CO_2 sequestration in geological reservoirs ?

One solution to counter the release into the atmosphere of carbon dioxide, by far the foremost greenhouse gas, consists in trapping it in deep subsurface geological formations.

To counter global warming, the European Union has committed itself to an 8% reduction of its emissions of **greenhouse gases** (**GHGs**). Each member state has been assigned an individual reduction quota, in compliance with Article 4 of the **Kyoto Protocol**. Thus, the target for France consists in keeping its emission levels for GHGs, estimated at about 494 million tonnes (Mt) for 2002, to 1990 values (476 Mt), over the

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 warmer spell, with a mean temperature

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

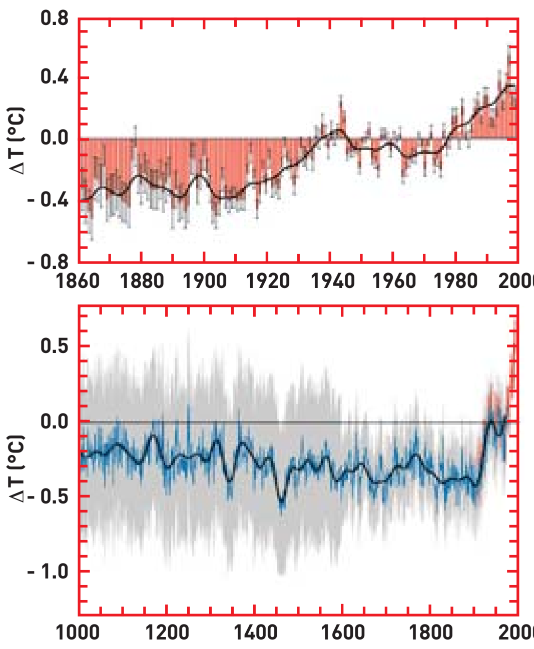

Figure 1. Departures in temperature (ΔT) from the average for the years 1961–1990, over the period 1860–2000, on a global scale (top), and over the past one thousand years in the northern hemisphere (bottom).

period 2008–2012. As regards actions concerning the industry and energy sectors (34% of overall GHG emissions, in terms of **CO_2** equivalent), these should address not only industrial processes, but also capabilities to capture and store such gases.

Existing chemical process allow the capture of 80% of the CO_2 emitted. (1) It is apparent that, were the CO_2 emitted in fumes from thermal power stations, i.e. 3–3.5 Mt CO_2/year per plant, to be captured, treatment of some of this would enable the set targets to be met. However, there then arises the issue of storage.

The options selected for consideration by the scientific community essentially involve CO_2 **sequestration** in deep geological formations. Many initiatives are

(1) Alain Feugier, "Une réponse à l'effet de serre: la séquestration du CO_2", DGEMP, *Énergies et matières premières, Lettre de la DGEMP*, No. 20, 2002.

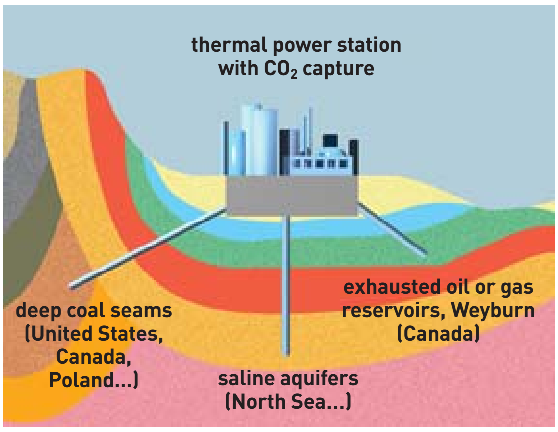

Figure 1.
Concept for subsurface CO_2 sequestration in geological formations.

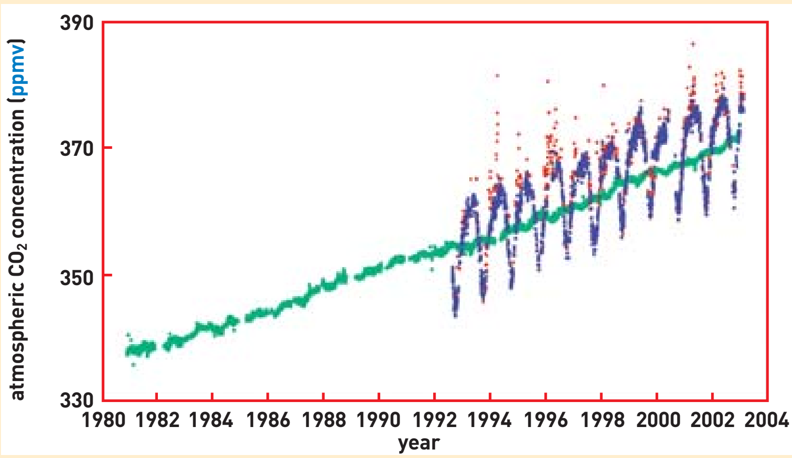

Figure 2.
Evolution of atmospheric CO2 concentration since 1980, as measured on a daily basis by the automatic stations of the Climate and Environmental Science Laboratory (LSCE: Laboratoire des sciences du climat et de l'environnement), since 1981 on Amsterdam Island (Indian Ocean), and since 1992 at 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.

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

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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).

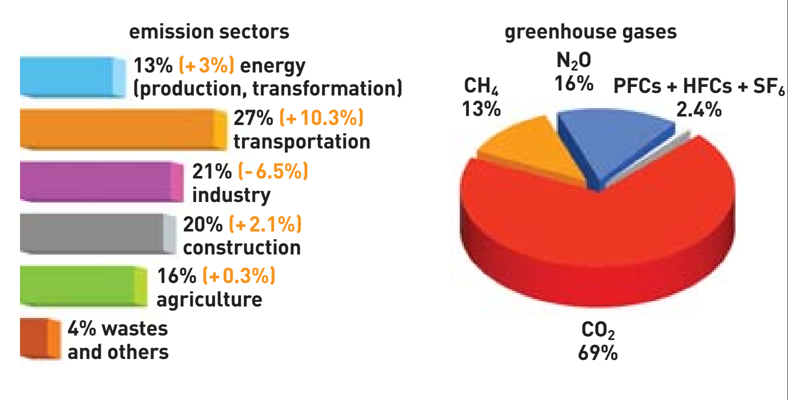

Figure 2.
Relative share of the various business sectors in GHG emissions in France, and growth of emissions in the absence of new measures (data for 2000; source: Centre interprofessionnel technique d'études de la pollution atmosphérique [CITEPA]; CO_2 = carbon dioxide; CH_4 = methane; N_2O = nitrous oxide; HFCs = hydrofluorocarbons; PFCs = perfluorocarbons; SF_6 = sulfur hexafluoride).

being conducted, around the world. Worthy of mention are the industrial experiments carried out by Norwegian oil group Statoil, beneath the North Sea seabed, (2) by EnCana in the Weyburn Field in Canada, (3) and scientific pilots such as the RECOPOL Program in Poland. (4)
In France, uncertainties remain high, as to the actual capacities of aquifer reservoirs or coal seams for sequestration of this gas, in industrial quantities (of the order of a million tonnes CO_2 per year). An initial approach of the issue was initiated, under the aegis of the GESTCO (Assessing European Potential for Geological Storage of CO_2 from Fossil Fuel Combustion) European research program. This program sought to assess the feasibility of large-scale geological storage of CO_2, through investigation of scenarios encompassing the entire source–transport–storage chain, for a number of representative geographical areas in Europe. In the Paris Basin, the deep Trias and Dogger formations should allow storage of several million tonnes CO_2.

(2) Injection of 1 Mt CO_2/year into a saline aquifer, since 1996.
(3) CO_2 recovered from coal gasification in the United States, and injected into a Canadian oilfield to enhance oil recovery, after transport by pipeline over 330 km.
(4) RECOPOL (for Reduction of CO_2 emission by means of CO_2 storage in coal seams in the Silesian Coal Basin of Poland) involves investigation of the capacity for permanent CO_2 sequestration in coal seams, of technical and financial feasibility, and sequestration security.

A number of possible solutions

Currently, it is found that technical solutions, as regards *capture*, require further improvement, as they remain too expensive, however transport raises no specific, unresolvable issues.
Sequestration proper involves a number of solutions. Former oil and gas fields, deep aquifers, bearing unusable saline water, and coal seams would provide excellent storage sites, provided stability and integrity of storage, and control of injected gas migration are demonstrated.
Many research programs are currently under way around the world, to develop the technology involved. 2004 saw the launch of the CASTOR European program, coordinated by **Institut français du pétrole** (**IFP**), directed at post-combustion capture, and investigation of four potential storage sites in Europe.
The **Intergovernmental Panel on Climate Change** (**IPCC**) is currently preparing a special report on this emerging technology, a first step towards recognition of this path as an eligible means of curbing world emissions of CO_2.

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Sleipner Platform, in the North Sea, operated by Norwegian group Statoil. A CO_2 injection experiment was carried out beneath the seabed, in this oilfield.