

The geological storage of CO₂

IFP Energies nouvelles' solutions for safe deployment

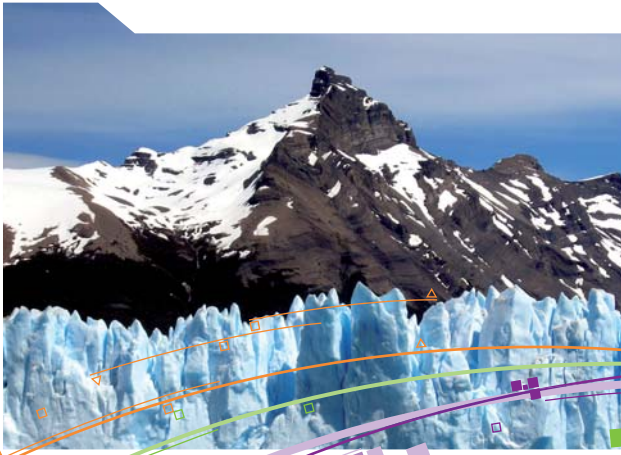
IFP Energies nouvelles is a public-sector research, industrial innovation and training center active in the fields of energy, transport and the environment. Its mission is to provide public players and industry with efficient, economical, clean and sustainable technologies to take up the challenges facing society in terms of climate change, energy diversification and water resource management. It boasts world-class expertise.



Capturing and storing CO₂ to combat the greenhouse effect

Combating global warming, which is due in large part to CO₂ emissions related to energy use, is now a huge planetary issue. IFP Energies nouvelles, which has always viewed environmental problems as a major concern spanning all of its research areas, has made this challenge one of its absolute priorities.

In addition to the effort to reduce CO₂ emissions, it is essential to capture CO₂ wherever feasible, which means primarily at industrial sites. IFP Energies nouvelles has for several years now been strongly committed to developing new technologies — capture, transport and underground storage — to reduce discharges of CO₂ into the atmosphere. IFP Energies nouvelles holds a cutting-edge position in this respect because many of the skills needed for this research are also used in the context of oil production. IFP Energies nouvelles is currently a leading player in this area, both at European and national levels.



CO₂ storage

the issues and challenges

There has been growing international awareness in recent years of the need to reduce greenhouse gas (GHG) emissions, with CO₂ being the primary target. Tackling climate change – due mainly to human activities and the intensive use of fossil fuels (oil, natural gas and coal) since the beginning of the industrial era – lies at the heart of the issue.

According to the IEA, CO₂ capture and storage (CCS) alone could contribute up to 19% to the reduction of global emission in 2050, i.e. around 5 Gt of CO₂ per year. Moreover, it is one of the solutions that will make it possible to develop initiatives aimed at improving energy efficiency as well as the gradual decarbonation of energy, particularly through the use of alternative energy resources and vectors (solar, wind and hydrogen for example).

CCS consists in capturing the CO₂ emitted by industrial facilities (principally power stations, but also cement plants, steel works, etc.) and storing it underground.

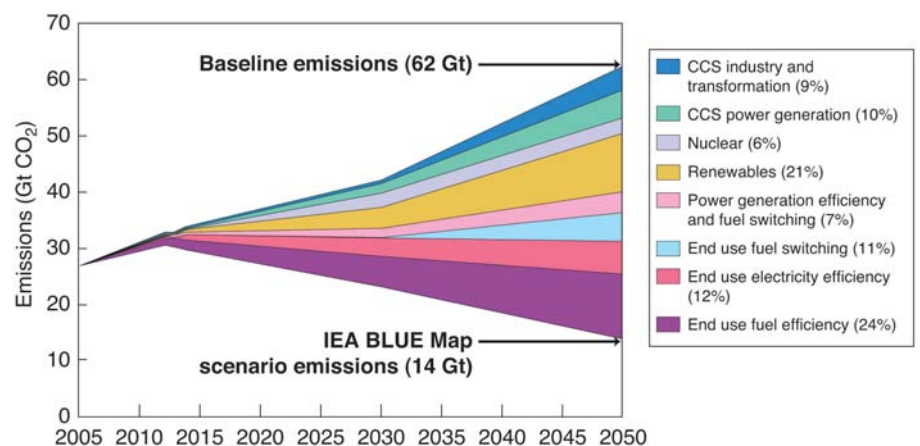
Various geological environments are being considered for CO₂ storage:

- deep saline aquifers;
- mature oil and gas fields
 - either after production in depleted reservoirs
 - or during production with the added benefit of helping to drain oil and gas from reservoirs (EOR/EGR processes);
- unexploitable coal seams;
- storage in mineral form in ultrabasic rocks.

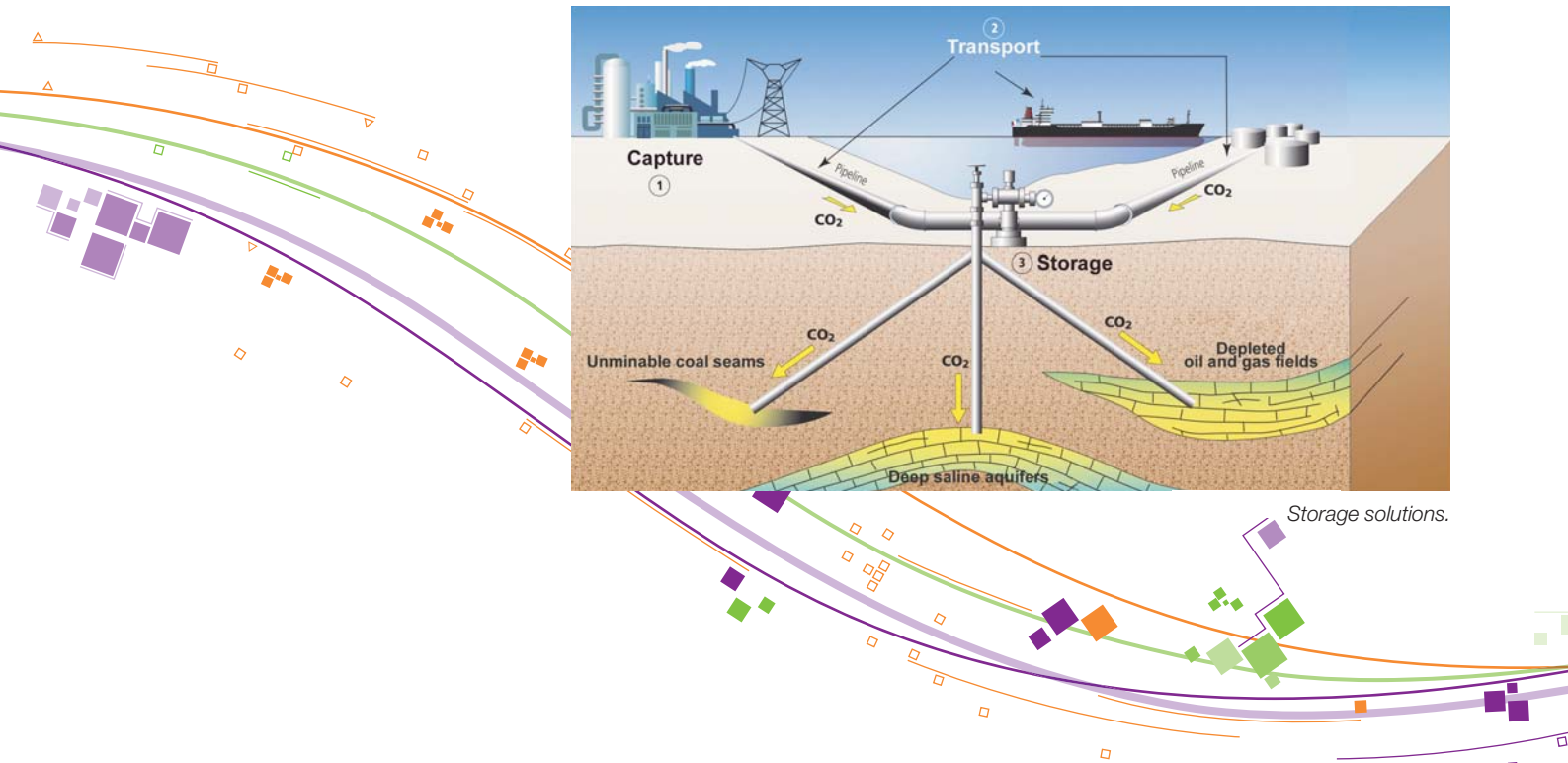
In terms of the scale of the challenge we face, only mature fields or saline aquifers will enable sufficient quantities to be stored. It is estimated that the potential CO₂ storage

capacity of mature fields could be around 900 Gt, but their global distribution is far from even. Saline aquifers have a far wider geographic distribution, but there is currently no economic benefit associated with them and little research has been carried out.

As a result, knowledge of them is limited but whilst their CO₂ storage potential remains uncertain it is likely that this capacity is significantly greater than that of mature fields.



In the IEA BLUE Map scenario, the CCS would contribute to cutting CO₂ emissions by 19% between now and 2050. Source: IEA.



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The development of a CCS industry carries with it a number of technological challenges:

- the main one concerns the need to reduce the costs associated with capture, which are currently between €60 and €80 per metric tons of CO₂ captured;
- in terms of transport, an appropriate infrastructure needs to be established (pipeline networks for example). Also, there is a requirement to consider the impact of other gases (oxygen, nitrogen, etc.) and the various impurities (NO_x, SO_x) the CO₂ may contain;
- without a doubt, the geological storage of CO₂ represents the segment of the CCS chain that will provide the focus for the widespread acceptance of the chain as a whole. The technology has to be shown to be safe in the short term (over a few decades of injection and storage monitoring) and the long term (several hundred to thousands of years) in order to be established as a viable permanent solution.

CO₂ storage makes use of proven technologies that have been employed in the oil industry for many decades already. However, although oil fields have demonstrated their capacity to contain fluids for millions of years, it remains to be shown whether or not they would react negatively to the injection of carbon dioxide. CO₂ dissolved in water represents a weak acid that may have an impact on the mineralogy and structure of the rock, and lead to the possible alteration of its mechanical as well as petrophysical properties. As far as saline aquifers are concerned, the challenges are even more numerous since little is known

about these geological layers. Much research will be required to identify zones that could feasibly contain large volumes of CO₂ over periods of time running to several hundreds of years.

IFP Energies nouvelles has significant expertise in the field of oil and gas reserve production and is extremely well placed to develop the technologies required to ensure the safe implementation of geological CO₂ storage solutions. An important objective is to develop the industrial software that will make it possible to model and monitor storage solutions, as well as optimize the injection and storage process.

The CO₂ injected into a saline aquifer migrates in a plume through the reservoir to the cap-rock, where it is trapped.



Storage facility lifecycle

Storage site selection and risk assessment (pre-operation phase - 3 to 5 years)

IFP Energies nouvelles is developing a multi-scale modeling workflow, covering all aspects from the basin to the area around the injection well. It is also looking at risk analysis which is absolutely crucial to the success of the site selection phase.

This comprises:

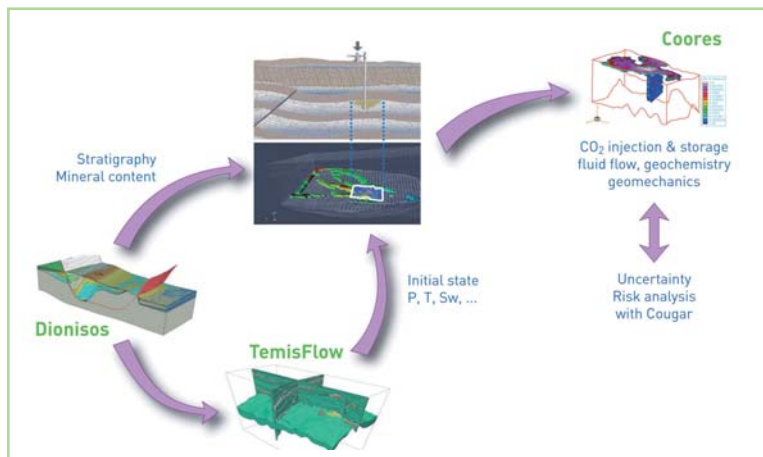
- regional screening using basin modeling (fluids and pressure with TemisFlow™, sedimentary deposits with Dionisos™);
- one thousand year time scale modeling of the evolution of a CO₂ plume with Coores™ software, which can be used to simulate the various types of storage under consideration and their behavior over long periods of time. It models the reactive flows of several fluids,

the petrophysical modifications associated with chemical reactions and, when used in combination with geomechanics software, the impacts due to the increase in pressure and changes in mechanical properties on the component and surrounding elements of the storage: well, cap and faults;

- a detailed analysis of fluid/rock interactions, from a sample scale right up to field scale;
- consideration of uncertainties on all scales (Cougar™ software).

Leak risk management also requires the monitoring of the sealing properties of faults and cap-rocks: in this field, IFP Energies nouvelles is working on the laws of fracture propagation in argillites and the mechanical behavior of faults.

The application of this complete workflow should make it possible to select storage sites that will meet the criteria established by the relevant authorities and hence optimize the evaluation of quantities that can be injected.



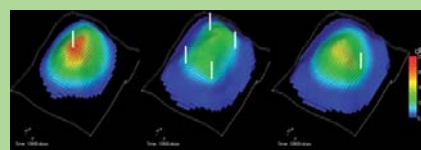
CO₂ storage from stratigraphic modeling to injection "process".

Coores™

Developed by IFP Energies nouvelles, Coores™ software is aimed at assessing the long-term effects of CO₂ storage on a geological site. Coores™ was developed over a period of several years and has now become a benchmark tool used in various projects, including those conducted in partnership with European partners. IFP Energies nouvelles' laboratories have been called upon to construct the geochemical models required to simulate reactive flows for the purposes of studying the effects of CO₂ on the mechanical resistance of rocks, and validating Coores™ on experiments using rock samples.

Within the context of the European Dynamis program (2006-2009), which examined the feasibility of a thermal power plant coupled with a CO₂ storage

and capture system, IFP Energies nouvelles' scientists turned to Coores™ to simulate CO₂ injection over a period of 30 years. Three different geological structures were used in the modeling, two aquifers and an old oil field located off the English and Danish coasts. By using the software, scientists were able to predict the behavior of CO₂ injected at the sites, making it possible to ensure and optimize its entrapment over a period of 1,000 years. For example, the influence of the number of wells and their positioning on the increase in pressure during injection were simulated using Coores™ for various scenarios. In particular, the research demonstrated that the positioning of a single well at the side of the structure makes it possible to reduce the pressure increase and hence preserve the integrity of the cap, whilst optimizing costs.



Modeling the evolution of CO₂ saturation after 30 years of injection with Coores™. On the left, a well at the top of the structure, in the center four wells around the summit, and on the right a well to the side of the structure.

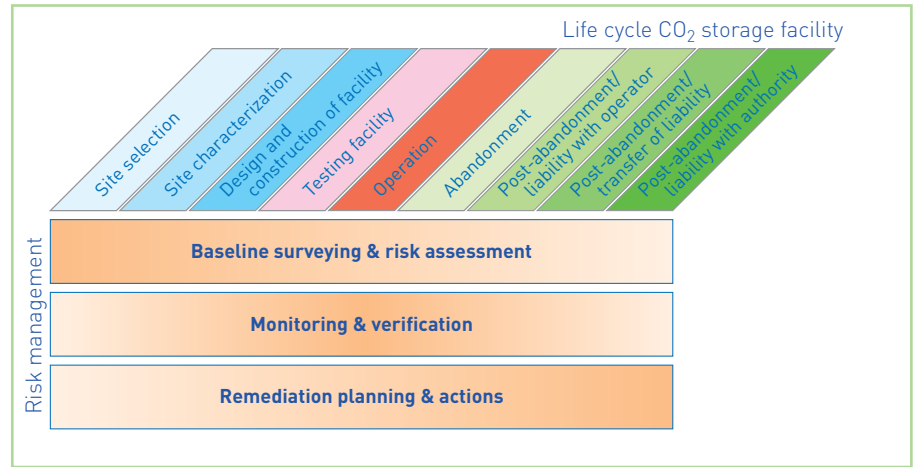


Modeling the evolution of pressure in the same conditions with Coores™.

Construction and injection (operation phase - 10 to 50 years)

Numerous additional data are collected in the wells during the operational injection phase. The measurements gathered are used to improve reservoir and cap-rock characterization and bring models up to date, thereby optimizing injection and reducing risks. The implementation of a raft of monitoring technologies adapted to each site makes it possible to verify the injection as well as cap-rock and well integrity, and monitor the evolution of the plume. It also means that a CO₂ mass assessment can be carried out in order to certify that the quantities injected have been properly trapped and can potentially therefore be subject to quota allocation.

IFP Energies nouvelles is conducting experimental studies in the laboratory in order to estimate reservoir injectivity as well as the

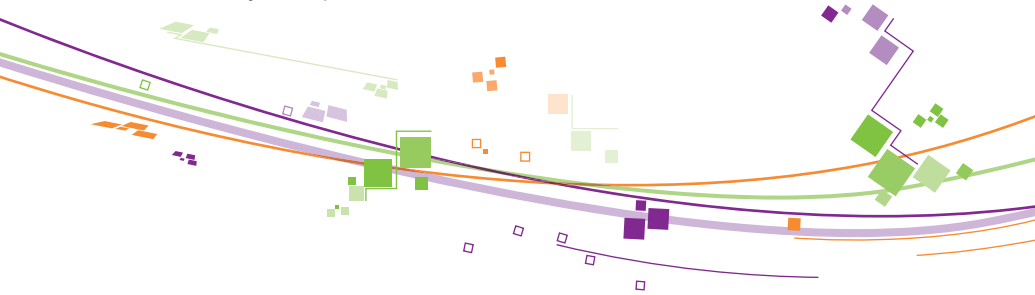


The storage workflow.

resistance of the cap-rocks and cements that will provide the seal. Ongoing research includes tests on the alteration, in the presence of CO₂, of Portland cements traditionally used in industry which have made it possible to examine the effects of dissolution and carbonation which can lead to their mechanical deterioration.

These tests have revealed the importance of ensuring the resistance of cement/metal interfaces. Furthermore, IFP Energies nouvelles has developed and patented new cement formulations that are better suited to the need for very long-term sealing capacity.

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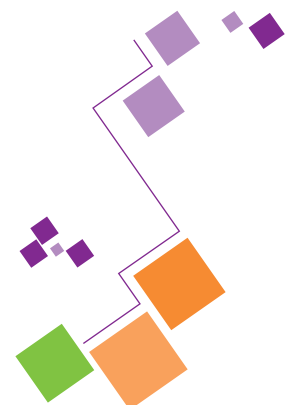
Dissolution and carbonation in the presence of CO₂, measured in the laboratory on a cement sample.

Reinjection of CO₂ in a natural gas field: the In Salah pilot

Operated by a joint-venture between BP, Sonatrach and Statoil, the In Salah gas field complex has had two injection wells in the Krechba region (Algeria) since 2005. Used to



inject CO₂ in an aquifer at a depth of 1,800 m in order to keep the natural gas field under pressure, In Salah is acting as a genuine underground laboratory: by interpreting the seismic and gravimetric measurements taken on site, IFP Energies nouvelles researchers are able to produce models that, for example, demonstrate how CO₂ behaves during the injection phase in the underground environment.



Flux chamber used to establish a geochemical baseline in the pre-injection phase.



Storage monitoring (post-operation phase - 1,000 years)

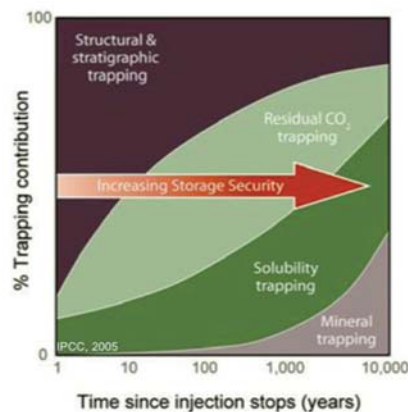
Once injection operations have come to an end, the operator needs to be able to prove to the monitoring authorities responsible for the site that the storage facility is in a state of stability for the future. It is to this end that an atmospheric environmental and aquifer monitoring system will be maintained. Due to the kinetics of CO₂ dissolution and mineralization phenomena, the risks of leaks gradually diminish over time.

IFP Energies nouvelles is developing site monitoring methodologies making particular use of seismic, micro-seismic, electric, electromagnetic, gravimetric and geochemical technologies, together with surface deformation measurements.

■ Regarding geochemical monitoring, IFP Energies nouvelles is focusing on the analysis of rare gases as tracers with a view to recognizing whether or not the CO₂ identified comes from the storage reservoir. By taking repeated measurements and comparing them with a baseline recorded during the pre-injection phase, it is possible to identify a potential CO₂ leak from a storage facility, through the study of the natural background noise.

■ IFP Energies nouvelles is also developing monitoring technologies based on seismic acquisition using permanent sensors, in particular the SeisMovie™ continuous monitoring system developed with CGGVeritas and GDF Suez, and marketed by CGGVeritas. In parallel, IFP Energies nouvelles is pursuing the development of μsics™ software, designed to locate micro-seismic events.

In addition, IFP Energies nouvelles is developing methodologies for updating models using data gathered from monitoring work in order to improve the accuracy of the models' predictions. Given that zero risk doesn't exist, it will be necessary to plan for remedial intervention in the event that monitoring activities should indicate CO₂ movements outside the reservoir. On this subject, IFP Energies nouvelles is examining innovative solutions, such as the addition of plugging agents to the CO₂ flow injected.



Sleipner

Installed in the North Sea, in Norwegian waters, the Sleipner pilot is "the" gold standard in the field of the geological storage of CO₂. In 1996, Statoil began injecting CO₂ from a natural gas field into an aquifer located 800 m below the ocean bed. So far, 11 Mt have been injected. Since 2008, IFP Energies nouvelles and its European partners have been conducting numerous studies on the site. One of them is designed to verify whether or not the CO₂ remains confined within the storage structure, beneath the principal cap-rock. They have also been able to use data collected from two seismic surveys conducted by Statoil in 1994 and 2006 to establish the first 3D images of the distribution of CO₂ inside the geological structure. This is an essential step prior to the development of a model portraying the evolution of CO₂ in a geologically complex natural environment.

IFP Energies nouvelles, a leader in pooling R&D efforts in the field of CO₂ storage



Well-head used for the CO₂ injection: the Total pilot unit is being used to test an integrated project for the geological capture and storage of CO₂ in the Lacq basin.

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A key French player

IFP Energies nouvelles is a stakeholder in a number of pilot projects being initiated on French soil. The Lacq project led by Total consists of an injection pilot unit in the depleted Rouse gas field in the south of France.

The objective of the France Nord project — partly financed by Ademe (the French Environment and Energy Management Agency) and led by a consortium of six major French industrial groups and five European research organizations (including three in France) — is to select an appropriate geological site for the storage of CO₂ in deep saline aquifers in the Paris basin.

A European player

Since the start of the millennium and as R&D efforts in the field of CCS have been stepped up, IFP Energies nouvelles has established its position as a world-class player by contributing to the majority of

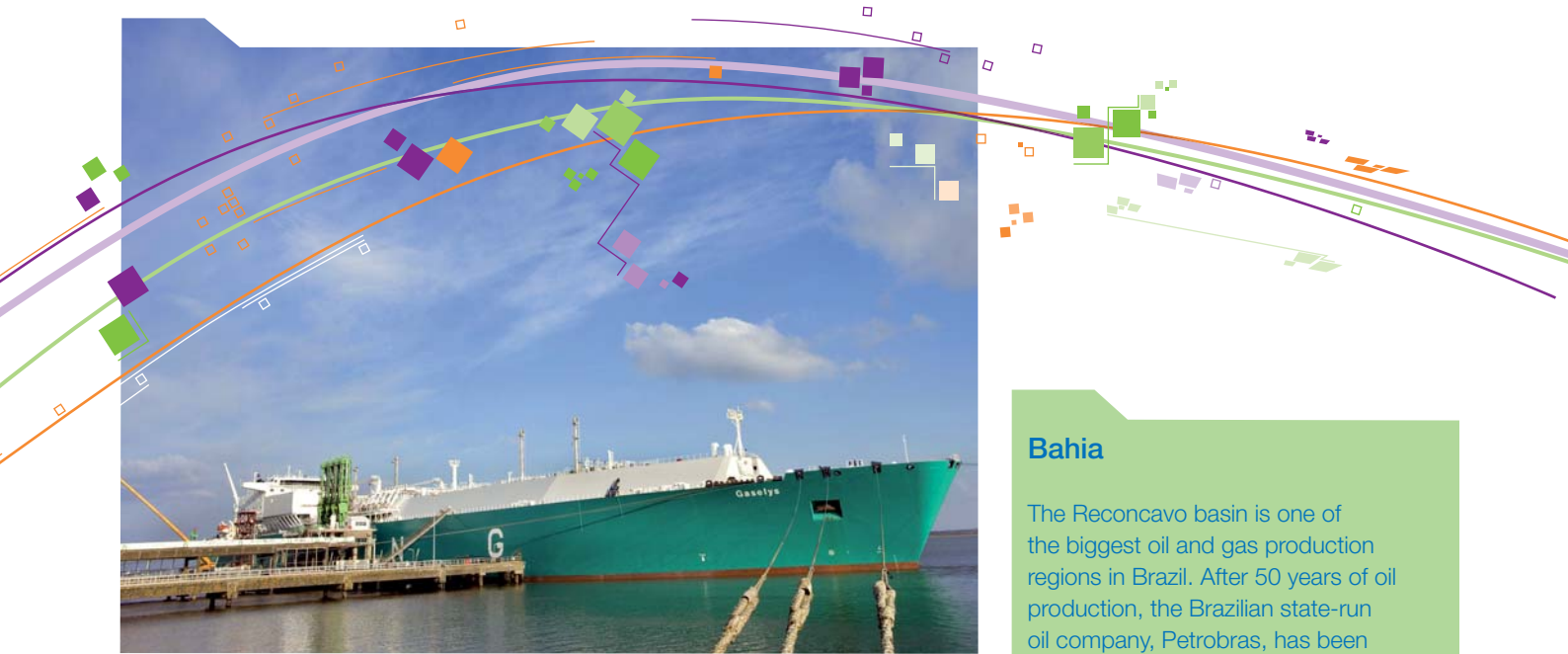
European research initiatives, often taking on the leading role (Castor, Coach, InCA-CO₂ projects, etc.).

The IFP Energies nouvelles-piloted European Castor project, which aimed to propose technologies to

ANR SOCECO₂ project

In the context of the ANR SOCECO₂ project, IFP Energies nouvelles has carried out a study on the potential and roll-out scenarios of CO₂ capture/storage solutions in France over the 2020-2050 period. The technical, economic and environmental evaluation of the CCS industry being conducted as part of the project aims to test whether the capture potential of major French CO₂ emitters match the capacities of the storage sites currently available. Several scenarios are being considered which take into account the limitations related to transport, the nature of the site (onshore/offshore) and the acceptability of the technologies by

those concerned. The study is focusing on the possibility of storing emissions from the Provence-Alpes-Côte d'Azur region in South-Eastern France in underground reservoirs located in the Mediterranean Sea, and storing emissions from the Lorraine, Île-de-France, Nord-Pas-de-Calais and Haute-Normandie regions in Northern France in the aquifer located in the Paris basin — if this is accepted by the local population. Otherwise, storage is planned either in depleted oil fields or in underground aquifers in the North Sea. The SOCECO₂ project brought together the expertise of major French CCS industry players, including Alstom, Apesa, BRGM, Cired, GDF Suez, Ineris and Total.



Transporting CO₂ by boat is more economical than an offshore pipeline for journeys over 500 km and than an onshore pipeline for distances greater than 1,000 km.

capture and store 10% of European CO₂ emissions, came to an end in 2008. It featured amongst the six success stories of the European Commission's Sixth Framework Program.

Furthermore, IFP Energies nouvelles has been closely involved in the Ecco and GeoCapacity European storage

projects. It still is working in the CO₂ReMove project, which aims at developing innovative research and technologies for the monitoring and verification of CO₂ geological storage.

Finally, IFP Energies nouvelles is a key player in three new European projects: CO₂Care, CGS Europe and SiteChar. The latter project, coordinated by IFP Energies nouvelles, will provide key data relating to the characterization of potential sites with a view to the industrial roll-out of CCS.

A major international player

IFP Energies nouvelles is also a major protagonist in CO₂ initiative networks on an international level. For example, it vice-chairs the ZEP platform (European Technology Platform for Zero Emission Fossil Fuel Power Plants).

Due to its wealth of experience and knowledge in the field of CCS, IFP Energies nouvelles' expertise is increasingly sought when new infrastructures and pilot projects are being set up throughout the world.

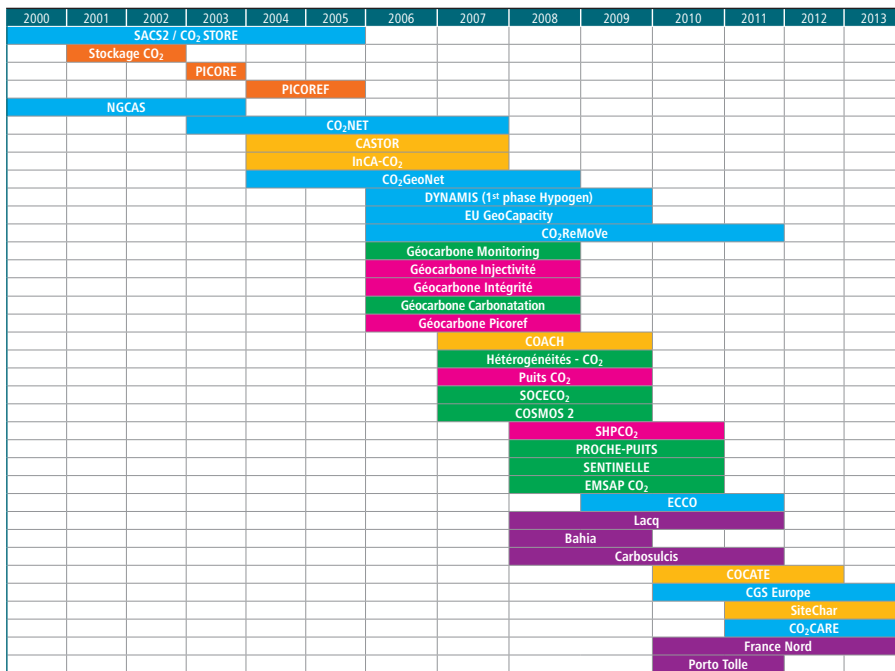


The world's first industrial pilot unit was installed in the Danish Dong Energy power station in Esbjerg as a part of the Castor project in 2006.

Bahia

The Reconcavo basin is one of the biggest oil and gas production regions in Brazil. After 50 years of oil production, the Brazilian state-run oil company, Petrobras, has been turning to enhanced oil recovery techniques using CO₂ injection. This system is interesting in terms of CCS research, since it represents a laboratory for the understanding of the medium-term behavior of CO₂ stored underground. The Bahia project, on which IFP Energies nouvelles and Petrobras worked together between 2007 and 2009, led to a better understanding of the effect of injecting 600,000 t of CO₂ into the site over an 18-year period. As part of this project, IFP Energies nouvelles assessed how the state of underground rocks evolves over time and verified whether the gases contained in these samples come from the surface or whether they have risen from the subsurface. Furthermore, thanks to the information provided by Petrobras, IFP Energies nouvelles was able to identify the data indicating the distribution of CO₂ in the oilfield using geophysical data. Simulations to determine exactly how this gas evolves over time have been carried out using Coores™ software.





IFP Energies nouvelles has established itself as a leader of national and European research projects in the field of CO₂ storage (see the list opposite). It builds on its recognized expertise to quickly forge and develop partnerships with industry players on an international scale.

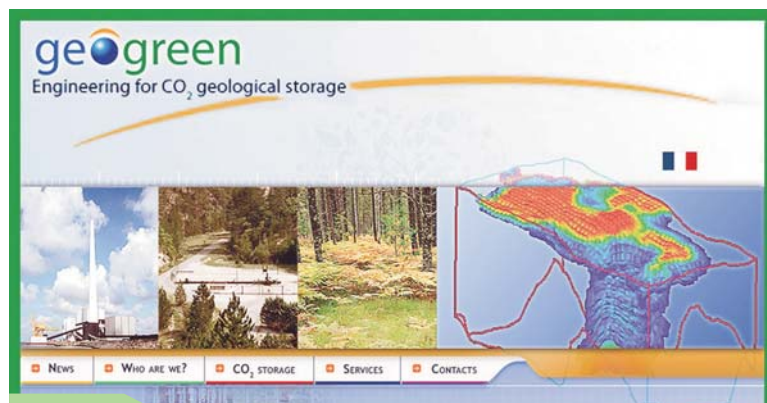
- European research project coordinated by IFP Energies nouvelles
- ANR research project coordinated by IFP Energies nouvelles
- Collaborative research project
- European research project in which IFP Energies nouvelles is participating
- ANR research project in which IFP Energies nouvelles is participating
- RTPG research project coordinated by IFP Energies nouvelles

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From research to industry

IFP Energies nouvelles has spent many years establishing a variety of technology transfer routes in order to find industrial outlets for its R&D work.

IFP Energies nouvelles is actively developing industrial partnerships, particularly through its involvement in pilot projects. This enables IFP Energies nouvelles to test the innovative technologies it conceives, as well as to prepare for the market launch of the software tools and equipments it develops.



Geogreen

The transport and storage of CO₂ is an emerging industrial sector, which is why IFP Energies nouvelles, Géostock and BRGM created the Geogreen company in 2007. Geogreen offers the industry players concerned a very broad range of services covering the entire chain, from transport to geological storage of CO₂, from upstream expertise to engineering and project development. In the longer term, it will offer services for the operation, monitoring and maintenance of injection sites, along with follow-up services related to the closure of storage sites.

Resources Business Unit

IFP Energies nouvelles' ambition is to develop new methods and technologies in order to push back the current boundaries of oil and gas reserves and provide access to new energy resources. Environmental responsibility is central to this research, particularly in terms of mitigating CO₂ emissions and protecting water resources.

The research programs deal with:

- the capture, transport and geological storage of CO₂;
- software and technologies for oil and gas exploration and production;
- eco-efficient water management;
- activities related to marine and offshore wind energies.



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