Which **industrial strategies** for the hydrogen pathway?

In more or less structured and/or proactive fashion, strategies for the deployment of a hydrogen pathway are taking shape in the industrialized countries most involved - in North America and Japan initially. In Europe, initiatives making for a more coordinated approach go hand in hand with major national and regional efforts, in France in particular.

An Opel (General Motors Group) fuel-cell vehicle was recently driven across Europe, from Hammerfest, north Norway, to Cabo da Roca, Portugal, the westernmost point on the European continent.

GM

R&D and deployment strategies in North America, Japan, and Europe

Each according to its own, developed nations are laying the groundwork for the industrial network charged with bringing to fruition, in concrete terms, the R&D expended on the hydrogen pathway.

Hydrogen appears as a highly attractive solution to a range of critical issues, such as global climate change and security of **fuel** supplies. The ensemble of actors being highly fragmented (automotive manufacturers, energy utilities, businesses concerned with infrastructures, vehicle-fleet operators and managers, governments, etc.), coordination of the various parties involved is a prerequisite for the deployment of hydrogen as a new vehicle fuel.
Governments needs must take the lead as regards setting the boundaries, and setting up conditions such as to guarantee security for investors. Formulation of a strategy must, therefore, take on board the underlying timeframes for a transition to cleaner fuels and propulsion systems. This involves, on the one hand, evaluating the minimum time span required for such a transition, and, on the other, assessing how much time is left, if serious problems are to be avoided. The areas for action are many. To mention but a few: policies to bring down **greenhouse gases** (**GHGs**), **hydrocarbon fuel** taxation, vehicle consumption standards, incentives for the development of generation capabilities involving **renewable energies**, and of hydrogen distribution infrastructure components, etc.

The United States: decisive initiatives

The United States, particularly since the outrages of 11 September 2001, regards security of fuel supplies as a major issue, giving a significant impulse to hydrogen. Activities already on hand, in the area of **fuel-cell** propulsion, thus found themselves directly bound up with hydrogen, as the fuel of choice. The decision of General Motors (GM) to go for hydrogen as *the*

clean fuel for fuel-cell vehicles (FCVs) is of prime importance in this respect. The “roadmap” drawn up by the US government takes on board these requirements and strategic decisions, when setting out ways of resolving critical pending issues (e.g. hydrogen production and storage, fuel cell cost reduction, distribution infrastructure, etc.) by 2015, to promote extensive deployment of mass-produced FCVs by 2020 at the latest.
In this context, creation is being mooted of a “hydrogen corridor,” running from California to Colorado, with service-stations every 160 km or so. The governor of the first-mentioned state has already signed an executive order committing his administration to building some 200 fueling stations by 2010. A number of US states (in particular Florida, Michigan, and Illinois) are developing hydrogen-vehicle fleet demonstration programs.

Canada: investments in infrastructure

In Canada, as part of the monies devoted to ensuring the Ottawa administration meets its obligations to curb GHG emissions in compliance with the **Kyoto Protocol**, some CAD130 million are earmarked for development and demonstration programs in the fuel cell sector, a significant part of this sum going to investments for the hydrogen infrastructure. One project plans to connect the United States border to the ski resort of Whistler, British Columbia, in time for the Winter Olympics of 2010, while another is to link Windsor, Ontario to Montreal, Quebec by a “hydrogen corridor” of over 900 km. Ideally, these corridors should enable local testing of hydrogen vehicles and infrastructure in the strategic regions, respectively, of Ontario, bordering on Michigan (involving e.g. Stuart Energy, Hydrogenics, and GM), and British Columbia (with corporations such as Ballard and Methanex).

Japan: a well-structured policy

As the second automotive market in the world, Japan has adopted a well-structured and coordinated policy in the areas of hydrogen and fuel cells. This elicits the consensus of industry, government, and civil society. Development of fuel-cell vehicle technology is deemed to be mainly the concern of industry, whereas initial deployment of the distribution infrastructure would involve government-supported actions. A number of conditions are inherently highly conducive to introduction of hydrogen-fed fuel-cell vehicles: Japan is an island-bound country, and average road distances are shorter, and maximum road speeds lower, than in Europe or the United States. Consequently, existing hydrogen storage technologies allow adequate travel ranges. Related electrical systems and maintenance infrastructures are being brought out on the market by way of **hybrid** electric-gasoline **vehicles** There is a coordinated approach, between government and industry, even as the country imports all of the energy required for production of its vehicle fuel.
Such vehicles are the ingredients making for a successful commercialization of fuel-cell vehicles, without even involving any dependence on export markets.

JHFC

Yokohama-Daikoku hydrogen station (fed by a steam-reforming unit), put in service under the aegis of the Japanese JHFC (*Japan Hydrogen and Fuel Cell*) demonstration project.

Europe: a more coordinated approach

Europe, lacking a consistent hydrogen and fuel cell strategy, has only recently set out on a more coordinated approach, through the setting up of the European Hydrogen and Fuel Cell Technology Platform, at the behest of the **European Commission**. Moreover, the European Union has committed itself to producing 12% of its overall energy requirements from renewable sources by 2010. It has further set itself the target of covering by 2020 at least 20% of all fuel requirements in the transportation sector from non-oil sources, including 5% from hydrogen. The first hydrogen-dispensing refueling stations are being put into service, within the European Union, under the aegis of the European CUTE and ECTOS Programs. Others are being built in Berlin, Munich, Malmö, and Milan. They should provide an ideal opportunity to set up local hydrogen-supply groups.

> Reinhold Wurster
L-B-Systemtechnik
Ottobrunn (Germany)

Shell Hydrogen

Some ten European cities, including Amsterdam (shown here), have begun trials of Citaro electric buses, powered by hydrogen-fed fuel cells.

A The many states of energy

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

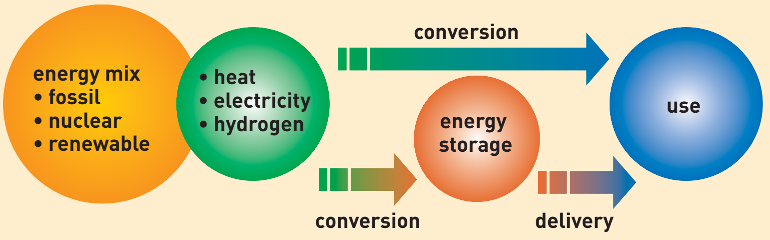


Figure 1.
The energy scheme.

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

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

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

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

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

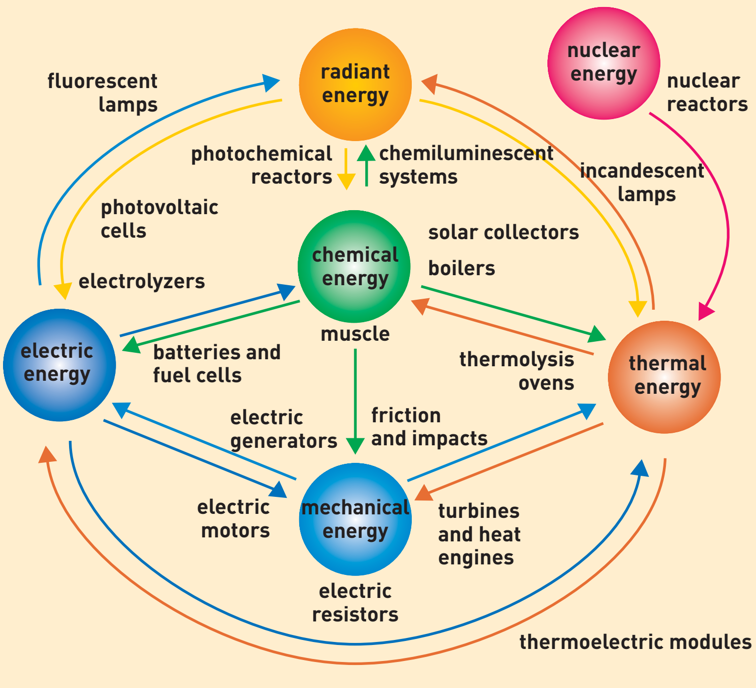
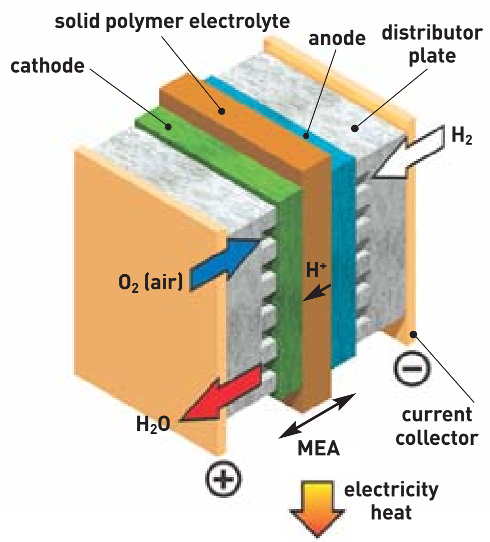


Figure 2.
Conversions of the six main forms of energy, with a few examples of energy converters.

C How does a fuel cell work?



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

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

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

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

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.

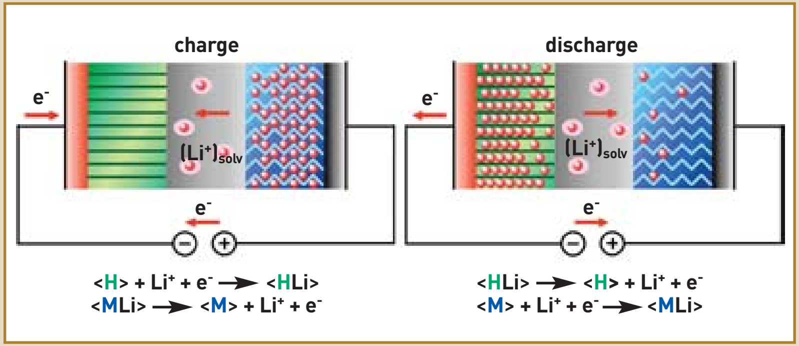
Up to the late 1980s, the two main technologies prevalent on the market were lead–acid storage batteries (for vehicle start-up, backup power for telephone exchanges...), and nickel–cadmium storage batteries (portable tools, toys, emergency lighting...). Lead–acid technology, more widely referred to as 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.

(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 (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 CO_2

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 °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/m². Contributing as it does an "additional radiative forcing" of 1.46 W/m², carbon dioxide (CO_2) accounts for more than half of this "additional greenhouse effect," well ahead of methane (0.48 W/m²), halocarbons (chlorofluorocarbons [CFCs], hydrochlorofluorocarbons [HCFCs], and hydrofluorocarbons [HFCs]), accounting for 0.34 W/m², and nitrogen dioxide (0.15 W/m²). Further, the ozone in the troposphere exhibits a *positive* radiative forcing of 0.35 W/m² (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/m²).

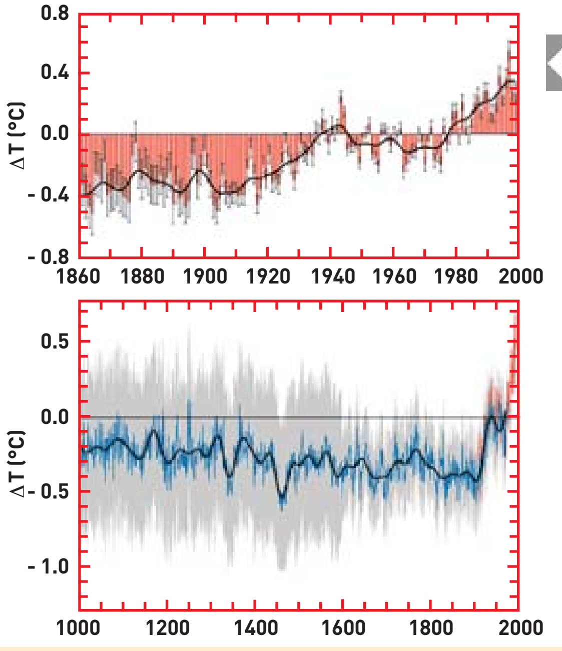
This addition to the natural greenhouse effect (155 W/m²) is small, corresponding to an increase of about 1%. Nevertheless, it is practically certain that this has contributed to the rise in mean temperature, for our planet, of about 0.5 °C, observed over the 20th century (see Figure 1). If nothing is done to curb these emissions, carbon dioxide concentration in the atmosphere (see Figure 2) could double by 2100. From current world consumption [1] of fossil fuels (7,700 Mtoe), the mass of CO_2 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, 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-

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

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 CO_2

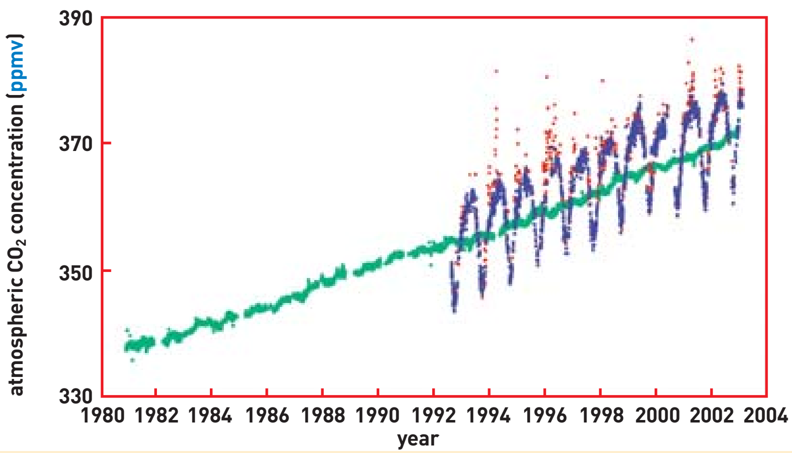


Figure 2.
Evolution of atmospheric CO2 concentration since 1980, as measured on a daily basis by the automatic stations of the Climate and Environmental Science Laboratory (LSCE: Laboratoire des sciences du climat et de l'environnement), since 1981 on Amsterdam Island (Indian Ocean), and since 1992 at 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 CO^2 (red plots), compared to oceanic atmosphere. Over the mean rise in CO_2 concentration is superimposed a marked seasonal modulation, due to plant vegetative cycle (chlorophyll photosynthesis), plants being CO_2 emitters in winter, and CO_2 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).