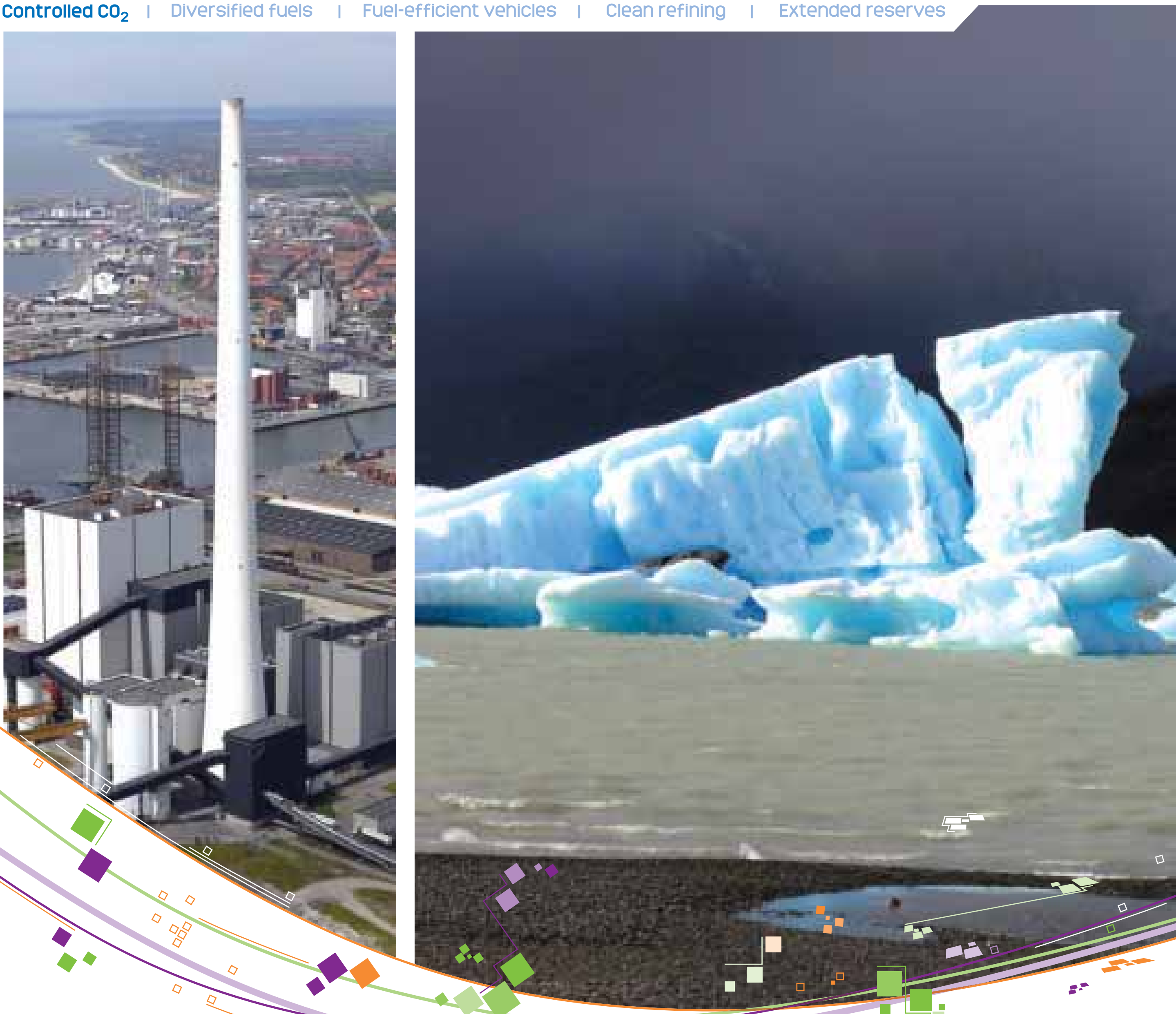


Capturing and storing CO_2 to combat the greenhouse effect

What IFP is doing

IFP
Innovation
Energy
Environment

As an international research and training center, **IFP** is **developing the transport energies** of the 21st century. It provides public players and industry with **innovative solutions** for a smooth transition to the energies and materials of tomorrow – **more efficient, more economical, cleaner and sustainable.**

To fulfill its mission, IFP has **five complementary strategic priorities:**

- capturing and storing CO_2 to combat the greenhouse effect,
- diversifying fuel sources,
- developing clean, fuel-efficient vehicles,
- converting as much raw material as possible into energy for transport,
- pushing back the boundaries in oil and gas exploration and production.

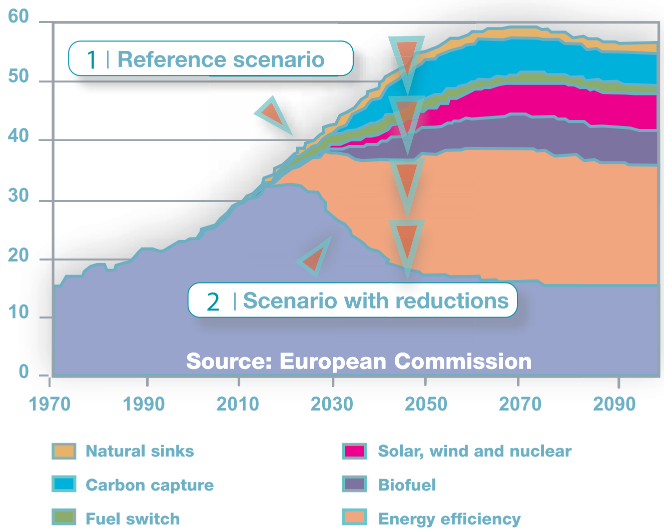
An integral part of IFP, its graduate engineering school prepares future generations to take up these challenges.

The stakes

The growing awareness of the international community and the convergence of the scientific data concerning climate change make it urgent to deploy, throughout the world, technologies to reduce emissions of greenhouse gases. Indeed, the growth of the world energy demand will prevent any rapid reduction of the use of fossil fuels - oil, natural gas, and coal - that are the main sources of greenhouse gas emissions. To reconcile the use of these resources with control of the emissions responsible for global warming, the capture and storage of CO_2 are a very promising approach; the economic and industrial stakes are high.

Anthropic emissions of CO_2 amounted to 26 billion tonnes in 2004. In a reference scenario extrapolating current trends, CO_2 emissions are set to double by 2050, to more than 50 billion tonnes of CO_2 a year. Continuing this trend would lead to an atmospheric concentration of CO_2 exceeding 1,000 ppm (parts per million) at the end of the 21st century, a concentration that is totally unacceptable in terms of its climate impact and its socio-economic consequences.

CO_2 emissions (Gt CO_2)



Key to the diagram: Growth of CO_2 emissions: 1) assuming no change of lifestyles (extrapolation of the current situation); 2) assuming a reduction of emissions and compatible with a temperature rise of no more than 2°C.

According to climatologists, it will be necessary to stabilize the CO_2 content at 450 ppm in order to hold global warming to less than 2°C, which should be sufficient to limit the impact on ecosystems and on the life of our societies. Beyond this level, the climate models indicate a high probability of profound changes occurring, with the possibility of a destabilization of the climate leading to catastrophes in the decades and the centuries to come.

The target of 450 ppm will require mankind to halve its CO_2 emissions with respect to current levels by 2050. In order to attain this objective, we must, starting now, do everything possible to slow the growth of emissions in the years to come, then reverse the trend from 2020/2025.

Given the differing levels of CO_2 emissions per capita across the world, halving emissions for the planet as a whole will entail reducing the emissions of industrialized countries by a factor of 4. This effort is requested of industrialized countries in order to avoid imposing excessively severe constraints on the CO_2 emissions of developing countries, as this would thwart their development. This constraint, aggravated by foreseeable population growth in these countries, would be an intolerable obstacle to the necessary and legitimate improvement of their standard of living.

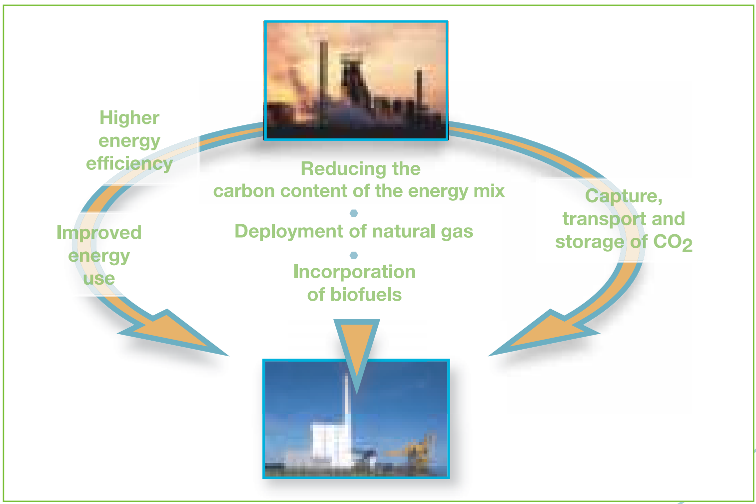
As a promoter of this aim, France has assigned itself the objective of cutting its CO_2 emissions by a factor of 4 by 2050.

Attaining this objective is an ambitious undertaking for mankind. Replacing the patterns of development and growth to which we have become accustomed by a development approach that uses less carbon, and doing so on a planetary scale, calls for profound changes in the way we produce and use energy, since this sector is one of the most important in terms of CO_2 emissions.

IFP is fully committed to this challenge.

Reducing emissions of CO_2

To meet the objective of reducing CO_2 emissions, IFP is exploring three approaches:



Reducing energy consumption

The first approach is to reduce energy consumption by improving the efficiency of energy converters, in particular internal combustion engines.
The rapid growth of road traffic - both for passengers and goods - makes action in this area especially important.

IFP is working to improve the efficiency of vehicle powertrains. This improvement must be achieved while complying with increasingly severe specifications for pollutant emissions on the local scale (nitrogen oxides - NOx -, particles, etc.).

For gasoline engines, IFP is working in particular on:
• downsizing, in which a smaller engine power is increased by turbocharging and other means;
• homogeneous combustion through spontaneous self-ignition of the charge (CAI combustion), which also serves to reduce emissions of pollutants;
• stratified combustion combined with direct gasoline injection.

With these technologies, the potential gain in CO_2 emissions can be as much as 15 to 25%. IFP's experimental results have in fact already achieved an improvement of up to 20% using the downsizing process on a base engine having a displacement of 1.8 liter.

In diesel engines, which consume less fuel and therefore emit less CO_2 than gasoline engines, IFP's work is aimed at maximizing efficiency while reducing emissions of such pollutants as particles and nitrogen oxides (NOx). For this, IFP is developing, in particular, new homogeneous combustion modes (NADI™).

Another way to improve powertrain efficiency and reduce CO_2 emissions is to use a hybrid propulsion system (pairing an internal combustion engine with an electric motor/generator). IFP's work in this area includes the development of system modelling tools that can be used, in particular, to estimate the impact of the components and architecture of a given hybrid vehicle on its performance and consumption. These tools can also be used to optimize energy

Development and validation of innovative low-emissions processes on the engine test bench.

management on board the vehicle so as to achieve low fuel consumption, and therefore lower emissions of CO_2. The potential fuel economy expected with such a vehicle is between 20 and 40%, depending on the level of hybridization employed.

Full Hybrid NGV demonstrator (CO_2 emissions < 80g/km).

Reducing the carbon content of the energy mix

A second approach is to reduce the carbon content of energy by favoring the use of natural gas or by incorporating in the fuel recycled carbon (biofuels and synfuels) and by developing hydrogen as an energy carrier.

IFP is deeply involved in the development of biofuels, in particular second-generation biofuels made from lignocellulosic biomass (straw, forest residues, etc.), which should make it possible to reduce the CO_2 emissions of the transport sector quite substantially.

As for the production of hydrogen as an energy carrier, the approaches that are favored are those that will improve the CO_2 balance. For small capacity units, the development work is aimed at the production of hydrogen from biomass, in particular bioethanol. For the large-scale production of hydrogen from fossil fuels, the processes which are considered include the capture and storage of CO_2.

Capturing, transporting, and storing CO_2

The third approach is to capture the CO_2 from industrial processes used for electricity, steel, and cement production, which emit it in large quantities, then store it underground so as to keep it out of the atmosphere. This approach therefore chiefly concerns large fixed sources of CO_2.

This brochure describes IFP's recent work in this field.

Diester Industrie's biodiesel production unit in Sète (France) using Axens' Esterfip-H™ technology.

The capture, transport, and storage of CO_2

This approach for reducing the CO_2 emissions consists in capturing the CO_2, transporting it to the place of storage, then injecting it underground to store it. The injection phase is followed by a phase of monitoring.

IFP's work concerns all these different steps, with the following objectives:

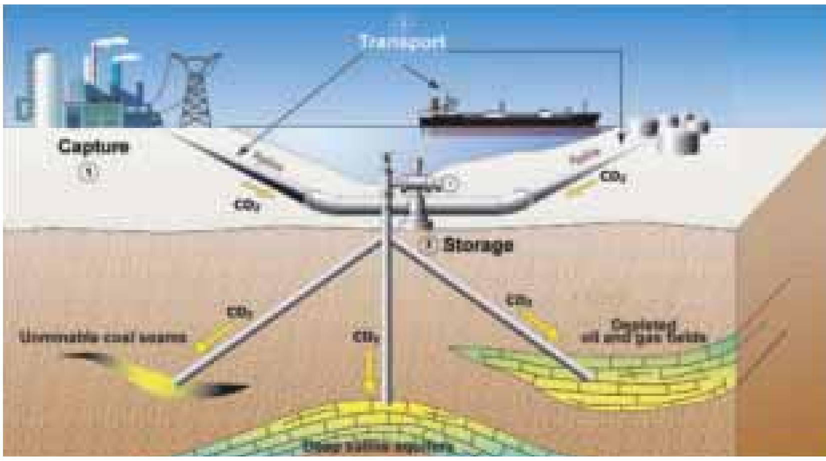
■ Develop innovative materials, products and processes to cut the cost and the energy penalty of capture:

• IFP is investigating various ways to capture CO_2 in flue gases, in particular the optimization of solvents and the way they are used;

• IFP is looking for new ways to implement oxycombustion, in order to obtain flue gases in which CO_2 is concentrated and easier to capture. New options which are considered, involve the direct transfer of oxygen from air by using solid phases undergoing an oxidation-reduction cycle (chemical looping combustion);

• Finally, IFP is committed to looking for new energy production processes that produce synthesis gas and hydrogen and incorporate the capture of CO_2.

■ Master CO_2 transport infrastructure through improved technologies.



Main options for the capture, transport and storage of CO_2. Capture/compression: 30-60 €/t - Transport: 3.5 €/t per 100 km - Injection/storage: 20 €/t for 1 Mt/yr. (7 €/t for 10 Mt/yr.).

IFP is studying various transport modes and developing the methods and tools needed to make this transport as safe and reliable as possible.

■ Select storage sites and ensure their safety and long-term viability by improving the modelling of the mechanisms of interaction between the injected CO_2 and the subsoil.

Three geological storage modes are being considered: storage in depleted oil and gas fields, in deep saline aquifers, and in unminable coal seams. IFP's work concerns the analysis, understanding, and modelling of interactions between the injected CO_2 and the rocks and fluids of the subsoil. Geochemical and geophysical monitoring methods, in particular seismic and microseismic methods, are also being studied to make it possible to control the propagation and the evolution of the stored gas and the integrity of the overburden of the storage facility.

A platform for CO_2 injection in the North Sea (Statoil – Sleipner site, Norway).

Pilot CO_2 capture facility. European Castor project (Dong – Esbjerg site, Denmark).

Post-combustion

CO_2 capture

From the economic standpoint, it is first of all in capture technologies that significant advances must be made in order to allow massive deployment of the CO_2 capture and storage approach. This step, in which the CO_2 is separated from the other combustion products (water vapor, nitrogen, etc.), accounts for approximately 70% of the total cost of the approach.

The CO_2 in combustion gases can be captured using techniques similar to those used to process natural gas, developed among others by IFP. The CO_2 is extracted in scrubbing columns by a chemical solvent that is then regenerated by distillation. Given the volumes to be treated, their low CO_2 concentration, and the very mechanism of chemical absorption, this process induces a large energy penalty. IFP is investigating new technologies, with emphasis on minimizing energy consumption and reducing the size and investment cost of the facilities. These technologies can be used both on new facilities and on existing ones, provided that the initial efficiency of the latter is sufficiently high.

As part of the IFP-led European Castor project, a pilot unit for the capture of CO_2 in the flue gases of a coal-fired power station is in operation since the beginning of 2006 (Dong company, Denmark). Capacity 1 t/h of CO_2; 5,000 Nm³/h of flue gases.

The work done at IFP concerns:

Solvents:

Research is aimed at identifying new solvents that require less energy for regeneration, are economical to produce and compatible with environmental constraints.

"Third-generation" bulk packings, IMTP line from Koch-Glitsch.

Equipment:

New equipment, in particular new column packings having a large contact surface area, are being developed to improve the effectiveness of the process and reduce the size and cost of the facilities.

Processes:

The capture processes are being optimized so as to improve their global performance, minimize their investment and operating costs, and ensure their reliability.

Concentrating
CO_2 for capture

Oxycombustion

Another way to capture CO_2 is first to operate the combustion step in the presence of oxygen rather than air. This combustion mode, called oxycombustion, produces combustion gases in which the CO_2 is more concentrated and can be separated, under pressure, at lower cost. The development of this process is less advanced than that of post-combustion capture. The option of oxycombustion capture is being considered primarily for new facilities. It can also be implemented in existing facilities, but this requires a revamping of the steam generators.

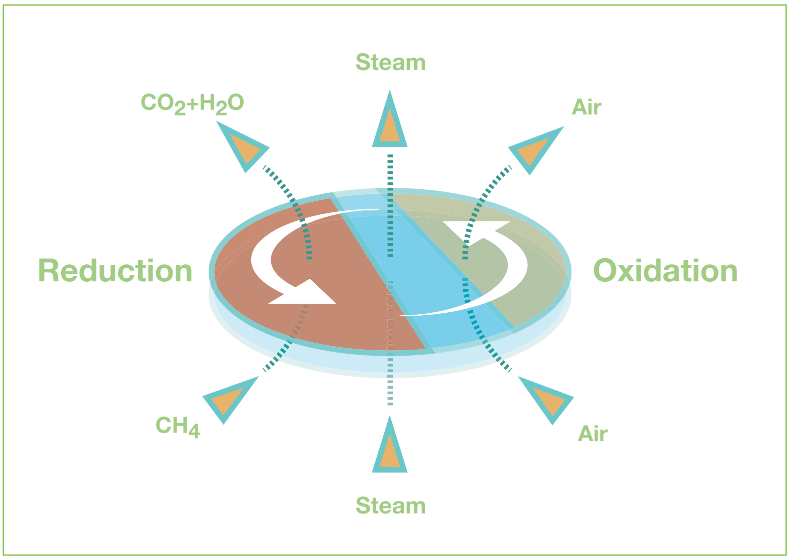
As part of the European Encap project and the ANR CLC-MAT precombustion CO_2 capture project, IFP is developing a Chemical Looping Combustion reactor and suitable metal oxides.

IFP is studying this technology with a view to adapting it to various fuels, in particular oil residues. IFP is also developing an innovative (flameless) homogeneous oxycombustion technology that eliminates the combustion hot spots that impose high constraints on the materials of steam generators.

While oxycombustion has major advantages for CO_2 capture, it requires the upstream separation of oxygen from air. This separation is generally achieved by cryogenic distillation, which is itself expensive and consumes energy. IFP is studying another oxygen combustion mode in which a metallic oxide undergoes oxidation-reduction cycles to supply oxygen (chemical looping combustion), thereby eliminating the need for bulky and expensive air separation facilities. IFP is developing new metallic supports that have high oxygen transfer capacities while being mechanically stable, relatively inexpensive, and compatible with environmental constraints. In addition, different ways of using such solid phases, in a fluidized bed or in a revolving reactor, are being tested.

Capture in a gas turbine

IFP is also studying a new gas turbine capture process in which CO_2 is concentrated by recycling the combustion gases and then captured under pressure and at a higher concentration. The economic merit of this process has been clearly demonstrated. It holds promise for applications both in large industrial units (such as gas liquefaction units) and for the capture of CO_2 in combined-cycle natural-gas-fired power stations.



Precombustion

CO_2 capture

To separate CO_2 under more favorable conditions of pressure and concentration, one alternative to the direct combustion of a fossil fuel is its conversion to a synthesis gas.

This is done by partial oxidation of a heavy feedstock (gasification of coal, petcoke or residue) or steam-reforming of natural gas that produces a mixture of hydrogen and carbon monoxide. After treatment with water, this synthesis gas is converted into a mixture of hydrogen and CO_2. The hydrogen can then be separated from the CO_2 and used either as is (for example in a refinery, for the deep conversion of heavy crudes) or as a fuel in a combined cycle for the production of electricity and/or of heat, or again as an input for the production of synthesis fluids by a Fischer-Tropsch type reaction.

This kind of centralized production of hydrogen from fossil fuels depends on the availability of processes that are very energy-efficient and environmentally-friendly – which means combined with CO_2 capture and storage technologies.

It is for this purpose that IFP is participating in the European Cachet, Dynamis, and Coach projects.

In the Cachet project, which includes several industrial partners (BP, Chevron, Norsk Hydro, NTUA, PDC, Shell, Siemens and Technip), IFP is developing the large-capacity HyGenSys process for the production of hydrogen from natural gas with capture of CO_2. This process includes a compact, energy-efficient, large-capacity natural gas steam reforming unit. Work has been focused mainly on the technological development of the reactor-exchanger, the key equipment in the process. The reactor has been modelled and sized by IFP, working with Technip, which studied its mechanical feasibility. The ultimate objective is the development of technologies for the large-scale production of electricity and hydrogen from natural gas for 400-MWe sites, with 90% capture of the CO_2 and a cost of $20-30 per tonne of CO_2 captured.

The Dynamis project, the first step in the ambitious European Hypogen program, is devoted to an industrial feasibility study of a hydrogen production unit with capture and storage of CO_2.

Coach, a project financed under the European Commission's 6^{th} Framework Programme, was launched following the signing of a co-operation agreement (memorandum of understanding) between the European Union and China on the fight against climate change. It brings together 20 partners (industrialists, research centers, government agencies), 8 of them Chinese, and is aimed at establishing the specifications of a demonstration operation with CO_2 capture in a coal-fired power station and storage in an oil reservoir, in China. The power station will be of the polygeneration type - designed to produce not only electricity but also heat, hydrogen, and synthetic fluids.

Transporting
and injecting CO_2

The transport of CO_2

After the capture phase, the CO_2 must be conveyed, sometimes over several hundreds of kilometers, to a place of storage. Currently, for the needs of the oil industry, it is transported in gas pipelines, in the supercritical state. This requires suitable compression and injection facilities. IFP is developing an alternative solution in which the CO_2 is transported and injected underground in the liquid state, at a temperature that remains close to the ambient temperature. Transporting and injecting CO_2 in liquid form could substantially reduce the corresponding investment costs.

Laboratory equipment used to work under reservoir conditions.

Result of an injection of CO_2 into a carbonate-containing rock.

The study of injectivity

The first step in a storage operation is to determine the flow rate at which it will be possible to inject the CO_2. This calls for characterizing its flow properties in a porous medium and therefore controlling all the physical and chemical phenomena relevant to its interactions with the geological medium.

In consequence, using technologies it developed for oil production, IFP is developing modelling tools and laboratory analysis methods to predict the flow of CO_2 in the subsoil in the vicinity of the injection well, where the gradients of CO_2 concentration, pressure, and temperature are high.

A special case, the reinjection of acid gases

IFP is also investigating the joint reinjection into the subsoil of CO_2 and other acid gases (in particular H_2S) resulting from the production of natural gas and its processing; indeed, an increasing number of gas reservoirs having high acid gas contents are exploited, for example in Central Asia. Here, IFP is engaged in research on the thermodynamic, geomechanical, and hydrodynamic modelling of these gaseous mixtures to improve our understanding of the interactions of these gases with the reservoir and the well, and thereby optimize their reinjection.

Pilot CO_2 injection facility.

Ensuring the safety
and long-term viability of CO_2 storage facilities

The various types of storage

IFP is studying the various types of geological storage that can be considered. Three main types are distinguished.

The first is depleted oil and natural gas reservoirs; these have the advantage of being well characterized. Furthermore, their hydrocarbon-tightness has been proven over millions of years. In addition, the injection of CO_2 can serve to enhance oil or gas production. However, while the storage capacities of these reservoirs are considerable (920 billion tonnes), they are handicapped by their uneven distribution over the planet.

Another storage option is the injection of CO_2 into unminable coal seams. This option is marginal given its small total world capacity, but may be attractive locally because of the coal bed methane production that the injection of CO_2 makes possible. IFP has accordingly taken part in the first European experiment on the storage of CO_2 in coal seams, in Poland.

The largest storage potential is found in deep saline aquifers. These underground water filled rock porous layers exist almost everywhere in the world, and could hold 10,000 billion tonnes of CO_2.

They are poorly known geological objects, as they were until now devoid of economic interest. Since the beginning of the 1990s, geologists have been analyzing them in view of the storage of CO_2. Today, while an inventory of the planet's principal sedimentary basins and an evaluation of their storage potential remain to be conducted, enough knowledge has been gained to start the transition from laboratory research to applications on the ground.

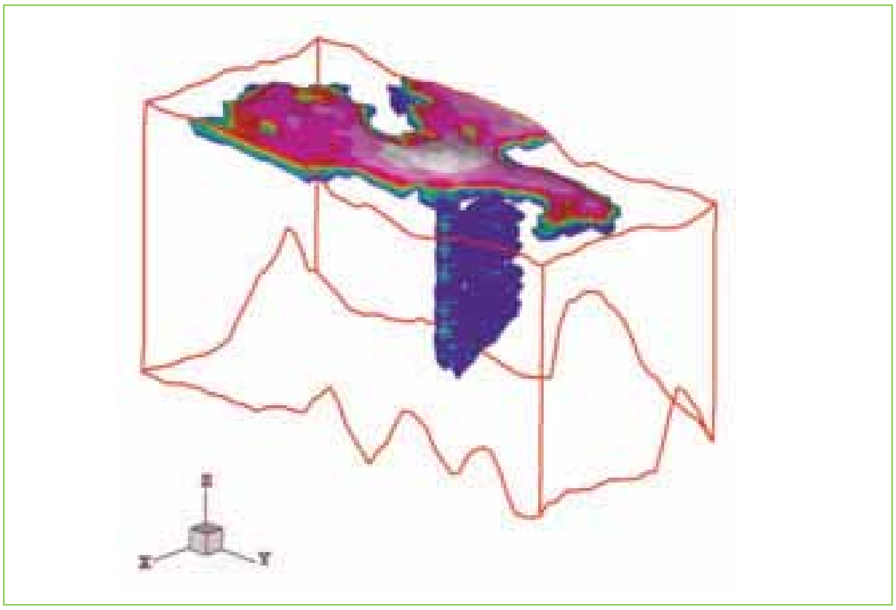
IFP is deeply involved in these research fields, in particular those concerning declining oil reservoirs and saline aquifers.

The selection and evaluation of storage sites

IFP is conducting experimental investigations in the laboratory aimed at a better understanding of interactions between CO_2, the fluids in place, and rocks. These observations provide input to the modelling tools it uses to evaluate and simulate the future of CO_2 in the subsoil, including the long term (several hundreds or even thousands of years).

For example, IFP has used its extensive experience in basin modelling and reservoir modelling to develop the Coores simulator, which models the hydrodynamic behavior of CO_2 in a porous medium, with allowance for all geochemical and geomechanical interactions. This simulator is used on an industrial scale for site evaluations complementing varied analyses: seismic and geochemical studies, coring, logging, etc.

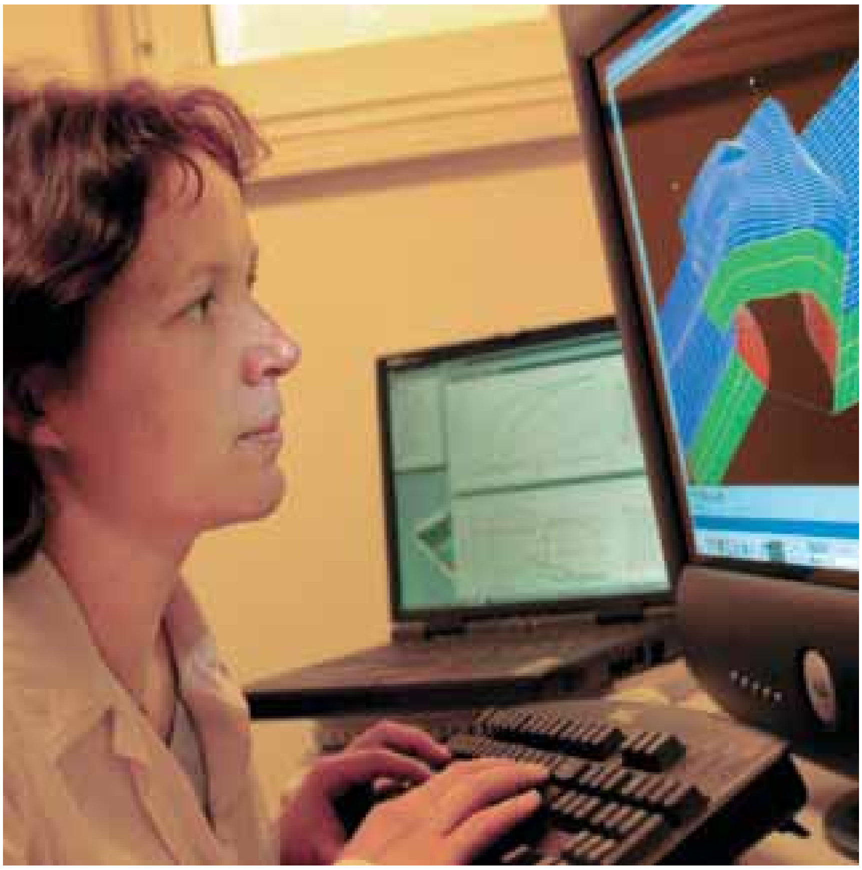
The model of the subsoil so constructed is used to estimate the injectivity, the propagation of CO_2 in the subsoil and the impact of geochemical and geomechanical transformations on the tightness of the overburden and of the well. This information is critical for judging the medium- and long-term safety of the storage facility.



Modelling the migration of CO_2 in a geological structure using Coores software developed by IFP.

The surveillance of storage sites

Tracking of the injected CO_2 and the post-injection monitoring of the site are essential to ensuring the safety of the storage. In this area, IFP is developing passive seismic surveillance techniques using permanent sensors installed in wells. IFP has in particular developed, with CGGVeritas and Gaz de France, the Seismovie™ permanent monitoring system. IFP is also developing tools for the analysis and interpretation of the passive microseismic data so acquired.



The post-injection monitoring of the site is essential to ensuring the salety of the storage.

IFP as coordinator
of R&D in the capture and storage of CO_2

IFP, through the research it is conducting either alone or in partnership with universities, research centers, and the industrialists concerned, has become a major player in the field of CO_2 capture and storage.

A French player

At the national level, IFP is working alongside other French players on many projects supported by the ANR (*Agence nationale de la recherche* – National Research Agency) or by the ADEME (*Agence de l'environnement et de la maîtrise de l'énergie* – Agency for the Environment and Energy Management). Thus IFP is developing with BRGM several software dedicated to CO_2 storage evaluation, design and monitoring. In addition to technological R&D projects in the fields of capture, transport, storage, monitoring, and site surveillance, IFP is also participating in projects concerning socio-economic aspects and the societal acceptability of geological storage of CO_2.

A European player

IFP is today also a leader in the field of CO_2 capture and storage at the level of the European Union and is fully committed to many European research projects.

For example, IFP is Vice-Chair of the ZEP (Zero emission fossil fuel power plants) technology platform, launched by the European Commission as a tool to promote a joint effort by the scientific and industrial communities to improve both energy efficiency and the capture and storage of CO_2 in the power generation sector.

IFP is also leading the Castor integrated project, which brings together more than 30 academic and industrial partners. Its object is to improve post-combustion capture techniques using solvents, by developing the largest pilot in the world to date, and to study 4 European storage sites.

IFP has also been entrusted with the task of leading the IncaCO_2 project, which promotes exchanges between European projects related to the CO_2 theme and disseminates the results obtained.

Finally, IFP is a contributor to the CO_2GeoNet network of excellence and chaired its first general assembly. IFP is also a participant in the Cachet, Encap, and Dynamis projects, part of the European Hypogen initiative aimed at the development of conventional power stations with zero CO_2 emission.

An international player

Internationally, IFP has in particular taken part in the Weyburn project, a Canadian CO_2 storage project associated with an enhanced oil recovery operation, the scientific accompaniment of which has been coordinated by the International Energy Agency (IEA). Moreover, IFP participates in the CCS Bahia project in the Reconcavo basin in Brazil, with Petrobras.

Finally, IFP is the leader of the Coach project, which, alongside with the technological stakes, is also intended to coordinate all projects executed under the co-operation agreement signed between the European Union and China concerning the fight against climate change.

At the level of international institutions, IFP is a participant in the various networks led by the "Green House Gas" program of the International Energy Agency (IEA-GHG program) and participates, alongside the ADEME, in meetings of the Executive Committee of the IEA-GHG. IFP is also a member of the French delegation to the Carbon Sequestration Leadership Forum (CSLF).

From research to industry

Over the years, IFP has created many channels for technology transfer in order to promote the industrial use of its R&D work. In the field of capture and storage of CO_2, IFP, in addition to its policy of filing for patents, has founded Geogreen, an industrial player in the storage of CO_2, together with Géostock and BRGM.

Geogreen is an international engineering services company specializing in the transport and geological storage of CO_2.
Geogreen is a joint venture of three major French players in the field: IFP, the Géostock company (underground storage of hydrocarbons), and BRGM. They are pooling their skills in order to establish a position in the world market for the geological storage of CO_2.
The perfect technical complementarity of Geogreen's experts enables it to offer the industrialists concerned a very broad range of services covering all aspects of the chain, from the transport of CO_2 to its geological storage, from upstream expertise to engineering and project development. In the longer term, it will offer injection site operating, monitoring, and maintenance services and follow-up services in connection with the closure of storage sites.

Innovation
Energy
Environment

Innovating for energy

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Photos: *Axens, Elsam/Dong, Getty Images, J.-J. Humphrey, IFP, X.* Design & layout: *Éditoria / 350709*