PANORAMA 2008

a look at ...

Clean coal technologies - The capture and geological storage of CO_2

There is no longer any doubt about the connection between carbon dioxide emissions of human origin and global warming. Nearly 40% of world CO_2 emissions are generated by the electricity production sector, in which the combustion of coal – developing at a roaring pace, especially in China – accounts for a good proportion of the total. At a time when the reduction of greenhouse gases has become an international priority, this growth is a problem. Unless CO_2 capture and storage technologies are implemented, it will be very difficult to contain global warming.

What is clean coal?

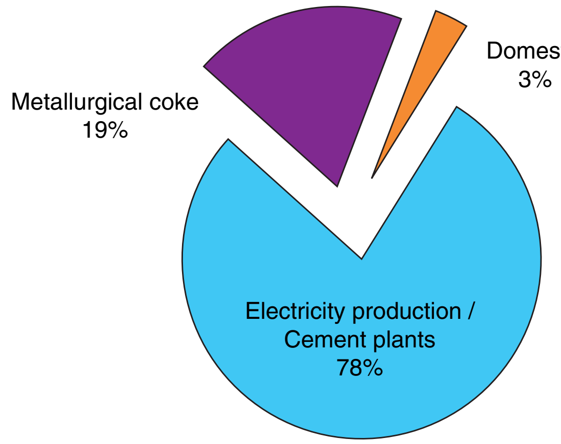
The idea of "clean coal" encompasses all of the technical solutions used to reduce the polluting emissions generated by the industrial use of coal. This mainly involves:

- Reducing the emissions of acid gases (SO_2), nitrogen oxides (NOx) and particles (using well-known methods that are not specific to coal);
- Improving the efficiency at power plants;
- And, much more recently, the capture and geological storage of CO_2 produced.

Coal is a strategic source of energy

A key primary energy source since the Industrial Revolution, coal is mostly used today in two sectors that, taken together, represent more than 78% of total coal consumption: the electricity production (steam coal) and the cement market, followed by the production of metallurgical coke (Figure 1).

Fig. 1 - World coal demand by sector



Source: IEA 2003

In 2005, coal covered about 25.3% of world energy demand (versus 35% for oil), far ahead of nuclear power and renewable energies (Table 1). According to IEA scenarios (reference scenarios as well as alternative scenarios postulating resolute public policy in favor of non-fossil energies), coal will continue to play an important role in the decades to come, in step with the power sector. In OECD countries, some of which rely on nuclear power, 38% of the electricity in 2030 will still be produced from coal. The proportion is higher (51%) for non-OECD countries, which have fewer nuclear reactors.

On the energy scene, coal prevails because it is present in abundance and cheap. Despite the fact that coal has been mined non-stop for two centuries, world reserves still amount to more than 400 billion tons oil equivalent

Table 1
World energy supply

	2005	2030 (reference scenario)
Coal	25.3%	28.2%
Oil	35.0%	31.6%
Naural gas	20.6%	22.3%
Nuclear	6.3%	4.8%
Hydroelectric	2.2%	2.3%
Biomass and waste	10.1%	9.1%
Other renewables	0.5%	1.7%
Total	100%	100%
	11,429 Gtoe	17,721 Gtoe

Source: IEA – World Energy Outlook 2007

(Gtoe), enough to cover more than 150 years of consumption *at the current rate*. This is way ahead of oil, whose conventional reserves total nearly 170 Gtoe (not including tar sands or extra-heavy crude), equivalent to more than 40 years of consumption *at the current rate*, and natural gas, whose reserves stand at nearly 150 Gtoe (60 years of consumption). As for the price, it remains one of the chief assets of coal technology (cf. Panorama datasheet about the liquefaction of coal). For the same quantity of energy produced, coal is about three times cheaper than heavy fuel oils obtained from oil, and four times cheaper than natural gas. In addition, the largest mines are located in countries considered to be politically stable (the United States, China and Australia, among others), so coal is regarded as a strategic fuel.

But it raises serious environmental issues

The use of coal as a primary energy source raises the usual environmental problems: mine gas is released during extraction; acidic gases, nitrogen oxides and particles are emitted; and mercury is discharged into the environment. However, modern installations using well established methods have solved these problems.

The main difficulty today is coal's contribution to the production of greenhouse gases (GHGs) and global warming. Considering all applications taken together, coal is responsible for 40% of the emissions generated by *all fossil energies*. Compared to natural gas and oil, coal presents a GHG balance (Table 2) heavily penalized by its:

- Low calorific value;
- High carbon content;
- Thermal efficiency (generally lower for coal-fired power plants).

Recovering mine gas

There is another significant source of GHGs: the emissions of methane absorbed by coal veins during the mining process. At the current price of hydrocarbons, recovering this mine gas can be economically viable either during mine operation (coal mine methane, or CMM) or after the mine has been abandoned (abandoned mine methane, AMM). Although mine gas recovery is not usually mentioned as such, it may be regarded as a first step in the reduction of GHGs in coal bed methane (CBM) technology. The latter, which includes the recovery of methane from virgin coal beds (VCBM), is developing fast. In 2005, for instance, it represented 50 billion Nm^3 in the United States (cf. Panorama datasheet on CBM).

Table 2
CO_2 emissions at power plants

Fuel & technology	Thermal efficiency	Tons/h CO_2 produced per 1,000 MW
Coal (old design)	30%	1,120
Coal (supercritical cycle)	48%	700
Natural gas (combined cycle)	58%	340

Source: IFP

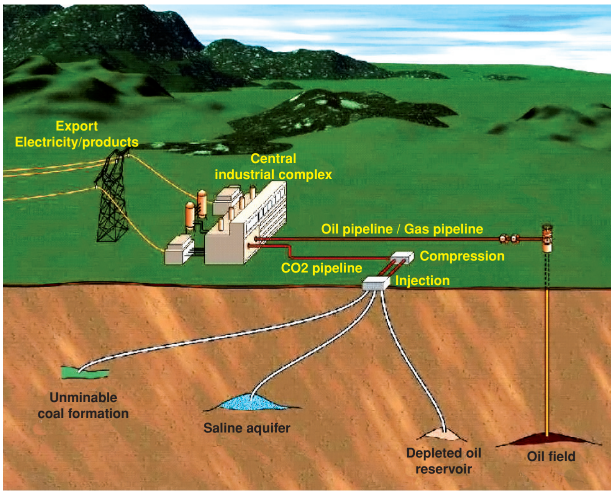
A coal-fired power plant of old design produces three times more GHGs than a combined cycle gas turbine power station, which is our reference. The first step is to build high-efficiency plants and reduce this factor to two. All of the most recent installations, especially in China, are being designed and sized to do this. But this is not good enough, compared to performance levels obtained by other technologies, especially the combined cycle for natural gas. The capture and geological storage of CO_2 (CSC) must be introduced to achieve greater progress.

CO_2 capture and storage

The capture of CO_2 seems to be a particularly good solution for coal-fired power plants, but the process can be applied to any thermal power plant (gas or fuel) or major emitting source, such as cement plants or the large furnaces used in chemical production processes.

Schematically, gaseous effluents containing all of the carbon dioxide produced by combustion go through a process designed to recover, concentrate and, in some cases, purify the CO_2, which is then transported by pipe or ship to a suitable geological reservoir (Figure 2).

Fig. 2 - Overview of CO_2 capture and storage



Source: IEA-2003

The current regulatory situation

In Australia, the regulatory framework for CO_2 capture and storage already exists. By 2008, a directive is expected in Europe, where no new coal-fired power plant may be granted a construction permit unless it is designed with "the best available technology". This is tantamount to imposing plant designs offering the best efficiencies, now in the vicinity of 48% (not including CO_2 capture). At a subsequent date – if Europe is to reach its GHG reduction targets, the time frame 2015-2020 seems realistic – additional installations can be built at these sites to capture the CO_2 at acceptable cost levels. In practice, this simply means leaving enough space near the smokestack for a postcombustion capture system and planning how to integrate the capture module into the industrial process.

Similarly, although CO_2 quality specifications have not been issued yet, it is prohibited to bury substances other than those captured. In the absence of a law regulating geological storage, an amendment was passed to permit CO_2 storage in the North Sea (OSPAR and the London Convention). It seems realistic to think that all thermal power plants built between now and 2020 can be equipped with capture systems. Older plants whose initial efficiency is high enough can be retrofitted at a later date.

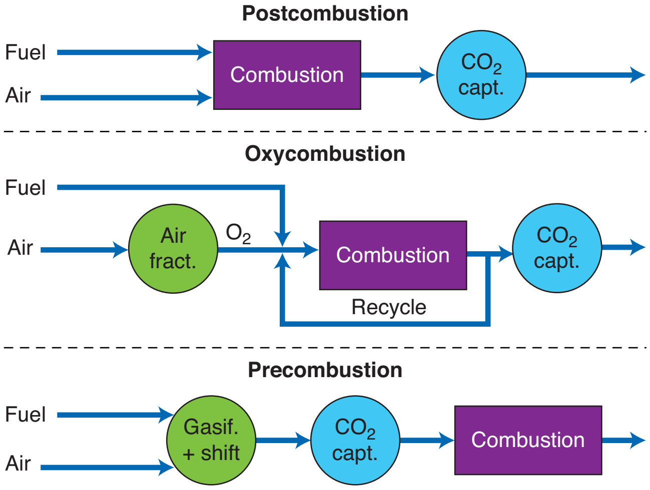
Finally, it has yet to be determined what roles will be played by the market (CO_2 allowances tradable on the market) and the regulatory environment.

CO_2 capture

CO_2 capture technologies mainly differ in the level of technical maturity, the concentration of CO_2 during capture and the "moment" of capture (Figure 3). It is thought that, by 2020-2030, they will have reached a stage of development sufficiently advanced for a new generation of processes to emerge.

- Postcombustion: this capture technology, the first to be developed, is derived from processes to remove hydrogen sulfide, used in some refining methods and at gas fields. The flue gases are sent through a basic solution, either composed of amines (e.g. methyl ethanol amine) or a solution of ammonia (Alstom process) to dissolve the CO_2. The solvent is heated and regenerated, and the CO_2 recovered. Postcombustion is the most mature of all capture technologies and significant research programs are underway to decrease its cost, especially by reducing the amount of energy used to regenerate the solvent and ensure its thermal degradation. The main advantage of postcombustion is that it can be implemented at any thermal power plant, even if its design is relatively out of date, provided that there is enough room near the smokestack and the thermal efficiency is reasonably high (knowing that CO_2 capture amputates part of this efficiency). Most of the demonstration projects in progress or planned are based on postcombustion. However, this method is penalized by a low concentration of CO_2, highly diluted with the nitrogen present in the air: generally, the CO_2 concentration is lower than 15% volume. This implies that a large volume of gas must be handled, which has a significant impact on the cost of capture. One cannot disregard the substantial loss of efficiency of about 8 to 10 points for a capture rate of about 80 to 85% *at a constant rate of electricity production*.

Fig. 3 - Principles governing the capture of CO_2



- Oxyfuel combustion: in this process, combustion takes place under pure oxygen, so flue gases are not diluted with atmospheric nitrogen. This yields a CO_2 concentration of more than 50%. As a result, the diameter of the capture equipment can be reduced, hence its cost. Depending on the situation, the process uses either an "amine" technology, as mentioned previously, or liquefaction based on chilling (cryogenics). Flue gases are recirculated in the combustion chamber to prevent very high temperature areas from forming inside the installation. This process is penalized by the significant cost of the oxygen production unit. The latter also consumes part of the electricity produced, which is also true of the absorbent regeneration process. Oxyfuel combustion has reached the "demonstration plant" stage. New options are being researched to transfer oxygen directly from the combustion air to the fuel (chemical looping).
- Precombustion: only implemented at new power plants, this process relies on a "gasification + shift" sequence (cf. Panorama datasheet on the liquefaction of coal). Once the fuel has been converted to hydrogen, the latter is burned in a combined cycle installation (gas turbine + steam turbine) with a thermal efficiency of about 58%. The CO_2 is recovered by means of dissolution in a solvent (e.g. methanol in the Rectisol process). One advantage is that this sequence obtains the best overall electricity efficiency. Furthermore, the CO_2 is recovered under optimum conditions (high pressure, concentrations exceeding 50%) and the technologies are already available. Disadvantages: precombustion requires the highest investment and gas turbines running on pure hydrogen are not yet available at industrial level. On the other hand, this process carries less of an energy handicap than postcombustion, which means that it can only be competitive if electricity and coal prices are fairly high.

Still at a very early stage of development, chemical looping is one variant of precombustion capture technology. Here, combustion takes place by reacting pulverized coal with a metal oxide, which supplies oxygen without requiring high-cost cryogenic distillation. The metallic phase is reduced during combustion, then transformed back into an oxide in a separate combustion chamber. The process is not penalized by the costs (capital and electrical consumption) of producing pure oxygen. This solution is one of the most credible runners in the race to bring capture costs below the target of EUR 20/t of avoided CO_2.

Hoped-for performance levels: with the development of innovative technologies, it may become possible to halve the loss of efficiency that capture entails, and significantly improve the rate of CO_2 capture *at a constant rate of electricity production*.

The problems of geological storage

After capture and transport to the storage site, the CO_2 is injected into a geological formation at a depth where it is in supercritical form:

- Deep saline aquifers containing brines unsuitable for human consumption;
- Oil or gas fields that are or in the process of being depleted;
- Deep unminable coal formations. Here, the injection of CO_2 leads to the release of a certain volume of coal bed methane (cf. Panorama datasheet on CBM).

Ocean storage of liquid CO_2 has been disqualified as a solution because of its impact on the organisms living at these great depths, the acidification of ocean water and the major risk of dissemination in an environment that is not closed (ocean currents).

In itself, injection does not present any particular technical problem, but to be effective against global warming, a minimum storage period of several centuries is required! Advanced geological studies are vital to ascertain the long-term leaktightness of a given sequestration site and that the CO_2 is chemically inert towards the formation (problems arise when CO_2 reacts with rock). Surveillance and monitoring must be implemented throughout the life of the storage site, due to the risk of leakage (even if low). Two types of storage site are of particular interest:

- Depleted oil fields. A great deal of experience has already been accumulated in this respect. For many years, production at declining fields has been boosted by injecting CO_2, which is a technique of enhanced oil recovery (EOR). In this way, the incremental production of crude covers the cost of storage. One disadvantage, in addition to the problems of corrosion and CO_2 attack on cement encountered at many production wells, is that some of the injected CO_2 can mix with the crude oil. This makes accounting and reporting much more complex, which may be why EOR techniques are not recognized under the Kyoto Protocol as GHG offset mechanisms.
- Storage in deep aquifers. Although these formations present fewer technical problems than oil or gas reservoirs, they remain virtually uncharacterized. Besides, they are generally available near industrial

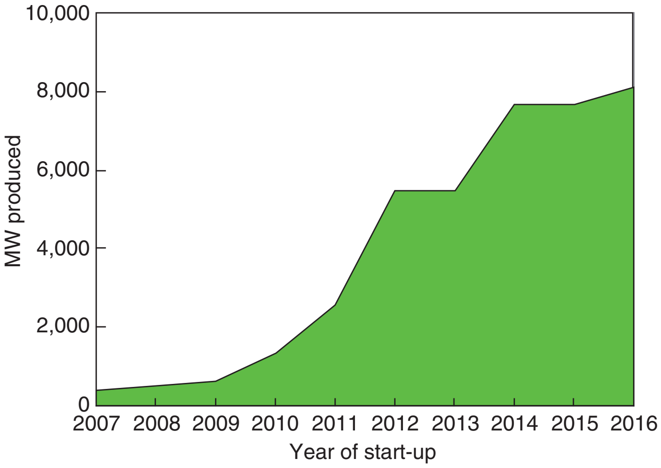
sites producing CO_2. On the other hand, they are not as well known as oil and gas reservoirs, having been studied far less.

Finally, despite the fact that enhanced oil recovery techniques have been used for years, the geological storage of CO_2 raises social acceptability issues.

Planned, in progress and completed projects

There are plans to bring many demonstration plants, then industrial-scale units, onstream in the years to come, as industry manifests considerable interest in this type of technology (Figure 4).

Fig. 4 - Capture projects in Europe



Source: IFP

In Europe, it is estimated that thermal power plants representing 8 GW in capacity will be equipped with capture technology by 2016. In other words, about 16 million tons of CO_2 will be stored in depleted oil and gas reservoirs (EOR) or in saline aquifers. The world estimate comes to 11 GW, a figure that only accounts in part for the tremendous potential represented by enhanced recovery of Canadian heavy oil.

The demonstration units operating today, which total nearly 4 million tons/year of CO_2, include:

- The Sleipner site run by Norsk Hydro: 1 million tons/year of CO_2 for ten years;
- The In Salah site in Algeria: 1.2 million tons/year.

Projects in progress:

- A pilot capture unit at Total's gas-fired power plant in Lacq is scheduled for start-up in late 2008. It will use a revamped 30 MW boiler to implement the Air Liquide oxycombustion process.
- The Castor project is the largest pilot demonstration plant for capture (not storage) so far. It involves 30 companies, including IFP, and 4 demonstration sites including the one in Esbjerg, Denmark.

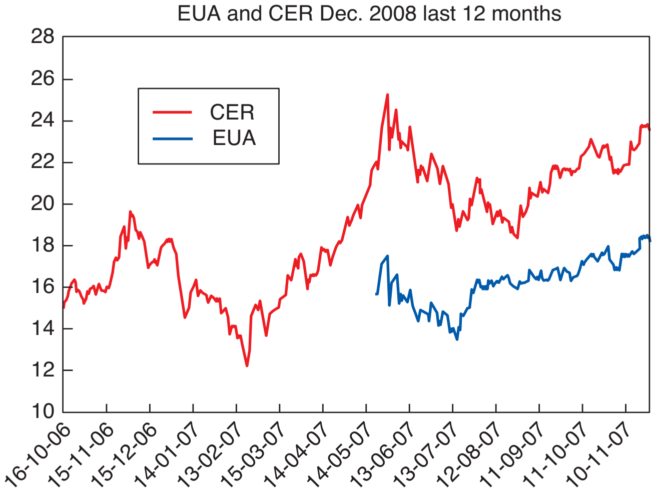
However, the realization of industrial projects will depend heavily on regulatory and economic conditions.

Economic considerations

Looking only at technologies that have already been demonstrated, the cost of the entire capture and storage chain for an installation of 10 million tons/year can range from nearly EUR 40 per ton of CO_2 avoided in best-case scenarios, to more than EUR 80/ton in worst-case scenarios. The capture process represents two-thirds of the cost. That's why most research projects are devoted to capture and reducing its cost by a factor of two by 2020.

For the purpose of comparison, the price per ton of CO_2 on the European short-term market collapsed in 2007 owing to a surplus of allowances allocated for Phase I of the Kyoto Protocol, but the 2008 price stands at EUR 24-25/t. As long as the market price for CO_2 remains lower than the storage cost, this pathway will not be able to grow. Its future is contingent upon a significant decrease in CO_2 emissions allowances.

Fig. 5 - Price of E.U. CO_2 - Forward price Dec. 2008 (red curve)



Conclusions

A preferred primary energy source for electricity production worldwide, coal continues to be penalized by high CO_2 emissions: it accounts for nearly 40% of all fossil energy emissions, at a time when the reduction of greenhouse gases has become an international priority.

Clean coal technologies - The capture and geological storage of CO_2

The first stage in reducing the environmental impact of using coal is underway, with the industrial development of high-efficiency thermal power plants. But this stage does not go far enough in the fight against global warming.

Researchers are working hard to develop economically viable CO_2 capture and geological storage solutions and to halve the cost per ton of CO_2 avoided within ten years. The large number of pilot and industrial projects offers an indication that significant development can be expected in this field by 2020, provided that two major challenges are met:

- The cost of capture must be reduced until the total cost of this pathway is lower than the market price of CO_2 allowances;
- The safety and long-term stability of storage solutions must be ensured, which is a prerequisite for social acceptability.

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