest to Dalkia, as system user, and SNECMA Moteurs, as potential system assembler. Moreover, inclusion, from the start of the program, of a partnership with the Orléans-Tours rectorate will make it possible to develop the training and teaching structures required to train the professionals and technicians taking part in the integration of such systems into the energy scene of the future.

The cogeneration market, evaluated as standing, in France, at some 10,000 MW in coming years, will probably open up from 2005, as a result of the implementation of European Directives promoting cogeneration (see [Box on Fuel cell cogeneration](#)). Fuel cells are deemed to be competitive on the market for residential cogeneration (1-100 kW), by comparison with other cogeneration techniques (gas micro-turbines, for instance). The 5-kW prototype will provide excellent experience, as regards the future "building block" for such modular systems to come.

The GECOPAC Program is crucial, as regards bringing SOFC work in France up to grade. It should enable mastery to be achieved, of the key technologies for SOFC systems. It will foster the emergence of an expertise and excellence center to be set up at Le Ripault, due to form an integral part for a European technological platform of prime importance.