Energy efficiency



# Potentials for energy savings remain considerable

The main sectors involved in energy consumption, in France, are industry, the residentialtertiary sector, and transportation. Over the past twenty years, while the relative share of energy consumption from industry has declined, the other sectors have experienced a marked rise in energy consumption. CEA is conducting major research efforts, addressing improved process energy efficiency, in these various sectors, where the potential for energy savings remains significant.



Haricot chevron plate, an innovative system in the area of heat exchanges. Improved energy efficiency in industry involves optimized heat transfers in heat exchangers.

**O**ver the years 1973-2002, final energy consumption for all sectors, in France (see Figure 1), rose by 21% (i.e. by 28.6 **Mtoe**). In industry, consumption fell by 21% (10.3 Mtoe), whereas consumption in the residentialtertiary sector rose by 25% (14.1 Mtoe), while that for transportation rose by 93% (24.6 Mtoe). If consumption trends remain unaltered, final energy consumption could rise by 40.6 Mtoe by 2020, mainly driven by the residential-tertiary and transportation sectors. **Carbon dioxide** ( $CO_2$ ) emission reduction targets, to comply with the Kyoto Protocol, and France's commitments under the aegis of European Union policy (see Box B, *The greenhouse effect and CO*<sub>2</sub>) entail, aside from the development of renewable energy sources, a very significant drive to improve energy efficiency in the residential-tertiary sector, and persistence with the efforts pursued over many years in industry.

#### Energy efficiency in the residential sector

In France, there are 29.6 million dwellings, of which 65% were built before 1975. The stock of domestic dwellings is thus relatively old, many of these dwellings featuring poor thermal insulation. The renewal rate for this stock stands at around 1%, which means upgrading may not be completed until after 2050.

Uses of energy in the residential sector are broadly dominated by *heating* requirements (see Figure 2). Indeed, 75% of total energy consumption (electricity, gas, fuel oil, wood), and 34% of electricity consumption, in households, may be assigned to heating. With renewal of the housing stock, and through efforts to fit extant buildings with thermal insulation, mean unit heating consumption declined, between 1973 and 2000, from 323 **kWh**/m<sup>2</sup>/year to 180 kWh/m<sup>2</sup>/year. New dwellings are able to achieve, nowadays, heating consump-



Figure 1. Final energy consumption, in France, by sector.



ier Sébart/Ademe 2

This house, in the Haute-Savoie *département* (French Alps), is fitted with 22 m<sup>2</sup> of rooftop photovoltaic collectors and 6 m<sup>2</sup> heat collectors, for production of domestic hot water. One solution, to achieve improved energy efficiency in housing, consists in developing energy systems allowing added-value utilization of such renewable energies as solar energy.



#### Figure 2.

Distribution of household electric energy consumption in France, by use. Brown products include household electric appliances, television sets, hi-fi...

tion of 110 kWh/m<sup>2</sup>/year, and builders are putting up, as of now, housing exhibiting consumption of less than 50 kWh/m<sup>2</sup>/year.

Uses related to *household electric equipment* (domestic cooling, household electric appliances), and the rise of *new, electronics-based technologies* (television sets, computers...) resulted in a net increase, between 1973 and 1998, from 18 kWh to 321 kWh per household.

Emerging uses of *comfort-enhancing equipment*, in particular air conditioning and regeneration, remain a marginal factor in France. However, significant penetration of air conditioning into the residential sector is to be foreseen, and may generate a marked rise in energy consumption.

Gains in energy efficiency are indispensable in this sector, for which the potential for energy savings is evaluated as standing at 200 **TWh**/year.

Improvement in dwelling energy efficiency index is to

be fostered through implementation of regulations covering both new and older housing, but equally through development and dissemination of high-performance technologies (<u>see *Energy efficiency in hou-*</u> *sing*), such as:

• *high-performance heat-generation systems*, for heating and domestic hot water, e.g. high-efficiency heat pumps using **greenhouse-effect** free fluids, high-efficiency wood- or gas-fired boilers, heat recovery systems, heat storage using PCMs (phase-change materials)...;

• energy systems enabling value-added utilization of renewable heat resources, whether solar or low-temperature geothermal, e.g. buried-collector ground-source heat pumps, solar collectors...;



Solar air-conditioning installation, used by Le Cellier des templiers winemaking cooperative, for air conditioning of its wine maturing cellars. 134 m<sup>2</sup> of vacuum-insulated rooftop solar collectors feed an absorption chiller with a refrigeration power of 50 kW.

Energy efficiency







• *integration* into new or older housing *of electric energy sources*, e.g. **photovoltaic** collectors;

• high-performance energy consumption monitoring and management systems, combining high-tech sensors and data-processing electronics.

#### **Energy efficiency in industry**

The share of industry in energy consumption has steadily declined over the past 30 years, in France, standing at 24% of final energy consumption in 2001. Final energy consumption, by branch of industry, shows the dominance of three sectors: chemicals, primary metals and ore extraction and transformation, and the agriculture and food industry (see Figure 3). Potentials for energy savings remain considerable. They are evaluated as amounting to 12 Mtoe. Figure 4 shows the available potential for **process**-related operations, as a function of added cost from the measure involved. Thus, if manufacturers accepted a  $\in$ 1,000 outlay to achieve a 1-toe gain, then aggregate energy savings would stand - as shown by Figure 4 - at 5.5 Mtoe.

Two thirds of such potentials may be achieved through implementation of energy-saving techniques concerning processes (see *Energy efficiency in industry*), such as:

• *improved heat-exchanger efficiency*, this representing a major direction for improved process performance (see Box);

• integration of a number of functions into a single piece



Figure 4.

Aggregate energy savings potential for industry, as a function of additional cost for the measure involved.





Final energy consumption in the industrial sector in 2000, by branch.

*of machinery or equipment*, as is the case of exchangerreactors, combining heat-transfer and chemical reaction functions in a single device. The expected gain in efficiency is associated to lower waste generation, and increased device safety;

• *development of diagnostic tools*, enabling maintenance operations to be anticipated, limiting losses in effectiveness in equipment and systems, as e.g. fouling sensors.

The remaining third may be achieved through measures concerning such "utilities" as cold production, heat- or cold-transfer fluid transmission (see *New refrigeration technologies*), heating and lighting of premises...

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In the area of heat exchangers, accurate understanding of flow has become a critical factor, with respect to design and optimization. Indeed, making flow **turbulent**, or turning it into a **two-phase** flow, is the best way to increase heat transfer between a fluid and a wall. That is why such complex flow is to be found in most industrial processes. For instance, in the case of compact heat exchangers, the fluctuating, three-dimensional, broad-energy-spectrum characteristics of turbulence are sought By way of illustration of this activity, mention should be made of fundamental work, carried out with assistance from Ademe, on the investigation of turbulent flow in compact heat exchangers. <sup>(1)</sup> By carrying through a systematic survey of the implementation of a variety of turbulence models and programs such as CEA's Trio\_U, FLUENT, and STAR-CD, <sup>(2)</sup> it was shown, through comparison with experimental findings, that, through discerning use of advanced turbulence models, of the LES <sup>(3)</sup> type, it



#### Figure 1.

Snapshot of the air-temperature field at a given time in a compact heat exchanger, obtained with the Trio\_U software. The gray plate corresponds to one of the plates positioned on either side of the fins, forming a channel. The blue arrow stands for the flow perpendicular to the fins, this being shown in the figure at right as a flow from left to right; the image shows a horizontal section at half fin height.

for, to optimize performance. However, these three aspects mean experimental measurements are difficult, and generalization of physical models is not readily achievable. Up to 5 years ago or thereabouts, use of numerical methods, for the analysis of this type of flow, was the preserve of highly skilled, wellversed scientists and research workers, and was often restricted to simple geometries. Over the past few years, growth in computer resources, and dissemination of fluid-mechanics computation programs, have resulted in numerical modeling now being available to all. Such methods are opening up a new field of investigation, by offering a major leap in our ability to predict heat transfers. Nevertheless, the gap remains great, between academic investigations, and industrial reality. Intensive validations, in particular, affected on realistic industrial problems, are still lacking.

Faced with this situation, work carried out by GRETh follows a twofold thrust. This involves, on the one hand, effecting industrial validation of advanced thermal simulation models, on the basis of heat exchanger-related problems, and, on the other, making such models, and their domains of validity, available to GRETh's manufacturers' club, through the software platform concept.

GRETh (Groupement pour la recherche sur les échangeurs thermiques: Research Group on Heat Exchangers), registered as a non-profit organization under French law, has the remit of disseminating scientific and technological findings from research work carried out in the area of heat exchangers, and enable value-added applications of its findings in industry. For that purpose, the GRETh Manufacturers' Club can call on support from laboratories at CEA (Grethe: Service Système multiénergies et gestion de l'énergie - Multi-Energy Systems and Energy Management Service), CNRS, and academe (LEGI: Laboratoire des écoulements géophysiques et industriels - Geophysical and Industrial Flow Laboratory), with privileged connections with thermics technical education centers, such as the Thermics and Energy Engineering University Technological Institute at Grenoble. The organization has opened itself to Europe, in particular by acting as coordinator to put in place the European SHERHPA (Sustainable Heat and Energy Research for Heat Pump Applications) Program.



#### Figure 2.

Image of a fluid flow in a plate and frame heat exchanger, obtained with the FLUENT software. In the example investigated here, chevron pitch is about 10 mm. Arrows show the direction of flow.

became feasible to have at hand a reliable preliminary sizing and optimization tool, for compact heat exchangers (see Figure 1 and Figure 2). A best-practice guide, intended for participants in the GRETh club, was drawn up, to specify the best way of approach for a modeling problem, concerning industrial turbulent flows. To follow up this activity, GRETh initiated in 2004 work on the modeling of two-phase industrial flows, in collaboration with thermalhydraulics teams from CEA's Nuclear Energy Division (CEA/DEN).

Making such methods available to manufacturers is equally a concern at GRETh. This involves working in collaboration with an industrial partner, giving him access to available resources, and closely involving him in tool implementation. Manufacturers who call on GRETh for breakthrough technological developments are well aware of the benefit accruing from association with a laboratory that endeavors to go beyond mere demonstration of the potentials of these new methods.

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(1) PhD dissertation presented by F. Michel in late 2003.

(2) FLUENT and STAR-CD: these are computational fluid dynamics programs, marketed by Fluent and CD-adapco Group respectively.
(3) LES (large eddy simulation): large-scale simulation, a promising technique for the prediction and analysis of turbulent flows. By contrast to direct simulation, representing as it does all scales with no approximation involved, this relies on scale separation. Thus, scales of a magnitude greater than an arbitrary value are directly determined by computation, whereas other scales are taken into consideration by way of a statistical model, known as a subgrid model.

## A The many states of energy

othing 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).

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, energyconsuming sites may be far removed from the production site, production



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

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.



## 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.

he 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 oxidationreduction 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<sup>+</sup>) 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:  $2 \text{ H}^+ + 1/2 \text{ O}_2 + 2 \text{ e}^- \rightarrow \text{H}_2\text{O}$ . 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

Ctorage 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,

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

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 cad-(nickel-cadmium storage mium 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 (<u>see Box on</u> <u>Operating principle of a lithium storage</u> <u>battery</u>). 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-lithiumbased 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.

### **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 (Li<sup>+</sup>) 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<sup>+</sup> 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.

1

## 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 pdoped 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 donoracceptor (D-A) type, effecting transport of holes (P<sup>+</sup>) to the anode (indium-tin oxide [ITO]), and of electrons (e<sup>-</sup>) 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.



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

## The greenhouse effect and CO<sub>2</sub>

he 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/m<sup>2</sup>. Without the greenhouse effect, mean temperature on Earth would stand at - 18 °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 °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<sup>2</sup>. Contributing as it does an "additional radiative forcing" of 1.46 W/m<sup>2</sup>, carbon dioxide  $(CO_2)$ accounts for more than half of this "additional greenhouse effect," well ahead of methane (0.48 W/m<sup>2</sup>), halocarbons (chlorofluorocarbons [CFCs], hydrochlorofluorocarbons [HCFCs], and hydrofluorocarbons [HFCs]), accounting for 0.34 W/m<sup>2</sup>, and nitrogen dioxide (0.15 W/m<sup>2</sup>). Further, the ozone in the troposphere exhibits a *positive* radiative forcing of 0.35 W/m<sup>2</sup> (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<sup>2</sup>).

This addition to the natural greenhouse effect (155 W/m<sup>2</sup>) 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 °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 <sup>(1)</sup> of **fossil** fuels (7,700 **Mtoe**), the mass of CO<sub>2</sub> 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,

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

8) ·····).

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 2–3 °C. Some models even yield a bracket of 1.5–4.5°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 °C, on average. Some 6,000–8,000 years ago, as Western Europe experienced a war-



## The greenhouse effect and CO<sub>2</sub>



#### 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: Laboratorie 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 CO<sup>2</sup> (red plots), compared to oceanic atmosphere. Over the mean rise in CO<sub>2</sub> concentration is superimposed a marked seasonal modulation, due to plant vegetative cycle (chlorophyll photosynthesis), plants being CO<sub>2</sub> emitters in winter, and CO<sub>2</sub> 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



National University of Ireland

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).